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LIST OF ACRONYMS

AB	Afterburner
AC	Advisory Circular
AECMA	European Association of Aerospace Industries
AGL	Above Ground Level
AH	Abstraction Hierarchy
AIA	Aerospace Industries Association
ATC	Air Traffic Control
BAP	Bank Angle Protection
BCA	Boeing Commercial Airplane
CAS	Crew-Alerting System(s)
CAST	Commercial Aviation Safety Team
CFIT	Controlled Flight Into Terrain
CFMI	CFM International
CR	Crew Response
CRM	Crew Resource Management
CRT	Cathode Ray Tube
DBE	Design by Exception
DECS	Digital Engine Control System
EEC	Electronic Engine Control
EGT	Exhaust Gas Temperature
EICAS	Engine Indication and Crew-Alerting System
E-MACS	Engine Monitoring and Control System
EPR	Engine Pressure Ratio
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FAR	Federal Aviation Regulations
FPMU	Fuel Pump Metering Unit
GE	General Electric
H	Hull Loss Without Fatalities
HBPR	High By-Pass Ratio
HF	Hull Loss With Fatalities
HP	High Pressure
I	Incident or Incidental
ICR	Inappropriate Crew Response
IFSD	In-Flight Shut Down
KB	Knowledge-Based
L/O	Liftoff
LBPR	Low By-Pass Ratio
LOC	Loss of Control
LP	Low Pressure
MCL	Master Caution Light
MCP	Mode Control Panel
MFD	Multifunction Display
MWB	Modern Wide Body

MWL	Master Warning Light
N1	Engine Fan Speed (Low Pressure Compressor and Last Stage Turbine Speed)
N2	Engine Core Speed (High Pressure Compressor and First Stage Turbine Speed)
N3	Engine High Core Speed (RR Only)
ND	Navigation Display
NR	Nonrecoverable
OEM	Original Equipment Manufacturer
Ops	Operations
P	Pressure
PDC	Performance Data Computer
PF	Pilot Flying
PFD	Primary Flight Display
PIC	Pilot-In-Command
PM	Pilot Monitoring
PNF	Pilot Not Flying
PP	Prevention Potential
PPP	Policy, Procedures, and Practices
PRGB	Proprotor Gearbox
PS	Propulsion Systems
PSD	Propulsion Safety Division
PSM	Propulsion System Malfunction
PW	Pratt & Whitney
R	Recoverable
R&D	Research and Development
RB	Rule-Based
rpm	Revolutions per minute
RR	Rolls Royce
RTO	Rejected Take Off
S	Substantial Damage
SB	Skill-Based
SDGE	Shutdown Good Engine
SDTGE	Shutdown/Throttled Good Engine
SIG	Simulator Issues Group
SOP	Standard Operating Procedure
T	Temperature
T/O	Takeoff
TAC	Thrust Asymmetry Compensation
TAT	Total Air Temperature
TBD	To Be Developed/Determined
TBV	To Be Verified or To Be Validated
TCAS	Traffic Collision Avoidance System
TGE	Throttled Good Engine
TLA	Thrust Lever Angle
TRA	Throttle Position

UCR	Undesired Crew Response
UNK	Unknown
USAF	United States Air Force
USMC	United States Marine Corp
V1	Takeoff Decision Speed

EXECUTIVE SUMMARY

Currently, a propulsion system malfunction (PSM) occurs about once every 20,000 flights on Western-built commercial transport turbojet aircraft. Historically, on such aircraft, PSM plus inappropriate crew response (ICR) events number two to three per year in revenue service. From 1958 to 1995, a PSM+ICR event occurred about once every 4 million flights, and a fatal PSM+ICR event occurred about once every 26 million flights. Partly in response to industry recommendations, the Federal Aviation Administration sponsored a follow-on study of PSM+ICR events to investigate and report the potential benefit of malfunction annunciations. This report documents the results of that study.

Aircraft incidents and accidents involving ICR are associated primarily with unannunciated (i.e., no engine indication and crew alert system (EICAS) alert) PSMs. The primary PSMs associated with ICR are Powerloss, Surge, and Stuck Throttle. The ICRs that occur are Rejected Takeoff Above V1 (go/no-go takeoff decision speed), Nonnormal Procedure Errors, Shutdown Good Engine, and Loss of Control. Typically, in PSM+ICR events, the crew does not initially recognize that a malfunction exists or is engine related, or does not correctly identify the malfunction or the affected engine, or does not correctly select or accomplish the appropriate nonnormal procedure. Most inappropriate crew responses to engine malfunctions, and nearly all fatal events, occur below 2000 feet in climb after takeoff or on approach and go-around. In some cases, autopilot and autothrottle engagement compensate for powerloss, mask thrust asymmetry, and delay crew awareness. Autothrottle can cause loss of throttle position awareness, and throttle positions may not accurately indicate engine state or performance during engine malfunction.

In general, a consistent contributing factor in PSM+ICR events is the lack of crew awareness of the existence, location, or type of the PSM, i.e., there is no clear, explicit indication or annunciation of the engine malfunction or the affected engine(s). In many cases, even when the crew is aware a malfunction exists, they are unaware that it is propulsion system related. High workload, limited time for analysis and assessment, autothrottle or autopilot engagement, and poor crew communication or resource management are often among the contributing factors.

Loss of Control events account for the majority of fatal PSM+ICR events and most fatalities. Typically, loss of control involves a significant thrust asymmetry combined with loss of airspeed control and/or attitude control. These events primarily involve failure to control airspeed and attitude. The PSMs associated with fatal loss of control events are Powerloss and Stuck Throttle at low altitude in Climb, Descent, and Approach and Go Around phases of flight. In general, by the time the crew detects thrust asymmetry and attributes it to a PSM, the ICR has either occurred or is unavoidable, i.e., it is often too late to prevent the loss of control. The event data suggest that airspeed and attitude awareness and control have the greatest potential to prevent or mitigate loss of control events. The event data also suggest that explicit annunciation of Thrust Shortfall, Engine Failure, and annunciation of differences between engine Throttle Positions or Engine Speeds have potential to prevent or mitigate loss of control ICR events.

Nonnormal Procedure Errors and Shutdown Good Engine events account for almost all the remaining fatal events and fatalities. Nonnormal Procedure Errors typically result from lack of

awareness of the specific PSM type, and involve failure to select or properly execute the appropriate nonnormal procedure. Shutdown Good Engine events on two engine aircraft typically result from lack of awareness of the affected engine, or a crew tendency to indict the engine at lowest power when presented with two engines at different power settings. The PSMs associated with these events are Powerloss and Surge at low altitude in Climb, Descent, and Approach phases of flight. Shutdown Good (i.e., nonmalfunctioning) Engine is of particular concern on two engine aircraft, but also of concern on three and four engine aircraft—particularly when the good engine shutdown is on the same side as the malfunctioning engine. Explicit alert annunciations of Thrust Shortfall, Engine Failure, and Engine Surge have potential to prevent or mitigate nonnormal procedure and shutdown good engine ICR events.

Malfunction annunciations have little or no potential to prevent Rejected Takeoff above V1 (RTO>V1). Above V1, malfunction annunciations increase the risk of causing RTO>V1 events. Of all ICR types, RTO>V1 events have the least potential safety benefit. Historically, only one RTO>V1 event involved fatalities. That event involved three fatalities and the RTO occurred after liftoff. The RTO>V1 event data indicate that malfunction annunciations above V1 are a contributing factor in 27% of RTO >V1 events. This suggests that malfunction annunciation to prevent RTO>V1 could increase, not reduce, the risk of RTO>V1. Consistent with existing flight deck design and operational philosophy, inhibiting such annunciations from V1 to some point after liftoff has greater potential for RTO>V1 prevention.

Except for RTO>V1, the PSM+ICR event data suggest that explicit annunciations which identify the presence of a PSM, identify the affected engine(s), and identify the specific type of PSM, have potential for ICR prevention and risk mitigation.

A Human Factors review and evaluation of the cognitive mechanisms involved in undesired crew response to propulsion system malfunctions was accomplished. Detection and interpretation tasks require substantial flight crew knowledge, effort, and time to identify and understand the malfunction and formulate an appropriate response. Consequently, detection and interpretation tasks increase the potential for crew error. Even when significant changes in airplane performance or engine parameters are detected, it can be very difficult to interpret or understand those changes and determine how to respond. Ideally the flight deck interface design and associated procedures should be as error proof as possible and aid the flight crew transition from malfunction detection to an appropriate response. The Human Factors review concluded that where a malfunction can be reliably detected, the crew should be alerted to the malfunction via a central alerting function such as EICAS, and also concluded that means should be provided for improving flight crew understanding of the malfunction at airplane system and mission levels.

From 1958 to 2001, there were 12 fatal hull loss and 13 nonfatal hull loss PSM+ICR events in the Western commercial transport turbojet fleet over approximately 396 million flights—typically involving powerloss, surge, or stuck throttle. Through 2001, the modern Boeing fleet (aircraft designed and certified in the 1980s and later, i.e., B-757/767 accumulated approximately 30 million flights, and is currently accumulating approximately 4 million flights per year. There are no PSM+ICR related hull loss without fatalities or hull loss with fatalities events in the modern Boeing fleet. Surge and powerloss are among the top PSMs currently

reported in service. PSM-related Nonnormal Procedure Errors, Shutdown Good Engine, and Loss of Control ICRs continue to occur in service. Analysis indicates that the potential for hull loss and fatal PSM+ICR within the modern fleet has been reduced through design improvements (primarily on newer aircraft), but still exists (primarily on older aircraft).

PSM+ICR prevention potential is the estimated opportunity, through PSM annunciation, to prevent or mitigate inappropriate crew response by providing timely awareness, correct understanding, and linkage to the appropriate nonnormal procedure. Review of historical PSM+ICR hull loss with fatality events indicates that ICR prevention potential through malfunction annunciation appears to exist in 50% or more fatal events. Events with prevention potential account for 88% of all PSM+ICR fatalities. Prevention potential also exists in nonfatal ICR events. Prevention potential is associated primarily with alert annunciation of Powerloss, Surge, and Failed Fixed Thrust malfunctions. Note that these estimates of prevention potential are based on review of available, but often limited, data, and are judgments. Judgment of prevention potential indicates only that the opportunity for prevention appears to exist, and that prevention is a possibility, not a certainty.

Detection capability and annunciation precedents exist for Powerloss (Thrust Shortfall and Engine Failure/Subidle), and between engine differences in Throttle Position and Engine Speeds (i.e., Throttle and N1 splits) on heritage Boeing aircraft. Validation that existing powerloss detection requirements address PSM+ICR is required for cross model implementation. Detection capability and annunciation precedents exist for Surge, but not on heritage Boeing aircraft. In general, propulsion experts agree that detection of surge is feasible. However, there are significant unresolved issues regarding development and validation of surge detection sensors and software. Development of surge detection requirements and demonstration and validation of reliable surge detection capability is required.

This study had narrow and limited focus, investigation into the detection potential of PSM+ICR related PSMs, and the prevention potential of annunciating those PSMs. The study concluded that PSM annunciation has potential benefit. However, the benefit cannot be quantified with absolute certainty, and the feasibility of implementing the various malfunction annunciations has not been assessed. The comparative feasibility and effectiveness of PSM annunciations versus other alternative solutions should be assessed, and the advantages and disadvantages of available solutions should be understood, before any regulatory, implementation, or other action is taken.

PSM+ICR events are understood with reasonable confidence. The challenge is to prevent very, very rare events—one fatal event every 26 to 33 million flights. For perspective, the entire modern Boeing fleet (717, MD-11, MD-90, 737NG, 757, 767, 747-400, and 777) had accumulated approximately 30 million flights through 2001. Indication, annunciation, and other improvements that address PSM+ICR have been implemented in the modern Boeing fleet, but gaps exist and PSM+ICR events still occur. Malfunction annunciations appear to offer PSM+ICR event prevention potential. Pilot qualification, training, policies, practices, and procedures also have prevention potential. However, PSM+ICR prevention is not certain or guaranteed.

Work on PSM detection requirements, validation and demonstration that desired detection is possible, and assessment of implementation feasibility, remain to be done. The study recommends follow-on work to define PSM+ICR-related surge and powerloss detection requirements, validate and demonstrate desired surge and powerloss detection capability, and determine surge and powerloss detection and annunciation implementation feasibility.

1. INTRODUCTION AND APPROACH.

1.1 INTRODUCTION.

This report summarizes the concepts, risks, issues, and conclusions of efforts to assess technical feasibility and operational appropriateness of providing indications of propulsion system malfunctions. The effort followed the technical approach, tasking, and schedule specified in the Propulsion System Malfunctions Program Plan (CDRL 3a) that was established to support the Federal Aviation Administration (FAA) in efforts to assess feasibility and appropriateness of providing indications and annunciations of propulsion system malfunctions.

1.2 APPROACH.

An integrated product team approach was used to bring together the multiple technical disciplines needed to assess the feasibility and appropriateness of providing indications of propulsion system malfunctions to flight crews. The overall goal was to answer questions concerning feasibility and appropriateness of propulsion malfunction indications, support Harmonization Terms of Reference 25.1305 committee efforts with useful data and information, and identify issues that should be emphasized in future research efforts. A task team was established consisting of Boeing engineers and subcontractors with extensive commercial airplane operations and technology research experience. The team included members from Boeing Commercial Airplanes (BCA) Propulsion Technology, BCA Flight Deck Research, BCA Simulation Lab/Test, and Boeing Phantom Works Engineering and Information Technology organizations. This team met regularly with FAA team members and Aviation Rulemaking Advisory Committee Powerplant Installation Harmonization Working Group representatives to facilitate flow of requirements and interim results.

A technical approach was established to facilitate systematic technical progress and maximum contribution by team member experts. The task breakdown and flow of technical activities for the program is shown in figure 1-1. The effort consisted of multiple technical paths that provided the essential information that was used to support the primary task of an overall assessment of the need, feasibility, risks, and known issues related to the implementation of propulsion malfunction indications and annunciations. An Operational Assessment path (highlighted in green) involved in-service data analysis and operational assessment of event information and summary reports to determine whether lack of annunciated information or presentation of annunciated information led to safety critical events. Critical types of propulsion malfunctions were identified and correlations made among factors present during the in-service incidents with a focus on defining and assessing annunciations to address the in-service incident scenarios. Issues related to current flight deck designs, crew response limitations, human factors, and lessons learned from previous programs were identified and considered throughout these efforts. A Technical Feasibility path (highlighted in red) provided for assessment of technical risk associated with surge, fail, and asymmetry detection. Technical experts and technical literature were used to make a high-level assessment concerning whether reliable detection (with respect to its intended use for indications) is feasible. Engine companies were approached to provide comments to this assessment. A final

Summary and Conclusions path (highlighted in black) provided for aggregation of information from the feasibility and appropriateness task paths to achieve a balanced assessment of opportunities and risk of approaches to address propulsion system malfunction (PSM) and inappropriate crew response (ICR) (PSM+ICR).

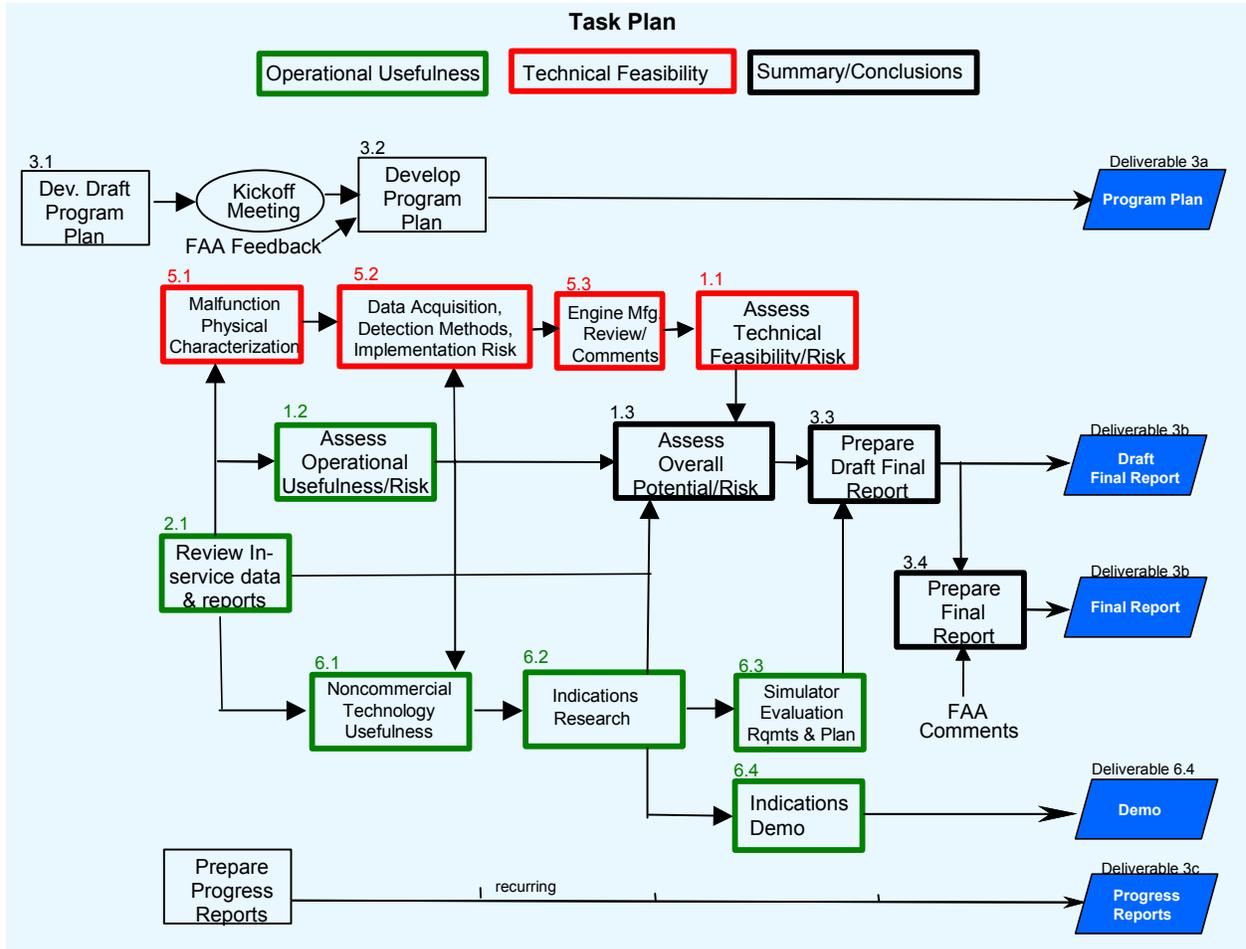


FIGURE 1-1. PROGRAM TASK PLAN

2. DISCUSSION, SUMMARY AND CONCLUSIONS, AND RECOMMENDATIONS.

2.1 DISCUSSION.

The Boeing has given considerable thought and discussion to the issue of PSM+ICR. It is important to note that this FAA contract had an intentionally narrow and limited focus investigation into the detection potential of PSM+ICR-related PSMs, and the prevention potential of annunciating those PSMs. This study concluded that PSM annunciation offers potential benefit, but that the benefit cannot be quantified with absolute certainty. Every effort was made to limit the potential for misinterpretation and over interpretation of the data, conclusions, and recommendations in this and accompanying reports. Nevertheless, given the quantity of data and complexity of the technical and operational issues, there is likely to be some degree of misinterpretation and over interpretation of the study data and results. Follow-on efforts will be needed to correct any misinterpretation and over interpretation and to ensure the data, conclusions, and recommendations are correctly understood and appropriately used.

PSM annunciations are one way, but not the only way, and may not necessarily be the best way, to address PSM+ICR. Although this study indicates that malfunction annunciations have the potential to reduce PSM+ICR, the feasibility of achieving those benefits through malfunction annunciation or other means has not been assessed or established. Such feasibility should be assessed and established before any regulatory, implementation, or other action is taken.

PSM annunciation is the only solution investigated in this study. Investigation and analysis has provided sufficient understanding to state that the data and analysis suggest that PSM annunciation has the potential to reduce the rate of PSM+ICR. But one can only say that PSM annunciation could (i.e., might), not would, reduce the rate of PSM+ICR. The data does not support stating that PSM annunciation is the preferred solution. PSM annunciation may, or may not, be the most feasible, and therefore, the preferred solution. It is important to consider alternative solutions, to understand the advantages and disadvantages of each solution, and to quantify the comparative feasibility and effectiveness of PSM annunciations versus other alternatives.

The approach to reducing PSM and PSM+ICR problems should not deflect industry attention and resources from other, more important, safety enhancements. The challenge is to identify and develop the most affordable and effective approaches to the problem. The Commercial Aviation Safety Team (CAST) implementation plan indicated that the best total approach may focus on crew training, development of standard operating procedures (SOPs), policy development, or safety culture rather than onboard hardware or software changes for the current fleet. New airplane designs may benefit from some new onboard hardware and software approaches. However, it could take decades after the introduction of those changes to new airplane designs to see a significant change to the overall accident rate.

2.2 SUMMARY AND CONCLUSIONS.

In general, a consistent contributing factor in PSM+ICR events is lack of crew awareness of the existence or location of a PSM, i.e., the lack of a clear and explicit indication or annunciation that a PSM exists, or lack of a clear and explicit indication or annunciation of the affected engine(s). In general, the crew should be made aware:

- that a propulsion system malfunction and/or symptom exists.
- of the specific engine affected.
- of the specific type or nature of the propulsion system malfunction or symptom, and the manner and extent of its affect on the engine and on subsequent operations.

ICR prevention potential through malfunction annunciation exists in 50% or more of fatal events. Fatal events with prevention potential account for 88% of all PSM+ICR fatalities. Prevention potential also exists in Hull Loss, Substantial Damage, and Incidental ICR events. Most prevention potential exists in the area of Loss of Control (LOC), followed by Other and Shutdown or Throttled Good Engine. The least prevention potential exists in the area of rejected takeoff above takeoff decision speed (RTO>V1). PSM annunciations offer little or no prevention potential for fatal RTO>V1 events. PSM annunciation above V1 during takeoff risks causing RTO>V1 events. Note that where prevention potential has been judged to exist, it means only that the event might have been prevented, not that it would with certainty have been prevented.

Most prevention potential is associated with Powerloss and Surge, followed by Failed Fixed Thrust malfunctions. The majority of these malfunctions appear to be detectable. The principal detection issue is reliable and meaningful detection—particularly in the case of Surge. There is less potential for ICR prevention or mitigation in the area of High Vibration, which is categorized as a secondary PSM, and the potential for ICR prevention or mitigation has yet to be determined or demonstrated for Thrust Asymmetry, which is considered an airplane-level effect, not a PSM.

Surge and Powerloss, the major types of PSM associated with ICR, are among the top three in-service PSMs currently reported.

The same type PSM+ICR events continue to occur in service: LOC, Other, Shutdown Good Engine, and RTO>V1. Ten post-Aerospace Industries Association (AIA) Report PSM+ICR events were documented: four Other, two LOC, three Shutdown Good Engine, and one RTO>V1. The list contains Fuel System PSM-related ICRs not reported or included in the AIA report data.

A Boeing study and analysis of PSM+ICR events suggested that explicit annunciation of the following PSMs could provide a potential safety benefit to the current worldwide fleet:

- Engine Failure (subidle)
- Engine Thrust Shortfall

- Significant Engine Surge
- Engine Overthrust

Malfunction annunciation, or other equivalent means, should be used to enhance timely crew awareness, understanding, and response to these PSMs. PSM+ICR event data indicated that, in most cases, annunciation delays on the order of 5 to 10 seconds would not significantly reduce the potential safety benefit. However, the earlier the detection and annunciation, the greater the overall potential benefit. Note the following considerations.

- Careful implementation of these PSM annunciations (i.e., how/where/when implemented/provided) is crucial to effectiveness. Implementations must accommodate diverse engine and airframe designs and operational philosophies. And the factors that have limited previous implementation must be considered and addressed.
- PSM annunciation has little or no RTO>V1 prevention potential or historical safety benefit but, instead, risks causing RTO>V1 events.
- A feasibility assessment for High Vibration and Stuck Throttle is required before implementation recommendations can be made.
- Each PSM annunciation must be evaluated for the relative feasibility of developing and implementing on a model-by-model basis and fleet-by-fleet basis for postproduction, in-production, and future production aircraft.

2.3 RECOMMENDATIONS.

The following PSMs should be assessed for feasibility of Flight Deck annunciation:

- Engine Failure (subidle)
- Engine Thrust Shortfall
- Engine Surge
- Engine Overthrust

Feasibility should be assessed for production, retrofit, and new and future airplanes. Feasibility assessment should include, but not be limited to, CAST analysis. Feasibility should include a relative assessment of malfunction annunciation versus other interventions such as crew resource management (CRM) and malfunction training, airspeed and attitude awareness enhancements, flight control protection, and compensation functions. Crew training, development of SOPs, policy development, or safety culture may be more feasible interventions than onboard hardware or software changes for the current fleet. Each PSM annunciation should be evaluated for the relative feasibility of development and implementation on a model-by-model basis and fleet-by-fleet basis for postproduction, in-production, and future production aircraft.

The following follow-on research efforts should be sponsored and supported:

- Follow-on research to define detection requirements, demonstrate/validate reliable Surge detection, and refine and validate Surge and Powerloss PSM annunciations.
- Engine manufacturer, airframe manufacturer, and airline collaboration on PSM annunciation and detection feasibility assessments, detection implementation requirements, and detection and annunciation validation activities.

Thrust Asymmetry, Stuck Throttle, and High Vibration annunciation require additional study and validation of potential benefit and risk before recommendations can be made in those areas.

The following follow-on research efforts could be sponsored and supported:

- A more comprehensive analysis of the Crew Error Classification versus Hull Loss with fatalities (HF) events is recommended to provide the insight required to develop the most effective error prevention strategies and designs and assess their effectiveness.
- Development and implementation of a formal process for reporting and documenting in-service ICR is recommended. Existing databases should be evaluated for their ability to capture and identify ICR-related events.

3. OVERALL PSM DETECTION AND ANNUNCIATION RISK/BENEFIT ASSESSMENT (TASK 1.3).

3.1 TERMS AND DEFINITIONS.

The following key terms and definitions related to PSM annunciations are used throughout this report. These are provided to ensure a common definition.

- Alert—A subset of annunciation. A nonnormal malfunction-specific or nonnormal condition-specific annunciation requiring crew awareness or action. Alerts are generally differentiated from normal annunciations by the use of aural and visual attention-getting components and messages designed to provide appropriate crew awareness and understanding, and elicit appropriate crew response by linking to a specific nonnormal procedure. Traffic Collision Avoidance System alerts, Ground Proximity Warning System alerts, Engine Indication and Crew-Alerting System (EICAS) alerts, dedicated alert lamps/indications and alert lamps/indications with aural are typical examples.
- Annunciation—A broad category of normal (i.e., nonalert) and nonnormal (i.e., alert) indications and/or aural designed to draw or focus crew attention and to support crew awareness or action. In general, a discrete indication and/or aural that provides event or condition information by occurring and clearing. An annunciation is displayed or occurs when its corresponding event or condition occurs. Annunciations are generally transient in nature and may be displayed on the Primary Flight Display (PFD), Navigation Display (ND), Engine, and other display formats.
- Engine Exceedance—Engine speed/thrust or other operating limit exceedance.
- Engine Failed Fixed Thrust—Engine failure to some intermediate engine speed/thrust level between idle and max power that creates the potential for commanded engine thrust to be either greater or less than actual engine thrust, i.e., creates the potential for thrust shortfall or overthrust.
- Engine Failure—Engine failure to subidle engine speed/thrust level. Engine combustion may or may not have ceased.
- Engine Flameout—Engine combustion has ceased. A subset of in-flight shutdown (IFSD).
- Engine Pressure Ratio (EPR)—The ratio of turbine discharge pressure to compressor inlet pressure. EPR is a measure of thrust provided by the engine. EPR indicators provide the ratio of the pressure of the air as it comes out of the turbine to the pressure of the air as it enters the compressor. EPR is a certified thrust-setting parameter.
- Inappropriate Crew Response—An event where the crew fails to follow the published procedures, operating policies, or training practices (PPP) in a timely manner. The following situations would be considered undesired crew response (UCR): (1) The crew wittingly or unwittingly executed the wrong PPP; (2) The crew wittingly or unwittingly

executed the PPP incorrectly; (3) The crew executed the correct PPP for the wrong reason(s); (4) The crew intentionally deviated from PPP; and (5) The crew encountered a situation where the PPPs, or the circumstances/information for their application, were vague, incorrect, conflicting, or nonexistent. This includes events where the crew was provided insufficient information and inadequate procedures, as well as events where the crew exhibited unacceptable performance.

- Indication—Typically provided by mechanical gage/dial or display. The Primary and Secondary engine parameters EPR, N1, exhaust gas temperature (EGT), N2, N3, oil pressure, oil temperature, vibration, fuel flow, etc.) are engine indications.
- Indication Annunciation—A subset of annunciation. A nonnormal malfunction-specific or nonnormal condition-specific annunciation requiring crew awareness or action displayed on or with the primary or secondary engine indications.
- Indication Feature—Normal indication feature implementation or enhancement. Indications and enhancements are provided to reduce crew integration activity and thereby reduce crew workload. Indication features generally involve collocation of related information (e.g., commanded and actual state information), presentation of control target and system limit indications, and other features, elements, and implementations that differentiate information and make it easier and quicker for the user to obtain desired information.
- In-Flight Shutdown—Commanded or uncommanded cessation of engine combustion in flight. This includes engine failure conditions such as Engine Fail Low conditions (e.g., flameout) and engine shutdown by either the flight crew or the engine control system.
- Modern Fleet—Aircraft designed and certified in the 1980s and later. B717, B737NG, B747-400, B757/767, B777, MD11, MD90, A319, A320, A321, A330, and A340.
- Nonrecoverable—Propulsion System Malfunction. A PSM from which the engine or engine controller will not automatically, or with crew action, recover to a normal level of functionality/performance. Typical Nonrecoverable events involve sense line or controller failures, foreign object damage, a failure of blades, seals, bearings, controllers, etc., and/or significant engine damage.
- Powerloss—Actual engine thrust is less than commanded engine thrust. Engine Thrust Shortfall, Partial Powerloss/Rollback, Engine Subidle, or Engine Flameout are powerloss examples.
- Recoverable—Propulsion System Malfunction. A PSM from which the engine automatically, or with crew action, recovers to commanded thrust and full range of normal functionality and performance. Most Recoverable events involve no engine component failures and no significant engine damage.

- Surge—Turbine engine surge is a sudden aerodynamic reversal of airflow in the engine compressor. The airflow reversal, which may be accompanied by audible sounds and vibration, occurs with the downstream high-pressure air in the compressor escaping forward out of the engine inlet. On modern high by-pass turbojet engines, the flow reversal is very rapid and usually produces a loud bang similar to an explosion. The intensity of the sound depends on the engine power setting or pressure ratio as well as the amount of expansion permitted by the inlet. Depending on the type of compression instability, there may be single, multiple, or continuous surges and associated engine parameter fluctuations, e.g., rapid decrease in rotor speeds, pressures, and fuel flow, and typically an EGT increase. There are three surge types: (1) Self-Recoverable, (2) Recoverable with Crew Action, and (3) Nonrecoverable. Meaningful Surge is defined as surge that requires crew action.
- V1 – Takeoff Decision Speed
- Vr – Takeoff Rotation Speed
- Undesired Crew Response—An event where the crew fails to follow the published PPPs in a timely manner. The following situations would be considered a UCR:
 - The crew wittingly or unwittingly executed the wrong PPP.
 - The crew wittingly or unwittingly executed the PPP incorrectly.
 - The crew executed the correct PPP for the wrong reason(s).
 - The crew intentionally deviated from PPP.
 - The crew encountered a situation where the PPPs, or the circumstances/information for their application, were vague, incorrect, conflicting, or nonexistent.

This includes events where the crew was provided insufficient information and inadequate procedures, as well as events where the crew exhibited unacceptable performance.

The overall assessment (task 1.3) was a joint flight deck and propulsion engineering task to summarize the detection feasibility and risks, and the operational benefits and risks, associated with detecting and annunciating certain PSMs associated with ICR.

To ensure understanding of the discussion, conclusions, and recommendations, it is particularly important that the reader distinguish between normal engine parameter indications with enhanced features, nonnormal engine parameter indication annunciations, and nonnormal alert annunciations.

3.2 BENEFIT/RISK ASSESSMENT OF PSM ANNUNCIATIONS.

The specific PSMs assessed and addressed in this report are:

- Powerloss—Engine Failure (Subidle/Flameout/etc.), and Thrust Shortfall (actual thrust less than commanded thrust)
- Surge—Recoverable with Crew Action and Nonrecoverable
- Failed Fixed Thrust—Stuck Throttle, Thrust Shortfall (actual thrust less than commanded thrust), and Overthrust (actual thrust greater than commanded thrust)
- High Vibration
- Thrust Asymmetry

The following sections discuss the general and specific operational benefits and risks of annunciation, and detection feasibility considerations, associated with the engine malfunctions listed above.

3.3 GENERAL OPERATIONAL BENEFIT AND RISKS OF PSM ANNUNCIATION.

The vast majority of PSM events do not result in ICR. And the majority of PSM+ICR events do not involve fatalities or catastrophic consequences. In general, adding annunciation adds complexity. A proper balance is needed; adding complexity (and the potential cost and risk of not operating properly) must be feasible and may only be worthwhile for the most severe consequence conditions.

3.4 POTENTIAL OPERATIONAL BENEFIT OF PSM ANNUNCIATION.

Potential operational benefits are based on the assumption of reliable detection and annunciation. Reliable implies consistent and meaningful detection and annunciation. The general benefit of annunciation is that it increases the likelihood of timely and appropriate crew awareness, understanding, and response. Consequently, crews are less likely to be misdirected into falsely believing some other condition or malfunction occurred and taking inappropriate or unnecessary action.

In general, the potential operational benefit of PSM annunciation is in mitigation of ICR events through correct crew response based on (1) timely crew awareness that a PSM exists; (2) understanding of the specific PSM that exists, and therefore, the appropriate procedure that should be used; and (3) identification of the specific engine(s) affected by the PSM. With respect to reducing ICR events, any annunciation must accomplish these objectives.

3.5 OPERATIONAL RISKS OF PSM ANNUNCIATION.

Distraction during High Crew Workload Flight Phase is the first operational risk identified with PSM annunciation. The risk associated with annunciation (indication or alert), in general, regardless of whether the annunciation is true or false, relates to UCR to the annunciation itself, not the malfunction being annunciated. This is primarily a concern in flight phases where the crew does not have time to assess the indication or alert, e.g., during takeoff above V1, or on short final approach and flare. Anything designed to attract crew attention, risks crew distraction and UCR. Typically, in takeoff and approach phases, annunciations are temporarily inhibited, where the risk of delaying annunciation is far outweighed by the risk of ICR such as RTO>V1 or low-altitude go-around.

False Annunciation is the second operational risk identified with PSM annunciation. The immediate risk of false annunciation is (1) unnecessary distraction and (2) erroneous crew awareness, understanding, and response. The crew may be distracted from accomplishing important tasks, may become confused by noncorroborating or conflicting indications, or may take action that unnecessarily affects airplane operation or capability. The longer-term risk of repeated false annunciation is potential loss of alert and alerting system credibility and possible crew failure to respond when required. If a false alert occurs repeatedly, the crew can quickly become desensitized to the alert and ignore or otherwise fail to respond to the alert when valid. The crew may also begin to question other valid alerts. In all cases, crew workload and error potential are unnecessarily and undesirably increased. The acceptability of false annunciation is proportional to the criticality of the condition and crew response.

Failure to Annunciate/Detect is the third operational risk identified with PSM annunciation. The risk associated with failure to annunciate when the crew knows an annunciation exists, (i.e., is part of the airplane design) and may be relying on its presence or absence, is primarily that crew response may not occur, or may occur too late. In the absence of an alert, detection/awareness and interpretation/understanding is more difficult and error prone. This is likely more so than if there was no annunciation as part of the airplane design, and the crew was responsible to monitor for condition. In the absence of an alert, and particularly when little time is available for evaluation, there is the general increased risk that crew response may be erroneous or inappropriate.

3.6 GENERAL DETECTION FEASIBILITY CONSIDERATIONS.

This section describes the general detection feasibility considerations. Issues centered around malfunction detection, identification, timing, and recoverability are discussed.

3.6.1 Identification of Malfunctioning Engine.

One aspect of a PSM that results in an ICR is the ability of the crew to determine which engine may be malfunctioning. From a crew detection perspective, this problem manifests itself in two ways. First, the crew is unaware that any malfunction or the type of (engine) malfunction that has occurred. Second, once the crew is aware that a PSM has occurred (usually through cues

such as noise, vibration, or change in attitude), the crew is unable to determine from existing indications or annunciations which engine is affected.

The feasibility of detection or identification of which engine is affected is intuitive, given that a malfunction has been identified. The risk lies in the inability to detect all engine malfunctions (miss detects). This risk increases if attempting to detect recoverability versus nonrecoverability as defined herein. Except for the subtle condition, the risk of missed detection increases further when the power setting of the malfunctioning engine is low.

3.6.2 Detection Time Lag Rule.

Tasks 2.1 and 1.2 analyses suggest that providing an annunciation for events during the takeoff phase of flight is not beneficial or effective from V1 to 400 feet above ground level (AGL). Such annunciations unacceptably increase the risk of causing more RTO>V1 events than they prevent. It was assessed that training for surge recognition is a more effective means to mitigate the risk of RTO>V1. Accepting this conclusion, the rule for detection concepts is that immediate determination of a detected PSM is not required to achieve a safety benefit in LOC, Shutdown Good Engine, and Other ICR events. Restated, some given amount of time can be allowed after the actual occurrence of the PSM before detection and annunciation is required. This is referred to as the Time Lag Rule. Continuing with the theme of the PSM+ICR that have the highest safety concern, the Time Lag Rule applies to all PSM categories being studied herein. PSM+ICR event data indicate that, in most cases, annunciation delays on the order of 5 to 10 seconds would not significantly reduce the potential safety benefit. However, the earlier the detection and annunciation, the greater the overall potential benefit.

3.6.3 Recoverability/Nonrecoverability.

The task 5.2 report (see appendix E) documents work performed by a subcontractor relating specifically to Surge events and whether they are recoverable or nonrecoverable. The recoverability/nonrecoverability detection scheme developed in this work fuses the results of the surge detection algorithm (described below) with an additional algorithm to determine whether the engine would recover from the surge or not. It is important to provide a definition of recoverability in context of this work. A surge that will recover (Recoverable Surge) is defined as a PSM after which the engine will respond to engine control (automatic or crew input) to provide any normal requested power setting and thrust. Conversely, a Nonrecoverable Surge is defined as a PSM after which the engine, although it may run surge-free at some power setting(s), is not able to produce requested thrust at all possible normal power settings.

3.6.4 Detection Feasibility.

The task 5.2 report stated that the recoverability detection scheme "... operates in much the same fashion as the surge detection except that it waits for ... [engine parameters] ... to respond normally to TRA and Bleed, meaning that the engine is back in control." This scheme was successful in determining whether an engine would recover from a surge event or not. The time required was on the order of 3 to 5 seconds. Recall that the Time Lag Rule applies. The subcontractor reports that the addition of a vibration monitor to the aforementioned could

improve the robustness (no missed detects, no false positives) of the surge detection/recoverability scheme.

The subcontractor stresses the fact that claims of success are based on a single data point in the case of nonrecoverable surge. In addition, the engines with events categorized as Recoverable were not directly challenged to high power during the same flight, but rather, ground tests were performed to establish surge margin. With these qualifiers, the research performed by the subcontractor nevertheless appears promising. Follow-on demonstration and validation of detection reliability using a larger data set is required before any final determination of surge detection reliability and feasibility can be made.

A determination on the recoverability/nonrecoverability of other categories of PSM could be made in the same manner. The risk remains in (1) the ability to accurately model the engine that, in part, leads to (2) the ability to detect all categories of PSM. Again, this risk increases at low power settings. One possible method to reduce the risk at low power settings is to adopt a crew procedure that challenges the engine to higher power settings. This is, in essence, the second part of the current Surge procedure where the crew is instructed to advance the engine power setting to see if the engine will run surge-free. With existing instrumentation, this same procedure could provide data to reliably assess whether the PSM is recoverable or nonrecoverable.

3.6.5 False Detection Risk Discussion.

Depending on the operational effects in terms of hazard classification (i.e., major, hazardous, or catastrophic), the system design reliability should be commensurate with the hazard classification. If a false annunciation creates a hazardous situation, then a false warning reliability would need to be on the order of $1e-7$ or better per flight hour.

3.6.6 Failure to Detect Risk Discussion.

Depending on the operational effects in terms of hazard classification (i.e., major, hazardous, or catastrophic), the system design reliability should be commensurate. If failure to detect creates a hazardous situation, then a failure to warn reliability would need to be at least an order of magnitude less than the condition being detected to provide annunciation design margin.

3.6.7 Recoverability Research Recommendations.

A tristate detection concept should be explored in relation to the recoverability/nonrecoverability of a PSM. The three states to consider are (1) normal operation (recoverable), (2) Malfunctioning (nonrecoverable), and (3) Indeterminate. Research to identify the combination of parameters and their appropriate values to make a high confidence determination of state 1 and state 2 is needed. The validity of using the suggested engine challenge procedure needs to be studied for instances when the parametric data is in the Indeterminate state. This engine challenge procedure should result in a high confidence determination of the engine being in state 1 or state 2.

3.7 POWERLOSS ANNUNCIATION POTENTIAL OPERATIONAL BENEFITS/RISKS.

This section discusses potential detection and annunciation benefits and risks associated with powerloss. Powerloss is defined as engine failure (subidle/flameout/etc.), thrust shortfall, or partial powerloss or rollback.

3.7.1 Powerloss Annunciation Potential Benefits.

As previously stated, crew awareness of PSM and identification of affected engine(s) must be provided to mitigate ICR risk. The task 1.2 report identified an operational safety benefit from a powerloss annunciation that provides timely crew awareness and identifies the affected engine(s). Per the task 1.2 report analysis, the failure to timely detect and consequent lack of timely awareness of powerloss is associated with all type ICR events in general, and fatal and hull loss LOC events in particular.

Annunciation of a Powerloss PSM would provide crew awareness that actual thrust is lower than commanded thrust on one or more engines. It is expected that such awareness would prompt the crew to assess the powerloss impact on flight operations and subsequently respond in an appropriate manner that ensures continued safe flight and operation. The annunciation should prompt a crew response to control any associated thrust asymmetry; act to safely configure, restore, or secure the affected engine(s); and re-evaluate the flight plan.

The task 1.2 report analysis indicated that the potential safety benefit of powerloss annunciation accrues to LOC and RTO>V1 events. The RTO>V1 risk from annunciation during takeoff roll, as discussed in section 3.6.2. A powerloss annunciation in this flight phase is not recommended because true or false detection and annunciation of powerloss during takeoff roll below V1 could undesirably distract the crew or prompt an unnecessary and inappropriate RTO>V1 and inappropriate crew concern for asymmetric reverse thrust. However, combining the detection of this PSM with other appropriate airplane system functions to aid the crew in maintaining airplane control, e.g., B777 Thrust Asymmetry Compensation (TAC), may be of benefit.

3.7.2 False Powerloss Detection Risks.

The AIA report LOC events generally occurred in high workload phases of flight, e.g., approach/go-around or takeoff climb. False or nuisance alerting of powerloss during approach might prompt the crew to change aircraft configuration or might delay or otherwise affect a go-around decision. False or nuisance alerting of powerloss during takeoff climb might prompt the crew to change aircraft configuration or prompt an unnecessary air turn back. In both these cases, workload would unnecessarily increase and crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase-related tasks.

3.7.3 Failure to Annunciate/Detect Powerloss Risks.

Failure to detect and annunciate a powerloss on approach risks the crew being unaware that go-around capability and performance are affected. Failure to detect and annunciate a powerloss on takeoff may risk the crew being unaware that takeoff and climb capability and performance are affected. Both cases, combined with crew failure to maintain appropriate airspeed and attitude, can lead to LOC.

3.7.4 Confidence of Correct Powerloss PSM Detection.

Detection of a subtle condition is considered highly feasible. A separate determination of airplane-level annunciation feasibility is required. Current production models apply a detection scheme that primarily compares the engine high-pressure spool speed to some prescribed level. The prescribed level is determined from the engine idle thrust model, which is dependent on flight condition. The risk associated with this scheme lies in setting the level, below which subtle is declared, such that false detects are minimized (e.g., undershoot from pull back) and is considered very small.

At or above idle, detection of thrust shortfall is also considered feasible. One method to detect thrust shortfall is by determining both commanded and actual thrust from an engine model. Commanded thrust is determined from the power-setting input, whereas actual thrust is calculated using the power-setting and engine parametric data.

Identification of an actual thrust, some prescribed amount lower than the commanded thrust, would be identified as a thrust shortfall. For example, existing applications use prescribed difference in commanded to actual thrust of approximately 10% to activate Engine Failure and Thrust Loss logic.

The risk of false or missed detects using this method lies in the current method to measure thrust. In reality, thrust is not measured on-wing. What is measured is a parameter that is used to indicate that an assumed thrust has been obtained, i.e., a sensed parameter that relates to thrust and increases and decreases as thrust increases and decreases. This method was certified through the development of a model of the test stand's and/or instrumented airplane's measured thrust and the indication parameter. This model was developed to ensure that a minimum thrust is attained. The thrust may be higher due to, in varying degrees, engine configuration, engine to engine variation, engine age, etc. Additionally, the model was not developed to provide a thrust indication during a transient. Most importantly, the model does not include an indication/thrust relationship for a damaged engine (i.e., if the engine is damaged, the thrust to indication parameter relationship is unknown). The risks in using this method increase as the commanded thrust decreases (i.e., the determination of actual thrust, from parametric data, to compare to a commanded thrust is more difficult at low power settings). This is because the inaccuracies of the thrust to indication parameter model described above become more pronounced at low power. The increased risk of missed detection during a transient or at low power settings may lead to an inhibit of the detection algorithm in these operational states. This inhibit leaves open the operational risk of missed detection at low power, leading to the crew being unaware that

higher power will not be obtained from the failed engine if commanded. Only when the higher power is commanded would the detection method provide a valid result and the crew be alerted.

3.7.5 Powerloss Detection Further Research.

The engine challenge procedure described above is one possible method to reduce the risk of missed detection of a Powerloss PSM for an engine at low power. Research into what would trigger the use of this procedure is needed. The determination, based on existing algorithms using parametric data, of the engine being in the Indeterminate state, as described in section 3.6.7, may be that trigger. Specifically, a Powerloss PSM with the following characteristics should be investigated.

- The malfunctioning engine does not immediately experience a powerloss to idle or subidle condition.
- The flight crew takes action (for some reason) to reduce the power setting on the malfunctioning engine.
- The engine indications suggest the malfunctioning engine is responding to the crew action.
- The engine indications suggest the malfunctioning engine is running to schedule (at low power).

Further research is recommended to reliably detect a low power Powerloss PSM, i.e., powerloss at or near idle power. Currently, engine controls are designed to ensure operational stability at low or idle power. The current methods for determining thrust are less accurate at low power than at higher power. This leads to more ambiguity when using an actual to commanded thrust comparison algorithm. Different methods of using existing data or different data capture capabilities may lead to a more reliable determination of actual to commanded thrust validity.

3.8 SURGE ANNUNCIATION POTENTIAL OPERATIONAL BENEFITS AND RISKS.

The term compressor surge is used to describe the audible sound heard due to a sudden aerodynamic reversal of flow in the engine's compressor operation. A reversal of flow occurs with the downstream high-pressure air in the compressor escaping forward through the inlet. This reversal of flow is rapid and produces a very loud audible bang, similar to an explosion, for modern high by-pass ratio engines. The intensity of the noise depends on the engine power setting or pressure ratio as well as the amount of expansion permitted by the inlet. Depending on the type of compression system instability, there may be single, multiple, or continuous multiple loud bangs, and associated engine parameter fluctuations. The effects of a compressor surge result in a rapid decrease in rotor speeds, pressures, and fuel flow, and typically an increase in EGT.

There are three type of surge: (1) Self-Recoverable (typically recovers within 5 seconds without any crew intervention), (2) Recoverable with Crew Action (the crew reduces power and surging

stops and the engine returns to normal functionality at all normal power settings/operating conditions), and (3) Nonrecoverable, including (a) where the engine surge cannot be stopped and (b) where the engine does not recover to normal operation at all power settings or operating conditions (i.e., the surge may stop at low power but resume when power is advanced). With the exception of RTO>V1 events, the surge types associated with ICR are primarily types 2 and 3.

3.8.1 Surge Annunciation Potential Benefits.

As previously stated, crew awareness of PSM and identification of affected engine(s) must be provided to mitigate ICR risk. The task 1.2 report identified an operational safety benefit from a surge annunciation that provides timely crew awareness and identifies the affected engine(s). Per the task 1.2 report analysis, the failure to timely detect and consequent lack of timely awareness of surge is associated with Other, Shutdown/Throttled Good Engine (SDTGE), and RTO>V1 events in general, and with fatal and hull loss Other and SDTGE events in particular.

Annunciation of a Surge PSM would provide crew awareness that surge is occurring on one or more engines. For surge, that automatically recovers, it is expected that awareness will ensure the crew is not misdirected into falsely believing some other condition or malfunction occurred and taking inappropriate or unnecessary action. For surge that does not automatically recover, the annunciation would direct the crew to the appropriate checklist procedure, prompt the crew to reduce power on the affected engine(s), and subsequently respond in an appropriate manner that ensures continued safe flight and operation. This response should involve controlling any thrust asymmetry that might result, acting to safely configure, restore, or secure the affected engine(s), and re-evaluating the flight plan. Engine-specific annunciation of surge should prevent Shutdown Good Engine events (SDGE) and the procedural errors frequently associated with PSM+ICR events in the Other category.

The task 1.2 report analysis indicated that the potential safety benefit of surge annunciation accrues to Other and SDTGE events. The RTO>V1 risk from annunciation during takeoff roll was discussed in section 3.6.2. A surge annunciation in this flight phase is not recommended because true or false detection and annunciation of surge during takeoff roll below V1 could undesirably distract the crew or prompt an unnecessary and inappropriate RTO>V1 or prompt the crew to inappropriately reduce power below safe altitude.

3.8.2 Surge Detection/Annunciation Risks.

False detection and annunciation of surge during takeoff roll below V1 could prompt an unnecessary RTO>V1. False detection and annunciation of surge during takeoff climb, cruise, or descent could prompt an unnecessary thrust reduction or engine shutdown. False or nuisance alerting of surge during approach might prompt the crew to change aircraft configuration or might delay or otherwise affect a go-around decision. In all in-flight cases, workload would unnecessarily increase and crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase-related tasks.

Failure to detect and annunciate a surge on approach risks the crew being unaware that go-around capability and performance may be affected. This can lead to an unexpected airspeed

loss and consequent LOC. Failure to detect and annunciate a surge on takeoff may risk the crew being unaware that takeoff and climb capability and performance are affected. Additionally, in the absence of an explicit annunciation, the crew may take inappropriate action such as SDGE, or the loud bangs and vibration that typically accompany engine surge may misdirect the crew to believe that some other condition exists.

3.8.3 Confidence of Correct Surge PSM Detection.

The detection of a compressor surge is considered highly feasible. However, there does exist some degree of risk for determining meaningful versus not meaningful surge. A separate determination of airplane-level annunciation feasibility is required. Technical experts from Boeing agree that, from a first principles standpoint, the engine burner pressure is the primary indicative parameter for surge. In some current applications, a Surge event is detected and flagged as part of the central maintenance computer data. The engine exhaust gas temperature is an additional indicator for surge. Using these parameters on existing airplanes is problematic in the response of the sensors used to measure them. In the case of the burner pressure, the sensors must produce accurate pressure, with a rapid response, in a range from 15 to 450 psi. Existing production-quality sensors do not support such ranges at the needed rates. The transient nature of a Surge event is damped by the slow responsiveness of the thermocouples or other temperature-measuring devices used to capture engine exhaust temperature. Advances in sensing of these parameters (i.e., high response, high reliability, low cost) are an opportunity for future research.

A caveat in the detection of surge is whether or not it is meaningful. It has been defined that a meaningful surge is one in which crew action is required. The corollary to this is an engine that has or is experiencing a surge that the control system cannot accommodate or recover to its pre-surge state. In this case, the detection scheme would be to identify a surge after the control logic has attempted to maintain engine control. This is supported by the results from the task 5.2 report (see appendix E) on work performed by a subcontractor for this study and broaches the subject of recoverability/nonrecoverability, as detailed below. The ability to reliably and immediately detect (no false indications) meaningful (crew action required) surges is high risk. However, the ability to provide a meaningful surge indication for a continuously surging engine, say three or more surge cycles (e.g., after 5 seconds of persistent surge), is feasible.

As stated above, a surge detection scheme was developed by a subcontractor as part of this contract effort. The scheme employs a derivative limit for various parameters combined with a cross correlation of those parameters. The derivative functions are based on engine component performance maps derived empirically from the data. This algorithm successfully detected the surges identified in the data provided. In addition, the data contains what are agreed to be false detects of a Surge event. The subcontractor's algorithm was successful in avoiding false detects on this data. However, the algorithm was not validated with extensive data. The accuracy of the subcontractor's surge detection scheme should be improved with the use of engine original equipment manufacturer component performance data. Additionally, the subcontractor's task 5.2 report (appendix E) concludes that a means to more reliably detect a surge is possible with data available from a full authority digital engine control (FADEC)-controlled engine with at least one qualifier. Most health management data capture is performed at 1 Hz. This data

capture rate leaves detection methods vulnerable to the engine control logic attempting to accommodate to the PSM. The task 5.2 subcontractor recommended a data capture rate of 50 ms or less. This is more than accommodated by the data rates available to the engine control. However, the response of the sensors remains an issue. In summary, reduction of the risks associated with false or failure to detect a Surge PSM is dependent on the implementation of enhancements of existing methods and may also include the need for engine sensor enhancements.

3.8.4 Surge Detection Further Research.

Highly reliable, low cost means to sense burner pressure with a rapid response in a range from 15 to 450 psi is considered technology that would improve the detection of meaningful Surge events. The same is true for sensing the engine exhaust gas temperature in regards to its damped responsiveness existing thermocouples or other temperature-measuring devices.

3.9 FAILED FIXED THRUST ANNUNCIATION POTENTIAL OPERATIONAL BENEFITS AND RISK.

A Failed Fixed Thrust is defined as Stuck Throttle, Thrust Shortfall (actual thrust less than commanded thrust), and Overthrust (actual thrust greater than commanded thrust). The occurrence of a stuck throttle on modern aircraft has been greatly reduced. A Failed Fixed (i.e., stuck) Thrust due to nonthrottle causes (e.g., fuel management unit failures) is of greater concern on modern aircraft, mainly because of the lack of split-throttle cues that aids in detection and understanding.

3.9.1 Failed Fixed Thrust Annunciation Potential Benefits.

Again, the general theme of crew awareness and identification of affected engine(s) must be accommodated to mitigate ICR risk. An operational benefit from an annunciation that accomplishes these tasks for a Failed Fixed PSM is supported by analysis of the task 1.2 report. Failed Fixed Thrust events include physically stuck thrust levers and the engine failing to a fixed thrust level (i.e., a failure in the engine controller).

As with other PSMs, crew awareness of the PSM and identification of the affected engine(s) must be provided to mitigate ICR risk. Task 1.2 identified an operational safety benefit from a Failed Fixed Thrust annunciation that provides timely crew awareness and identifies the affected engine(s). Per the task 1.2 report analysis, the failure to timely detect and consequent lack of timely awareness of a Failed Fixed Thrust annunciation is associated with HF LOC and SDGE events in general, and HF LOC events in particular. The AIA report Stuck Throttle events in general, and the HF events in particular, appear to involve sufficient time and opportunity for prevention potential from earlier crew intervention had the stuck throttle been annunciated or otherwise called to the crew's attention near the time it became stuck.

Annunciation of a Failed Fixed Thrust PSM would provide crew awareness of an engine thrust malfunction on one or more engines and of an actual or potential thrust asymmetry. It is expected that awareness would ensure the crew maintains airplane airspeed and attitude control

and focuses attention on the correct (i.e., malfunctioning) engine. The annunciation would direct the crew to the appropriate checklist procedure, prompt the crew to control power on the affected engine(s), and subsequently respond in an appropriate manner that ensures continued safe flight and operation. This response should involve controlling any thrust asymmetry that might result, acting to safely configure, restore, or secure the affected engine(s), and re-evaluating the flight plan. Engine-specific annunciation of surge could prevent LOC and SDGE events.

The task 1.2 report analysis indicated that the potential safety benefit of Failed Fixed Thrust annunciation accrues to LOC and SDGE events. The RTO>V1 risk from annunciation during takeoff roll was discussed in section 3.6.2. Any annunciation in the takeoff flight phase is not recommended because true or false detection and annunciation of surge during takeoff roll below V1 could undesirably distract the crew, prompt an unnecessary and inappropriate RTO>V1, or prompt other inappropriate crew action below safe altitude.

3.9.2 Failed Fixed Detection/Annunciation Risks.

False detection and annunciation of engine Failed Fixed Thrust during takeoff roll below V1 could prompt an unnecessary RTO>V1. False detection and annunciation during takeoff climb is unlikely until first thrust reduction. At thrust reduction in cruise and in descent, a false alert could lead the crew to accomplish an unnecessary procedure and might prompt the crew to shutdown a good engine. False or nuisance alerting during approach might prompt the crew to unnecessarily go-around or shutdown a good engine. In all in-flight cases, workload would unnecessarily increase and crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase-related tasks. Note that a difference in commanded versus actual is equivalent to false or misleading display. This is highly unlikely, and the probability of its occurrence has been determined to be acceptable. It is more likely that false annunciation would be a normal transient due to a temporary difference in commanded and actual versus a persistent or false difference. Such normal nuisance transients would be distracting and disruptive of normal flight operations, and it is likely they would occur in unusual, unanticipated circumstances, where such a distraction is undesirable.

Failure to detect and annunciate engine Failed Fixed Thrust risks the crew being unaware that a difference in commanded and actual thrust exists. This is typically a difficult condition for crews to accurately diagnose, particularly in time-critical situations, and could result in the shutdown of the good/unaffected engine or combined with crew failure to maintain airspeed and attitude control could lead to LOC.

3.9.3 Confidence of Correct Failed Fixed Thrust PSM Detection.

Detection of an engine failed to a fixed thrust condition is considered feasible with relatively low risk. A separate determination of airplane-level annunciation feasibility is required. Detection of a failed fixed thrust condition would use actual versus commanded thrust monitoring. This monitoring scheme would differentiate thrust shortfall and overthrust conditions and the magnitude of each condition.

Detection of a stuck throttle is meaningful, and therefore required, only in the case of autothrottle engagement. The detection of this PSM would involve determination of the autothrottle mechanism being able to move the thrust lever or be based on throttle or thrust split. This type of PSM on current turbofan engines with electronic controls is much less likely to occur.

3.9.4 Failed Fixed Thrust Further Research.

The following two areas of further investigation are suggested:

- Investigate what actual thrust versus commanded thrust thresholds would be required to provide prevention/mitigation for Failed Fixed Thrust PSM-related PSM+ICR events. This follow-on activity could investigate whether existing implementations, e.g., B777 thrust shortfall alerting, would provide adequate thresholds and timeliness for Failed Fixed Thrust PSM detection.
- Investigate what overthrust alerting means and what thresholds should be used. Overthrust alerting has not been implemented on any existing model.

3.10 HIGH VIBRATION ANNUNCIATION POTENTIAL OPERATIONAL BENEFITS AND RISKS.

The correlation between vibration and PSM+ICR is indeterminate. Vibration may or may not accompany powerloss, surge, and other engine malfunctions. Vibration may exist but not be associated with an engine malfunction or any serious safety concern. Vibration detection/sensing is susceptible to error. Engine vibration operating limits are not specified for most engines. Therefore, while vibration may be a corroborating indication, in general, it cannot be relied upon to be present or meaningful.

3.10.1 High Vibration Annunciation Potential Operational Benefits.

The task 1.2 analysis does not identify high vibration as a primary PSM associated with HF or hull loss without fatalities (H) events. Where high vibration is identified as the primary PSM in the AIA report data, the events are incidental. Consequently, the operational and safety benefit of High Vibration annunciation is questionable and likely not very great in terms of PSM+ICR prevention/mitigation. Powerloss and Surge events may, or may not, involve High Vibration. Where high engine vibration exists, an explicit High Vibration annunciation could direct or redirect crew attention to the affected engine, but only if the vibration was high enough to trigger the vibration annunciation. The benefit of a High Vibration annunciation may be primarily in using it to alert the crew to possible engine malfunction, or in using it in conjunction with other indications.

3.10.2 High Vibration Detection/Annunciation Risks.

False detection and annunciation of high vibration during takeoff roll below V1 could prompt an unnecessary RTO>V1. False detection and annunciation of high vibration during takeoff climb, cruise, or descent could prompt an unnecessary thrust reduction, engine shutdown, diversion, or

air turn back. False or nuisance alerting of High Vibration during approach might prompt the crew to change aircraft configuration or might delay or otherwise affect a go-around decision. In all in-flight cases, the workload would unnecessarily increase and crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase-related tasks.

Failure to detect and annunciate high vibration appears to entail little more risk than the current lack of existing annunciation. As previously noted, High Vibration events alone are typically all incidental events. In the absence of an explicit annunciation, the crew may not identify the high vibration as a PSM and may be misdirected to take other inappropriate action based on whatever condition they believe to be causing the vibration.

3.10.3 Confidence of Correct High Vibration PSM Detection.

Engine vibration is currently monitored and indicated on all Boeing production models. Most airplanes and aerospace engines are designed and operate such that any expected level of engine vibration does not present a safety concern. Restated, in general, there is no prescribed engine vibration level that requires annunciation for safety. The task 2.1 and 1.2 report analyses suggest that annunciating engine vibration has potential for reducing ICR resulting from PSM. Vibration is useful, but not as the sole parameter or means in determining if a malfunction exists. Vibration monitoring has two potential uses:

- Establishing and annunciating a vibration threshold could be established well above normal vibration magnitude and duration ranges and used to annunciate high vibration levels indicative of a possible engine malfunction. This would provide the crew awareness that is often lacking in PSM+ICR events. This proposal is supported by current design and operational practices.
- Vibration could be used as an additional parameter in a malfunction detection algorithm designed to determine whether or not a malfunction exists. In this case, it is recommended that engine vibration monitoring be used, in combination with other monitoring, to produce an appropriate annunciation for ICR mitigation through correct crew awareness and action. Identifying vibration levels to support other annunciations is considered highly feasible and is supported by current design practice.

The primary risk in detection for annunciation is determining the threshold level.

3.10.4 High Vibration Further Research.

Further research would be required to determine vibration threshold levels for each engine class (e.g., CF6, CFM56-X, PW405X, Trent8XX, etc.) and may require tuning for a specific engine within a class. Additionally, vibration levels can show themselves at different levels and at different power settings. For example, a recent engine experienced a shift in the compressor rotor stack between stages 3 and 4 in the high-pressure compressor, which resulted in high vibrations at low power and little to normal vibrations at high power.

3.11 THRUST ASYMMETRY.

Thrust asymmetry is considered an airplane-level effect, not a PSM. Thrust asymmetry may, or may not, be due to a PSM.

When due to a PSM, Thrust Asymmetry is consequential and circumstantial in that it is a potential, but not certain, result of a PSM affecting thrust. Depending on the circumstances, thrust asymmetry can follow the PSM quickly, slowly, or not at all. The malfunctions responsible for thrust asymmetry can, and often do, occur well in advance of a thrust asymmetry. The thrust asymmetries of concern are unintentional, can be characterized as a throttle or thrust split, or as a difference between desired or commanded thrust (resulting in either overthrust or thrust shortfall on the affected engine), and are a symptom/consequence of a PSM. The PSMs with potential to cause thrust asymmetry are Engine Fail Low/Powerloss, Engine Fail High/Runaway, Engine Failed Fixed Thrust (where commanded and actual thrust differ), Stuck Throttle, and Surge with Powerloss. Thrust asymmetry can result from rapid Powerloss events, slow Powerloss events, engine failure to respond to commanded thrust, and stuck throttle.

Thrust asymmetry is a contributing factor in many LOC events. However, as previously noted, loss of airplane control is due primarily to failure to control airspeed or attitude. Most LOC events are low-altitude, high-power events involving takeoff, climb, or go-around climb power. Most LOC events also involve nonrecoverable malfunctions or involve recoverable malfunctions with insufficient time and altitude to attempt or complete engine recovery. Therefore, in most PSM situations, thrust asymmetry is unavoidable and the primary crew objective is to control, not correct, the thrust asymmetry.

3.11.1 Thrust Asymmetry Annunciation Potential Benefits and Risks.

Engine Indication or alert annunciation of Thrust Asymmetry is problematic in that Thrust Asymmetry may, or may not, be due to a propulsion system malfunction. In addition, Thrust Asymmetry is nonspecific and does not aid the crew in determining which engine is malfunctioning or why the engine is malfunctioning. There are sufficient potential risks associated with Thrust Asymmetry annunciation (including nuisance alerts) to outweigh the potential benefit. Additionally, there are easier and more effective means of addressing the problems caused by Thrust Asymmetry (e.g., LOC). Thrust Asymmetry occurs as the result of a significant thrust shortfall or overthrust. Of the PSMs which underlie significant Thrust Asymmetry, all except Stuck Throttle, can be sensed as thrust shortfall or overthrust. Stuck Throttle is a concern only when it occurs with autopilot engaged. There are no autothrottle or autoflight control laws that use split throttle or differential thrust. Therefore, split throttle/thrust is reliably detectable if throttle lever position or engine thrust is known/sensed and compared.

The goal of any Thrust Asymmetry indication or annunciation should be to make consequential Thrust Asymmetry intuitively obvious at the airplane level versus the engine system level. Thrust Asymmetry may be best indicated to the crew on the Primary Flight Display where its effects for most PSM events must generally be addressed through airplane-level control.

Risks Associated with False Detection and Annunciation were not assessed, and Risks Associated with Failure to Detect were not assessed.

3.11.2 Confidence of Correct Thrust Asymmetry PSM Detection.

Thrust Asymmetry is an airplane system response to individual PSM events or conditions. The primary consideration for detecting thrust asymmetry is confidence in determining thrust from a given engine. Thrust asymmetry is defined as a prescribed difference in the validated thrust levels from the individual engines. The detection of Thrust Asymmetry, as defined above, is considered highly feasible.

The difference in validated thrust may, or may not be, due to an engine malfunction. This ambiguity adds risk to detection.

The risks in the current methods to detect a deviation in commanded to actual thrust, described in section 3.7, must be reiterated. The models used to determine a difference in commanded to actual thrust are based on a relationship of an indicated parameter for a healthy engine at steady state. If the PSM can be detected with this model, the risk is low. Again, this qualifier further supports the application of the Time Lag Rule to detection methods designed to mitigate the risk of ICR due to PSM.

3.12 THE PSM BENEFIT, DETECTION POTENTIAL, AND RISK SUMMARY.

The potential operational benefit of PSM annunciation, detection potential and risk, and operational risk are summarized as follows:

- Powerloss in the form of Engine Failure (subidle/flameout/etc.). High potential operational benefit and effectiveness. Low detection and operational risk.
- Powerloss in the form of Thrust Shortfall (actual thrust less than commanded thrust). High potential operational benefit and effectiveness. Low detection and operational risk.
- Surge Recoverable with Crew Action and Surge Nonrecoverable. High potential operational benefit and effectiveness. Moderate to high detection risk and low to moderate operational risk. Surge or any other engine malfunction annunciation on ground above V1 may introduce operational risk that could outweigh any potential benefit of such annunciation.
- Failed Fixed Thrust in the form of Thrust Shortfall (actual thrust less than commanded thrust). High potential operational benefit and effectiveness. Low detection and operational risk.
- Failed Fixed Thrust in the form of Overthrust (actual thrust greater than commanded thrust). High potential operational benefit and effectiveness. Low detection and operational risk.

- Failed Fixed Thrust in the form of Stuck Throttle. High potential operational benefit and effectiveness. Low detection and operational risk. Potential safety benefit is to be developed/determined (TBD).
- High Vibration. Potential operational benefit of annunciation varies because high vibration may or may not be malfunction-related. Moderate potential effectiveness. Moderate detection and low operational risk.
- Thrust Asymmetry. Unknown/indeterminate potential operational benefit. Low annunciation effectiveness. Unknown/indeterminate operational risk. High detection potential. Indeterminate meaningful detection potential and moderate detection risk of meaningful thrust asymmetry. Indeterminate operational risk.

4. OPERATIONAL ASSESSMENT—TASKS 2.1, 1.2, 6.2, AND 6.1.

4.1 IN-SERVICE DATA ASSESSMENT (TASK 2.1).

As part of an FAA research contract, the BCA Flight Deck and Propulsion groups reviewed and analyzed PSM+ICR event data to investigate the potential of Flight Deck engine malfunction annunciations to prevent or reduce UCR to certain PSMs.

4.1.1 Research Objective and Goal.

The principal research objective was to evaluate PSM+ICR events, identify contributing factors, assess the detection and prevention potential (PP) of PSM annunciations, and establish a framework for understanding UCR to PSM. The principal goal was to promote understanding of these events and develop recommendations pertaining to Propulsion System sensing and Flight Deck indication in general, and PSM detection and Flight Deck annunciation in particular. It was intended that the recommendations transcend specific aircraft models, design, and operational philosophies to the maximum extent possible and practicable.

4.1.2 Task 2.1 Overview and Background.

“PSM+ICR [Propulsion System Malfunction Plus Inappropriate Crew Response] is now the dominant contributor (25 percent of hull loss and fatal accidents over the past 5 years [mid 1990s]) to propulsion-related turbofan and turboprop airplane accidents.” [Flight Safety Foundation (FSF) PSM+ICR Report Section 2 Introduction page 6.] For the 10-year period, 1992 to 2001, PSM+ICR events are the largest single contributor to propulsion-related turbofan and turboprop airplane accidents. PSM+ICR alone accounts for 26.5% of all propulsion system-related accidents [Boeing Propulsion System Accident Statistic Summary].

Task 2.1 consisted of:

- A detailed in-depth review and analysis of the 80 in-service turbofan events in the AIA and European Association of Aerospace Industries (AECMA) joint 1998 Project Report on PSM+ICR.*
- A review and analysis of post-AIA report in-service PSM data and PSM+ICR events.

*It is assumed that the 80 AIA report events do not document the total population of PSM+ICR events, but that they are reasonably representative of the overall nature and distribution of PSM+ICR events.

The overall objective of these reviews was to achieve an in-depth understanding of PSM+ICR events and assess the potential of Flight Deck engine indications, annunciations, and procedures to address UCRs to PSMs. Specific tasks were to:

- determine if the lack or availability of propulsion malfunction indications and annunciations/alerts were contributing factors in the crew responses that occurred in these events.
- identify other event factors contributing to the crew responses that occurred in these events.
- identify the safety concerns associated with each major malfunction and crew response.
- identify potential solutions and develop recommendations regarding UCRs to PSMs.

Review of the AIA PSM+ICR Report events produced the following products:

- A set of potential Flight Deck PSM annunciation/alert changes. This set was provided to task 1.2 for operational assessment of their potential to address the crew response-related safety concerns identified in task 2.1.
- A set of malfunction-related recommendations. This set was provided to propulsion for Task 5.1 Malfunction Characterization and propulsion Task 5.2 Malfunction Investigation and Study for detection potential.

Boeing and other databases were reviewed for post-AIA report in-service PSM and PSM+ICR events. Available event data were reviewed for the period 1995 to 2001. The IFSD data were reviewed from 1995 to 2001. PSM data were analyzed and reported for 2000 and 2001.

The objective of the data reviews was to:

- validate and complement the task 2.1 report conclusions and recommendations that resulted from reviewing the AIA report events.
- provide additional insight into PSMs in general, and PSM+ICR events in particular, which would support and guide efforts to reduce PSM+ICR events in the current and projected in-service fleet.

The PSM data review included:

- examining the current Boeing fleet for PSM and PSM+ICR events in general, and for Surge, Powerloss, Engine Fail, and Vibration events in particular.
- producing an overall quantitative sense of the distribution of PSM events in general, and Surge, Powerloss, Engine Fail, and Vibration events in particular, for the Boeing in-service fleet.

- identifying post-AIA Report PSM+ICR events.
- putting the PSM+ICR events into numerical perspective and context, i.e., supported/enabled event frequency and conditional probability calculations.

The IFSD data reviewed documents cross-model and model-specific IFSD events from 1995 to 2001, and documents the PSMs involved in 2000 and 2001. The IFSD review also documented engine restart/recovery in general, and Surge-related IFSD and restart/recoverability in particular.

4.1.3 Discussion of Inappropriate Crew Response.

The AIA report does not include a complete definition or characterization of ICR. ICR is a useful, but potentially misleading term. Crew response, particularly to system malfunctions, is part of a larger system of aircraft operation wherein the primary crew responsibility is to fly the airplane. Inappropriate, when used to describe crew response, may be misleading when implying crew blame, and by implying that the resolution of such occurrences rests solely or primarily with crew changes or qualifications. Crew response should be viewed in a system context and may be more effectively addressed through a broader combination of design, training, operations, and procedure changes.

Based on a review of the AIA report events, it would be inappropriate to generally assume or infer that the crew response in all the AIA report events was wrong or egregious. In some cases, crew response may have been wrong or egregious. But in many other cases, the crew action taken can be viewed as the most appropriate course of action under the existing circumstances, given the available information and time. Regardless, most of the AIA report event crew responses are considered undesirable.

Based on AIA report events, the apparent definition of ICR is any PSM event where the crew failed to follow the published PPP in a timely manner. Thus, the following situations would be considered UCRs:

- The crew wittingly or unwittingly executed the wrong PPP for the situation.
- The crew wittingly or unwittingly executed the PPP incorrectly.
- The crew executed the correct PPP for the wrong reason(s).
- The crew intentionally deviated from PPP given the situation and information available.
- The crew encountered a situation where the PPPs, or the circumstances/information for their application, were vague, incorrect, conflicting, or nonexistent.

Any definition or term for UCR should avoid the need to subjectively judge the advisability of the crew actions in an event. Rather, the definition should provide an objective basis for collecting data for the study and prevention of such UCR. Event data can therefore include events where the crew was provided insufficient information and inadequate procedures, as well

as events where the crew exhibited unacceptable performance. Regardless, data collection and study is greatly facilitated by unqualified crew support, and such support is better assured by neutralizing the issue. It has been suggested, and is therefore recommended, that wherever it is possible to do so without confusion, the term Crew Response (CR) or Propulsion System Malfunction+Crew Response (PSM+CR) be used to identify safety, accident, and incident events where the combined malfunction and crew response were contributing factors. There is little chance for confusion or problem when these terms are used in the context of safety, accident, or incident issues which require attention and resolution.

4.1.4 Task 2.1 Review and Analysis Methodology.

This section describes the review and analysis methodology and includes discussion of the AIA report event data and PSM+ICR category characterizations and related conclusions.

4.1.4.1 The AIA PSM+ICR Report Data Review and Analysis.

Each AIA PSM+ICR Report event was individually reviewed. The circumstances and factors in each event were analyzed from an operational perspective to assess if and how the PSM, PSM effects, crew awareness or lack of awareness, and other factors present influenced the crew response. The AIA report event analysis was limited to the AIA report events and is therefore primarily operational, not statistical. There was no formal analysis of the data for statistical significance. Such analyses for statistical significance would have required additional information and effort beyond the scope of this work.

In general, the PSM, PSM effects, crew knowledge/awareness, and the role of various other factors were assessed for significance in the crew response that occurred. Specifically, for each event, what could be determined in the following areas was documented and assessed for relevance to PSM detection and Flight Deck indications and annunciations.

- Recoverability or nonrecoverability of the PSM
- Engine indication(s) availability and use
- PSM annunciation(s) presence and use
- Cues (aural, tactile, and visual) presence and use
- Autopilot/Autothrottle engagement
- Thrust Asymmetry
- Crew intent, i.e., was the crew response intentional or unintentional

Conservatively, where explicit information was not provided or available, significance was listed as unknown. Assumptions were made or conditions were inferred only where it was reasonably reliable to do so. For example, it was assumed that autopilot was not engaged for takeoffs and that LOC events were not intentional.

The majority of events appeared to involve crews that are well within the range of acceptable crew qualification and competency. Therefore, a basic assumption is that the crews involved in these events are qualified and competent to at least a minimum acceptable level. Based on this assumption, to a limited extent, crew awareness or lack thereof was sometimes inferred. For

example, even a minimally or marginally competent flight crew is expected to understand the importance of maintaining engine out minimum control airspeed, attitude control, and engine parameters balanced or within operating limits. Therefore, in incidents where the flight crew failed to maintain these things, it was generally inferred that the crew was unaware of the condition—at least for some period of time. Lack of awareness was either explicitly reported, or patently obvious, in many events. Such lack of awareness usually occurred where

- there was no explicit annunciation or alert for the PSM involved,
- the PSM was masked by low power, autothrottle, or autopilot, or
- the PSM symptoms were easily interpretable as some other non-engine-related condition, i.e., lent themselves to such misdirection as a tire, gear, structure, or nonengine airplane system problem.

Based on the event data review and analysis, associated safety concerns and recommendations were developed regarding

- potential Flight Deck annunciations that should be assessed for operational appropriateness and potential effectiveness, and
- PSMs that should be investigated and studied to determine detection potential.

4.1.4.2 The PSM and IFSD Data Review.

The PSM data review included:

- Each PSM event was reviewed in detail to ensure characterization consistent with AIA report events.
- The overall frequency/distribution of PSM Symptoms was numerically quantified, combined with fleet statistics, and used to calculate various estimated rates of PSM and PSM+ICR occurrence.
- Surge recoverability, powerloss, and IFSD analyses were accomplished.
- Specific post-AIA report PSM+ICR events were identified.

An In-Flight Shutdown data review was used to document and chart

- the overall frequency and distribution of PSM Symptoms associated with 2000 and 2001 IFSDs and
- an IFSD restart analysis.

4.1.5 The Review and Analysis of AIA PSM+ICR Report Events.

This section includes a general discussion of the AIA report event data, PSM+ICR category characterizations and related conclusions, AIA PSM+ICR Report event analyses and related conclusions, and general and specific PSM+ICR-related safety concerns based on the preceding event analyses.

4.1.5.1 The PSM+ICR Report Events Overview.

The AIA PSM+ICR Report consisted of 80 turbofan events divided into four CR categories: LOC (11 events), Other (13 events), Rejected Takeoff (30 events), and SDTGE (27 events).

The AIA PSM+ICR Report documented the PSM Symptoms in these 80 turbofan events as a percent of total. Per the AIA report, five Symptoms represent 91% of the PSMs involved in ICR: Compressor Stall/Surge (63%), Powerloss (14%), Stuck Throttle (6%), Fire Warning (5%), and No Response to Throttle Command (3%).

Except for some other top-level phase of flight and geographic region event distribution summaries, charts of airplane generation versus hazard, and chronological accident rate charts, the AIA report contains no additional turbofan event data reduction.

It was a task 2.1 objective to review and analyze the AIA report events in-depth to achieve understanding sufficient to identify the contributing event factors and assess the potential of Flight Deck engine indications, annunciations, and procedures changes to address the ICRs observed. The following sections document that review and analysis.

4.1.5.2 The PSM+ICR Category Characterizations and Related Conclusions.

The in-service data used in the PSM+ICR report consisted of 80 turbofan events divided into four CR categories: LOC, Other, RTO, and SDTGE. The following sections characterize those categories and document related conclusions.

4.1.5.2.1 Loss of Control Event Characterization and Related Conclusions.

Most LOC events involved significant thrust asymmetry and low airspeed or unusual attitude at the time control is lost. All 11 LOC events involved thrust asymmetry as a contributing factor. Thrust asymmetry, while a contributing factor, was not however the root/primary cause of LOC. Two of eleven events primarily failed to maintain or control airspeed, and seven of eleven other events primarily failed to maintain or control attitude. As a secondary factor, most events involving failure to maintain and control attitude also resulted in failure to control airspeed (both

high and low). The remaining two events were on-ground Reverse Thrust events involving the rapid development of thrust asymmetry following a PSM, where airspeed and attitude control were not factors. LOC events predominately involved failure to maintain airplane airspeed and control airplane attitude.

The LOC event data indicated that airspeed and attitude awareness and control has potential for ICR prevention and risk mitigation in this category. Therefore, principal design and operational emphasis should be placed on airspeed and attitude awareness and control in events involving thrust asymmetry. LOC event data further suggested that engine malfunction annunciations that identify the presence of a PSM and identify the affected engine(s) also have potential for ICR prevention and risk mitigation. Note that these observations are particularly true for a single-engine go-around.

4.1.5.2.2 Other (O) Event Characterization and Related Conclusions.

The 13 Other events consisted of 4 Engine Surge events, 5 Engine Fail/Surge events, 1 Engine Fail/Subidle event, 2 Excess Vibration events, and 1 Engine Shutdown for low oil quantity event. The Other events are categorized and described below to provide understanding of the type and nature of events in this category.

Seven of thirteen events involved failure to follow proper procedure or operating practice, a misidentification of failure, or failure to detect a PSM.

- Two events involved a rushed approach and long landing, with runway excursions. It was unclear if, but unlikely that, an added PSM annunciation would have affected the outcome of these two events.
- Three other events involved failure to follow nonnormal engine shutdown procedures: one failure to shutdown and two improper shutdown procedures. In the two improper shutdown procedure events, the crew identified and shutdown the malfunctioning engine, but failed to follow the correct shutdown/secure procedure. It is possible, but questionable, that lack of annunciation linked to a specific procedure contributed to the crew responses. The crew knew they had a PSM and knew the correct engine. Further annunciation does not appear to offer any benefit.
- In one takeoff event, the crew properly rejected takeoff at approximately 80 kts, but misidentified a nonrecoverable PSM noise, vibration, and surge as a tire failure. Even though the crew took the correct action, this event was classified as ICR because the crew misidentified the failure and RTOed for the wrong reason. This event illustrates lack of correct interpretation and understanding that explicit annunciation can provide.
- In one cruise phase event, the crew failed, over a period of 7 minutes, to detect loss of thrust on an engine and consequent loss of airspeed from 250 to 180 knots. After an autothrottle power reduction, the engine had failed to respond to autothrottle power-up command. The crew successfully intervened when the autopilot, unable to hold altitude and track, finally disconnected. This incident illustrates the potential for lack of crew

detection and awareness due to automation masking of the malfunction. Similar events have resulted in LOC because the crew was unprepared to handle the automation disconnect. Explicit PSM annunciation can provide more timely crew awareness.

Of the remaining 6 of 13 events:

- Two events involved a low-altitude takeoff dual-engine surge and powerloss on a two-engine aircraft, where the crew failed to reduce power on one or both surging engines. In both events, dual/all engines were malfunctioning on a two-engine aircraft at low altitude. It is possible that Surge annunciations and associated procedures might have provided sufficient crew awareness and response to prevent the resulting Hull Losses and fatalities.
- One event, control flight in terrain (CFIT), continued takeoff after surge and powerloss below V1. A second same-side engine was shutdown after takeoff for Fire Warning. The aircraft failed to gain altitude and crashed 5 miles from the runway.
- One event involved RTO and subsequent crew Shutdown of Good Engine based on information from the air traffic control (ATC). The malfunctioning engine (compressor blade failure) continued to vibrate the aircraft until the engine shut itself down.
- One event involved excess pitch and stickshaker at liftoff after a single-engine powerloss.
- One event involved a 3-minute period where the crew could not reliably determine which engine on a two-engine aircraft was continually surging.

Some of these Other events are questionable PSM-related ICR (e.g., the rushed approaches and failures to shutdown or complete shutdown procedures). Some are questionable as ICR (e.g., the RTO for the wrong reason). But most events are relevant to the issues of PSM-related ICR in that they illustrate an apparent lack of crew awareness or correct understanding—contributing factors in most PSM+ICR events. Many events appear to indicate that the lack of PSM-related annunciation was a contributing factor in the crew response. In other events, the data suggested that the lack of PSM annunciations is, or may have been, a contributing factor in the crew response.

The Other event data indicated and suggested that engine malfunction annunciations that identify the presence of a PSM and identify the affected engine(s) offer potential for ICR prevention and risk mitigation in this category.

4.1.5.2.3 Shutdown Good Engine Event Characterization and Conclusions.

There were 22 events where the crew shutdown a good engine, i.e., an engine that was not malfunctioning. Some of these shutdowns were intentional, i.e., the crew shutdown the engine they had mistakenly identified was malfunctioning. In other events, good engine shutdowns were unintentional, i.e., the crew correctly identified the malfunctioning engine but mistakenly shutdown a different, properly functioning engine. In most cases, crew intent can be reliably determined. In-flight, all good engine shutdowns on two-engine aircraft were intentional. On three- and four-engine aircraft, there were a mix of intentional and unintentional good engine shutdowns.

Of the 22 Shutdown Good Engine events, 9 were intentional, 6 were unintentional, and 7 were of unknown intention (3 appear intentional, and 4 appear unintentional). All but 1 of the 22 Shutdown Good Engine events occurred in flight (see table 4-1). In the one on-ground Good Engine Shutdown event, the crew shutdown both engines on a two-engine aircraft, and it cannot be determined from event data if the crew did so intentionally or unintentionally.

TABLE 4-1. CREW INTENT—SHUTDOWN GOOD ENGINE

Number of Engines	Two	Three	Four
Number Events	7	2	13
Crew Intent (To Shutdown Good Engine)	6 Intentional (In Flight) 1 Unknown (On Ground)	2 Unknown	4 Intentional 5 Unintentional 4 Unknown

Ninety-three percent of the three- and four-engine aircraft were three-crew aircraft (14 of 15). Flight engineer errors were cited in 3 of 15 events and were possible in another 3 of 15. All flight engineer errors were unintentional engine rundowns or shutdowns. The extent to which three-crew interaction, delegation of responsibility, and flight engineer panel interface issues were contributing factors in the engine shutdown is unknown.

There were five Throttled Good Engine (TGE) events. All occurred on two-engine aircraft during takeoff rotation or takeoff climb. Three appear intentional, and two appear unintentional.

The Shutdown/Throttled Good Engine (SDTGE) event data indicate that engine malfunction annunciations that identify the presence of a PSM and identify the affected or unaffected engine(s), particularly on two-engine aircraft, has potential for ICR prevention and risk mitigation in this category.

4.1.5.2.4 RTO>V1 Event Characterization and Related Conclusions.

Of the 30 RTO events, 27 involved RTO above the V1 takeoff decision speed, many of which involved runway excursions (off the side or overrun). The remaining three events were two aborts below V1 and one abort at V1, all of which overran the runway end due to crew braking procedure errors (see table 4-2).

TABLE 4-2. REJECTED TAKEOFF POINT RELATIVE TO V1, ROTATION, AND LIFTOFF

RTO< or at V1 ^{1,4}	RTO>V1 ⁴ < Rotation ²	RTO at Rotation	RTO>Liftoff
3 (1 H, 2 S)	18 (2 H, 5 S, 11 I)	6 (3 S, 3 I)	3 (1 HF ³ , 2 H)

1. There were two events where the RTO occurred below V1, and one event where the RTO occurred at V1. All three events overran the runway end due to crew braking-related errors.
2. In one event, the flight officer flying attempted to RTO. The captain intervened and the takeoff was successfully completed.
3. The one HF event PSM initiated, and the abort occurred after liftoff.
4. 37% of the RTO events (11 of 30) occurred approaching, at, or just past V1.

S = substantial damage

I = incidental damage

H = Hull Loss without fatalities

The event database indicated that there are many different contributing factors to RTO runway overruns. Poor crew communication and coordination, poor/delayed crew braking, thrust reverser lockouts per minimum equipment list dispatch, failure to deploy spoilers, poor weather and contaminated runway conditions (e.g., snow, rain, and ice), Captain Pilot Not Flying (PNF), transfers of control confusion, many malfunctions at or near V1, etc. In a few events, the PSM for which the crew rejected takeoff also reduced thrust reverser capability.

In 27% of the RTO events (8 of 30), the RTO was initiated on the basis of an indication light, annunciation/alert, or crew callout.

- Three events involved ENGINE FAIL annunciations/alerts.
- Three events involved FIRE WARNING annunciations/alerts or callouts.
- One event involved a THRUST REVERSER UNLOCK indication.
- One event involved an EGT exceedance indication/annunciation.

The RTO event data indicated that malfunction annunciations above V1 are a contributing factor in RTO>V1. This suggests that inhibiting such annunciations from V1 to some point after liftoff has potential for ICR prevention and risk mitigation in this category. The data suggested that malfunction annunciation to prevent RTO>V1 might increase, not reduce, the risk of RTO>V1.

4.1.5.3 The AIA PSM+ICR Report Event Analyses and Related Conclusions.

4.1.5.3.1 Overall PSM and Hazard Analysis.

Table 4-3 summarizes the primary malfunctions/symptoms and hazard associated with each crew response category: LOC, Other, RTO, and SDTGE. Note that other, secondary, malfunctions/symptoms such as vibration may also be present in these events. Table 4-3 also shows the average numerical hazard, number of fatalities, and recoverability associated with each crew response category. Of the 81 events, 12 involved HF, 11 involved H, 11 involved S, and 47 were I. Figure 4-1 charts the type and occurrence of PSMs listed in table 4-3. Figure 4-2 charts the CR associated with each PSM listed in table 4-3.

TABLE 4-3. CREW RESPONSE, MALFUNCTIONS, HAZARD, AND PSM RECOVERABILITY

CR and Primary PSM/Symptom	Hazard	Numerical Hazard	Number of Fatalities	PSM Recoverability
Loss of Control (11) Powerloss (7) 5 Engine Fail w/Surge 1 Engine Subidle 1 Unknown Stuck Throttle (2) 1 at Climb power 1 at Idle power Thrust Reverser (2) 2 Fail to Deploy	7 HF, 2 H, 1 S, 1 I 5 HF, 1 H, 1 S 4 HF, 1 H 1 S 1 HF 2 HF 1 H, 1 I	4.36	336 (7 events)	3 R, 5 NR, 3 Unknown
CR and Primary PSM/Symptom	Hazard			
Other (13) Powerloss (6) 5 Engine Fail w/Surge 1 Engine Fail/Subidle Surge (4) Excess Vibration (2) Low Oil Quantity (1)	3 HF, 3 H, 0 S, 7 I 2 HF, 1 H, 3 I 2 HF, 1 H, 2 I 1 I 1 HF, 1 H, 2 I 2 I 1 H	2.69	44 (3 events)	0 R, 11 NR, 2 Unknown
CR and Primary PSM/Symptom	Hazard			
Shutdown/Throttled Good Engine (27) Surge (14) Powerloss (6) 4 Thrust Shortfall Stuck Throttle (3) 1 at Idle 1 at Medium to High 1 at High Fail Fixed/Subidle (1) Excess Vibration (1) Fire Warning (2)	1 HF, 1 H, 0 S, 25 I 1 HF, 1 H, 0 S, 12 I 6 I 3 I 1 I 1 I 2 I	1.96 ¹	47 (1 event)	10 R, 14 NR, 3 Unknown Shutdown ³ Throttled ⁴
CR and Primary PSM/Symptom	Hazard			
RTO>V1 (30) Surge (19) Powerloss (6) 2 Engine Fail w/Surge 3 Thrust Shortfall 1 Perceived Warning/Indication (4) Severe Vibration (1)	1 HF, 5 H, 10 S, 14 I 1 HF, 3 H, 6 S, 9 I 1 H, 2 S, 3 I 1 H, 2 S, 1 I 1 I	2.33 ²	3 (1 event)	5 R, 16 NR, 9 Unknown

1. Numerical Hazard: Shutdown Good Engine on two-engine aircraft = 2.14. Shutdown Good Engine on same side as malfunctioning engine on four-engine aircraft = 2.0. Throttled Good Engine on two-engine aircraft = 1.6.
2. Numerical Hazard for RTO with wheels on ground (i.e., RTO before liftoff) is 2.15.
3. Recoverability vs Nonrecoverability: Shutdown Good Engine = 7 R, 13 NR, 2 unknown.
4. Recoverability vs Nonrecoverability: Throttled Good Engine = 3 R, 1 NR, 1 unknown.

R = Recoverable

NR = Nonrecoverable

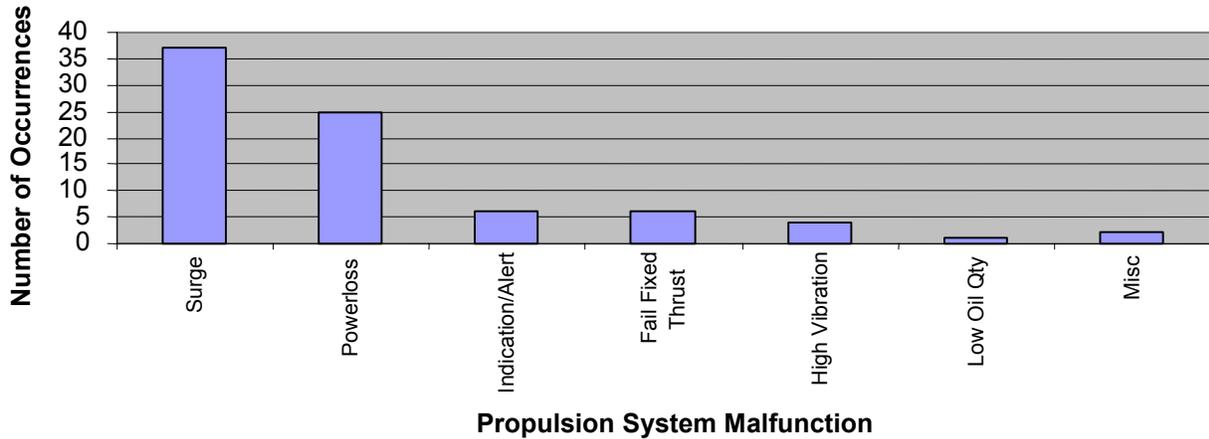


FIGURE 4-1. THE AIA REPORT PROPULSION SYSTEM MALFUNCTIONS

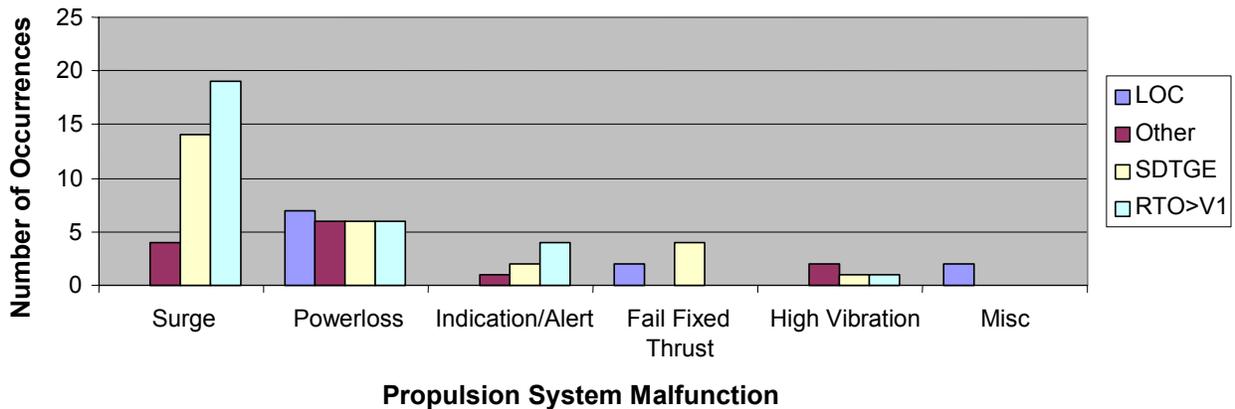


FIGURE 4-2. THE AIA REPORT CREW RESPONSE CATEGORY AND PSM

Table 4-3 is sorted by ICR with the greatest number of HF events, then with the greatest number of overall fatalities. The event database included numerical hazard levels 1 through 5 assigned to each event. These values were used to calculate an average numerical hazard for each CR category. The average numerical hazard is greatest for LOC, followed by Other, RTO>V1, and SDTGE. Excluding TGE events, the average numerical hazard for SDGE on a two-engine aircraft equals 2.14. Excluding RTOs after liftoff, the average numerical hazard for RTO>V1 equals 2.15. The event data indicated that there are no fatalities for RTO>V1 when the RTO is initiated on ground. There were three RTO>V1 events that initiated after liftoff. Only one of these three RTOs after liftoff involved fatalities. That one event accounts for all three RTO>V1 fatalities.

The average numerical hazard listed in table 4-3 is based on individual event numerical hazards whose assignment/determination are subjectively assigned values. Therefore, numerical hazard is not considered an objective measure of actual hazard and was included only for rough order of magnitude comparisons. For the purposes of this analysis, the number of fatalities was

considered the primary objective measure of the actual and potential hazard, and the potential safety benefit, associated with each CR category.

With respect to reducing PSM-related ICR using PSM annunciations, the hazards and fatalities for events in each CR category suggest:

- The greatest potential safety benefit is in addressing LOC, Other, and SDTGE-related PSMs and events.
- The least potential safety benefit is in addressing RTO>V1-related PSMs and events.

4.1.5.3.2 Recoverable Versus Nonrecoverable Engine Malfunctions.

Recoverable (R) engine malfunctions are those events/cases where the engine automatically, or with crew action, recovers to commanded thrust and full range of functionality/performance. Most R events involve no engine component failures and no significant engine damage.

Nonrecoverable (NR) engine malfunctions are those events/cases where the engine or engine controller will not automatically, or with crew action, recover to a normal level of functionality/performance. Typical NR events involve sense line or controller failures, foreign object damage, a failure of blades, seals, bearings, controllers, etc., or significant engine damage.

Of the 81 AIA report event ICRs, table 4-4 shows that 22% involved R PSMs (18 of 81), 57% involved NR PSMs (46 of 81), and recoverability could not be determined in the remaining 21% of events (17 of 81). Overall, and in each ICR category, the majority of event PSMs are NR. In HF events, 17% involved R PSMs (2 of 12), 58% involved NR PSMs (7 of 12), and recoverability could not be determined in the remaining 25% of events (3 of 12). It is known that in one of the three HF events where recoverability is unknown, the malfunctioning engine was not operating when the aircraft struck the ground. The engine-operating state at the time of impact is not known in the remaining two events.

TABLE 4-4. PROPULSION SYSTEM MALFUNCTION RECOVERABILITY

	Recoverable PSM	Nonrecoverable PSM	Unknown
All Events (81)	18	46	17
HF Events (12)	2	7	3

The AIA report PSM recoverability data suggested that both R and NR PSMs, but nonrecoverable PSMs in particular, should be investigated for detection potential.

4.1.5.3.3 Overall Summary of Number of Crew and Number of Events Versus Number of Engines.

Of the 80 AIA report events, 12 involved HF, 11 involved H, 11 involved S, and 46 were I.

Of the 80 event aircraft, 43% were two-engine aircraft (34 of 80), 16% were three-engine aircraft (13 of 80), and 41% were four-engine aircraft (33 of 80). Eighty-eight percent of the two-engine aircraft were two-crew aircraft (30 of 34). Ninety-two percent of the three-engine aircraft (12 of 13) and 91% of the four-engine aircraft (31 of 33) were three-crew aircraft with flight engineer. All of the three- and four-engine, two-crew aircraft events were incidents.

Table 4-5 shows that most of the two-crew aircraft involved in AIA report events are two-engine aircraft. Only three of the three- and four-engine aircraft involved in AIA report events were two-crew.

TABLE 4-5. NUMBER OF CREW AND NUMBER OF EVENTS VERSUS NUMBER OF ENGINES ON AIRCRAFT

Number of Engines	Two	Three	Four
Number of Flight Crew	88% Two Crew (30 of 34)	92% Three Crew (12 of 13)	91% Three Crew (31 of 33)
Number of ICR Events	43% (34 of 80)	16% (13 of 80)	41% (33 of 80)

The AIA report event data indicated that PSM+ICR is not limited to engine number or crew size.

4.1.5.3.4 Overall Summary of Engine Type (HBPR Versus LBPR) Versus Events.

Table 4-6 shows that 61% of all events involved high by-pass ratio (HBPR) engines (49 of 80). Thirty-nine percent of all events involved low by-pass ratio (LBPR) engines (31 of 80).

TABLE 4-6. EVENTS VERSUS ENGINE TYPE

Engine Type	HBPR	LBPR
All Events	61% (49 of 80)	39% (31 of 80)

The engine type data suggested that PSM detection potential investigation and study should include both HBPR and LBPR turbofan engines. However, the existing and future fleet trend towards predominately HBPR engines suggested there is more potential benefit in focusing on HBPR engines.

4.1.5.3.5 Surge and Powerloss Events.

The AIA/AECMA Project Report documents that Surge and Powerloss events account for 77% of the PSMs observed in the event database. It is often not clear from event data if Surge or Powerloss is the initial PSM symptom. Both usually follow from some primary failure, e.g., a seal, bearing, blade, controller, fuel flow loss, or other such failure. In many cases, Surge is a secondary PSM symptom that results from rapid engine deceleration.

Surge and Powerloss events can be characterized as either R or NR. Table 4-7 shows that 51% of the RTO, SDTGE, and Other Surge events were NR. Twenty-seven percent were R either without or with crew action. It is not known how many R surges require, or do not require, crew action to recover. In general, most

- NR engine surges are accompanied by significant sustained powerloss or an engine subidle condition, and
- R engine surges are not accompanied by significant or sustained powerloss.

TABLE 4-7. THE AIA PSM+ICR REPORT SURGE EVENTS RECOVERABILITY

	R	NR	Unknown
RTO, SDTGE, and Other AIA Report Surge Events	27% (10 of 37)	51% (19 of 37)	22% (8 of 37)

4.1.5.3.5.1 Surge Events.

Surge events were the main PSM in RTO>V1 and SDTGE, and a minor PSM in Other events. There were 37 RTO, SDTGE, and Other Surge events. Table 4-7 shows that 27% were R (10 of 37), 51% were NR (19 of 37), and recoverability could not be determined in 22% of the events (8 of 37). It was not determined how many R surges did or would have recovered without crew action versus with crew action.

4.1.5.3.5.2 Powerloss Events.

As table 4-3 shows, Powerloss events were distributed evenly across all event categories: LOC, Other, RTO>V1, and SDTGE. Table 4-8 shows that where recoverability from Powerloss can be determined, most Powerloss events were NR.

TABLE 4-8. POWERLOSS RECOVERABILITY

	R	NR	Unknown
Powerloss Events	16% (4 of 25)	52% (13 of 25)	32% (8 of 25)

The Surge and Powerloss event data suggested that both R and NR Surge and Powerloss should be investigated and studied for detection potential. The data also suggested more potential ICR prevention and risk mitigation benefit in focusing on NR Surge and Powerloss.

4.1.5.3.6 Flight Phase, Altitude, and Power.

Table 4-9 shows that most of the 80 PSM events initiated during the Takeoff and Climb phase of flight. Most (67%) of the HF events occurred at relatively low altitudes in climb after takeoff or during go-around. However, 33% of the 12 HF events in the AIA report database initiated in other (lower power) flight phases. Sixty-seven percent of all HF events initiated at high (takeoff/climb) power between 50 and 2000 feet. Thirty-three percent of all HF events initiated

at medium and low power. Note that the Cruise PSM event initiated at climb power, but the associated SDGE occurred at low engine power.

TABLE 4-9. FLIGHT PHASE, ALTITUDE, POWER, AND EVENT CORRELATIONS

Flight Phase	Takeoff (Ground Roll)	Climb	Cruise	Descent	Approach/ Go-Around
Number of Events	36	27	10	2	5
Number of HF Events	0	8	1 ¹	1	2 ²
HF Event Altitudes	0	50' to 2000' ³	FL 290	7200'	200' to 300'

1. The Cruise PSM event initiated at Climb power, but the associated ICR (SDGE) occurred at low engine power.
2. The Descent and Approach PSM events initiated at Climb power, but the associated ICRs (LOC) occurred at high/go-around power.
3. Most appear to initiate below 500'.

As table 4-3 shows, most HF events were LOC (7 of 12), followed by Other (3 of 12), then SDGE (1 of 12), and then RTO (1 of 12). Note that the RTO event occurred after liftoff and has been included in the Climb phase in table 4-10 to differentiate ground and in-flight events.

TABLE 4-10. FLIGHT PHASE, ALTITUDE, PSM SYMPTOM, AND HAZARD CORRELATION

Flight Phase (Number of Events)	Takeoff (Ground Roll)	Climb	Cruise	Descent	Approach/ Go-Around
Surge (37)	17	15	5	-	-
Surge HF (3)		2 < 300'	1 at FL290 ¹		
Powerloss (25)	10	7	5	1	2
Powerloss HF (7)		5 < 2000'			2 < 300' ²
Stuck Throttles (5)		2		1	2
Stuck Throttles HF (2)		1 at 1500'		1 at 7200'	

1. PSM event initiated at Climb power, but the ICR (SDGE) occurred at low engine power.
2. PSM events initiated at low to medium power, but the ICRs (LOC) occurred at high/go-around power.

Fifty-eight percent of the 12 HF events were Powerloss (7 of 12), 2 of which also involved Surge effects. Twenty-five percent of the HF events were Surge (3 of 12), 2 of which also involved Powerloss. The remaining 17% of HF events involved Stuck Throttles (2 of 12). One Throttle Stuck at idle power in the Descent phase of flight, and one Throttle Stuck at climb power in the Climb phase of flight.

Table 4-11 shows the distribution of events as a function of event category and phase of flight with notes that qualify the associated power settings.

TABLE 4-11. EVENT CATEGORY VERSUS FLIGHT PHASE

Flight Phase	Takeoff (Ground Roll)	Climb	Cruise	Descent	Approach
LOC (11) ¹	9		1	1	-
Other (13) ²	5	7	1	-	-
SDTGE (27) ³	2	14	8	1	2
SDGE (7) ⁴	1	3 (FL120-290)	1	-	2
RTO (30) ⁵	27	3 (< 50')	-	-	-

1. Most LOC events involve high-power thrust asymmetry and low airspeed at the time control is lost. However, the majority of the PSMs in these LOC events (6 of 11) initiated in Cruise, Descent, Approach, and Landing at low to medium power levels and normal airspeeds and attitudes. The remaining 5 of 11 events initiated at Takeoff or Climb power levels and at normal airspeeds and attitudes.
2. All Other events involve high power/thrust levels: Takeoff, Go-Around, Climb, or maximum Cruise thrust.
3. Most SDTGE events (20 of 27) are Climb, Cruise, Descent, and Approach phase events, not Takeoff phase high-power events. Seven of twenty-seven events are Takeoff phase events. All five TGE events are Takeoff phase events at or below 500 feet altitude.
4. SDGE on two-engine aircraft.
5. All RTO events occurred at Takeoff Power settings.

The data in tables 4-9, 4-10, and 4-11 suggest that all flight phases and power settings (low, medium, and high) should be considered in Flight Deck engine indication and PSM annunciation assessments and in Propulsion investigations/studies of malfunction detection potential.

4.1.5.3.7 Thrust Asymmetry Role/Significance.

Event data indicated that thrust asymmetry was a significant factor in the crew response in 19% of the events (15 of 81). Thrust asymmetry was not a significant factor in 69% of the events (56 of 81). Significance could not be determined in 12% of the events (10 of 81): 4 TGE events, 2 SDGE events, 2 Other events, and 2 LOC events.

Thrust asymmetry was a significant factor in 5 HF, 4 H, 1 S, and 5 I events. Table 4-12 shows the relationship between thrust asymmetry, flight phase, and hazard. Table 4-13 shows the relationship between thrust asymmetry and the four CR categories.

TABLE 4-12. SIGNIFICANT THRUST ASYMMETRY VS FLIGHT PHASE, PSM SYMPTOM, AND HAZARD

Flight Phase (Number of Events)	Takeoff/Landing (On Ground)	Climb	Cruise	Descent	Approach/ Go-Around
Thrust Asymmetry Significant to CR (15)	4	4	3	1	3
7 Powerloss	1 H	1 HF	1 S, 2 I		2 HF
4 Stuck Throttles		1 HF, 1 I		1 HF	1 I
3 Reverse Thrust	2 H, 1 I				
1 Surge	1 H				

TABLE 4-13. SIGNIFICANT THRUST ASYMMETRY VS CREW RESPONSE

CR	LOC	Other	SDTGE	RTO>V1
Thrust Asymmetry Significant to CR (15)	9 (5 HF, 2 H, 1 S, 1 I)	2 (1 H, 1 I)	3 (3 I)	1 (1 H)

Nine of the eleven LOC events involved thrust asymmetry as a significant contributing factor. All HF events, and half of the H events involving significant thrust asymmetry were LOC events. However, as previously described, thrust asymmetry was not the root/primary cause of LOC. Most LOC events involve failure to maintain or control airspeed. Airspeed and attitude control were not factors in only two on-ground reverse thrust events involving the rapid development of thrust asymmetry following a PSM.

Two of thirteen Other events involved thrust asymmetry as a significant contributing factor: one H and one I event: a reverse thrust-related runway excursion H event and a cruise engine subidle I event, where autopilot and autothrottle were engaged. It is unknown, but possible, that thrust asymmetry was a significant factor in two additional Other events: a CFIT HF event and an overpitch/stickshaker at rotation incident event.

One Shutdown and two TGE events involved thrust asymmetry as a significant/contributing factor—all were incidents. The SDGE event involved a throttle stuck at idle combined with autothrottle engaged as a contributing factor in the shutdown of the good engine.

One RTO>V1 H event involved thrust asymmetry as a significant/contributing factor. In this event, the flight officer, who was the pilot flying, overcorrected for the thrust asymmetry produced by the initial engine malfunction. This overcorrection apparently misled the captain to believe that both engines on the two-engine aircraft were malfunctioning, and he initiated an RTO. A hull loss resulted.

Analysis of thrust asymmetry in the AIA report event data indicated that prior to the development of a significant thrust asymmetry, there are earlier detectable symptoms of potential

or impending thrust asymmetry. Specifically, such PSM symptoms as thrust shortfall, excess thrust, overthrust, and various autothrottle and engine control malfunctions. The data suggested that focusing on airspeed, attitude and PSM awareness, versus thrust asymmetry, represents greater potential for ICR prevention and risk mitigation.

4.1.5.3.8 Autopilot and Autothrottle Role/Significance.

4.1.5.3.8.1 Autopilot Significance.

Event data indicated that the autopilot was a significant factor in the CR in 3 of 81 events (4%): 2 LOC (1 HF and 1 S) and 1 Other (1I) event. In 71 of 81 events (88%), it could be reliably determined or inferred that the autopilot was not a significant factor in the CR. In 7 of 81 events, significance could not be determined. The autothrottle was engaged in all three events where autopilot was a significant factor.

4.1.5.3.8.2 Autothrottle Significance.

Event data indicated that the autothrottle was a significant factor in the CR in 7 of 81 events (8%): 3 LOC, 1 Other, and 3 SDGE events. The three LOC events were 2 HF and 1 S events. The Other and SDGE events were all incidental events. In 62 of 81 events (77%), it could be reliably determined or inferred that the autothrottle was not a significant factor in the CR. In 12 of 81 events, significance could not be determined.

- LOC: Autopilot and autothrottle were both engaged in one Stuck Throttle LOC event and in an Engine Powerloss/Subidle LOC event. In the Stuck Throttle event, the throttle stuck at idle, the autothrottle created the thrust asymmetry, and the autopilot masked the thrust asymmetry. In the Powerloss/Subidle event, both the autothrottle and autopilot masked the thrust asymmetry. The autothrottle alone was engaged in one LOC.
- Other: Autopilot and autothrottle were engaged together and were known contributing factors in one Other event—a cruise engine subidle Incidental event involving loss of thrust on an engine and the consequent loss of airspeed from 250 to 180 knots. After an autothrottle power reduction, the engine had failed to respond to the autothrottle power-up command. Both the autothrottle and autopilot masked the thrust asymmetry. The crew successfully intervened when the autopilot, unable to hold altitude and track, finally disconnected.
- SDGE: There were three SDGE events where autothrottle only was engaged (i.e., autopilot not engaged). These were all Stuck Throttle events where the crew misinterpreted the low/idle power engine as failed and shut it down. One of these events was in Climb, and two were on Approach. All involved two-engine aircraft.

Analysis of AIA report event data for autopilot and autothrottle use indicates potential ICR prevention and risk mitigation will benefit in annunciating PSMs that are masked or obscured by autopilot or autothrottle engagement. Specifically, throttle splits, engine fail low and fixed, and possibly thrust asymmetry.

4.1.5.3.9 Engine Indications and PSM Annunciations—Significance in ICR.

Engine indications were available in most events. Indications and annunciations were a significant factor in the CR in 21% of events (17 of 81). They were not significant in 20% of events (16 of 81). Significance could not be determined in 59% of events (48 of 81) due to the lack of specific reference or inference to engine indications or annunciations.

RTO>V1 accounted for 8 of the 17 events (47%) where indications and annunciations were a significant factor in the CR. As previously noted in the characterization of RTO>V1, 27% of the RTO>V1 events (8 of 30) were initiated on the basis of an indication light, annunciation/alert, or crew callout.

Analysis of PSM+ICR event data suggested that the presence of indications and annunciations is a contributing factor in RTO>V1 events. Conversely, event data suggested that the lack of PSM-related engine indications and annunciations is, or may be, a contributing factor in the other ICR categories where UCR to PSMs occur, particularly in SDGE on two-engine aircraft and LOC events.

4.1.5.3.10 Overall Summary Cues: Aural, Tactile, and Other Indications.

Aural bangs and booms and tactile airplane vibration and shudder that exceed crew experience and expectations often accompany surge events—even recoverable ones. The event data did not indicate or suggest that, to any significant degree, crews are misinterpreting PSMs such as Surge as some other problem (e.g., bomb, tire, etc.). However, anecdotal evidence and reports indicated that misinterpretation/misdirection is more prevalent than the data indicated. There were three reported events, all RTOs, where such explicit misinterpretation occurred: two thought the Surge effects were main landing gear tires, and one thought the Surge effects was a bomb.

It can often be inferred from the data that, in general, crews know they have a PSM but believe it has resulted from or may have caused severe engine damage. There are many contributing factors in the crew decision to shutdown an engine, not all are safety-related. It is plausible, in the absence of any explicit indications to the contrary, that crews may be convinced that a violent/ high-power surge has caused severe engine damage, and may then elect to shutdown the affected engine as a precaution. This is particularly likely, and undesirable, in the case of a violent but recoverable engine surge. Commercial transport aircraft are designed to safely fly with an In-Flight Engine Shutdown. However, unnecessary IFSD is undesirable, particularly on a two-engine aircraft, where it reduces available thrust and propulsion redundancy. Unnecessary IFSD is undesirable, but not unsafe.

Powerloss events are generally within the crew's experience and expectation. Powerloss events are accompanied by airplane-level effects, such as thrust asymmetry, that manifest to the crew as attitude (yaw, roll, pitch) and airspeed effects. The primary concern with powerloss is automation (autopilot and autothrottle) masking of significant thrust asymmetry or slow/late recognition of a PSM. Lack of PSM awareness combined with a belief that thrust from both engines is available, may result in a complacent or distracted crew losing aircraft state awareness

and consequently LOC if the crew does not maintain aircraft single-engine or other operating speeds.

Analysis of aural, tactile, and other indications data suggested that an explicit PSM annunciation that identifies the malfunction and guides the crew to an appropriate nonnormal checklist procedure may be of potential ICR prevention and risk mitigation value, particularly in the case of recoverable Surge events.

4.1.5.3.11 Crew Error Classification.

Table 4-14 shows that 67% of the HF events in the AIA report involved knowledge-based errors. Knowledge-based errors occur in situations where the crew is faced with novel and unfamiliar situations. The problem solving required in these unfamiliar situations is goal-driven and based on an analysis of the environment and the overall aims of the person. Errors arise from selecting the wrong goal, incomplete or inaccurate knowledge, and human limitations in terms of information processing. Specifically, the more complex the problem, the more data that must be integrated, and the less time available alone and in combination to process the information; all of which increase error potential.

Fifty-eight percent of the HF events in the AIA report involved skill-based errors. Skill-based errors occur in situations where the crew executes a very familiar task without consciously thinking about how it is executed. Skill-based errors result from doing the right thing incorrectly, or intending to do something but because of distraction or memory failure, not completing the action.

Twenty-five percent of the HF events in the AIA report involved rule-based errors. Rule-based errors occur in situations where the crew is consciously following a rule or procedure from memory or checklist. Rule-based errors typically involve misclassification of situations leading to the application of the wrong rule or the incorrect recall of procedures. Rule-based errors result from either not doing something that should be done or result from doing the wrong thing.

TABLE 4-14. CREW ERROR CLASSIFICATION VERSUS HF EVENTS

Error Classification	Skill	Rule	Knowledge
HF Events (12)	58% (7 of 12)	25% (3 of 12)	67% (8 of 12)

There was insufficient time in task 2.1 to complete a comprehensive analysis of the Crew Error classification versus HF events. Such analysis would likely provide additional insight into effective error prevention strategies and designs.

The Crew Error classification versus HF events data indicated that the following are of potential benefit in ICR prevention/reduction:

- Providing crew awareness that a PSM exists
- Providing and linking to explicit procedures for the PSM
- Reducing the crew integration/interpretation tasks
- Increasing the time available to the crew
- Facilitating the crew response

Specifically, an explicit PSM annunciation that identifies the affected engine and guides the crew to an appropriate nonnormal checklist has potential to prevent/reduce ICR and mitigate the risk of crew error.

4.1.5.4 General and Specific PSM+ICR Safety Concerns From Event Analyses.

4.1.5.4.1 General Safety Concerns.

General PSM+CR-related safety concerns are as follows:

- Those PSMs that create or have potential to create significant thrust asymmetries—These are primarily PSMs that cause engine failure at high, low, and fixed power settings. Both powerloss and surge are engine fail low symptoms. Stuck throttle is an engine failed fixed. There was only one engine fail high event (runaway) in the AIA event database. This occurred on landing at thrust reverser deployment, which prevented deployment of the affected engine thrust reverser. There were three Stuck Throttle-related overthrust events, all on two-engine aircraft with autothrottle engaged. In the most notable event, a B737 on approach at 700 feet, a throttle stuck at medium power. To control speed, the autothrottle reduced the engine it could still control to idle. The crew, believing the engine at idle had flamed out, shutdown that engine and landed, thus operating the engine with the stuck throttle.
- SDGE on a two- or four-engine aircraft when one of the engines is malfunctioning—This significantly reduces available engine power and in the worst-case, results in an unpowered aircraft. Even when both engines are functioning normally, it reduces available engine power by 50% and unnecessarily increases the risk of unpowered flight. There were three such instances in the AIA report event database, all involving stuck throttles. Note that regardless of where the throttle was stuck (low or high), invariably, the crew shutdown the engine at the lowest or idle power.
- SDGE on a four-engine aircraft on the same side as a malfunctioning engine—This creates both the significant thrust asymmetry usually associated with LOC events, and the reduced power increased the risk concerns listed above.
- The presence or lack of PSM-related engine indications and annunciations appear to be contributing factors in UCRs to PSMs—Many events indicate that the presence or lack of PSM-related engine indications and annunciations is a contributing factor in UCR to a

PSM. In many cases, it appears that the crew does not initially know a PSM exists until the malfunction reveals itself at high power, through low airspeed, through unusual attitude, or some combination of the three. In other cases, the crew may know a PSM exists, but cannot determine, due to lack of information or time, the specific nature of the malfunction, which engine is malfunctioning, or the extent of the malfunction. Only a few events explicitly indicate or suggest that crews are misinterpreting PSM as some other event (e.g., bomb). However, anecdotal information indicates that misinterpretation and misdirection may often play a significant contributing role in UCR.

4.1.5.4.2 Specific CR Category Safety Concerns.

Specific concerns associated with each CR category are documented in the following paragraphs. In general, a consistent contributing factor is lack of crew awareness of the existence or location of a PSM, i.e., the absence of an explicit indication or annunciation that a PSM exists and which identifies the affected engine(s).

4.1.5.4.2.1 Loss of Control.

The principal concern associated with LOC is a PSM that results in significant thrust asymmetry combined with loss of airspeed and/or attitude control. The PSMs associated with HF LOC events are Powerloss and Stuck Throttle at low altitude in Climb, Descent, and Approach/Go Around phases of flight. In general, by the time the crew detects Thrust Asymmetry and attributes it to a PSM, the ICR has either occurred or is unavoidable, i.e., it is generally too late to prevent the ICR or significantly mitigate the situational risk.

4.1.5.4.2.2 Other Events.

The principal concern associated with Other events is PSM, where the crew fails to follow established procedure, e.g., engine shutdown/secure or RTO<V1. The cause of these CR is not clear, but it is suspected that the lack of PSM information may have played a role. The PSMs associated with HF Other events are Engine Fire, Powerloss, and Surge at low altitude in Takeoff Climb phase of flight.

4.1.5.4.2.3 Shutdown/Throttled Good Engine.

The principal safety concern associated with SDGE is shutting down the good engine on a two-engine aircraft. In general, when engine shutdown is intentional, this ICR can be attributed to the lack of knowing which specific engine is affected.

The one catastrophic HF event in this category occurred on a two-engine aircraft and involved a nonrecoverable engine surge that initiated at FL290. The crew reduced power to idle, then shutdown the good engine 2 minutes later. The malfunctioning engine failed on approach, and the crew was unable to restart the good engine before crashing short of the runway.

There are three other similar, but incidental, events in the SDGE category.

1. Event no. 42 (ID # 85/MWB/2/I). A B767-200 experienced engine stall/surge at FL390 with airframe buffet. The crew idled then shutdown the left engine and diverted. The left engine was restarted during driftdown (at or below FL290?). After landing, a borescope examination found nothing wrong with the left engine, but found a 13th and 14th stage high-pressure compressor damage on the right engine. It is unknown what would have happened had the crew not restarted the good engine and stressed the damaged engine on a single-engine approach.
2. Event no. 66 (ID #*93/MNB/2/I) illustrates an observed crew's tendency to unwittingly but inappropriately indict low-power versus high-power engine states. When presented with two engines operating at different power levels, e.g., one operating normally at low power and one failed at a higher-power state, event data indicate that crews often assume the low-power engine has failed subidle or flamed out. This UCR frequently occurs in Stuck Throttle and Engine Control Malfunction events and has been observed in other contexts. The no. 1 engine throttle on a B737-400 on final approach at 700 feet apparently stuck. To maintain approach speed, the autothrottle reduced the no. 2 engine throttle to idle. The crew apparently mistook the no. 2 engine thrust reduction as a flameout, shut the engine down, and landed with one engine.
3. In a post-AIA report event, a B777 on approach experienced a right engine control fault that resulted in the right engine failing fixed at intermediate power. To maintain speed, the autothrottle reduced the left engine power to idle. In response to the left engine at idle and the right engine failed fixed at higher power, the crew shutdown the left engine.

Notes: These three incidental events where the crew shutdown the good engine on a two-engine aircraft differ from the HF event of primary concern in that the PSM-affected engine was recoverable or remained useable, and in two of three instances, the crew was able to restart the good engine before landing.

Although autothrottle was a significant contributing factor in two of the events described above, the AIA report contains two similar Engine Shutdown events (no. 41 (ID #85/EWB/4/I-2) and no. 71 (ID #94/MWB/4/I) where the autothrottle was not engaged and crew throttle reduction and consequent engine indication changes were similarly misinterpreted. There are also events in other categories where the autothrottle was not engaged and falling engine indications were significant factors in the UCR that occurred.

A secondary concern associated with SDGE is, in general, shutting down any nonmalfunctioning good engine on a four-engine aircraft with a malfunctioning engine. Of more specific concern on four-engine aircraft is the thrust asymmetry associated with shutting down the nonmalfunctioning good engine on the same side as the malfunctioning engine.

4.1.5.4.2.4 RTO>V1.

The principal safety concern associated with RTO>V1 is RTO after liftoff. In general, this occurs because the crew believes the aircraft is not airworthy or capable of safe flight. In the AIA event data, there were no fatalities associated with RTOs that initiated on the ground. The general concern relates to the potential for runway excursion/overrun into irregular terrain, gear collapse, and striking an obstacle or obstruction causing cabin damage and fire.

4.1.6 Review and Analysis of Post-AIA Report PSM, IFSD, and PSM+ICR Data.

4.1.6.1 Propulsion System Malfunction Data.

The PSM data used in this report is limited to Boeing aircraft currently in production. How accurately the data represents the worldwide fleet PSM rate is uncertain. Follow-on research is proposed to validate the PSM data and related calculations in this section.

Reportable events and issues fall into one of several categories: General, Airplane Handling Characteristics and Performance, Structures, Occupant Safety, Mechanical Systems, Electrical Systems, and Propulsion Systems. Some events and issues repeat or clarify requirements that exist in Title 14 Code of Federal Regulations 21.3. Within the various categories, the following are among reportable events:

- Incorrect, misleading, or confusing Flight Deck indications that could have hazardous effects.
- Conditions resulting in serious injury to operator personnel or passengers.
- Any event where multiple systems have been involved that were intended to be independent and isolated.
- Uncontained high-energy rotor failures.
- Environmental, operational, or (common cause) failure conditions that adversely affected more than one engine, or that adversely affected one engine and could have adversely affected more than one engine. (Bird Strike events need not be reported under this item.)
- Failures or conditions that resulted in or could have resulted in an ignition source in a fuel tank.
- Engine separation, loss of thrust, loss of thrust control, uncommanded thrust change, engine flameout, or engine shutdown (other than normal shutdowns at the end of an operation).
- Failures or conditions that may significantly reduce propulsion system reliability or that may otherwise affect the safety of extended range missions.

PSM reports originate as Field Service telex messages. These telexes are processed and posted on a web-based bulletin board for 90 days, and then archived on a quarterly basis. On-site or regional field service representatives cover approximately 95% of Boeing’s customers, thus covering most of the Boeing in-service fleet. The PSM database contains data for all Boeing aircraft—in-production and postproduction.

4.1.6.1.1 2000 and 2001 Propulsion System Malfunctions.

Table 4-15 and figure 4-3 document reportable 2000 and 2001 Propulsion System Malfunctions. Table 4-15 contains the number of occurrences, the percent of total occurrences, and a calculated rate of occurrence for each malfunction. Figure 4-3 illustrates the number of occurrences of each malfunction.

TABLE 4-15. 2000 AND 2001 PROPULSION SYSTEM MALFUNCTIONS

PSM	Number of Occurrences	Percent of Total	Rate/Flight
Surge	227	26.2	1.28E-05
Oil System	182	21.0	1.03E-05
Powerloss	149	17.2	8.42E-06
High Vibration	63	7.3	3.56E-06
Light/Message/Indication	32	3.7	1.81E-06
Overheat	29	3.3	1.64E-06
Failed Fixed Thrust	27	3.1	1.53E-06
Engine Exceedances	26	3.0	1.47E-06
Bird Strike	24	2.8	1.36E-06
Engine Parameter Anomaly	23	2.7	1.30E-06
Fuel System/Fuel Leak	21	2.4	1.19E-06
Fire Warning (Actual)	18	2.1	1.02E-06
Inside Smoke/Fumes	14	1.6	7.91E-07
Fire Warning (False)	13	1.5	7.34E-07
Thrust Control Problem	5	0.6	2.82E-07
Other	5	0.6	2.82E-07
Autothrottle Anomaly	4	0.5	2.26E-07
Miscellaneous Fire System	3	0.3	1.69E-07
Fail High Thrust	2	0.2	1.13E-07
Total	867	100.0	4.90E-05

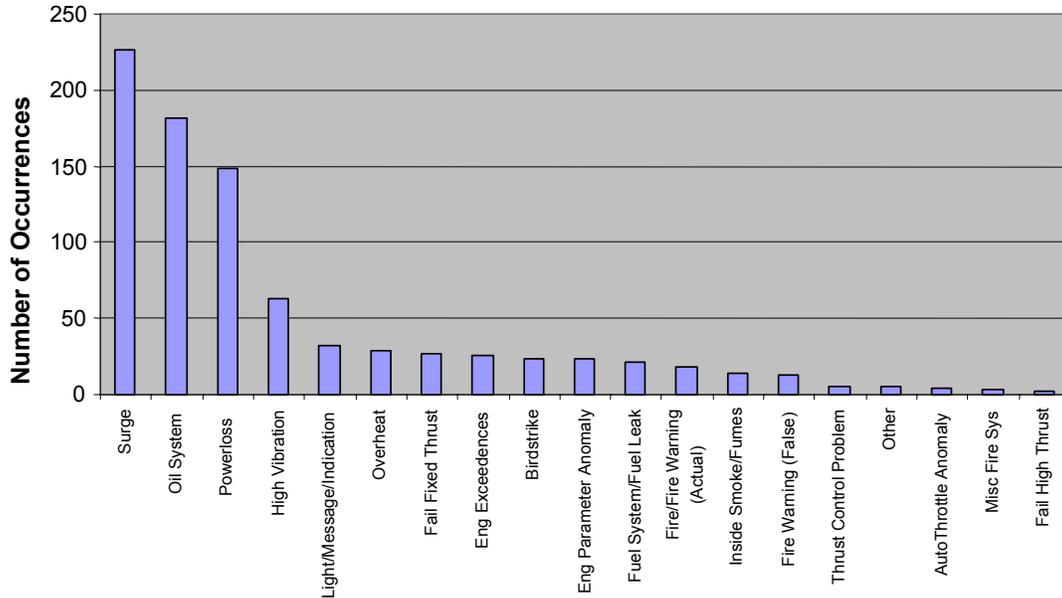


FIGURE 4-3. 2000 AND 2001 PROPULSION SYSTEM MALFUNCTIONS

To enable comparison of PSM and AIA report event data, PSM data was filtered to remove Preflight, Taxi, and Postflight malfunctions. In addition, certain PSMs were grouped into larger more general categories such as Powerloss.

Table 4-15 documents the overall likelihood of a PSM in the flight phases, where the occurrence of UCR is a safety concern, is on the order of 1 in every 20,000 flights. Table 4-15 documents and figure 4-3 illustrates the PSMs most likely to occur are Surge, Oil System, Powerloss, or High Vibration. Surge, Powerloss, and High Vibration are associated with such ICRs as RTO>V1, LOC, and SDGE. Notably, Oil System malfunctions are not significantly associated with ICR, even though 88% of the Oil System malfunctions result in IFSD.

4.1.6.1.2 Surge Recoverability and IFSD Analysis.

Table 4-16 and figure 4-4 document PSM Surge event data. Not all in-service Surge events on in-production Boeing aircraft are documented in the PSM data shown. Many minor Surge events occur without, and do not require, crew awareness. A meaningful surge is defined as a surge sufficient to get or require crew awareness or action. The Surge events in the PSM data were of sufficient magnitude and duration to get crew awareness and are, therefore, considered meaningful. The table and figure show that the percentages of recoverable (44.1%) and nonrecoverable (43.2%) surges documented in the PSM data are about equal. Approximately 43% of all surges listed are nonrecoverable. These nonrecoverable surges generally result in IFSD of the affected engine. Approximately 44% of all surges listed are recoverable. Observations regarding Surge events:

- Approximately 14% of all surges self-recovered without crew action. Surges that self-recovered without crew action generally involve no IFSD.

- Most, about 80%, of the recoverable surges (24% of all surges listed) that involve crew action to recover do not involve IFSD.
- About 20% of recoverable surges (6% of all surges listed) that involve crew action to recover also involve IFSD.
- About half of all Surge events (49.4%) involve IFSD of the affected engine. The potential to reduce the overall number of IFSDs associated with Surge events is limited to the 6% of overall Surge events involving both recoverable surge and IFSD.

TABLE 4-16. SURGE RECOVERABILITY AND IFSD ANALYSIS

Surge Type (R vs NR)	Number of Occurrences	Percent of Total
Nonrecoverable	98	43.2
Recoverable—Crew Action	69	30.4
Recoverable—No Crew Action	31	13.7
Recoverability Unknown	29	12.8
Total	227	
Recoverable—Crew Action: No IFSD	55	79.7
Recoverable—Crew Action: IFSD	14	20.3

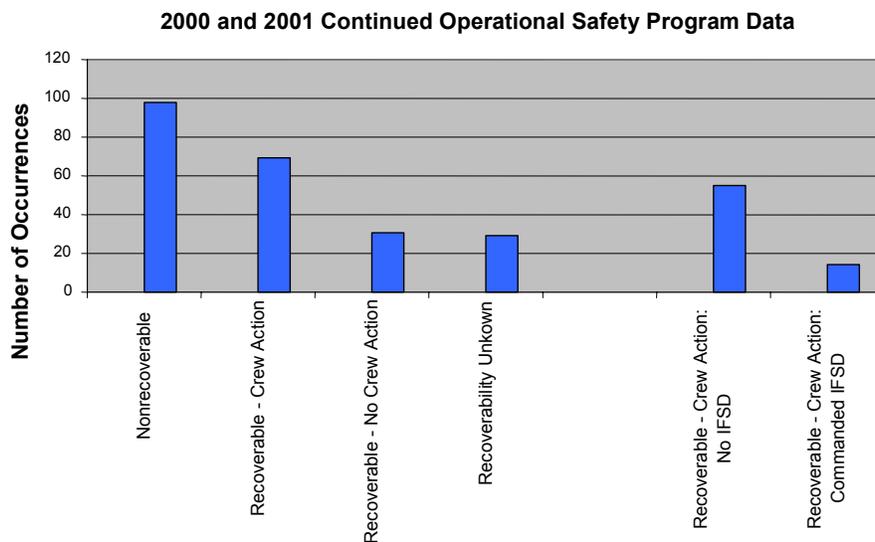


FIGURE 4-4. SURGE RECOVERABILITY AND IFSD ANALYSIS

4.1.6.1.3 Engine Powerloss/Failure Analysis.

Table 4-17 and figure 4-5 document Powerloss and Engine Failure event data. Most Engine Failure events result in powerloss. The table and figure show a breakdown of the events that have been generalized as Powerloss.

Most Powerloss events are engine flameouts (44.3%). Partial powerloss, powerloss to low thrust, and thrust shortfall account for 37.2% of Powerloss events. About 15% of Powerloss events involve failures at some fixed intermediate power level. Failed Fixed Thrust events have the potential to become either Overthrust or Underthrust conditions. Only about 1% of powerloss/engine failure events involve failure to a high-thrust condition.

TABLE 4-17. ENGINE POWERLOSS/FAILURE ANALYSIS

PSM	Number of Occurrences	Percent of Total
Flameout	81	44.3
Powerloss/Fail Low Thrust	38	20.8
Thrust Shortfall	30	16.4
Fail at Fixed Thrust	27	14.8
Fail High Thrust/Overspeed	2	1.1
Total	178	

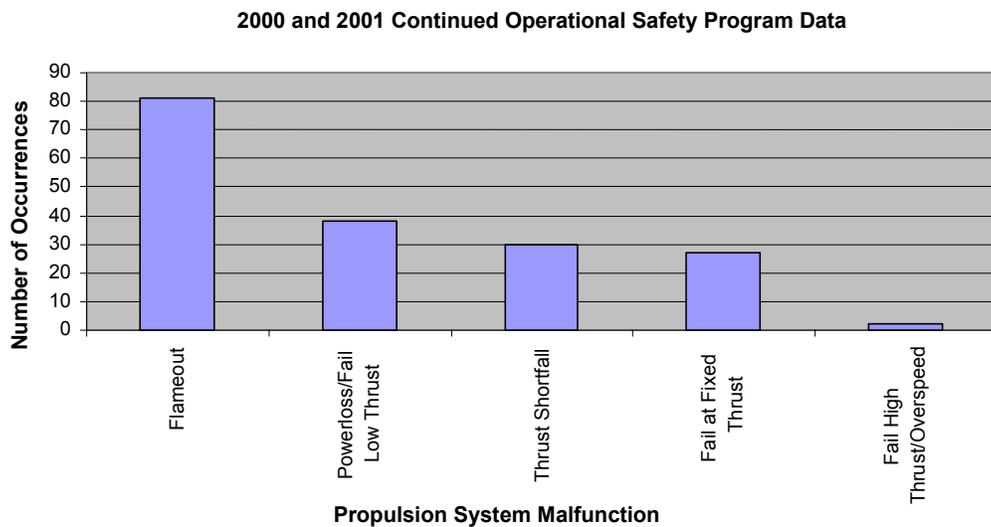


FIGURE 4-5. ENGINE POWERLOSS/FAILURE ANALYSIS

4.1.6.1.4 In-Flight Shutdown Analysis.

Table 4-18 and figure 4-6 document 736 PSM events and the number of IFSDs associated with each PSM type.

In-Flight Shutdown is defined as a cessation of engine combustion. IFSD may be crew commanded (e.g., via the fuel cutoff switch or fire handle) or may result directly from the PSM (e.g., flameout). Within the crew-commanded IFSD category, there are PSMs where the crew, by procedure, must shutdown the engine, e.g., Fire Warning. There are other PSMs where more crew discretion exists regarding IFSD, e.g., Oil System, Powerloss, Surge, and Vibration.

TABLE 4-18. 2000 AND 2001 IFSD ANALYSIS

PSM	Number of Events	IFSD	No IFSD	Unknown
Oil System	182	157	21	4
Nonrecoverable Surge	96	96	0	0
Powerloss/Thrust Control	90	32	5	53
Flameout	81	81	0	0
Recoverable Surge	69	14	55	0
Engine Vibration	63	47	14	2
Self-Recoverable Surge	31	0	31	0
Overheat Warning	29	7	22	0
Fire Warning	26	26	0	0
EGT Indication	17	6	10	1
Bird Strike	16	5	11	0
Fuel Leak	9	1	7	1
Start System	13	7	6	0
Bleed System	11	0	9	2
Thrust Reverser	3	1	2	0
Totals	736	480	193	63

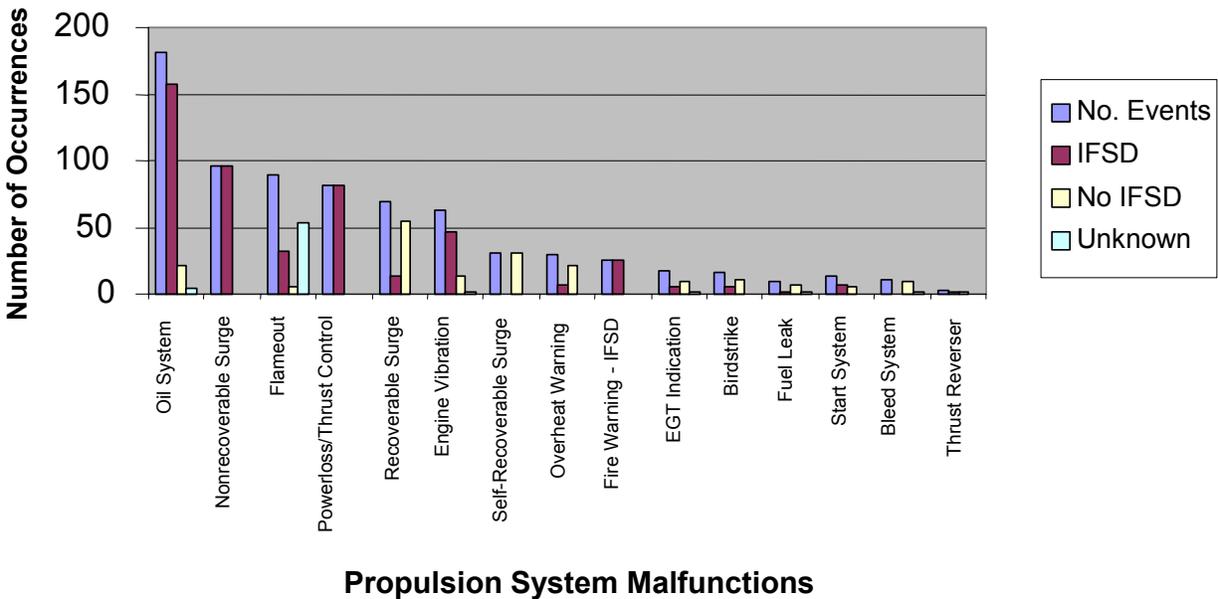


FIGURE 4-6. 2000 AND 2001 IFSD ANALYSIS

Not all the PSMs listed in table 4-15 were analyzed for IFSD. On-ground events were not included in table 4-18 and figure 4-6, e.g., eight RTOs were not included in Bird Strike and two landing roll reverse thrust events were not included in Nonrecoverable Surge. In addition, Flameout, which was included in table 4-15 as a powerloss, is treated separately in table 4-18 to differentiate non-crew-commanded from crew-commanded IFSD events.

Observations:

- Of the 736 PSM events (table 4-18):
 - 65% of the PSM events involved an IFSD—most were crew-commanded
 - 26% of the PSM events did not result in an IFSD
 - IFSD could not be determined in 9% of the PSM events
- Of the 480 (65%) PSM events that involved IFSD (table 4-18):
 - 33% of IFSDs (157 of 480) were Oil System-related
 - 56% of IFSDs (270 of 480) were Surge, Flameout, Vibration, or Powerloss-related
 - All Nonrecoverable Surge events involved IFSD
 - All Flameout events involved IFSD
 - Most High Vibration events involved IFSD
 - Where it can be determined, most Powerloss events involved IFSD. However, IFSD cannot be determined in more than half the Powerloss events.
- Of the 193 (26%) PSM events that involved IFSD (table 4-18):
 - None of the Self-Recoverable Surge events involved IFSD
 - Most Recoverable Surge, Bird Strike, and Fuel Leak events did not involve IFSD

The majority of In-Flight Shutdown events involved malfunctions associated with UCR, specifically Surge, Vibration, or Powerloss/Flameout.

4.1.6.1.5 Engine Restart Analysis.

IFSD events are derived from the PSM data. Part of the IFSD data includes a restart analyses based on PSM event and other data. Table 4-19 and figure 4-7 document and illustrate the total number of Boeing IFSDs reported from 1995 through 2001. The table and chart also document and illustrate

- The number of in-flight restart attempts and the number of successful in-flight restart attempts.
- Where no restart attempt was reported, a restart analysis based on event and postevent data that classifies each as restartable, nonrestartable, or unable to determine.

TABLE 4-19. 1995-2001 IFSD RESTART ANALYSIS

	1995-2001
Total IFSDS	1602
Restarts Attempted	140 (9%)
Successful Restart Attempts (63%)	88 (6%)
Unsuccessful Restart Attempts (37%)	52 (3%)
No Restart Attempt Reported	1462 (91%)
Analysis: Restartable (11%)	157 (10%)
Analysis: Nonrestartable (87%)	1268 (79%)
Analysis: Unable to Determine (2%)	37 (2%)

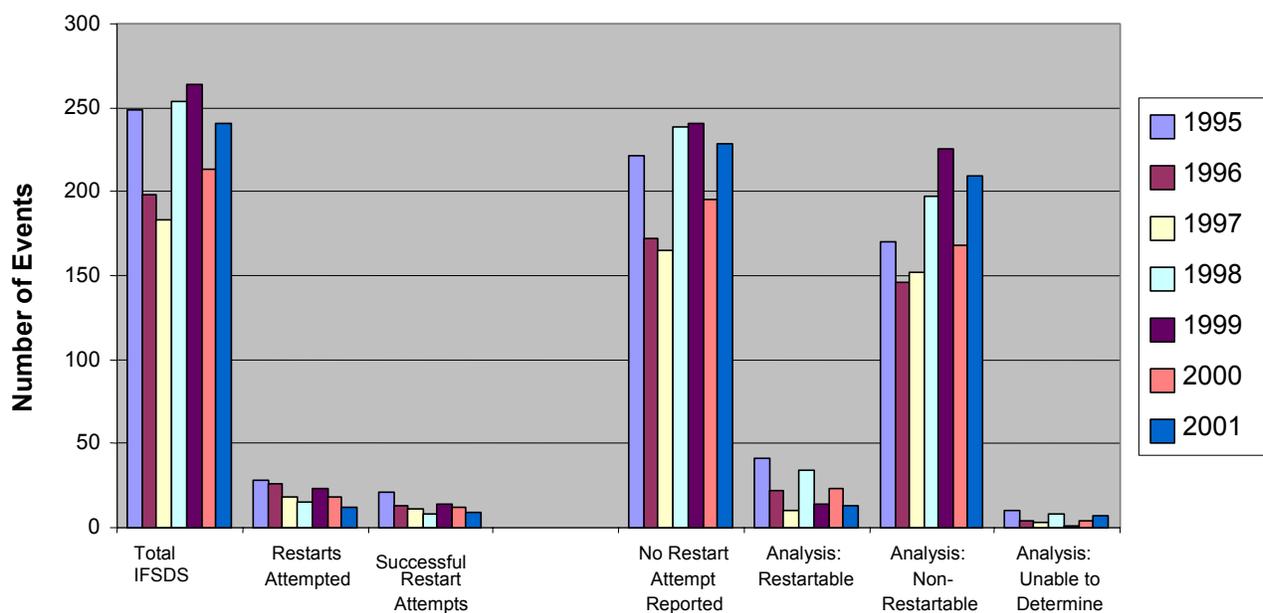


FIGURE 4-7. 1995-2001 IFSD RESTART ANALYSIS

In approximately 9% of the 1602 IFSD events listed, in-flight restart was attempted (140/1602). Sixty-three percent (88/140) of these in-flight restart attempts were successful (5.5% of the 1602 IFSDs).

In the 91% of the 1602 IFSDs where no restart attempt was reported (1472 events), by analysis

- 87% (1268/1472) were nonrestartable (79% of the 1602 IFSDs),
- 11% (157/1462) were restartable (10% of the 1602 IFSDs), and
- 2% (37/1452) were unable to determine (2% of the 1602 IFSDs).

Most (82%) IFSD events listed are not restartable (1320 of 1602). Only 15% of IFSDs are restartable (245 of 1602). Ninety-one percent of IFSD events did not involve a reported restart attempt. Nine percent of IFSD events involved a reported in-flight restart attempt—more than half (63%) of the restart attempts were successful.

As previously noted, the majority of IFSD events involved malfunctions associated with UCR. The IFSD restart data and analysis indicated that such malfunctions are typically nonrecoverable.

4.1.6.2 Post-AIA Report PSM+ICR Events on Boeing Aircraft.

The PSM and IFSD data reviews combined with anecdotal knowledge and ad hoc processes were used to identify 10 post-AIA Report PSM+ICR events in the period between 1996 and 2001: 2 H, 1 S, and 7 I. Three of these events, all incidents, were fuel leak- or fuel imbalance-related. These fuel events are listed separately below, and they are excluded from post-AIA report PSM+ICR rate calculations to allow comparison with the AIA report rates that also excluded such fuel-related events. Because the databases and processes used were Boeing-related, the results contain only Boeing aircraft. Similar post-AIA report PSM+ICR events are known to occur on other manufacturer's aircraft but are not documented here.

The remaining seven post-AIA report events involved two Other, two LOC, two SDGE, and one RTO>V1.

The following seven examples of in-service PSM+ICR events are arranged in chronological order of occurrence.

- An Other category RTO runway overrun involving loss of engine power during takeoff and resulting in aircraft hull loss (1996 H events).
- An Other category RTO runway excursion involving low-engine EPR indication and causing substantial aircraft engine damage (1997 S events).
- An LOC runway excursion during RTO involving an engine failed high (1997 H event).
- A SDGE during descent involving an overthrust condition where actual thrust failed to above-commanded thrust on one engine. The good/unaffected engine fuel control switch was selected off then on (1997 I event).
- An LOC shortly after takeoff involving compressor stall/surge, misidentification of the initial malfunction, and then failure to maintain directional and airspeed control. The initial malfunction was misidentified as gear/tire-related (1998 I event).

- A SDGE during a descent from FL410 involving an engine failed low. The crew was attempting to restart the left engine during this descent. Autothrottle reduction of power on the right engine was misinterpreted as a right engine flameout. About 8 seconds after the first attempt to restart the left engine, a rapid relight of the right engine was initiated (2000 I event).
- A RTO>V1 involving bird strike and associated high EGT. Takeoff was rejected at 149 knots, and the airplane came to a stop near the end of the runway with seven of the eight tires destroyed (2000 I event).

The following three events, all fuel leak- or fuel imbalance-related incidents, are excluded from post-AIA report PSM+ICR rate calculations to support comparison with the AIA report rates that also excluded such fuel-related events. Note, however, that these UCR fuel events exhibit the same underlying contributing factors of inadequate crew awareness, incorrect understanding, and incorrect response.

- A SDGE during descent due to suspected fuel leak. Visual Fluid indications near the engine turned out to be deicing fluid (2000 I event).
- An Other category fuel leak event involving failure to shutdown engine. The engine experiencing a significant fuel leak was not shutdown (2001 I event).
- An Other category fuel imbalance event involving inadvertent dual-engine shutdown during climbout. Flameout of both engines on a two-engine aircraft was inadvertently induced. Engine flameout was due to crew-induced suction feed combined with unweathered fuel (2001 I event).

Accident and incident event data indicate that UCR to PSM continues to occur in-service. But, as previously noted, there is no formal process that identifies and documents ICR in general, or PSM-related ICR in particular. These investigators estimate that

- most ICR-related events involving fatalities or hull loss are identified and documented in FAA and Boeing databases by the rigorous accident reporting and investigation protocols involved.
- approximately 75% of the ICR events involving substantial damage are identified and documented in FAA and/or Boeing databases by the reporting protocols involved.
- less than 50% of the incidental ICR events that occur in-service are identified and documented in FAA and/or Boeing databases and explicitly identified as inappropriate or UCR.

Based on these estimates, and the process by which the events listed below were gathered, it is certain that these 11 events do not accurately quantify post-AIA report PSM+ICR nor do they fully quantify and characterize UCR to malfunctions or conditions in other nonpropulsion airplane system areas.

4.1.6.3 The AIA Report PSM+ICR and 2000-2001 PSM Data Comparison/Analysis.

4.1.6.3.1 The AIA Report PSM+ICR and 2000-2001 PSM Data Comparison.

Table 4-20 and figure 4-8 document a comparison of AIA report PSM+ICR and 2000-2001 PSM data. Most major PSM occurrences correlate to AIA report PSM+ICR occurrences. The notable exception is Oil System malfunctions, which seldom involve, or are associated with, ICR. Note that the only AIA report Oil System-related PSM+ICR involved an air turn back that resulted in a rushed approach and long landing. Therefore, the single correlation between Oil System PSM and ICR is highly questionable. The Task 1.2 Operational Assessment will investigate the correlation between PSM and ICR correlations, or lack thereof.

TABLE 4-20. RELATIVE RANKING OF AIA PSM+ICR AND 2000-2001 PSM EVENT DATA

Primary PSM/Symptom	PSM+ICR Number of Occurrences	PSM+ICR Percent of Occurrences	2000-2001 PSM Number of Occurrences	2000-2001 PSM Percent of Occurrences
Surge	37	45.7	227	26.2
Oil System	1	1.2	182	21.0
Powerloss	25	30.9	149	17.2
High Vibration	4*	4.9	63	7.3
Light/Message/Indication	6	7.4	32	3.7
Overheat			29	3.3
Failed Fixed Thrust	6	7.4	27	3.1
Engine Exceedances			26	3.0
Bird Strike			24	2.8
Engine Parameter Anomaly			23	2.7
Fuel System/Fuel Leak			21	2.4
Fire/Fire Warning (Actual)			18	2.1
Inside Smoke/Fumes			14	1.6
Fire Warning (False)			13	1.5
Thrust Control Problem			5	0.6
Other	2	2.5	5	0.6
Autothrottle Anomaly			4	0.5
Miscellaneous Fire System			3	0.3
Fail High Thrust			2	0.2
TOTALS	81		867	

* From table 4-3, vibration was considered a primary PSM or symptom in events 32, 42, 55, and 57. However, vibration is known to be present in at least ten PSM+ICR events (32, 42, 46, 53, 55, 68, 73, 76, and 77).

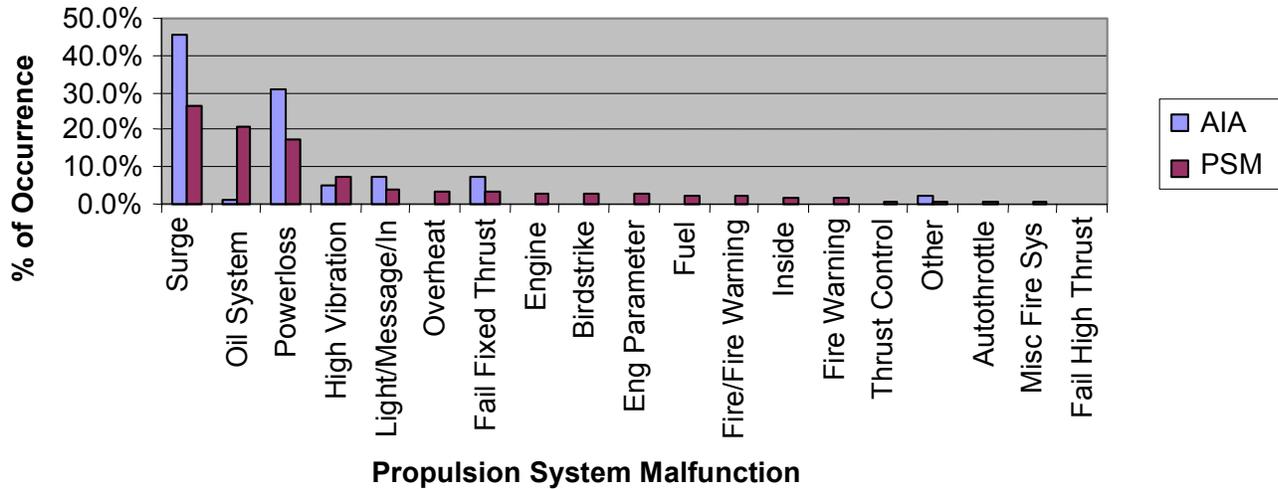


FIGURE 4-8. THE AIA REPORT PSM+ICR VERSUS 2000-2001 PSM EVENT DATA

4.1.6.3.2 AIA Report PSM+ICR and 2000-2001 PSM Data Analysis.

AIA PSM+ICR report and 2000-2001 PSM data were combined with fleet flight statistics to calculate various frequencies of occurrence and conditional probabilities of ICR and PSM. AIA PSM+ICR event data spanned 1968 through 1996. Conditional probability is defined as the probability of an UCR given a PSM. Per Western turbojet fleet statistics, the 308 million flights from 1958 through 1996 were used for the AIA PSM+ICR frequency calculations. The 17.7 million flights in 2000 and 2001 together with 2000 and 2001 PSM data were used for the PSM frequency calculations.

Table 4-21 documents the frequency all AIA report PSM+ICR event types (HF, H, S, and I), the frequency of 2000-2001 PSM events, and the current conditional probability of an ICR event in terms of PSM events.

Table 4-22 documents the frequency of Hull Loss type AIA report PSM+ICR events (HF and H), the frequency of 2000-2001 PSM events, and the conditional probability of a Hull Loss ICR event in terms of overall PSM events. Based on the investigation and reporting protocols associated with Hull Loss events, the values in table 4-22 are considered reasonably accurate estimates.

TABLE 4-21. THE PSM AND PSM+ICR FREQUENCY AND PROBABILITY OF HF, H, S, OR I EVENT

Primary PSM/Symptom	AIA PSM+ICR Frequency Per Flight	2000-2001 PSM Frequency Per Flight	Conditional Probability of ICR/PSM
Miscellaneous	6.5E-09	2.8E-07	1:44
Failed Fixed Thrust	2.0E-08	1.5E-06	1:79
Light/Message/Indication	2.0E-08	1.8E-06	1:93
Powerloss	8.1E-08	8.4E-06	1:104
Surge	1.2E-07	1.3E-05	1:106
High Vibration ³	1.3E-08	3.6E-06	1:274
Subtotal ¹	2.6E-07	2.84E-05	1:109
Total (All PSMs) ²	2.6E-07	5.0E-05	1:190

1. Subtotal based only on the PSM events listed in table 4-21.
2. Total based on the 81 AIA report PSM events listed in table 4-21 and the 867 PSM events listed in tables 4-15 and 4-20.
3. Vibration was considered a primary PSM or symptom in four events (32, 42, 55, and 57). However, vibration is known to be present in at least ten PSM+ICR events (32, 42, 46, 53, 55, 57, 68, 73, 76, and 77).

TABLE 4-22. THE PSM AND PSM+ICR FREQUENCY AND CONDITIONAL PROBABILITY OF HF OR H EVENT

Primary PSM/Symptom	AIA PSM+ICR Frequency	2000-2001 PSM Frequency	Conditional Probability of ICR/PSM
Miscellaneous	3.3E-09	2.8E-07	1:87
Failed Fixed Thrust	6.5E-09	1.5E-06	1:236
Powerloss	3.3E-08	8.4E-06	1:259
Surge	2.6E-08	1.3E-05	1:493
Light/Message/Indication	3.3E-09	1.8E-06	1:559
High Vibration ³	No H or HF events	3.6E-06	
Subtotal ¹	7.5E-08	2.84E-05	1:379
Total (All PSMs) ²	7.5E-08	5.0E-05	1:671

1. Subtotal based only on the PSM events listed in table 4-21.
2. Total based on the 81 AIA report PSM events listed in table 4-21 and the 867 PSM events listed in tables 4-15 and 4-20.
3. Vibration was considered a primary PSM or symptom in four events (32, 42, 55, and 57)—all incidental. However, vibration is known to be present in two HF events (53 and 77) and one H event (46).

4.1.6.3.3 Observations.

- The expected frequency of any AIA report PSM+ICR event (HF, H, S, or I) is $2.6E-07$ per flight, or approximately one event in every 3.8 million flights.
- The expected frequency of an AIA report PSM+ICR Hull Loss event (HF or H) is $7.5E-08$ per flight, or approximately one event in every 13.3 million flights.
- The expected frequency of any PSM is $5.0E-05$ per flight, or approximately one event in every 20,000 flights.
- The expected frequency of a Surge, Powerloss, High Vibration, Light/Message/Indication, Failed Fixed Thrust, or Miscellaneous PSM is $2.84E-05$ per flight, or approximately one event in every 35,211 flights.
- The conditional probability of any AIA report PSM+ICR event (HF, H, S, or I) per 2000-2001 PSM event is 1:109, or 1 PSM+ICR event in every 109 PSM events.
- The conditional probability of a AIA report PSM+ICR Hull Loss (HF or H) event per 2000-2001 PSM event is 1:379, or 1 PSM+ICR event in every 379 PSM events.

Failed Fixed Thrust, Powerloss, and Surge are among the most likely ICR-related PSM events to occur with Hull Loss.

Oil System PSM, although one of the most likely to occur, is one of the least likely to involve ICR.

The expected frequency of any AIA report PSM+ICR event (HF, H, S, or I) per flight is $2.6E-07$, or approximately one event in every 3.8 million flights. The likelihood of a Surge, Powerloss, High Vibration, Light/Message/Indication, Failed Fixed Thrust, or Miscellaneous PSM-related UCR is 1 per 109 such PSM events, or as stated, approximately one event in every 3.8 million flights.

The expected frequency of any AIA report PSM+ICR Hull Loss event (HF or H) per flight is $7.5E-08$, or approximately one event in every 13.3 million flights. The likelihood of Hull Loss due to Surge, Powerloss, High Vibration, Light/Message/Indication, Failed Fixed Thrust, or Miscellaneous PSM-related ICR is 1 per 379 PSM events, or as stated, approximately one event in every 13.3 million flights.

4.1.6.4 Post-AIA Report Data Summary, Calculations, and Comments.

4.1.6.4.1 General.

Post-AIA report data show that the same PSMs reported in the AIA event data are still occurring and are major contributors to the overall PSM rate. The 2000-2001 PSM data provide an overall perspective of the distribution and frequency of PSMs, in general, and of the PSMs associated with ICR in particular. The PSM data document PSMs that both are, and are not, associated with

ICR. This knowledge supports comparative analyses of the PSMs associated with ICR versus those that are not associated with ICR. Such comparative analysis helps validate the current understanding of PSM+ICR contributing factors and supports development and assessment of strategies for ICR prevention and risk mitigation.

The 2000-2001 PSM data does not specifically document or identify ICR events. The data reports system and component failures, and airplane or airplane system design, manufacturing, and operational issues. The data contains ICR events, but only incidentally, and not by design. ICR events in the data are not explicitly identified or easily distinguished. Because there is no formal process to document or quantify PSM+ICR, discovery is, therefore, primarily through anecdotal knowledge and ad hoc processes.

The list of post-AIA report PSM+ICR events in section 4.1.6.2 shows that all the same types of ICR observed in the AIA report data continue to occur in service: LOC, Other, SDGE, and RTO>V1. Additionally, in the Other category, the list documents Fuel System Leak and Imbalance-related ICR not reported in the AIA report. Specifically, the list includes engines leaking fuel not shutdown, good engines not leaking fuel intentionally shutdown for suspected fuel leaks, and good engines unintentionally shutdown by fuel system mismanagement during balancing.

The same type PSM+ICR events continue to occur in service: LOC, Other, SDGE, and RTO>V1. Ten post-AIA report PSM+ICR events were documented: four Other, two LOC, three SDGE, and one RTO>V1. The list contains Fuel System PSM-related ICR not reported or included in the AIA report data.

4.1.6.4.2 Post-AIA Report PSM+ICR Rate Calculations for Boeing Aircraft.

The following calculations are based on the seven post-AIA report events listed in section 4.2 (2 H, 1 S, and 4 I), and on 56,384,786 flights for all legacy Boeing aircraft from 1996 to 2001. As table 4-23 shows:

- The expected frequency of any post-AIA report PSM+ICR event (HF, H, S, or I) is $1.2E-7$ per flight, or approximately one event in every 8.1 million flights.
- The expected frequency of a post-AIA report PSM+ICR HF or H event is $3.5E-8$ per flight, or approximately one event in every 28.2 million flights.
- The expected frequency of a post-AIA report PSM+ICR S or I event is $8.9E-8$ per flight, or approximately one event in every 11.3 million flights.

Table 4-23 calculations indicate that the post-AIA report PSM+ICR rate for HF and H events has decreased by a factor of about 2.1, and overall decreased by a factor of about 2.2. Note, however, that the post-AIA report events are limited to Boeing aircraft. Both the AIA report and postreport S and I events are believed to be underreported and do not include fuel imbalance- and fuel leak-related events.

TABLE 4-23. THE AIA REPORT VERSUS POST-AIA REPORT PSM+ICR RATES

Hazard Level	AIA Report PSM+ICR Rate	Post-AIA Report PSM+ICR Rate
HF	3.9E-08 per flight (one event in every 25.7 million flights)	No HF Events
H	3.6E-08 per flight (one event in every 28 million flights)	3.5E-8 per flight (one event in every 28.2 million flights)
HF and H	7.5E-08 per flight (one event in every 13.3 million flights)	3.5E-8 per flight (one event in every 28.2 million flights)
S and I	1.9E-07 per flight (one event in every 5.3 million flights)	8.9E-08 per flight (one event in every 11.3 million flights)
HF, H, S, and I	2.6E-07 per flight (one event in every 3.8 million flights)	1.2E-7 per flight (one event in every 8.1 million flights)

4.1.7 Task 2.1 Report Conclusions and Recommendations.

The greatest potential for ICR prevention or mitigation is in the areas of Powerloss, Surge, and Failed Fixed Thrust, which are categorized as primary PSMs or symptoms. There is less potential for ICR prevention or mitigation in the area of High Vibration, which is typically considered a secondary PSM or symptom, and the potential for ICR prevention or mitigation has yet to be determined or demonstrated for Thrust Asymmetry, which is considered an airplane-level effect, not a PSM.

4.1.7.1 General.

The spreadsheet in appendix A contains selected event data from the AIA report event database. Additionally, it contains columns that document the event/data review. Specifically, these columns document the review assessment of PSM recoverability, and significance of indications, annunciators, thrust asymmetry, autopilot, and autothrottle to the crew response. Columns also document annunciation prevention potential and malfunction detection potential. This document provides traceability back to each event in the database and to the AIA report. The AIA Report Volume II contains detailed information and a narrative of each event organized by ICR and identified by event number. Appendix A and AIA Report Volume II can be correlated by event number.

In addition, there are two columns that output other tasks: (1) Potential Flight Deck PSM Annunciations and (2) Recommended Propulsion Detection/Investigation/Study PSMs.

- The Potential Flight Deck PSM Annunciations are output to task 1.2 for Operational Assessment of usefulness/effectiveness as Flight Deck PSM Indications or alerts. Where there are multiple potential annunciators listed for a given event, they are qualitatively ordered from most to least likely potential. Some are identified with question marks to indicate that their potential to effect positive change in crew response is considered questionable. Recommendations are summarized in the following section.

- The Recommended Propulsion Detection/Investigation/Study PSMs are output to task 5.1 for Malfunction Characterization and to task 5.2 for Malfunction Investigation/Study of detection potential. The recommendations are qualified wherever possible to identify the specific nature of the PSM to aid in selection of PSMs for investigation and study. Recommendations are summarized in a following section.

4.1.7.1.1 Potential Flight Deck Annunciation Recommendations.

The following are recommended for task 1.2 assessment for usefulness/effectiveness and acceptability as potential indications or alerts:

- Powerloss
 - Engine Failure (flameout or subidle)
 - Thrust Shortfall (commanded thrust greater than actual thrust)
- Surge
 - Self-Recoverable
 - Recoverable with crew action
 - Nonrecoverable
- Failed Fixed Thrust
 - Engine Failed Fixed Thrust (no response to throttle/commanded power)
 - Stuck Throttle (throttle split)
- High Engine Vibration
- Thrust Asymmetry

4.1.7.1.2 The PSM Characterization and Investigation/Study Recommendations.

The following recommendations are provided to support the task 2.1 input of safety concerns to task 5.1 and task 5.2. The PSMs listed are recommended for task 5.1 and task 5.2 to determine malfunction detection potential.

4.1.7.1.3 The PSM Characterization Recommendations.

It is recommended that Propulsion (task 5.1) characterize the following engine malfunctions:

- Recoverable and Nonrecoverable Surge at low (Flight Idle), medium (Cruise), and high (Takeoff and Climb) power settings to help determine the potential to detect these malfunctions and to help determine the potential to differentiate recoverable and nonrecoverable malfunctions at each of these power settings.

- Recoverable and nonrecoverable Powerloss at low (Flight Idle), medium (Cruise), and high (Takeoff and Climb) power settings to help determine the potential to detect these malfunctions and to help determine the potential to differentiate recoverable and nonrecoverable malfunctions at each of these power settings.
- Nonrecoverable Engine Fail Low (Thrust Shortfall and Subidle), Engine Failed Fixed (Thrust Shortfall or Excess), and Engine Fail High (Thrust Overthrust).

4.1.7.1.4 The PSM Investigation/Study Recommendations.

It is recommended that Propulsion (task 5.2) investigate/study high by-pass ratio turbofan engines for detection potential of the following PSMs:

- Recoverable and Nonrecoverable Surge at low (Flight Idle), medium (Cruise), and high (Takeoff and Climb) power settings to determine the potential to detect these malfunctions and to determine the potential to differentiate recoverable and nonrecoverable malfunctions at each of these power settings.
- Precursors to Recoverable and Nonrecoverable Surge. While there is potential for engine-related indication, annunciation, and procedure changes to influence/prevent ICR of RTO>V1, the potential is small and questionable. For RTO type events, a more effective strategy would be to detect and indicate/annunciate PSMs or impending surge well below V1. Investigation and analysis should examine engine operation and parameters in the seconds and minutes before the malfunction event to determine the feasibility/capability of detecting or predicting the malfunction event. Analysis should, for example, include and focus upon engine start, taxi, run-up to full thrust, and once at full thrust on the extended period before event onset.

The data indicated that Surge should be a task 5.1 and 5.2 study focus. SDTGE events from the PSM+ICR AIA report indicates that tasks 5.1 and 5.2 should select and analyze High By-Pass Ratio engine surge events, which initiate at Climb or Cruise power settings and which include engine data at lower and idle thrust settings.

The preponderance of NR engine malfunctions (hard failures of blades, seals, bearings, controllers, etc.) indicated that these should be subjects of analysis and study. Again, it is recommended that R and NR engine surges be separately and comparatively analyzed with focus on NR and differentiating R versus NR events. Finally, it is strongly recommended that investigation and analysis be conducted not just at takeoff but throughout the range of possible power settings.

LOC event data also indicated that tasks 5.1 and 5.2 should select and analyze engine powerloss, engine rundown, and failure events that initiate or occur at Climb or Cruise power settings and that include engine operation at lower and idle thrust settings. LOC event data also indicated that some attention should be focused on events that initiate at Takeoff power. It is, therefore, recommended that Takeoff power events also be used for purposes of comparing to the medium- and low-power events, and could be used as an alternative to medium and low-power events

provided they include sufficient engine data at intermediate and idle thrust settings to support analysis. Analysis indicated that R and NR engine powerloss, engine rundown, and failure should be separately and comparatively analyzed—with focus on NR and differentiating R versus NR malfunctions.

4.1.7.1.5 Miscellaneous Recommendations.

- A more comprehensive analysis of the Crew Error Classification versus HF events is recommended to provide the insight required to develop effective error prevention strategies and designs and assess their effectiveness.
- It is recommended that a formal process for reporting and documenting in-service ICR be developed and implemented. Existing databases should be evaluated for their ability to capture and identify ICR-related events.
- Follow-on research with Engine OEMs and airline operators is recommended to validate the PSM data rates, the PSM-based calculations, and the conclusions and recommendations in this report.

4.1.7.2 Traceability Task 2.1 Conclusions and Recommendations.

The spreadsheet in appendix A contains data selected from each of the 80 turbofan events in the AIA PSM+ICR Report event database. The event number for each event is included. Additionally, the spreadsheet tables contain columns that document the event/data review. Specifically, these columns document the review assessment of PSM recoverability and the significance of indications, annunciations, thrust asymmetry, autopilot, and autothrottle to the CR. In addition, the columns document the estimated ICR prevention potential of malfunction annunciations and the estimated malfunction detection potential. The event number provides traceability back to each event in the AIA PSM+ICR Report event database and the AIA report. Volume II of the AIA report contains detailed information and a narrative for each event—organized by ICR and identified by event number. The event number correlates the appendix A spreadsheet and AIA Report Volume II.

The spreadsheets also contain two columns that document task 2.1 output to other/subsequent contract tasks: (1) Potential Flight Deck PSM Indications/Annunciations and (2) Recommended Propulsion Detection/Investigation/Study PSMs. A subset of these PSMs has been recommended for top-level characterization.

The Potential Flight Deck PSM Indications/Annunciations are output to task 1.2 for Operational Assessment of Potential Flight Deck PSM Indications/Annunciations. Where there are multiple potential indications/annunciations listed for a given event, they are qualitatively ordered from most to least likely potential effectiveness. Some are identified with question marks to indicate their potential to effect positive change in CR is questionable.

The Recommended Propulsion Detection Investigation/Study PSMs are output to task 5.1 for malfunction characterization and to task 5.2 for Malfunction Investigation/Study of detection

potential. The recommendations are qualified wherever possible to identify the specific nature of the PSM to aid in selection of PSMs for investigation and study.

4.2 OPERATIONAL ASSESSMENT OF PSM ANNUNCIATIONS (TASK 1.2).

This section describes tasks and results involving operational assessment of potential PSM indications and annunciations.

4.2.1 Engine Indication and Crew-Alerting Systems.

Figure 4-9 illustrates the B777 flight deck layout. This layout is representative of Boeing commercial transport aircraft in general, and representative of the layout and location of engine and crew-alerting controls and indications in particular. Engine thrust and fuel control levers are located on the forward aisle stand. Engine start and other controls are typically located on the overhead panel. Engine indications are located on the center forward panel. Crew-alerting indications and controls are typically located on the forward and glareshield panels.

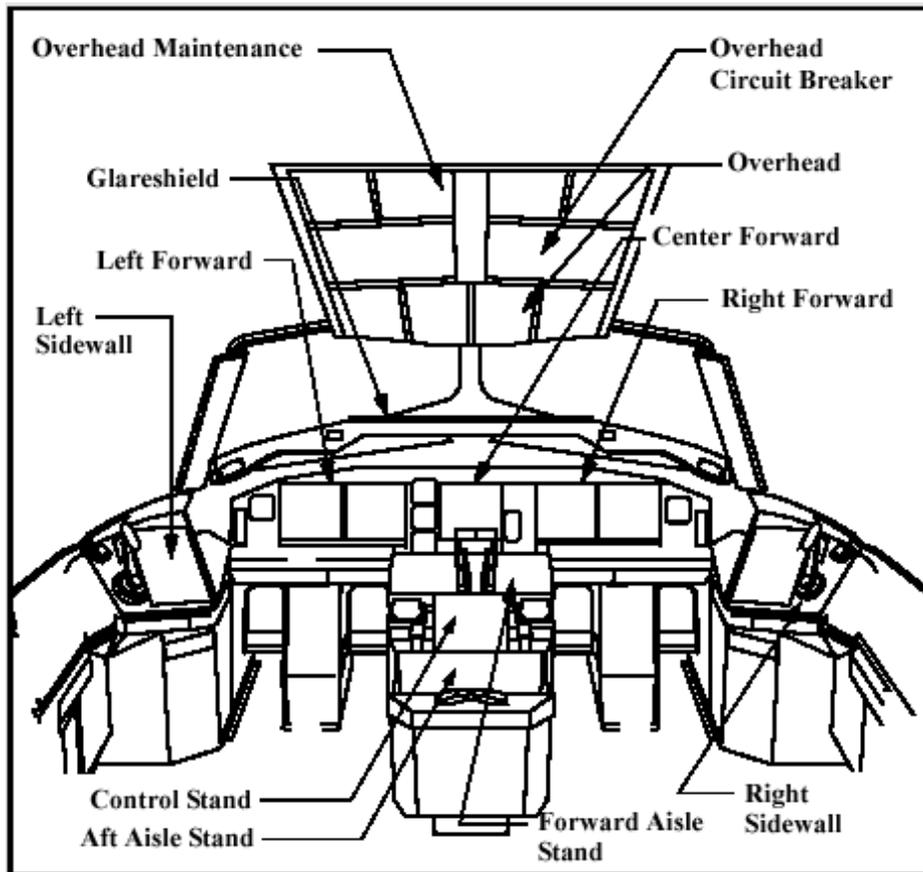


FIGURE 4-9. B777 FLIGHT DECK LAYOUT

Figure 4-10 shows the B777 flight EICAS display format. This format is representative of Boeing EICAS aircraft. EICAS is displayed on the center forward display.

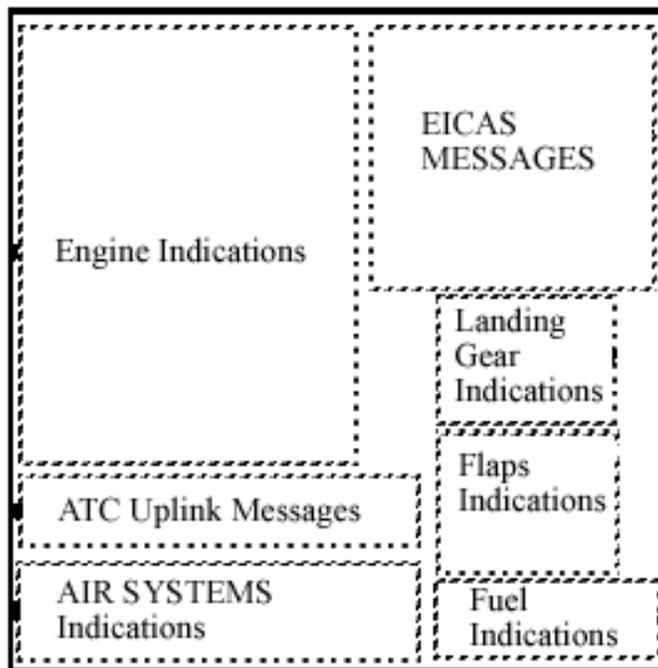


FIGURE 4-10. B777 EICAS DISPLAY FORMAT

The EICAS found on modern U.S.-built transport aircraft were introduced in the 1980s. The B757 and B767 were the first Boeing aircraft equipped with EICAS. EICAS was then implemented on subsequent Boeing aircraft. The B757/767, B747-400, and the B777, therefore, represent a chronological evolution and refinement of EICAS. Within a particular model, e.g., the B767, newer derivative versions like the B767-400 incorporate many of the refinements that were introduced on later aircraft such as the B747-400 and the B777. Generally however, differences within a particular aircraft model are minimized to keep commonality.

Engine indication and crew alerting differences across the various Boeing airplane models are factors that must be considered in analyzing engine malfunction-related UCR and in assessing potential remedies. Differences in crew alerting are most significant between the B737 and the EICAS airplanes (B747-400, B757, B767, and B777). Differences in crew alerting are relatively insignificant within the B737 model and within EICAS models.

Differences in engine indication are greatest within the B737 because the development of the various B737 models spans several decades. Differences in engine indication are less within the EICAS models, and less between the B737-600/700/800/900 and the EICAS models. The display-based indications on the B737-600/700/800/900, B747-400, B757, B767, and B777 enable a higher degree of cross-model commonality. Table 4-24 documents cross-model EICAS differences.

TABLE 4-24. CROSS-MODEL ENGINE INDICATION AND CREW-ALERTING SYSTEMS

Aircraft Model	Engine Manufacturer	Engine Indications	Alerting System	Number In-Service*
B737-200	P&W	Electro-Mechanical	Dedicated + Master Caution	1144
B737-300/400/500	CFMI	LED Module	Dedicated + Master Caution	1987
B737-600/700/800/900	CFMI	Electronic Display	Dedicated + Master Caution	1182
B747-400	P&W/GE/RR	Electronic Display	EICAS	581
B757/767	P&W/GE/RR	Electronic Display	EICAS	1880
B777	P&W/GE/RR	Electronic Display	EICAS	413

* Approximate Q4/2002.

4.2.2 Engine Indication System.

Four major transport category high-bypass turbofan engine manufacturers supply Boeing aircraft: Pratt & Whitney (P&W), General Electric (GE), Rolls-Royce (RR), and CFMI International (CFMI). P&W, GE, and RR are used on the B747, B757, B767, and B777 aircraft. P&W is used on the B737-200, and CFMI is used on the B737-300 and on subsequent B737 aircraft models.

P&W, GE, and CFMI engines are dual-rotor engines, meaning there are two distinct sets of rotating components. Therefore, on P&W, GE, and CFMI engines, two engine speeds are indicated: N1 and N2. RR engines are trirotor engines, meaning there are three distinct sets of rotating components. Therefore, on RR, three engine speeds are indicated: N1, N2, and N3.

P&W and RR use EPR as the primary thrust-setting parameter. GE and CFMI use N1 as the thrust-setting parameter and do not display EPR.

The following sections provide an overview of engine indications, indication enhancements, and indication annunciations on the B777 commercial transport airplane. The B777 was selected to overview because of the high degree of commonality between the modern engine indications on EICAS (B747-400, B757, B767, and B777) and B737-600/700/800/900 airplanes, and because the B777 represents the most current Boeing EICAS implementation.

Appendix F lists the B737-200, B737-300/400/500, B737-600/700/800/900, and B777 engine indications. The spreadsheet shows the historical evolution of engine indications and provide background and context, which support report discussions.

4.2.2.1 Engine Indications.

Engine indications may be discrete dedicated mechanical instruments/indicators, display-based indications, or a combination of dedicated indicators and display indications. On modern

transport category aircraft, display-based engine indications are categorized as either primary or secondary. Primary engine indications include the thrust-setting parameter and are displayed full-time. Secondary engine indications may or may not be displayed full-time. When not displayed full-time, secondary engine indications are pilot selectable and also automatically display for certain conditions.

4.2.2.1.1 Primary Engine Indications.

Figure 4-11 illustrates the full-time B777 primary engine indications display. The following indications are provided:

- EPR (Engine Pressure Ratio)—Primary Thrust Control on P&W and RR engines
- N1—Primary Thrust Control on GE and CFMI engines
- EGT

Note: Total Air Temperature and Thrust Reverser (in-transit and deployed) indications are also displayed on the primary engine indication display.

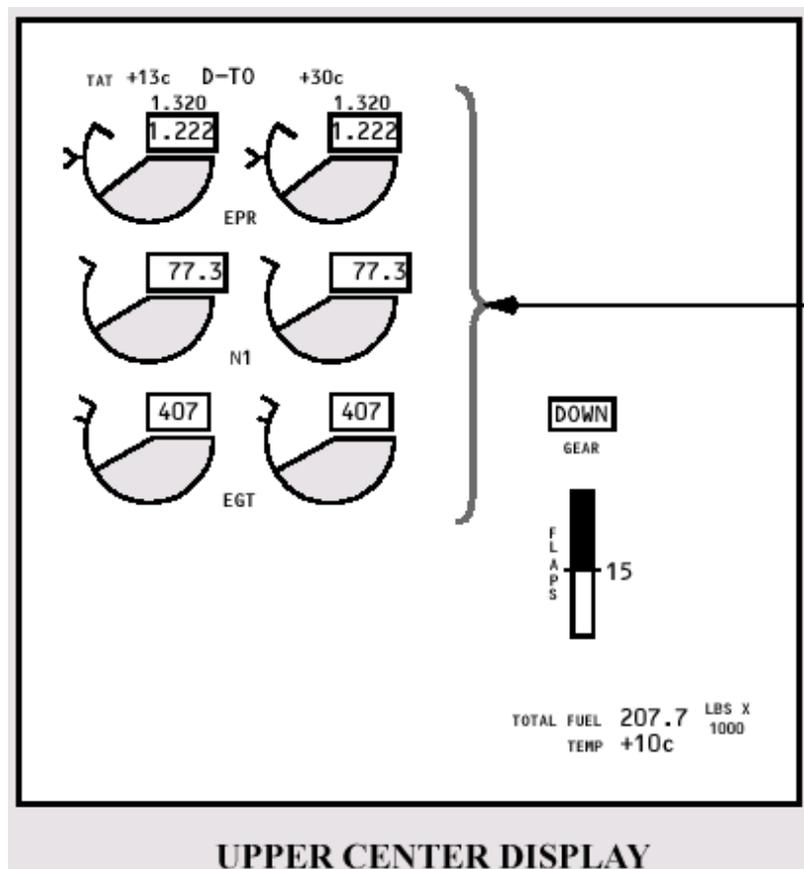


FIGURE 4-11. B777 PRIMARY ENGINE INDICATIONS

4.2.2.1.2 Secondary Engine Indications.

Figure 4-12 illustrates the part-time pilot selectable B777 Secondary Engine Indications display. The following indications are provided:

- N2 (Engine core speed. Engine intermediate spool speed on a three-spool engine.)
- N3—RR only. (Engine core speed on a three-spool engine.)
- Fuel Flow
- Oil Pressure
- Oil Temperature
- Oil Quantity
- Vibration

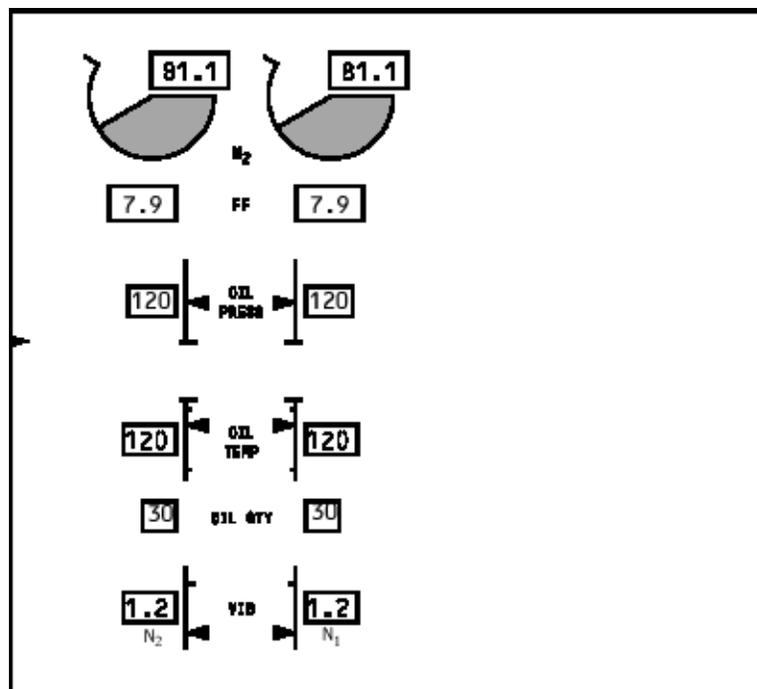


FIGURE 4-12. B777 SECONDARY ENGINE INDICATIONS

4.2.2.1.3 Additional Engine Indications/Parameters.

Additional engine parameters are available on other displays, but are provided for maintenance purposes, and are not intended for flight crew use. Generally, these parameters are available from the Electronic Engine Control (EEC) or FADEC. Certain parameters, e.g., Thrust Lever Angle, are indicated only on maintenance display formats and currently support engine indication features such as commanded thrust indication. Other parameters, alone or in combination, may be used to support potential new indications, new indication features, and new indication annunciations/alerts.

4.2.2.2 Engine Indication Annunciations and Alerts.

The following paragraphs summarize B777 airplane engine indication annunciations and alerts. With exceptions, the engine indication annunciations described are generally provided on all EICAS and B737-600/700/800/900 airplanes.

4.2.2.2.1 Automatic Display of Secondary Engine Indications.

The B777 and other EICAS airplane secondary engine indications are automatically displayed when:

- the displays initially receive electrical power.
- a FUEL CONTROL switch is moved to CUTOFF in flight.
- an engine fire switch is pulled in flight.
- a secondary engine parameter is exceeded.
- engine N2 or N3 revolutions per minute (rpm) is below idle in flight.

When the secondary engine parameters are automatically displayed due to any of the listed conditions, they cannot be cleared until the condition is no longer present.

B737 secondary engine indications are automatically displayed when

- the Common Display System initially receives power.
- selected by the Multifunction Display (MFD).
- in flight, an engine start lever moved to CUTOFF.
- in flight, an engine fails.
- a secondary engine parameter exceeds normal operating range.

When the secondary engine indications are automatically displayed, they cannot be cleared until the condition is no longer present.

4.2.2.2.2 B777 Engine Indications, Annunciations, and Alerts.

Commanded thrust is indicated for EPR (P&W and RR) and N1 (GE and CFMI). This indication is provided on the EPR or N1 indication on all EICAS and B737-600/700/800/900 airplanes.

The N1, N2, N3, EGT, oil pressure, and oil temperature indications have operating limits indicated by red lines. If one of these indications reaches the red line, the digital readout, box, and pointer change color to red for that indication. EPR exceedances are not annunciated. Note: If an N1, N2, N3, or EGT red line is exceeded, the box enclosing the digital readout remains red after the exceeded limit returns to the normal range. The red box color can be canceled to white or recalled to red by pushing the cancel/recall switch on the display select panel. An indication changes color back to white when it returns to the normal operating range.

The EGT indication has a maximum takeoff limit displayed by a red line. If EGT reaches the maximum takeoff limit, the digital indication, box, pointer, and dial all change color to red. The indication displays amber when maximum continuous limit is reached.

The oil pressure vertical indications have caution ranges displayed by amber bands. If oil pressure reaches the caution range, the digital readout, digital readout box, and pointer all change color to amber. An engine-specific EICAS caution alert is also provided—ENG OIL PRESS L/R.

The oil temperature vertical indications have caution ranges displayed by amber bands. If oil temperature reaches the caution range, the digital readout, digital readout box, and pointer all change color to amber. An engine-specific EICAS advisory alert is also provided—ENG OIL TEMP L/R.

For low oil quantity, the oil quantity digital readout changes to black text on a white background. The white text LO is displayed adjacent to the readout.

For high engine vibration, the vibration digital readout changes to black text on a white background.

4.2.2.2.3 B777 Engine Alerts.

Engine-specific EICAS alerts are provided for engine fail subidle, thrust shortfall, engine shutdown, low oil pressure, and high oil temperature. The following EICAS alerts are provided.

- ENG FAIL L or ENG FAIL R
- ENG THRUST L or ENG THRUST R
- ENG SHUTDOWN L or ENG SHUTDOWN R
- ENG OIL PRESS L or ENG OIL PRESS R
- ENG OIL TEMP L or ENG OIL TEMP R
- And alerts for various other engine system failures or nonnormal conditions and configurations.

4.2.2.2.4 B777 Compact Display Format.

In compact format, primary and secondary engine indications are combined on the same display.

4.2.2.2.4.1 Pratt & Whitney Engines.

The EPR and N1 displays are the same as the normal displays. All other indications change to digital readouts only. If an amber or red-line parameter for a digital indication is exceeded, the digital indication changes color to amber or red (as does the box that appears around an EGT or

an N2 indication for a red-line exceedance). If the EGT or N2 red line is exceeded, the red color of the box around the digital indication can be returned to white (if the exceeded parameter has returned to normal) by pushing the display select panel CANCEL/RECALL switch.

4.2.2.2.4.2 General Electric Engines.

The N1 and EGT indications are displayed as they are normally (moving pointer/round dial and digital indications). All other indications change to digital readouts only, with the exception that the N2 digital readout is boxed if a parameter is exceeded. If an amber or red-line parameter for a digital indication is exceeded, the digital indication changes color to amber or red (as does the box that appears around the N2 indication for a red-line exceedance). If the N2 red line is exceeded, the red color of the box around the digital indication can be returned to white (if the exceeded parameter has returned to normal) by pushing the display select panel CANCEL/RECALL switch.

4.2.2.2.4.3 Rolls-Royce Engines.

The EPR and N1 displays are the same as the normal displays. All other indications change to digital readouts only. If an amber or red-line parameter for a digital indication is exceeded, the digital indication changes color to amber or red (as does the box that appears around an EGT, N2, or N3 indication). If the N1, N2, N3, or EGT red line is exceeded, the red color of the box around the digital indication can be returned to white (if the exceeded parameter has returned to normal) by pushing the display select panel CANCEL/RECALL switch.

Primary and secondary engine indications are displayed on EICAS in compact format whenever:

- the secondary engine display is automatically selected and the lower MFD is failed, unpowered, or is occupied.
- the secondary engine display is manually selected to the lower center MFD, and when the lower MFD is failed, unpowered, or occupied with EICAS.

4.2.3 Crew-Alerting Systems.

The centralized crew-alerting systems (CAS) found on modern U.S.-built transport aircraft were introduced in the 1980s. These systems were based on FAA-funded research intended to standardize crew alerting. The B757 and B767 were the first Boeing aircraft to implement EICAS. The B747-400 was the first Boeing aircraft to implement EICAS as the primary means of crew alerting, and the B777 followed and further refined EICAS. The B737 is a pre-EICAS airplane and as such does not incorporate many of the CAS elements and features found in EICAS. However, the specific means of B737 crew alerting is equivalent to EICAS. Therefore, the differences are not detailed or compared. Both the EICAS and the B737 provide appropriate, acceptable, and effective crew alerting. Any proposed annunciations should be implemented in a manner consistent with the applicable aircraft indications and alerting systems.

The following sections provide an overview of the B777 CAS. The B777 was selected for overview because of the high degree of commonality between the EICAS airplanes (B747-400, B757, B767, and B777), because the B777 represents the most current Boeing EICAS implementation, and because the B777 CAS is the current baseline for future Boeing aircraft.

4.2.3.1 General.

The principal elements of centralized crew alerting on EICAS airplanes are

- A combined Master Warning Light (MWL)/Master Caution Light (MCL) and reset switch in the primary forward field of view. Two are installed: one located on the glareshield directly in front of each flight crew member. The upper half of this reset switch is a red indication light labeled WARNING. The lower half of this reset switch is an amber indication light labeled CAUTION. These lights illuminate whenever a warning or caution alert message is displayed in the EICAS message area. Pushing the reset switch extinguishes the light and in some warning cases silences the associated warning aural.
- Warning and Caution aural. A warning aural sounds whenever the MWL illuminates. A limited number of unique warning aural are used to differentiate certain warning groups, e.g., Bell for fires, Siren for configuration warnings, etc. An EICAS caution aural (four short consecutive beeps) sounds whenever the MCL illuminates. The same aural is used for all caution alerts.
- An EICAS message alert field, shown in figure 4-10. Alert messages are prioritized, time-ordered, and color- and position-coded. Alert messages can be cancelled and subsequently recalled.

4.2.3.2 Engine Indication and Crew-Alerting System Alert Levels.

The following definitions are used to establish the appropriate level and means of EICAS alerting for both airframe and nonairframe systems-related alerting. These alert-level definitions are consistent with B737 crew alerting.

- Time-critical warning alerts are used where immediate, usually memorized, flight path-related crew action is required. The aural component of time-critical warning alerts is a voice message such that secondary references are not necessary prior to taking action. The visual components are red. Typical time-critical warnings on EICAS airplanes consist of a red glareshield MWL, a synthetic voice aural, and an accompanying red text message on the PFD, e.g., WINDSHEAR or ENG FAIL.
- Warning alerts are used where immediate crew awareness and timely crew action is required. The visual components of warnings are red. The aural component of warning alerts is an aural tone. Typical EICAS warnings consist of a red glareshield MWL, an aural tone, and an accompanying red text message on the EICAS display.

- Caution alerts are used where immediate crew awareness is required and subsequent crew action may be required. The visual components of cautions are amber. The aural component of EICAS caution alerts is a single unique caution tone. Typical EICAS caution alerts consist of an amber glareshield MCL, a caution aural tone, and an accompanying amber text message on the EICAS display.
- Advisory alerts are used where routine crew awareness is required. Subsequent crew action may be required. The visual components of advisories are amber. There is no immediate awareness requirement and thus no aural component requirement for advisory alerts. Typical EICAS advisory alerts consist of an amber text message on the EICAS display, indented to differentiate amber advisory and caution EICAS messages.

4.2.3.3 Engine Indication and Crew-Alerting Systems Inhibits.

Nonnormal alert annunciations (indications, master warning/caution lights, aural tones, and messages) are partly or wholly inhibited during certain phases of operation, e.g., Pre- and Post-Flight, Engine Start, Engine Shutdown, Takeoff, and Landing. The purpose of such inhibits is to eliminate, operationally, unnecessary or inappropriate indications and to ensure the flight crew is not distracted during high workload critical phases of flight operation. Takeoff and landing inhibits, in particular, are used to guard against undesired flight crew responses such as RTO above V1 or unnecessary go-around on short final. The following sections document selected inhibits relevant to Task 1.2 Operational Assessment.

4.2.3.3.1 Takeoff Inhibits.

All advisory-level EICAS alert messages, MCLs, and caution aural are inhibited from 80 knots to 400' radar altitude or 20 seconds after rotation. Caution messages are not inhibited. An option is available to inhibit to 800' radar altitude or 30 seconds after rotation.

The MCLs and caution aural for engine failure are inhibited from 65 kts to 400'/800' radar altitude or 20/30 seconds after rotation. The engine failure voice alert, associated MWLs, and PFD ENG FAIL indications are inhibited beginning just prior to V1.

MWLs and aural are inhibited from V1 to 400' radar altitude or 25 seconds after inhibit begins. Warning messages are not inhibited. Takeoff configuration warning alerts (MWLs, aural, and messages) are inhibited from V1 to landing.

EGT indications are inhibited from changing to amber during takeoff or go-around for 5 minutes.

4.2.3.3.2 Landing Inhibits.

MCLs and caution aural are inhibited from 200' radar altitude to 75 kts for all but a selected set of caution alerts directly relevant to the approach and landing operation (e.g., AUTOPILOT, NO AUTOLAND, AUTOTHROTTLE DISC, SPEEDBRAKES EXTENDED, etc.). Caution messages are not inhibited.

4.2.3.3.3 Other.

In takeoff, landing, and other phases of flight, the automatic display of secondary engine indications varies between models. In general, the current design and operational philosophy is that amber (caution or advisory level) engine indication annunciations should not automatically display during takeoff. Secondary engine indications are generally automatically displayed for red exceedance (warning level) indications and for other conditions previously described.

Display (automatic or not) for vibration is implemented differently on different Boeing models due to differing vibration system designs and detection capabilities, the difficulty of establishing meaningful engine vibration annunciation levels, and operational concepts and FAA policies existing at the time of design certification. With possible exceptions, on the B757/767, the secondary engine indications are required to be displayed continuously during takeoff because there is no high vibration level established for automatic pop-up for vibration. On the B747-400, continuous display was considered undesirable, so a high vibration level was established and is automatically displayed during takeoff, or during any flight phase, for vibration at this level. On the B777, automatic display during takeoff for vibration was considered undesirable, so the automatic display for vibration is inhibited during takeoff (but is not inhibited for other phases of flight). On the B777, continuous display of the secondary engine indications is not required during takeoff.

4.2.4 Flight Deck Design and Operational Philosophy, Requirements, and Guidelines.

Appendix G contains a set of selected generalized flight deck design and operational philosophies and interface design requirements and guidelines applicable to transport category commercial airplanes. These selected objectives, guidelines, and requirements are applicable to the design and development of flight deck controls, indications, and annunciations in general, and engine-related indications and annunciations in particular. The objectives, guidelines, and requirements are also relevant to the operational assessment of new indications and annunciations intended to prevent or reduce engine malfunction-related UCR, and they are a basis for the conclusions and recommendations herein. The objectives, guidelines, and requirements are provided to aid in understanding how report conclusions and recommendations are reached. Also included in appendix G are applicable Title 14 Code of Federal Regulations* and Advisory Circular (AC) guidance. The following paragraphs contain key excerpts from appendix G.

4.2.4.1 Flight Deck Design and Operational Philosophy.

The operational hierarchy, listed in order of importance to flight safety, is:

- Flight path control
- Navigation/guidance

* Title 14 Code of Federal Regulations is referred to as Federal Aviation Regulations (FAR) herein.

- Aircraft separation
- Communication
- System operation

System designs should adhere to proven design concepts of simplicity, fault tolerance, error tolerance, and appropriate use of redundancy and automation.

Human engineering design principles should be used, and human factors considered, as part of the flight deck interface design process. These principles should be used to provide a safe, efficient, and comfortable working environment.

Crew Alerting and Systems design should correlate with Flight Crew Training philosophy. In particular, the Flight Crew Training philosophy is reflected in flight deck alerting and switch labeling. The training paradigm is to provide the flight crew with an appropriate awareness of nonnormal conditions, a procedure where crew action is required, and an accurate description of all systems controls and what they actually control. This philosophy paradigm provides accurate mental models of system state and configuration, what system controls actually do, and how each system fits into the overall architecture. Since it is not possible to provide checklist procedures for all conceivable situations, flight crews may have to use system controls for purposes other than the primary intended purpose. Accurate systems knowledge reduces the potential for erroneous use of controls in these unanticipated situations.

Alerting should be implemented based on a demonstrable need for crew awareness or action and minimal risk of inappropriate or undesired crew distraction, response, or desensitization.

Alert presentations must not degrade flight operations.

Flight deck design should optimize pilot workload. The design should allow pilots to focus on total flight operations rather than on subsystem monitoring, control, troubleshooting, or problem solving.

4.2.4.2 Flight Deck Interface Design Guidelines and Requirements.

The following are generalized flight deck interface design requirements and guidelines applicable to the development of engine indications and annunciations. These requirements and recommendations are also relevant to the operational assessment of new indications and annunciations and are a basis for the conclusions and recommendations herein.

- Primary flight and thrust controls must incorporate visual and tactile feedback to the flight crew.
- The consequences of false or nuisance alerting should be assessed, and the potential for false or nuisance alerting must be minimized.
- The consequences of failure to alert must be assessed, and the potential for failure to alert should be minimized.

- Alert presentations must provide combinations of visual, aural, or tactile elements to attract attention and define the alert condition sufficiently for appropriate crew action or awareness.
- Alert conditions must be indicated on the forward panels such that determination of when to take action can be made by the pilot without further reference.
- Alert annunciations must automatically clear when the alert condition no longer exists.
- System information should be automatically displayed, or be readily available, when the information is required to assess a failure or take action.

4.2.4.3 Applicable Federal Aviation Regulations.

4.2.4.3.1 Power Plant Instruments, FAR 25.1305.

FAR 25.1305 documents FARs applicable to Power Plant Instruments. The following FAR 25.1305 excerpts document-required power plant instruments applicable to this operational assessment.

25.1305 (c) For turbine engine-powered airplanes:

- (1) A gas temperature indicator for each engine.
- (2) A fuel flowmeter indicator for each engine.
- (3) A tachometer (to indicate the speed of the rotors with established limiting speeds) for each engine.

25.1305 (d) For turbojet engine powered airplanes:

- (1) An indicator to indicate thrust, or a parameter that is directly related to thrust, to the pilot. The indication must be based on the direct measurement of thrust or of parameters that are directly related to thrust. The indicator must indicate a change in thrust resulting from any engine malfunction, damage, or deterioration.
- (2) A position indicating means to indicate to the flight crew when the thrust reversing device is in the reverse thrust position, for each engine using a thrust reversing device.
- (3) An indicator to indicate rotor system unbalance.

4.2.4.3.2 Equipment, Systems, and Installations, FAR 25.1309.

The following applicable requirements are excerpted from FAR 25.1309.

FAR 25.1309, Equipment, Systems, and Installations:

- (a) The equipment, systems, and installations whose functioning is required by this subchapter, must be designed to ensure that they perform their intended functions under any foreseeable operating condition.
- (b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that:

- (1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and
 - (2) The occurrence of any other failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions is improbable.
- (c) Warning information must be provided to alert the crew to unsafe system operating conditions, and to enable them to take appropriate corrective action. Systems, controls, and associated monitoring and warning means must be designed to minimize crew errors which could create additional hazards.
- (d) Compliance with the requirements of paragraph (b) of this section must be shown by analysis, and where necessary, by appropriate ground, flight, or simulator tests. The analysis must consider:
- (1) Possible modes of failure, including malfunctions and damage from external sources.
 - (2) The probability of multiple failures and undetected failures.
 - (3) The resulting effects on the airplane and occupants, considering the stage of flight and operating conditions, and
 - (4) The crew warning cues, corrective action required, and the capability of detecting faults.

4.2.4.3.3 Cathode Ray Tube Certification, AC 25-11.

AC 25-11 provides guidance for certification of cathode ray tube (CRT)-based electronic display systems used for guidance, control, or decision-making by the pilots of transport category airplanes. The AC states in paragraph 4.a “The use of electronic displays allows designers to integrate systems to a much higher degree than was practical with previous airplane flight deck components. With this integration can come much greater simplicity of operation of the airplane through automation of navigation, thrust, airplane control, and the related display systems.”

Information Separation g. Attention-Getting Requirements. (1) Some electronic display functions are intended to alert the pilot to changes: navigation sensor status changes (VOR flag), computed data status changes (flight director flag or command cue removal), and flight control system normal mode changes (annunciator changes from armed to engaged) are a few examples. For the displayed information to be effective as an attention-getter, some easily noticeable change must be evident. A legend change by itself is inadequate to annunciate automatic or uncommanded mode changes. Color changes may seem adequate in low light levels or during laboratory demonstrations but become much less effective at high ambient light levels. Motion is an excellent attention-getting device. Symbol shape changes are also effective, such as placing a box around freshly changed information. Short-term flashing symbols (approximately 10 seconds or flash until acknowledge) are effective attention-getters. A permanent or long-term flashing symbol that is noncancellable should not be used.

4.2.5 Operational Assessment.

Task 2.1 identified the following propulsion system malfunctions, symptoms, and effects as potential flight deck annunciations for operational assessment of their potential to prevent or reduce the occurrence of PSM+ICR events.

- Powerloss—Engine Failure (subidle/flameout/etc.) or Thrust Shortfall (commanded thrust > actual thrust)
- Surge—Recoverable with Crew Action or Nonrecoverable
- Failed Fixed Thrust—Stuck Throttle, Thrust Shortfall (commanded thrust > actual thrust), Overthrust (commanded thrust < actual thrust)
- High Vibration
- Thrust Asymmetry

These potential annunciations are applicable to all flight phases and power settings in general, and to Takeoff Climb, Cruise, and Approach/go-Around flight phases and power settings in particular. Alert annunciations during takeoff roll above V1, during takeoff climb, and during approach and landing are often inhibited or limited because of their potential to unnecessarily distract the crew and prompt undesired RTO above V1, or unnecessary Go-Around.

The following sections reiterate the safety concerns identified in task 2.1, provide additional task 2.1 data analysis, and assess the potential of the annunciations listed above to address UCR to engine malfunctions. Additional sections assess existing annunciations and the benefits and risks associated with new/additional annunciations.

4.2.5.1 Safety Concerns and Focus—Task 2.1 Data Analysis.

As noted in the task 2.1 report: For the purposes of hazard analysis, the number of fatalities was considered the primary objective measure of the actual and potential hazard, and the potential safety benefit, associated with each ICR category.

Twelve of the 81 AIA PSM+ICR Report events involved fatalities. Table 4-25 summarizes these HF events by crew response category and associated malfunctions. The table is organized from most to least number of HF events. For Powerloss and Surge events, the primary malfunction is listed first, with secondary or consequential malfunction listed second. Most, but not all, LOC and Other events involved no survivors. Most of the people involved in the RTO>V1 event survived.

Table 4-25 shows that for HF events:

- Powerloss is associated with LOC, Other, and SDGE events—the three crew response categories, which account for the majority of HF events and fatalities. Powerloss is not associated with RTO>V1 HF events, and is not the primary PSM in Shutdown Good Engine HF events.
- Surge is associated with all types of HF crew response events. Surge is not the primary PSM in LOC HF events.

- Stuck Throttle, which is equivalent in important respects to engine failed fixed thrust, is associated primarily with LOC HF events.

TABLE 4-25. INAPPROPRIATE CREW RESPONSES TO PSMs AND ASSOCIATED SAFETY DATA

CR	Propulsion System Malfunction	Number of HF Events	Number of Fatalities
LOC	Powerloss w/Surge (Engine Fail Low)	5	135
	Stuck Throttle (Engine Failed Fixed Thrust)	2	201
Other	Powerloss w/Surge (Engine Fail Low)	2	9
	Surge w/Powerloss (Engine Fail Low)	1	35
SDGE	Surge w/Powerloss	1	47
RTO>V1	Surge	1	3

Table 4-26 summarizes each HF event. Within each category of crew response, the table is organized first by phase of flight and then by the altitude at which the malfunction occurred. The AIA report event number is listed along with a brief narrative and an estimate of the crew response prevention potential and malfunction detection potential.

Table 4-26 shows that the HF events listed occur in Takeoff Climb, Cruise Climb, Descent, and Approach/Go-Around. However, most events occurred in the Takeoff Climb phase (8 of 12), and most of those occurred below 400 feet AGL (5 of 8). The flight phase distribution of HF malfunctions and events is representative of the overall AIA report events in general. Therefore, addressing the HF events in particular is expected to address AIA report events in general.

As table 4-26 shows, in most cases, the degree of malfunction awareness cannot be determined from event data. However, it can often be inferred from event data that the crew was initially either unaware that a PSM existed, unaware of the specific engine affected, or unaware of the nature of the PSM. For example, in the SDGE case listed in table 4-26, the crew was aware of a malfunction, but unaware of which engine was actually affected.

Of the 12 HF events in table 4-26, 58% (7 of 12) occurred outside the EICAS alert takeoff and approach phase inhibits, described in section 4.2.3.3. The remaining 42% of events (5 of 12) occurred within the EICAS alert takeoff inhibit period. Therefore, EICAS alerts in general, and EICAS alert attention getters such as the MCLs and aural in particular, are available in the majority of these events. For those events occurring during EICAS alert inhibits, the engine indication annunciations, it is envisioned, could accompany and complement each alert and might provide sufficient crew awareness to produce the desired crew response. However, such indication annunciations could only be provided if implemented in a manner that would acceptably minimize the risk of them causing an RTO>V1 or other UCR.

TABLE 4-26. INAPPROPRIATE CREW RESPONSES TO PSMs AND ASSOCIATED EVENTS

LOC					
No. of Engines	Flight Phase (Altitude)	Malfunction	Recoverability	Malfunction Awareness	Number of Fatalities
2	T/O Climb (UNK Low >L/O)	Powerloss (Engine Fail Low)	NR	Yes	7
No. 34. Engine no. 1 failed shortly after takeoff. Crew rushed air turn back, selected flaps and gear down simultaneously and attempted a downwind landing. Banking to final approach, the aircraft wingtip contacted the ground and the airplane crashed. No Prevention potential. Detection potential.					
4	T/O Climb (UNK Low >L/O)	Powerloss w/Surge (Engine Fail Low)	UNK	UNK	3
No. 37. The airplane had aborted takeoff and returned to hanger for engine maintenance because the no. 4 engine was making popping sounds above 1.7 EPR. Cargo was offloaded and after takeoff the airplane veered to the right and crashed. Prevention potential unknown. Detection potential unknown.					
2	T/O Climb (450')	Powerloss (Engine Fail Low)	NR	UNK	31
No. 43. After takeoff, smoke and fire were reported coming from the right engine. The aircraft climbed to 700 feet AGL then rolled into a steep bank and crashed on airport property in a nose-down attitude. Catastrophic engine failure was listed as a contributing factor. Prevention potential unknown. Detection potential.					
2	T/O Climb (1500')	Stuck Throttle (Engine Fail Fixed at Mid Power)	R	No	60
No. 74. With autothrottle engaged, R throttle stuck above climb power which caused L throttle to move to idle over a 42-second period. Bank angle increased due to thrust asymmetry and aircraft rolled, inverted, and nose-down crashed at high speed. Prevention potential. Detection potential.					
2	Descent (7200')	Stuck Throttle (Engine Fail Fixed at Idle Power)	R	No	141
No. 61. With autopilot and autothrottle engaged, R throttle stuck at idle on level off. As L engine power increased, autopilot compensated with aileron. As L engine thrust approached 80%, the airplane began to bank right. Passing 50 degrees right bank, right roll control wheel input occurred and the right throttle was advanced. With symmetrical thrust, right bank continued to increase and the airplane crashed at high thrust, high speed, in a nose-low 155 degree right bank. Prevention potential. Detection potential.					
2	Approach/Go-Around (200')	Powerloss w/Surge (Engine Fail Low)	NR	UNK	71
No. 77. Structural failure of first stage compressor blade led to powerloss. Crew initially unaware of engine malfunction and single-engine operation, allowed irreversible loss of airspeed. Event data indicates that the engine malfunction initiated on approach. Prevention potential. Detection potential.					
2	Approach/Go-Around (300')	Powerloss (Engine Fail Low)	UNK	UNK	23
No. 10. Crew initiated go-around. Loss of thrust/engine failure contributed to loss of control. It is assumed that the crew did not initially realize that an engine malfunction existed. Prevention potential. Detection potential.					

TABLE 4-26. INAPPROPRIATE CREW RESPONSES TO PSMs AND ASSOCIATED EVENTS (Continued)

Other					
No. of Engines	Flight Phase (Altitude)	Malfunction	Recoverability	PSM Awareness	Number of Fatalities
4	T/O Climb (125')	Powerloss w/Surge	UNK	UNK	4
No. 81. After takeoff, the aircraft apparently failed to climb and struck a radio mast on rising ground about 4.5 miles beyond the end of the runway. Report stated the no. 4 engine may have failed and the cowl from the no. 3 engine was found on the runway. Prevention potential unknown. Detection potential unknown.					
2	T/O Climb (300')	Surge w/Powerloss (Dual Engine Fail Low)	UNK	UNK	35
No. 51. Both engines began continuous surge due to bird strike shortly after liftoff. A climb to 1400 feet AGL was accomplished, but both engines quit running during the following air turn back and the aircraft crashed in a clearing. Prevention potential. Detection potential.					
4	T/O Climb (2000')	Powerloss w/Surge (Engine Fail Low)	NR?	UNK	5
No. 1. The no. 2 engine failed 1 minute after takeoff. Compressor disk cut the fuel line resulting in a fuel fire, and the crew failed to close the pylon shutoff valve and failed to shutoff the boost pumps. On approach, the no. 3 engine fell off. Prevention potential unknown. Detection potential unknown.					
SDGE					
No. of Engines	Flight Phase (Altitude)	Malfunction	Recoverability	PSM Awareness	Number of Fatalities
2	Cruise Climb (29,000')	Surge	NR	Yes	47
No. 53. Approaching 29,000 feet in climb, the left engine surged. Crew reduced power on both engines, declared an emergency, and subsequently shutdown the right engine believing it to be the affected engine. On approach, the left engine failed after power was increased. Attempt to restart the right engine was unsuccessful and the aircraft crashed short of the runway. Prevention potential. Detection potential.					
RTO>V1					
No. of Engines	Flight Phase (Altitude)	Malfunction	Recoverability	PSM Awareness	Number of Fatalities
3	After Liftoff (9')	Surge w/Powerloss	NR	UNK	3
No. 78. Shortly after rotation and liftoff, a loud bang and powerloss occurred, and the flight crew aborted the takeoff. Prevention potential unknown. Detection potential.					

4.2.5.2 Inappropriate Crew Response Prevention Potential.

Prevention potential is the estimated opportunity, through PSM annunciation, to prevent or mitigate ICR by providing timely awareness, correct understanding, and linkage to the appropriate nonnormal procedure. As previously noted in the task 2.1 report, the LOC, SDGE, and Other event data suggest that annunciations that identify the presence of a PSM, identify the affected engine(s), and identify the specific type of PSM offer potential for ICR prevention and risk mitigation.

The determinations of prevention potential in this report are best estimates made based on available and often limited data and somewhat subjective judgments. The judgment that prevention potential exists, indicates only that opportunity appears to exist and that prevention may be possible. Uncertainty as to the degree of prevention potential exists in all cases where prevention potential has been identified. While it may appear possible that malfunction annunciation has the potential to prevent PSM-related ICR, there is no unequivocal certainty that malfunction annunciation would prevent these events. Where prevention potential has been identified, the degree of potential may range from low to high. Therefore, positive assessments of prevention potential should not be interpreted to mean that the event would have been prevented. In all cases where prevention potential has been judged to exist, it means that only the event might have been prevented.

Note that the following assessments of prevention potential are made only with respect to malfunction annunciation. Where malfunction annunciation potential has been assessed to exist, there may be other, alternative interventions with equal or greater prevention potential. Where malfunction annunciation potential has been assessed to not exist, there may be other interventions that do provide prevention potential.

4.2.5.2.1 The AIA Report HF and H Event Prevention Potential Assessment.

Table 4-27 documents the estimated potential for malfunction annunciations to prevent or reduce the occurrence of UCR in the AIA report HF and H events.

- 43% of the HF and H events (10 of 23) are estimated to have prevention potential.
- 30% of HF and H events (7 of 23) appear to have no prevention potential.
- Prevention potential could not be determined in 27% of events (6 of 23) and was, therefore, listed as unknown.
- HF events with prevention potential account for 88% of all PSM+ICR-related fatalities (377 of 430).

Table 4-27 also documents the estimated malfunction detection potential. It is estimated that the majority of malfunctions are detectable. The principal detection issue is reliable and meaningful detection, particularly in the case of surge. Note that the estimated potential for malfunction detection does not include or represent an assessment of detection reliability.

Tables 4-28, 4-29, and 4-30 correlate malfunction, crew response, and estimated prevention potential. The tables summarize the estimated potential malfunction annunciations have to prevent or reduce the UCRs associated with HF and H events. Cases where the prevention potential could not be determined (i.e., was indeterminate) are also included to show where additional prevention potential might exist.

TABLE 4-27. ESTIMATED ICR PREVENTION POTENTIAL—AIA REPORT HF AND H EVENTS

No. and Type of Events	Crew Response	Crew Response Prevention Potential	Malfunction Detection Potential ¹
12 HF	7 LOC 3 Other 1 SDGE 1 RTO>V1	6 (50%) With Prevention Potential 1 (8%) No Prevention Potential ² 5 (42%) Unknown Prevention Potential	10 (83%) With Detection Potential 2 (17%) Unknown Detection Potential
11 H	2 LOC 3 Other 1 TGE 5 RTO>V1	4 (36%) With Prevention Potential 6 (55%) No Prevention Potential ² 1 (9%) Unknown Prevention Potential	7 (64%) With Detection Potential 2 (18%) Unknown Detection Potential 2 (18%) Not Applicable

1. Does not include, consider, or assess the reliability with which detection could be accomplished. Includes three special cases where the relationship between malfunction and CR is questionable, and three RTO>V1 events.
2. Assessments do not include, or rule out, prevention potential from other kinds of interventions.

TABLE 4-28. ESTIMATED ICR PREVENTION POTENTIAL—12 AIA REPORT HF EVENTS

	7-LOC 4 PP, 1 NP, 2 IP	3-Other 1 PP, 2 IP	1-SDGE 1 PP	1-RTO>V1 1 IP
Powerloss (Fail Low)	2 x	x		
Surge	X	1 x	1	x
Stuck Throttle (Fail Fixed)	2			

PP=Prevention Potential. NP=No Potential. IP=Indeterminate Potential. x= Indeterminate Potential.

TABLE 4-29. ESTIMATED ICR PREVENTION POTENTIAL—11 AIA REPORT H EVENTS

	2-LOC 1 PP, 1 NP	3-Other 1 PP, 1 NP, 1 IP	1-TGE 1 PP	5-RTO>V1 1 PP, 4 NP
Powerloss (Fail Low)	1			1
Surge		1 x	1	
Stuck Throttle (Fail Fixed)				

PP=Prevention Potential. NP=No Potential. IP=Indeterminate Potential. x= Indeterminate Potential.

TABLE 4-30. COMBINED ICR PREVENTION POTENTIAL—23 AIA REPORT HF AND H EVENTS

	9-LOC 5 PP, 2 NP, 2 IP	6-Other 2 PP, 1 NP, 3IP	2-SDTGE 2 PP	6-RTO>V1 1 PP, 4 NP, 1 IP
Powerloss (Fail Low)	3 x	x		1
Surge	X	2 xx	2	x
Stuck Throttle (Fail Fixed)	2			

PP=Prevention Potential. NP=No Potential. IP=Indeterminate Potential. x= Indeterminate Potential.

Table 4-30 shows:

- With respect to crew response, most prevention potential exists in the area of LOC, followed by Other and Shutdown or TGE. Least prevention potential exists in the area of RTO>V1.
- With respect to malfunctions, most prevention potential is associated with Powerloss and Surge, followed by Stuck Throttle (e.g., Failed Fixed Thrust) malfunctions.

4.2.5.2.2 The AIA Report S and I Event Prevention Potential Assessment.

The remaining 58 S and I events in the AIA report were assessed for prevention and detection potential.

Overall, 93% of the S and I events are estimated to have detection potential. Table 4-31 documents the assessment of malfunction annunciation potential to prevent or reduce UCR in these events.

- 24% of S and I events are estimated to have prevention potential (14/58)
- 38% of S and I events appear to have no prevention potential (22 of 58)
- Prevention potential could not be determined in the remaining 38% (22 of 58) and was, therefore, listed as unknown.

Neglecting the 24 RTO>V1 events, which as a group are estimated to have little or no potential for prevention through PSM annunciation, for the remaining 34 S and I events:

- 41% of S and I events have prevention potential (14 of 34)
- 24% of S and I events have no prevention potential (8 of 34)
- Prevention potential is unknown in the remaining 35% (12 of 34).

TABLE 4-31. ESTIMATED ICR PREVENTION POTENTIAL—AIA REPORT S AND I EVENT TYPES

No. and Type of Events	Crew Response	Crew Response Prevention Potential	Malfunction Detection Potential ¹
11 S	1 LOC 10 RTO>V1	1 (9%) With Prevention Potential 6 (55%) No Prevention Potential ² 4 (36%) Unknown Prevention Potential	11 (100%) With Detection Potential
47 I	1 LOC 7 Other 25 SDGE 14 RTO>V1	13 (28%) With Prevention Potential 16 (34%) No Prevention Potential ² 18 (38%) Unknown Prevention Potential	43 (91%) With Detection Potential 4 (9%) Unknown Detection Potential

1. Does not include, consider, or assess the reliability with which detection could be accomplished. Includes three special cases where the relationship between malfunction and CR is questionable, and three RTO>V1 events.
2. Assessments do not include, or rule out, prevention potential from other kinds of interventions.

The 11 S events involved 1 LOC and 10 RTO>V1 events. The 47 I events involved 1 LOC, 7 Other, 25 SDTGE, and 14 RTO>V1 events. Most of these events are estimated to have detection potential. Table 4-32 summarizes the prevention potential by crew response.

- 67% of the LOC and Other events have prevention potential (6 of 9).
- 38% of the SDGE events have prevention potential (8 of 21). Note that most of the events with prevention potential are events where the shutdown was intentional. Sixty-two percent (13 of 21) of the SDGE events are known or suspected unintentional shutdowns. There is no or indeterminate prevention potential in most of the unintentional shutdown events.
- All the TGE events have malfunction detection potential, but prevention potential is indeterminate and is suspected unlikely in all such events.
- None of the 24 RTO>V1 events can be determined to have prevention potential—58% (14 of 24) have no prevention potential, and prevention potential cannot be determined in the remaining 42% (10 of 24) of events.

TABLE 4-32. ESTIMATED ICR PREVENTION POTENTIAL—AIA REPORT S AND I EVENTS

11 S Events	1 LOC 1 PP	0 Other	0 SDTGE	10 RTO>V1 6 NP, 4 IP
47 I Events	1 LOC 1 NP	7 Other 5 PP, 2 NP	21 SDGE 8 PP, 5 NP, 8 IP 4 TGE 4 IP-Unlikely PP	14 RTO>V1 8 NP, 6 IP

PP=Prevention Potential. NP=No Potential. IP=Indeterminate Potential.

4.2.5.2.3 Post-AIA Report Event Prevention Potential Assessment.

In the post-AIA report period, 1996-2001, 10 post-AIA report PSM+ICR events were identified: 2 H, 1 S, and 7 I. The post-AIA report events were evaluated for prevention and detection potential. Overall, most events are estimated to have detection potential. Table 4-33 documents the potential that malfunction annunciation has to prevent or reduce UCR in these events.

- 40% of events are estimated to have prevention potential (4 of 10)
- 30% of events appear to have no prevention potential (3 of 10)
- Prevention potential could not be determined in the remaining 40% (4 of 10) and was therefore listed as unknown.

The post-AIA report events involved two LOC, four Other, three SDGE, and one RTO>V1. Table 4-34 summarizes the prevention potential by crew response. Four events, one LOC, one Other, and two SDGE, are estimated to have prevention potential.

4.2.5.3 Existing Indications, Alerts, and Functions PSM+ICR Prevention Potential.

Current model aircraft support improved primary flight control awareness and control and support improved engine state and malfunction awareness and engine control in several ways. Such improved awareness acts to reduce the occurrence and mitigate the hazard of PSM+ICR events. The following sections summarize the primary flight control, engine indication, and alert annunciation enhancements on current Boeing aircraft.

TABLE 4-33. ESTIMATED ICR PREVENTION POTENTIAL—POST-AIA REPORT EVENTS

No. and Type of Events	Crew Response	Crew Response Prevention Potential	Malfunction Detection Potential*
2 H	1 LOC 1 Other	1 (50%) No Prevention Potential 1 (50%) Unknown Prevention Potential	2 With Detection Potential
1 S	1 Other	1 (0%) No Prevention Potential	1 With Detection Potential
7 I	1 LOC 2 Other 3 SDGE 1 RTO>V1	4 (57%) With Prevention Potential 1 (14%) No Prevention Potential 2 (29%) Unknown Prevention Potential	4 With Detection Potential 3 Unknown Detection Potential

* Does not include, consider, or assess the reliability with which detection could be accomplished. Assessments do not include, or rule out, prevention potential from other kinds of interventions.

TABLE 4-34. ESTIMATED ICR PREVENTION POTENTIAL—POST-AIA REPORT EVENT TYPES

2 H Events	1 LOC NP	1 Other IP	0 SDTGE	0 RTO>V1
1 S Events	0 LOC	1 Other 1 NP	0 SDTGE	0 RTO>V1
7 I Events	1 LOC PP	2 Other 1 PP, 1 IP	3 SDGE 2 PP, 1 IP	1 RTO>V1 NP

PP=Prevention Potential. NP=No Potential. IP=Indeterminate Potential.

4.2.5.3.1 Primary Flight Control Indications, Annunciations, and Alerts.

In general, the PFDs on modern aircraft provide greater integration of airspeed, attitude, altitude, and vertical speed and heading associated operating limits. PFDs also provide information such as Mode Control Panel (MCP) targets and Autothrottle and Autopilot modes. The B777 aircraft specifically provides:

- PFD Airspeed Tape amber maneuver and red minimum (stick shaker) speed band indications provide full-time awareness of current airspeed relative to maneuver margin and stick shaker speeds.
- An AIRSPEED LOW caution alert to ensure awareness whenever airspeed drops below minimum maneuver speed.
- Stall and Overspeed Protection. The aircraft cannot be trimmed to speeds above maximum operating speed or below minimum maneuvering speed. Continuous forward

column force is required to maintain airspeed above V_{mo}/M_{mo} . Continuous aft column force is required to maintain airspeed below minimum maneuvering speed.

- A PFD Pitch Limit Indicator (stick shaker pitch attitude) displays continuously flaps down and flaps up whenever airspeed drops below minimum maneuver speed.
- Roll envelope BAP. BAP engages whenever the airplane bank angle exceeds approximately 35 degrees. Control wheel forces are applied to roll the airplane back within 30 degrees of bank.
- PFD attitude indications of excessive bank and slip/skid.
- A BANK ANGLE voice callout is provided whenever the airplane bank angle exceeds approximately 35, 40, and 45 degrees.
- TAC is provided. Whenever engine thrust differs by 10% or more, TAC automatically adds rudder to minimize yaw.

Generally, there is good cross-model coverage for low airspeed indication, pitch limit indication, and bank angle voice callout. However, many implementations are recent or optional, e.g., Bank Angle Callout became available in the mid 1990s, and speedtape is not the basic indication on some models. Not all models alert to low airspeed prior to stick shaker, and only the fly-by-wire aircraft have control functions such as BAP and TAC.

4.2.5.3.2 Engine Indication and Indication Annunciations.

In general, the EICAS display and other similar systems on current aircraft provide greater integration of engine indications, alerts, and airframe system information. Display-based engine indications in particular allow enhanced presentation of engine parameters and nonnormal/malfunction annunciations.

As illustrated and discussed in section 2, the B777 aircraft specifically provides:

- Commanded and actual thrust indications.
- Grey round dial scale fill.
- Primary and secondary engine indication annunciations when limits are reached or exceeded.
- Auto display of secondary engine indications when parameter limits or thresholds are reached or exceeded.

Generally, there is good cross-model coverage for commanded thrust indication, high EGT, and high engine thrust. Not all models provide indication fill, or indication annunciation for engine subidle, thrust shortfall, and high vibration. Indication annunciation is not provided for within limits overthrust and throttle/thrust splits.

4.2.5.3.3 Engine Malfunction EICAS Alerts.

Crew alerting is the accepted means in the modern flight deck to assure timely crew awareness and appropriate crew response. The B777 specifically provides EICAS or other alerting for engine failure and thrust shortfall.

Current aircraft EICAS alert coverage, or equivalent, is provided for engine failure (subidle), but it is optional on some models. Some models provide thrust shortfall and throttle/thrust split alerting. One model provides surge alerting, otherwise surge alerting is not provided. Engine overthrust, overtemperature, high vibration, and thrust asymmetry alerting is not provided.

Engine Failure (subidle, flameout, etc.), Surge, Stuck Throttle, and Failed Fixed Thrust are considered engine malfunctions. These malfunctions are usually the consequence of a physical failure or degradation of the engine, a product of the operating environment, or a combination of the two. High vibration and thrust asymmetry may or may not be malfunction-related and are, therefore, considered symptoms. This differentiation of malfunctions and symptoms is somewhat arbitrary and arguable, but it is assumed for discussion purposes.

4.2.5.3.4 The ICR Prevention Potential—Hull Loss (With and Without Fatalities) Events.

The ICR prevention potential of modern aircraft primary flight control, engine state, and engine malfunction indications, annunciations, and alerts is discussed and assessed in the following sections. Prevention potential is assessed by ICR type for those combinations of ICR and malfunction type previously identified as having prevention potential.

LOC events are shown in table 4-30. Hull Loss LOC events are shown to be associated with thrust asymmetry, powerloss, and stuck throttle.

4.2.5.3.4.1 Thrust Asymmetry.

Thrust asymmetry typically induces yaw that induces roll and possibly pitch changes, which affect attitude and may affect airspeed. As noted in the task 2.1 report, the LOC event data suggest that airspeed and attitude awareness and control represent the greatest potential for LOC prevention and risk mitigation. The task 2.1 report also notes that thrust asymmetry is primarily associated with LOC in general, and fatal LOC events in particular. As previously described, existing low airspeed indication, pitch limit indication, and bank angle voice callout act to address LOC events in general, and the roll and pitch effects associated with thrust asymmetry in particular. Further benefit accrues where airspeed low alerts and bank angle and slip/skid indications are provided.

4.2.5.3.4.2 Powerloss.

Fatal LOC events are associated with powerloss. Therefore, benefit accrues where powerloss indications and alerts are provided to ensure crew awareness. As previously described, there is complete cross-model indication of powerloss through the commanded thrust indication on the

actual thrust indication, but incomplete cross-model indication of engine dial and tape fill, which enhances cross comparison of multiengine indications. There is incomplete cross-model annunciation of subtle engine failures. There is indication, but no annunciation, of partial or complete powerloss on the engine indications. Partial powerloss, i.e., thrust shortfall, is alerted on only one model.

4.2.5.3.4.3 Stuck Throttle (Engine Failed Fixed Thrust).

Fatal LOC events are associated with stuck throttle—stuck low and stuck high. As discussed, the occurrence of stuck throttles on modern aircraft is greatly reduced and has been succeeded by Failed Fixed Thrust conditions. Therefore, benefit accrues where indications and alerts are provided to ensure crew awareness of conditions where thrust fails fixed and results in thrust shortfall or overthrust. These may be identified by throttle splits, thrust splits, and differences in commanded and actual thrust. As previously described, there is complete cross-model indication of failed fixed thrust through the commanded thrust indication on the actual thrust indication, but incomplete cross-model indication of Failed Fixed Thrust through comparison of multiengine dial and tape fill. Thrust stuck low, i.e., thrust shortfall, is alerted on only one model. Thrust stuck high, i.e., overthrust, is not alerted on any model.

4.2.5.3.4.4 Surge.

Surge may accompany LOC powerloss events when powerloss is caused by severe engine damage, or powerloss causes rapid engine deceleration. Surges of concern are those that require crew action to recover, and those that are nonrecoverable. EGT exceedance and high vibration may, or may not, accompany surge. As previously described, there is complete cross-model annunciation of high EGT. EGT amber and red exceedance annunciations on the primary display are provided on all Boeing models. However, the amber maximum continuous limit indication is inhibited for 5 minutes after Takeoff or Go-Around—the phases of flight where powerloss-related surge most often results in LOC. Cross-model annunciation of High Vibration, and auto display of the secondary engine vibration indication, is incomplete. There are no Surge or High Vibration alerts on most models, and the only existing surge alert is inhibited in the phases of flight where powerloss-related Surge LOC events have occurred.

SDTGE events are shown in tables 4-28, 4-29, and 4-30. Both fatal and nonfatal Hull Loss SDTGE events are shown to be associated with surge. Surges of concern are those that require crew action to recover, and those that are nonrecoverable. EGT exceedance and high vibration may, or may not, accompany surge. As previously described, there is complete cross-model annunciation of high EGT. Amber and red EGT exceedance annunciations on the primary display are provided on all Boeing models. However, the maximum continuous limit indication is inhibited for 5 minutes after Takeoff or Go-Around. TGE events are typically nonfatal and usually occur in early Takeoff Climb. SDGE events usually occur in late Climb, Cruise, Descent, and Approach phases of flight where the EGT indication can provide crew awareness. The one existing Surge alert provides crew awareness and supports crew response. There are no Surge or High Vibration alerts on most models. In addition, cross-model annunciation of high vibration, and auto display of the secondary engine vibration indication, is incomplete.

Other (O) events are shown in tables 4-28, 4-29, and 4-30. Hull Loss with both fatalities and without fatalities Other events are shown to be associated with surge. These events typically fail to execute or complete the correct procedure. Surge typically involves failure to reduce power on the surging engine, which usually leads to eventual engine failure. In general, a specific alert annunciation must be provided to ensure the crew accomplishes a specific procedure. Surge alert on one model provides crew awareness and guides crew response. However, there are no Surge alerts on most models.

RTO>V1 events are shown in tables 4-28, 4-29, and 4-30. Hull Loss without fatalities RTO>V1 events are shown to be associated with powerloss. See LOC powerloss discussion of powerloss-related indications, indication annunciations, and alerts in section 3.7.

High vibration posed unique issues with respect to PSM+ICR. Correlation between vibration and PSM+ICR is indeterminate/unclear. Vibration may or may not accompany powerloss, surge, and other engine malfunctions. Of the 23 Hull Loss events, only 2 specifically cite severe or high vibration in the PSM+ICR event data. Both events (no. 46 H (with no prevention potential) and no. 53 HF (with prevention potential)) involved surge. In the H case, the crew reported lateral airframe vibrations so severe the engine indications were unreadable. The HF case, a surge event involving SDGE and later powerloss and failure of the affected engine involved high vibration on the affected engine even after it was reduced to idle power. In this case, an explicit High-Vibration annunciation might have redirected the crew's attention to the affected engine. Note that vibration is known to be present in HF event 77 (with prevention potential). But the degree and character of vibration is indeterminate in terms of its detection and annunciation potential and utility.

Finally, vibration may exist but not be associated with an engine malfunction or a significant safety condition. Vibration detection/sensing is susceptible to error. Engine vibration operating limits are not specified for most engines. Therefore, while vibration may be a corroborating indication, it cannot be relied solely upon to be present or meaningful.

4.2.5.3.4.5 Summary and Conclusions.

Powerloss (Thrust Shortfall and Engine Fail Low), Surge, Stuck Throttle, High Vibration, and Thrust Asymmetry are the engine malfunctions and symptoms associated with fatal and other type events in the AIA report. These malfunctions, or their equivalents, are also significant occurrences in the task 2.1 report 2000 and 2001 PSM data and are associated with post-AIA report PSM+ICR events.

ICR prevention potential through malfunction annunciation exists in 50% or more of fatal events. Fatal events with prevention potential account for 88% of all PSM+ICR fatalities. Prevention potential also exists in Hull Loss, Substantial Damage, and Incidental ICR events.

Most prevention potential exists in the area of LOC, followed by Other and Shutdown or Throttled Good Engine. Least prevention potential exists in the area of RTO>V1.

Most prevention potential is associated with Powerloss and Surge, followed by Failed Fixed Thrust malfunctions.

The majority of these malfunctions appear to be detectable. Detection potential appears to exist in all cases where prevention potential is identified. The principal detection issue is reliable and meaningful detection, particularly in the case of surge and vibration.

The lack or presence of PSM annunciation could favorably affect the likelihood of timely crew awareness and could, thus, decrease the likelihood of ICR. Low airspeed and pitch limit indications and annunciations and bank angle voice callout reduce the likelihood of LOC events with prevention potential, but do not address the SDTGE, Other, and RTO>V1 events with prevention potential.

4.2.6 Desired/Required Crew Awareness and Response—Potential Annunciations.

The first step in assessing the operational value of a potential annunciation is definition of desired crew awareness/understanding and response. In general, the crew should be made aware

- that a propulsion system malfunction or symptom exists.
- of the specific engine affected.
- of the specific type or nature of the propulsion system malfunction or symptom, and the manner and extent of its affect on the engine.

The crew should/must understand the operational implications of the PSM and its potential affect on subsequent near- and long-term operations and continued safe flight and landing.

In general, awareness and understanding help ensure appropriate crew response and should lead directly/unambiguously to a specific nonnormal procedure. It is expected per basic airmanship, not per published procedure, that the initial response to any engine malfunction must be to fly the airplane, e.g., control airspeed, attitude, and flight path, not diagnose engine problems. After establishing/ensuring basic airplane control, the following generalized actions are typical for the following engine malfunctions and symptoms. Note that actual procedures may vary from aircraft to aircraft and are often situational-dependent.

- Engine Fail (unresponsive to throttle)
- Engine Fail (subidle). Control or correct thrust asymmetry. Attempt engine restart or shutdown engine.
- Thrust Shortfall. Control or correct thrust asymmetry.
- Engine Failed Fixed Thrust (thrust shortfall or overthrust). Control or correct thrust asymmetry. Attempt recovery of normal engine function.
- Engine Fail High Thrust (overthrust). Control or correct thrust asymmetry. When phase of flight circumstances and operating procedures allow, reduce thrust to within limits, use or shutdown the engine.

- Engine Surge. When phase of flight operating procedures allow (e.g., above safe altitude), reduce power on the affected engine until surging stops or idle is reached. If surging continues at idle, the engine may be shutdown.
- High Engine Vibration. When phase of flight operating procedures allow (e.g., above safe altitude), reduce power on the affected engine until vibration returns to acceptable levels or idle is reached. Note: Engine vibration may be used in conjunction with other indications or annunciations to corroborate engine malfunction and identify affected engine.
- Thrust Asymmetry. Maintain airspeed and attitude control. Identify and disposition the root cause problem.

4.2.6.1 Potential Safety and Operational Benefits and Risks.

The potential benefits associated with detection and annunciation of Powerloss, Surge, Engine Fail Low/Fixed/High Thrust, High Vibration, and Thrust Asymmetry have been documented in previous sections. Table 4-16 summarized these benefits in terms of value (safety potential), effectiveness (crew response prevention potential), and potential risk.

Potential benefits are based on the assumption of reliable detection and annunciation. Reliable implies consistent and meaningful detection and annunciation. The general benefit of annunciation is that it ensures appropriate crew awareness and response. Crews are not misdirected into falsely believing some other condition or malfunction occurred and taking inappropriate or unnecessary action.

Potential risk is assessed based on (1) the risk associated with annunciation in general, (2) the risk associated with false or nuisance annunciation, and (3) the risk associated with failure to annunciate when the crew knows an annunciation exists and may be relying on its presence or absence.

4.2.6.1.1 General Risks Applicable to All Malfunctions.

- Distraction During High Crew Workload Flight Phase. The risk associated with annunciation (indication or alert) in general, regardless of whether the annunciation is true or false, relates to UCR from the annunciation itself, not the malfunction being annunciated. This is primarily a concern in flight phases where the crew does not have time to assess the indication or alert, e.g., during takeoff above V1 or on short final approach and flare. Anything designed to attract crew attention, risks crew distraction and UCR. Typically, in Takeoff and Approach phases, annunciations are temporarily inhibited where the risk of delaying annunciation is far outweighed by the risk of ICR such as RTO>V1 or low altitude go-around. Additionally, risk varies within range/limits versus out of range/limits malfunction annunciations. There is lower risk associated with annunciation of out-of-limit (high or low) parameters and more risk of nuisance associated with detecting nonnormal conditions within normal parameter range.

- **False Annunciation.** The immediate risk of false annunciation is (a) unnecessary distraction and (b) erroneous crew awareness, understanding, and response. The crew may be distracted from accomplishing important tasks, may become confused by noncorroborating or conflicting indications, or may take action that unnecessarily affects airplane operation or capability. The longer-term risk of repeated false annunciation is the potential loss of alert and alerting system credibility and possible crew failure to respond when required. If a false alert occurs repeatedly, the crew can quickly become desensitized to the alert and ignore or otherwise fail to respond to the alert when valid. The crew may also begin to question other valid alerts. In all cases, crew workload and error potential are unnecessarily and undesirably increased. The acceptability of false annunciation is proportional to the criticality of the condition and crew response.
- **Failure to Annunciate/Detect.** The risk associated with failure to annunciate when the crew knows an annunciation exists, and may be relying on its presence or absence, is primarily that crew response may not occur, or may occur too late. In the absence of an alert, detection/awareness and interpretation/understanding is more difficult and error-prone. In the absence of an alert, and particularly when little time is available for evaluation, there is the general increased risk that crew response may be erroneous or inappropriate.

4.2.6.1.2 Malfunction Annunciation Benefits and Risks Discussion.

Powerloss (Engine Fail Subidle/Flameout or Thrust Shortfall) can be annunciated (indicated and/or alerted) as an Engine x Fail Low (e.g., flameout or subidle), or as an Engine x Thrust Shortfall (e.g., actual and commanded thrust disagree).

4.2.6.1.2.1 Benefits of Powerloss Annunciation.

As tables 4-28, 4-29, and 4-30 showed, the potential benefit of Powerloss annunciation accrues to LOC and RTO>V1 events. Annunciation would provide crew awareness of a powerloss on one or more engines. It is expected that such awareness would prompt the crew to assess the powerloss impact on flight operations and subsequently respond in an appropriate manner that ensures continued safe flight and operation. This response should involve controlling any associated thrust asymmetry that might result; acting to safely configure, restore, or secure the affected engine(s); and re-evaluating the flight plan.

4.2.6.1.2.2 Risks Associated With False Detection and Annunciation of Powerloss.

The RTO>V1 risk from annunciation during takeoff roll has been discussed. False detection and annunciation of powerloss during takeoff roll below V1 could prompt an unnecessary RTO and inappropriate crew concern for asymmetric reverse thrust. The AIA report LOC events generally occurred in high workload phases of flight, e.g., Approach/Go-Around or Takeoff Climb. False or nuisance alerting of powerloss during approach might prompt the crew to change aircraft configuration or might delay or otherwise affect a go-around decision. False or nuisance alerting of powerloss during Takeoff Climb might prompt the crew to change aircraft configuration or prompt an unnecessary air turn back. In both cases, workload would unnecessarily increase and

crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase-related tasks.

4.2.6.1.2.3 Risks Associated With Failure to Detect and Annunciate.

Failure to detect and annunciate a powerloss on approach risks the crew being unaware that go-around capability and performance are affected. Failure to detect and annunciate a powerloss on takeoff may risk the crew being unaware that takeoff and climb capability and performance are affected. Both cases can lead to LOC.

Surge can be annunciated (indicated and/or alerted) as an Engine x Surge.

4.2.6.1.2.4 Benefits of Surge Annunciation.

As tables 4-28, 4-29, and 4-30 showed, the potential benefit of Surge annunciation accrues to LOC, Other, and SDGE events. Annunciation would provide crew awareness of a surge on one or more engines. For surge that automatically recovers, it is expected that awareness will ensure the crew is not misdirected into falsely believing some other condition or malfunction occurred and taking inappropriate or unnecessary action. For surge that does not automatically recover, the annunciation would direct the crew to the appropriate checklist procedure, prompt the crew to reduce power on the affected engine(s), and subsequently respond in an appropriate manner that ensures continued safe flight and operation. This response should involve controlling any thrust asymmetry that might result; acting to safely configure, restore, or secure the affected engine(s); and re-evaluating the flight plan. Engine-specific annunciation of surge could prevent SDGE events and the procedural errors frequently associated with PSM+ICR events in the Other category.

4.2.6.1.2.5 Risks Associated With False Detection and Annunciation of Surge.

False detection and annunciation of surge during takeoff roll below V1 could prompt an unnecessary RTO, or prompt the crew to inappropriately reduce power below safe altitude. False detection and annunciation of surge during Takeoff Climb, Cruise, or Descent could prompt an unnecessary thrust reduction or engine shutdown. False or nuisance alerting of surge during Approach might prompt the crew to change aircraft configuration or might delay or otherwise affect a go-around decision. In all in-flight cases, workload would unnecessarily increase and crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase-related tasks.

4.2.6.1.2.6 Risks Associated With Failure to Detect Surge.

Failure to detect and annunciate a surge on Approach risks the crew being unaware that go-around capability and performance may be affected. This can lead to LOC. Failure to detect and annunciate a surge on takeoff may risk the crew being unaware that takeoff and climb capability and performance are affected. Additionally, in the absence of an explicit annunciation, the crew may take inappropriate action such as SDGE, or the loud bangs and vibration that typically accompany engine surge may misdirect the crew to believe that some other condition exists.

Engine Failed Fixed Thrust (Thrust Shortfall or Overthrust) can be annunciated (indicated and/or alerted) as an Engine x Failed Fixed Thrust (no thrust response to throttle/commanded power). The special case of Failed Fixed Thrust due to a stuck throttle can be annunciated (indicated and/or alerted) as an Engine x Failed Fixed Thrust (no throttle response to command), Throttle Split, Thrust Split, Autothrottle Disconnect, or Autothrottle x Fail.

4.2.6.1.2.7 Benefits of Stuck Throttle Annunciation.

As tables 4-28, 4-29, and 4-30 showed, the potential benefit of stuck throttle annunciation accrues to LOC events. The AIA report Stuck Throttle events involved autothrottle engagement. AIA report Stuck Throttle events in general, and the HF events in particular, appear to involve sufficient time and opportunity for earlier crew intervention had the stuck throttle been annunciated or otherwise called to the crew's attention near the time it stuck.

However, the post-AIA report data contained UCR to Engine Failed Fixed Thrust events. Engine Failed Fixed Thrust events are more difficult to detect because they do not involve throttle split and must instead be detected by a difference in commanded and actual thrust—either by correlation of throttle position and engine thrust, indication of commanded versus actual thrust, or alert annunciation. In the post-AIA report events, benefit accrues to SDGE events where commanded thrust was less than actual thrust and the crew misinterpreted the low/good engine as failed.

Annunciation of a Failed Fixed Thrust PSM would provide crew awareness of an engine thrust malfunction on one or more engines and of actual or potential thrust asymmetry. It is expected that awareness would ensure the crew maintains airplane airspeed and attitude control and focuses attention on the correct (i.e., malfunctioning) engine. The annunciation would direct the crew to the appropriate checklist procedure, prompt the crew to control power on the affected engine(s), and subsequently respond in an appropriate manner that ensures continued safe flight and operation. This response should involve controlling any thrust asymmetry that might result; acting to safely configure, restore, or secure the affected engine(s); and re-evaluating the flight plan. Engine specific annunciation of surge could prevent LOC and SDGE events.

4.2.6.1.2.8 Risks Associated With False Detection and Annunciation of Engine Failed Fixed Thrust.

False detection and annunciation of engine Failed Fixed Thrust during takeoff roll below V1 could prompt an unnecessary RTO. False detection and annunciation during Takeoff Climb is unlikely until first thrust reduction. At thrust reduction, in Cruise and in Descent, a false alert could lead the crew to accomplish an unnecessary procedure and might prompt the crew to shutdown a good engine. False or nuisance alerting during Approach might prompt the crew to unnecessarily go-around or shutdown a good engine. In all in-flight cases, the workload would unnecessarily increase and crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase-related tasks.

Note that the most likely false annunciation would be a normal temporary transient difference in commanded and actual, versus a persistent or false difference. Such normal nuisance transients

could be distracting and disruptive of normal flight operations, and it is possible they could occur in unusual unanticipated circumstances where such distraction is undesirable.

4.2.6.1.2.9 Risks Associated With Failure to Detect Engine Failed Fixed Thrust.

Failure to detect and annunciate engine Failed Fixed Thrust, risks the crew being unaware that a difference in commanded and actual thrust exists. This is typically a difficult condition for crews to accurately diagnose, particularly in time-critical situations, and could result in the shutdown of the good/unaffected engine, or combined with crew failure to maintain airspeed and attitude control, could lead to LOC.

High Vibration can be annunciated (indicated and alerted) as an indication annunciation, an auto display of vibration indication, and as an alert annunciation.

Correlation between vibration and PSM+ICR is indeterminate/unclear. Vibration may or may not accompany Powerloss, Surge, and other engine malfunctions. Of the 23 AIA report Hull Loss events, only two specifically cite severe or high vibration in the PSM+ICR event data. Both events (no. 46 H (estimated no prevention potential) and no. 53 HF (estimated with prevention potential)) involved surge. In event no. 46, the crew reported lateral airframe vibrations so severe that the engine indications were unreadable.

Finally, vibration may exist but not be associated with an engine malfunction. Vibration detection/sensing is susceptible to error. Engine vibration operating limits are not specified for most engines. Therefore, while vibration may be a corroborating indication, in general, it cannot be relied upon to be present or meaningful.

4.2.6.1.2.10 Benefits of High Vibration.

As tables 4-28, 4-29, and 4-30 show, vibration is not listed as the primary PSM or symptom in any HF or H events. Where severe or excessively high vibration is identified as the primary PSM or symptom in the AIA report data, the events are incidental. However, vibration is known to be present in at least ten PSM+ICR events—two of which are hull loss with fatalities. Powerloss and Surge events may involve high vibration. For example, the AIA report HF Surge event involving Shutdown of Good Engine, involved high vibration on the affected engine even after it was reduced to idle power. In this case, an explicit High Vibration annunciation might have redirected crew attention to the affected engine. Otherwise, the benefit of High Vibration may be primarily in using it with other indications.

4.2.6.1.2.11 Risks Associated With False Detection and Annunciation of High Vibration.

False detection and annunciation of high vibration during takeoff roll below V1 could prompt an unnecessary RTO. False detection and annunciation of high vibration during takeoff climb, cruise, or descent could prompt an unnecessary thrust reduction, engine shutdown, diversion, or air turn back.

False or nuisance alerting of high vibration during approach might prompt the crew to change aircraft configuration or might delay or otherwise affect a go-around decision. In all in-flight

cases, workload would unnecessarily increase and crew distraction could delay, prevent, or otherwise affect proper aircraft configuration or accomplishment of other flight phase related tasks.

4.2.6.1.2.12 Risks Associated With Failure to Detect High Vibration.

Failure to detect and annunciate high vibration entails little more risk than the current lack of existing annunciation. As previously noted, where severe or excessive vibration is identified as the primary PSM or symptom, the events are incidental. In the absence of an explicit annunciation, the crew may not identify the high vibration as engine-related, and may be misdirected to take other inappropriate action based on whatever condition they believe to be causing the vibration.

4.2.6.1.2.13 Thrust Asymmetry.

Thrust Asymmetry is an airplane-level effect, not a PSM. Thrust Asymmetry may, or may not, be due to a PSM.

When due to a PSM, Thrust Asymmetry is consequential and circumstantial in that it is a potential, but not certain, result of a PSM affecting thrust. Depending on the circumstances, thrust asymmetry can follow the PSM quickly, slowly, or not at all. The malfunctions responsible for thrust asymmetry can, and often do, occur well in advance of a thrust asymmetry. The thrust asymmetries of concern are unintentional, can be characterized as a throttle or thrust split, or as a difference between desired or commanded thrust (resulting in either overthrust or thrust shortfall on the affected engine), and are a symptom/consequence of a PSM. The PSMs with potential to cause thrust asymmetry are Engine Fail Low/Powerloss, Engine Fail High/Runaway, Engine Failed Fixed Thrust (where commanded and actual thrust differ), Stuck Throttle, and Surge with Powerloss. Thrust asymmetry can result from rapid powerloss events, slow powerloss events, engine failure to respond to commanded thrust, and stuck throttle.

Thrust asymmetry is a contributing factor in many LOC events. However, as previously noted, loss of airplane control is primarily due to failure to control airspeed and/or attitude. Most LOC events are low-altitude, high-power events involving takeoff, climb, or go-around climb power. Most LOC events also involve nonrecoverable malfunctions or involve recoverable malfunctions with insufficient time and altitude to attempt or complete engine recovery. Therefore, in most PSM situations, thrust asymmetry is unavoidable, and the primary crew objective is to control, not correct, the thrust asymmetry.

General alert philosophy is to ensure timely crew awareness of nonnormal conditions, which require crew awareness and response. In practice, alerts are provided at the earliest or most appropriate point. The alert is used to focus crew attention on the nonnormal condition, which best ensures appropriate crew awareness and response. The consequences of engine thrust malfunction are well trained and well understood. Once the crew is aware of an engine malfunction, awareness of thrust asymmetry, or the potential for thrust asymmetry, is expected to immediately follow, particularly if the malfunction is thrust-related. It is best left to the flight crew to put their awareness of an engine malfunction into the proper context of the current phase of flight and other existing relevant circumstances.

Engine indication or alert annunciation of thrust asymmetry is problematic in that Thrust Asymmetry may, or may not, be due to a PSM. In addition, Thrust Asymmetry is nonspecific and does not aid the crew in determining which engine is malfunctioning or why the engine is malfunctioning. There are sufficient potential risks associated with Thrust Asymmetry annunciation (including nuisance alerts) to outweigh the potential benefit. Additionally, there are easier and more effective means of addressing the problems caused by thrust asymmetry (e.g., LOC). Thrust asymmetry occurs as the result of a significant thrust shortfall or overthrust. Of the PSMs that underlie significant thrust asymmetry, all except stuck throttle can be sensed as thrust shortfall or overthrust. Stuck throttle is a concern only when it occurs with autopilot engaged. There are no autothrottle or autoflight control laws that use split throttle or differential thrust. Therefore, split throttle/thrust is reliably detectable if the throttle lever position or engine thrust is known/sensed and compared.

The goal of any Thrust Asymmetry indication or annunciation should be to make consequential thrust asymmetry intuitively obvious at the airplane level versus the engine system level. Thrust Asymmetry may be best indicated to the crew on the Primary Flight Display where its effects for most PSM events must generally be addressed through airplane-level control.

4.2.6.1.2.14 Stuck Throttle.

The reported incidences of stuck throttle on modern aircraft in general, and on current Boeing production aircraft in particular, are much lower than on older aircraft. This is attributed to differences in autothrottle mechanism design between current and older generation aircraft. For example, differences in autothrottle mechanism design are estimated to reduce the incidence of stuck throttle by two orders of magnitude—from approximately 200 events per year to about 1 event every 2 years.

4.2.6.1.3 Summary of Annunciation Benefits and Risks.

Table 4-35 summarizes an assessment/estimate of the Safety Potential (Benefit), ICR Prevention Potential, and Potential Operational Risks associated with a new engine indication annunciation or alert annunciation for the malfunctions and symptoms listed.

- Potential Safety Benefit is the estimated potential the annunciation has to prevent PSM+ICR events in general, and fatal and Hull Loss events in particular. This estimate is based primarily on task 2.1 data analysis of the number of fatalities and events the annunciation has the potential to prevent.
- ICR Prevention Potential is the estimated effectiveness of an engine indication annunciation and/or an alert annunciation to provide a level of crew awareness and understanding sufficient to prevent ICR to the PSM. This estimate is based primarily on PSM+ICR event data review and analysis.
- Potential Operational Safety Risk is the estimated operational safety risk associated with the annunciation. This estimate is based primarily on the preceding risk benefit discussions.

TABLE 4-35. POTENTIAL BENEFIT, EFFECTIVENESS, AND RISK OF NEW ANNUNCIATION/ALERT

Malfunction or Symptom	Potential Safety Benefit	ICR Prevention Potential	Potential Operational Safety Risk
Engine Failure (subidle/flameout)	H	H	L ³
Engine Failed Fixed Thrust	H	H	L ⁴
Engine Surge	H	H	L-M ⁵
High Vibration ¹	L-M ¹	M ¹	L ⁵
Thrust Asymmetry ²	I ²	L	I ²

H=High. M=Medium. L=Low. I=Indeterminate.

1. See Vibration discussion.
2. See Thrust Asymmetry discussion.
3. Based on existing B777 engine failure alerting.
4. Based on existing B777 thrust shortfall alerting.
5. Operational risk is a function of annunciation threshold and detection reliability, i.e., probability of false alerting.

Table 4-36 shows task 2.1 report PSM data on surge recoverability. Overall, recoverability can be estimated in about 87% of the events. Where recoverability can be estimated, about half the events are recoverable and half are nonrecoverable. Of the recoverable events, one-third recover without crew action and two-thirds require crew action to recover. So most Surge events are either nonrecoverable or require crew action to recover.

TABLE 4-36. TASK 2.1 REPORT PSM SURGE EVENT DATA

Surge Type (R versus NR)	Number of Occurrences	Percent of Total
Nonrecoverable	98	43.2
Recoverable—Crew Action	69	30.4
Recoverable—No Crew Action	31	13.7
Recoverability Unknown	29	12.8
Total	227	
Recoverable—Crew Action: No IFSD	55	79.7
Recoverable—Crew Action: IFSD	14	20.3

In general, table 4-37 shows that where recoverability can be determined, a majority of the AIA report PSM+ICR Surge events, and about half of the 2000-2001 PSM Surge events, involve nonrecoverable surge. The AIA report data indicate that Hull Loss Surge events in particular, predominately involve nonrecoverable surge.

TABLE 4-37. THE AIA REPORT PSM+ICR AND 2000-2001 SURGE EVENT DATA

	Recoverable	Nonrecoverable	Unknown
RTO, SDTGE, and Other AIA Report Surge Events	27% (10 of 37)	51% (19 of 37)	22% (8 of 37)
2000-2001 PSM Surge Events	44% (100 of 227)	43% (98 of 227)	13% (29 of 227)

The potential operational safety benefit in differentiating recoverable and nonrecoverable PSMs in general, and Surge in particular, is that the nonrecoverable malfunctions are usually associated with fatal hull loss events. Self-recoverable surges are of much lesser, if of any, concern and therefore annunciation of them is of minimal value.

In addition, as table 4-36 shows, IFSD data analysis indicates that there may be potential to reduce the number of IFSDs associated with Surge events requiring crew action to recover.

Based on AIA report event data and estimates of prevention potential, Surge annunciation should focus on annunciation of nonrecoverable and recoverable with crew action Surge events. Fatal and nonfatal Hull Loss event data indicate that Surge annunciation could be useful for persistent continuous Surge events requiring crew action to recover or mitigate effects of nonrecoverable surge. To be useful in ICR prevention, such annunciations do not require immediate detection and annunciation. Based on AIA report event data and estimates of prevention potential, a 10- to 15-second delay in Surge annunciation would still allow an operationally acceptable, useful, and effective annunciation. An annunciation that a recoverable surge has occurred has little safety value.

4.2.6.2 Summary, Conclusions, and Preliminary Recommendations.

4.2.6.2.1 Summary.

The AIA report shows that PSM+ICR events are not limited to Boeing aircraft. No attempt was made to obtain or analyze data for other aircraft manufacturers. Boeing aircraft data is cited in this report primarily because it was readily available to the Boeing investigators involved. Report analyses focused on Boeing Flight Decks primarily because the Boeing investigators involved have ready access to and expertise in the Boeing Design and Operational Philosophies and Flight Deck implementations.

Powerloss, Surge, and Stuck Throttle account for all fatal PSM+ICR events and most other PSM+ICR events. These malfunctions, or their equivalents, are major contributors in the 2000-2001 PSM data and the post-AIA report PSM+ICR events.

ICR prevention potential through malfunction annunciation exists in 50% or more of fatal events. Fatal events with prevention potential account for 88% of all PSM+ICR fatalities. Prevention potential also exists in Hull Loss, Substantial Damage, and Incidental ICR events.

Fifty percent of fatal, 36% of nonfatal Hull Loss, and 24% of other AIA report PSM+ICR events were assessed to have prevention potential. Prevention potential, or lack of, could not be determined in 42% of fatal, 9% of nonfatal, and 38% of other PSM+ICR events. Post-AIA report PSM+ICR events have similar or higher overall prevention potentials.

Most prevention potential exists in the area of LOC, followed by Other and Shutdown or TGE. The least prevention potential exists in the area of RTO>V1.

- PSM annunciations offer prevention potential for fatal LOC, SDTGE, and Other ICR category events.
- PSM annunciations offer little or no prevention potential for fatal RTO>V1 events. PSM annunciation above V1 during takeoff risks causing RTO>V1 events.
- For nonfatal Hull Loss events, PSM annunciations offer prevention potential in all ICR categories.

Most prevention potential is associated with Powerloss and Surge, followed by Failed Fixed Thrust malfunctions. The majority of these malfunctions appear to be detectable. The principal detection issue is reliable and meaningful detection, particularly in the case of surge.

Prevention potential is the estimated opportunity, through PSM annunciation, to prevent or mitigate ICR by providing timely awareness, correct understanding, and linkage to the appropriate nonnormal procedure. In all cases where prevention potential has been judged to exist, it is meant only to mean the event might have been prevented. Note that the prevention potential assessment herein focused only on the prevention potential PSM annunciation. PSM annunciation may not be the only, or necessarily be the most effective means of reducing the PSM+ICR rate or obtaining desired crew response. There may be other equally or more effective, or more feasible, means to address PSM-related ICR.

Between 1958 to 2001 there have been 12 HF and 13 H PSM+ICR events in the commercial transport turbojet fleet over approximately 396 million flights. The modern glass cockpit FADEC-powered fleet (aircraft designed and certified in the 1980s and later) have approximately 43 million flights and no PSM+ICR-related H or HF events.

Per task 2.1 report analysis of AIA report events, the expected frequency of a PSM+ICR event of

- any type (HF, H, S, or I) is rare, $2.6E-07$ per flight—one event in every 3.8 million flights.
- a Hull Loss (HF or H) is more rare, $7.5E-08$ per flight—one event in every 13.3 million flights.
- a fatal PSM+ICR event is very rare, $3.9E-08$ per flight—one event in every 25.7 million flights.

PSM+ICR rates, when calculated for combined AIA report and post-AIA report events, are only slightly improved over those cited here for AIA report events.

Many enhancements to airspeed and attitude awareness, engine indications, and PSM annunciations have been implemented on current aircraft models. But not all enhancements have been implemented on all aircraft models or all aircraft. Cross-model malfunction annunciation of Engine Failure (subidle), Engine Surge, and Engine Failed Fixed Thrust (Thrust Shortfall and Overthrust) malfunctions is generally incomplete.

4.2.6.2.2 Conclusions.

Based on the Boeing study, Flight Deck annunciation of the following PSMs could provide a potential safety benefit.

- Engine Failure (subidle)
- Engine Thrust Shortfall
- Engine Surge
- Engine Overthrust

Careful implementation of these PSM annunciations (i.e., how/where implemented and when provided) is crucial to effectiveness. Implementations must accommodate diverse engine and airframe designs and operational philosophies. And the factors that have limited previous implementation must be considered and addressed.

A feasibility assessment for High Vibration and Stuck Throttle is required before implementation recommendations can be made.

Lack of annunciation of Engine Failure (subidle), Thrust Shortfall, Overthrust, Surge and High Vibration can affect the likelihood of timely crew awareness and/or understanding of engine malfunction and may thereby decrease the likelihood of appropriate crew response.

Low airspeed and pitch limit indications, bank angle voice callout, low airspeed alert, and other airspeed and attitude awareness and control enhancements should reduce the likelihood of LOC events, but they do not address the Shutdown/Throttled Good Engine, Other, and RTO>V1 events.

Current production aircraft incorporate many engine indication enhancements, PSM annunciations (indications and alerts), and non-PSM indications, annunciations and alerts, which act to reduce the risk and hazard associated of PSM+ICR. All other factors being equal, this should reduce the rate of HF and H PSM+ICR events on these aircraft. However, an assessment of all other factors has not been made, and the overall effect of other factors, such as pilot experience, training, engine reliability, and fleet maturity, is therefore not known.

Overall analysis of historical and current PSMs and PSM+ICR events and rates, current aircraft enhancements, and miscellaneous qualitative assessments suggests that the future PSM+ICR rates on current production aircraft should be improved. But the degree of improvement cannot be determined. In the absence of additional preventative factors, it is possible for potentially

preventable PSM+ICR events in general, and HF and H PSM+ICR events in particular, to occur as the current fleet accumulates additional flights.

Potential operational safety benefit exists for Engine Failure (subidle), Engine Thrust Shortfall and Overthrust, and Engine Surge Malfunction annunciations (indications and/or alerts). The benefit varies per crew response (LOC, O, SDGE, RTO>V1).

Engine Failure (subidle), Engine Thrust Shortfall and Overthrust, and Engine Surge malfunction annunciations have the collective potential to reduce the HF PSM+ICR rate by as much as a factor of two or more and have the potential to also reduce H, S, and I PSM+ICR rates. Order of magnitude improvements are not possible because of the low number of PSM+ICR event occurrences.

Thrust Asymmetry annunciation potential benefit and effectiveness is indeterminate and has potential risk.

PSM annunciations above V1 during takeoff have the potential to increase the RTO>V1 rate.

The challenge is to change inappropriate human behavior to affect the outcome in one of several million flights without negatively changing or affecting the outcome in all the remaining several million flights, less the one of interest.

Some open issues need to be discussed:

- The feasibility of implementing new PSM annunciations must be assessed prior to any implementation commitment. Feasibility must be assessed for production, retrofit, and new/future airplanes.
- Any new malfunction annunciations must be developed/refined, tested, and validated prior to implementation. Testing and validation should include assessment of the effectiveness of annunciation to prevent, reduce, or mitigate PSM+ICR events.
- Reliable detection of meaningful Surge must still be demonstrated, tested, and validated before a Surge annunciation can be implemented.

4.2.6.2.3 Preliminary Recommendations.

It is recommended that the following PSMs should be assessed for feasibility of Flight Deck annunciation:

- Engine Failure (subidle)
- Engine Thrust Shortfall
- Engine Surge
- Engine Overthrust

Feasibility should be assessed for production, retrofit, and new/future airplanes. Feasibility assessment should include, but not be limited to, CAST analysis. Feasibility should include a relative assessment of malfunction annunciation versus other interventions such as CRM and malfunction training, airspeed and attitude awareness enhancements, flight control protection, and compensation functions. Crew training, development of SOPs, policy development or safety culture may be more feasible interventions than onboard hardware or software changes for the current fleet.

- Recommend the FAA sponsor and support:
 - follow-on research to demonstrate/validate reliable surge detection and to refine and validate specific PSM annunciations.
 - engine manufacturer, airframe manufacturer, and airline collaboration on PSM annunciation feasibility assessments, implementation requirements, and validation activities.
- Do not recommend Thrust Asymmetry, Stuck Throttle, and High Vibration annunciation without additional study and validation of potential risk and benefit.

4.3 HUMAN FACTORS CONSIDERATIONS (TASK 6.2).

The FAA requires that every Boeing airplane provide engine parameter indications in a dedicated area on the interface. Engine indications, generally, support two types of activities. First, during normal operating regimes, the engine indications support the crew in engine start and shutdown and in thrust setting and monitoring. Second, the engine indications support the flight crew in monitoring engine operational status and health. In addition, when there are engine problems that lead to nonnormal operations, engine indications support the use of nonnormal procedures. More generally, engine-related tasks can be broken into performance-monitoring and health-monitoring tasks.

4.3.1 Introduction.

In this section, the first discussion concerns the current indications and how they are used for performance-monitoring and health-monitoring tasks. Next, a review of the aspects of the current indications are discussed where enhancements may be desirable, followed by a discussion of how a human-centered approach to flight deck design can guide flight deck indications for engine-related tasks. Guidance is offered relating to supporting engine management tasks and, more specifically, the potential role of specific indication types. Relevant research on engine indications and on allocation of tasks to humans and machines is discussed to offer ideas about the types of enhancements that might make sense. In the final section, recommendations for improving engine indications in the short- and long-term are offered.

4.3.2 Engine-Related Flight Crew Tasks.

The following engine indications are provided on the flight deck interface to support engine-related flight crew tasks: N1, EPR (for some engine manufacturers), N2, EGT, fuel flow, oil pressure, oil quantity, oil temperature, and engine vibration. Note that these are split into primary and secondary indications, where the primary indications are N1, EPR, and EGT. The others are secondary indications. Primary indications must be displayed at all times; secondary indications can be selected for display by the flight crew and are automatically displayed (pop-up) under certain conditions. These indications are described in more detail in section 4.2.

Engine-related tasks can be separated into performance-monitoring tasks and health-monitoring tasks (which also include managing nonnormals). This distinction relates to the operational purpose underlying monitoring—why monitoring is important. Appendix B offers a more detailed model of monitoring processes, which provides the underlying foundation for monitoring behavior, including sources of error.

4.3.2.1 Engine Performance Monitoring.

Performance monitoring involves determining whether the engines (or propulsion system, which comprises fuel tanks and fuel transfer systems along with the engines) are responding normally (acceptably) to manual or autothrottle inputs. More specifically, the flight crew must determine whether the actual engine state equals, or is approaching, the commanded engine state.

Typically, performance-monitoring tasks are tied to significant propulsion system changes associated with a flight phase change or high-power maneuver such as Takeoff/Go-Around or Descent. In many cases, the magnitude of change in engine indications is large and often rapid. In the case of high-power operations, performance is at or near engine operating limits, where the potential for exceeding a recommended engine limit is increased. Failures in performance monitoring, e.g., lack of awareness that actual state does not equal commanded state, are often a major element in PSM events that result in crew error or UCR (see section 4.1).

4.3.2.1.1 Thrust Setting.

A primary flight crew task is setting the appropriate thrust level for a flight phase or maneuver. The engine indications that are used for thrust setting are primarily N1 or EPR, depending on the engine type. These parameters are stand-ins for actual thrust (true thrust, in pounds, is not derived and displayed). N1 and EPR indications also show commanded thrust, target thrust, and thrust limit to assist the crew in setting thrust.

4.3.2.1.2 Engine Start and Shutdown.

For engine start, the relevant engine indications are determined by whether the start is a manual start or is controlled by an autostart function (in some aircraft). For manual starts, the relevant engine indications used (by procedure) are core speed (N2 or N3), fan speed (N1), EGT, and oil pressure; fuel flow is also often monitored. For autostarts, the engine indications used (by procedure) are oil pressure and EGT—specifically, confirming oil pressure increase after initial

EGT rise. Although not required by procedure, turbine fan speed (N1) and fuel flow are also often monitored. If there is a starting anomaly during autostart, automated corrective actions are taken and, if the anomaly remains, an alerting message is presented to the flight crew.

For engine shutdown, no engine indications are required procedurally, but turbine speeds (N1, N2, N3), EGT, and fuel flow can be used to confirm that a shutdown is completed normally. The primary indication that an engine has not shutdown is a fuel shutoff valve alert, which can indicate that fuel is still being delivered to the engine. Engine indications can be used to confirm this and to confirm when the engine completes shutdown.

4.3.2.2 Crew Engine Health Monitoring (and Managing Nonnormals).

Crew health monitoring involves determining that the engines and propulsion system are not exceeding normal operational bounds, but may also involve evaluations relative to optimal performance. Typically, health monitoring seeks to confirm that long-term, steady-state indications are not changing significantly, i.e., they are not deviating from the expected/normal state. A primary concern here is human failure to detect deviations from normal in a timely way.

In the rare cases in which a PSM occurs, the flight crew must detect that a parameter value is out of bounds (or off expected value), understand what is occurring, and make an appropriate response. In the case that an EICAS message is used to alert the crew to a nonnormal condition, there is a direct link to a nonnormal checklist that can guide the response. In cases for which there is no EICAS message, the flight crew must identify an appropriate checklist (the so-called unannunciated nonnormal checklists) through their own interpretation of events. The important point is that the flight crew must move from observing engine indications to developing and executing a response. Possible flight crew actions include reducing throttles, shutting down an engine, or executing a nonnormal checklist (e.g., engine surge). Other flight control actions may be needed to manage the airplane.

4.3.3 Enhancement Opportunities for Current Indications.

Current engine indications evolved out of earlier flight deck designs in which individual parameters were presented to flight crews through mechanical (or electromechanical) analog gauges. This mechanical technology was restricted to presenting a single indication for each sensor (sometimes referred to as a single-sensor, single-indicator interface design). Later interface designs moved away from mechanical gauges to digital data presented on CRT or liquid crystal (LCD) displays. However, even though the interface technology shifted significantly, the presentation of engine parameters did not change substantially. The approach was still based on the presentation of individual parameters (in large part due to FAA regulations that require those parameters be displayed). One area of improvement, made possible by the new technology, was the enhancement of context for each indication. For example, individual indication formats changed to show the variation in expected and maximum values as the thrust reference value changed. And, more generally, indications became easier to read and understand. More recent Boeing models (737-NG and 777) use display formats that more clearly show limit exceedances and show the difference between commanded and actual values (see section 4.2).

Potential improvements to the current engine indications through a review of the research literature, as well as through discussions within Boeing and with airlines, have been identified. The two most significant areas center around two issues: detection of change and interpretation of change. A minor potential improvement involves the placement and normalization of the primary thrust indication.

4.3.3.1 Detection of Change.

There are typically eight or nine engine parameters displayed to the flight crew for each engine. In the most current Boeing production aircraft, they are split between primary (displayed full-time) and secondary engine displays (selectable displays). These parameters (with the exception of fuel flow, vibration, and oil quantity) are bounded by threshold values (operating limits). When a parameter exceeds a threshold value, the indication changes color to amber or red, depending on the type of limit and urgency of response.

In a few cases, an EICAS alert message is also generated. Typically, on Boeing models, an EICAS advisory- or caution-level message is generated for oil temperature and oil pressure exceedances. Also, an EICAS advisory message is generated when engine control is preventing exceedances in N1, N2, or N3. The other parameters (e.g., EGT) have no associated EICAS alerting messages but rely on flight crew detection of a color change in, or video reversal of, the indication. The secondary indications, normally hidden, automatically pop-up on the lower EICAS display when one of the secondary parameters has an exceedance.

To detect a change in an indication, flight crews, for the most part, are required to observe the indication. However, they may spend little time monitoring the upper EICAS display where the primary engine indications reside. Moreover, there are no procedural requirements for displaying (to monitor) the selectable secondary indications. In addition, for some conditions, the flight crew is required to use compacted indications instead of the standard engine indications. Specifically, a dual-engine failure leading to standby power or a transition to the use of the electronic checklist forces a switch to the compacted engine displays. These displays use a digital presentation (instead of an analog presentation) and are less familiar to the flight crew.

Crew training typically emphasizes the need to include the upper EICAS as part of the routine scan. However, as described below, one eye-tracking study shows that pilots monitor the upper EICAS approximately 1%-2% of the time (Mumaw, et al., 2000). Certainly, other indications, such as a yaw or engine-related noise, may motivate the crew to monitor engine indications, but without strong cues, engine indication changes may not be detected quickly.

Other types of engine parameter changes or anomalies can be even harder to detect because the indications change in more subtle ways. For example, thrust asymmetry may be quite subtle, especially when the thrust levers are in the same position and the asymmetry's effect on airplane performance is masked by an automated compensation. The crew may be required to detect a difference in position between two round-dial indications that are placed side by side. While there are no performance data on this task, it appears to be a relatively difficult task (especially if the crew is not looking for a difference). Also, detecting parameter changes within the normal

range (e.g., fluctuations, a trend towards limit values) may require careful, repeated monitoring of the engine indication.

In the case of secondary engine indications (e.g., oil quantity), trend monitoring is not done, and changes within the normal range (e.g., slow degradations) are unlikely to be monitored (or detected). If, for example, oil quantity is decreasing slowly over the first half of a long flight, the crew may not become aware of the situation until they are far from a diversion airport.

4.3.3.2 Interpretation of Change.

Another area to consider is the suggestion that flight crews have trouble interpreting the meaning of change when it is detected. Engine status is represented as a set of individual parameter indications, and the flight crew must derive higher-level descriptions of engine state from these individual indications. A Boeing study, described below, illustrates the problem.

Shontz (1996) conducted a simulator study regarding the handling of an engine surge. Shontz used a B767-200 full-flight simulator to simulate the effects of a surge. Shontz presented each pilot subject (B767-200-qualified instructor pilots) with one of three types of surges during takeoff and climb-out: self-recovering, recoverable with crew action (thrust lever reduction), and nonrecoverable (where engine shutdown was required). Pilots were unaware that the scenario would involve a surge (or any PSM); they were expecting a CFIT scenario.

Shontz found that only 3 of the 18 pilots were able to identify that a surge had occurred and which engine was surging within the 11 seconds available (before EGT reached the red line and made clear which engine had failed). Specific pilot responses varied by surge type.

None of the six pilots who experienced the self-recovering surge, which only lasted 3.5 seconds, took any action—thus, they made the appropriate response, which was no response, in this very brief window of opportunity. After the event, only two of the six pilots correctly identified the event as a surge; the other four had no idea what had happened.

In the case of the recoverable surge, the correct response is to reduce thrust and then restore it if the engine behaves as expected. Although all six pilots appropriately moved the thrust lever, only one did so within the 11 seconds (he also determined what event occurred). The other five pilots moved the thrust lever after EGT reached the red line. Notably, three of the pilots needlessly shutdown the engine. The two pilots who allowed EGT to go to the red line limit maintained the engine at idle instead of trying to restore full thrust after the surge.

In the case of the nonrecoverable surge, the correct response is to reduce thrust to determine how the engine responds. All six pilots took this action; two of them recognized a PSM within 11 seconds and brought the thrust lever back to idle, eventually shutting down the engine. The other four reduced the thrust lever to idle only after EGT reached the red line, and they eventually shutdown the engine (which was appropriate). However, these four did not recognize that a surge was occurring.

Thus, although few pilots understood what had occurred, most pilots eventually responded (or offered no response) in a safe and acceptable way. Pilot responses were prompted primarily by seeing EGT go to the red line. In fact, 9 of the 12 subjects (in the recoverable with pilot action and the nonrecoverable conditions) did not recognize that a PSM existed until the EGT red line occurred. Importantly, no pilot, given any type of surge, called for or reduced thrust on the wrong engine. However, none of the 18 pilots followed through as desired by calling for the stall/surge checklist. Instead, pilots called for a variety of checklists: engine shutdown, engine failure, and engine fire/severe damage. In summary, very few pilots appeared to get sufficient information in a timely manner from the engine indications available to them.

This single simulator study demonstrates that skilled pilots can fail to interpret/understand engine parameter changes and exceedances and, therefore, fail to follow through correctly. Similar reports come from airlines. They report, for example, that pilots can have difficulty knowing when to use the engine severe damage checklist because it is not clear when damage is severe. In general, the following conditions can be difficult for flight crews to recognize (or recognize in a timely manner) from the engine indications:

- Engine surge—identifying that a surge has occurred and to which engine, and being able to differentiate, before taking action, between recoverable with pilot action and not recoverable (shutdown required) types.
- Runaway engine—identifying the occurrence of a runaway engine, where the engine fails at high thrust (e.g., the engine fuel valve fails wide open). There is no response to throttle, so the engine cannot be controlled.
- Engine damage—specifically, being able to determine whether engine restart is possible.
- Severe engine damage—being able to determine whether a malfunctioning or failed engine must be shutdown or isolated (which requires the additional action of pulling the fire handle) due to severe damage. The flight crew has to determine which action to take based on an interpretation of engine conditions.
- Engine degradation—when engine parameters are trending toward or approaching limits, determining whether the degradation is operationally significant even though it has not exceeded the normal range.
- Engine vibration levels—determining when vibration is significant/meaningful and when power reduction is appropriate versus when shutdown is appropriate.

An example in-service event illustrates the larger point. At approximately 300 ft AGL after takeoff, the airplane experienced a continuous engine surge on the no. 3 engine. The flight crew initially believed they had a gear or tire failure, and the engine surge detection/recovery logic masked the engine indications. A correct diagnosis was further delayed because severe vibration made it difficult for the crew to read the flight deck instruments. As a consequence, the flight crew became inappropriately distracted by the failure, eventually neglecting airplane airspeed,

altitude, and heading. A CFIT was narrowly avoided. The no. 3 engine EGT gauge exceedance annunciation eventually made clear which engine was affected.

The point here is that even when a flight crew detects significant changes in airplane performance or engine parameters, which in the case of surge may be brief, transient changes, it can be very difficult to interpret or understand those changes (or perhaps, even determine which engine is affected) and determine how to respond. Detection and interpretation tasks require substantial knowledge, effort, and time on the part of the flight crew to identify and understand the PSM and formulate the appropriate response. This time will not always be available. A further complication is that because airplane systems are becoming more reliable, pilot training in systems is trending away from detailed, in-depth systems knowledge. This training trend leaves pilots a little less well prepared to reach the correct understanding and initiate the most appropriate response.

There is a range of potential consequences for failing to detect or correctly interpret a PSM, e.g., shutdown an engine unnecessarily or fail to correct a thrust asymmetry. These actions, in turn, can lead to a range of airplane effects, from reduced capability on an engine to more serious cases such as LOC. The AIA PSM+ICR report (section 4.1) further describes the ways in which flight crew confusion can lead to airplane damage, a hull loss, or even fatalities.

4.3.3.3 Thrust Indication.

Two issues have been raised regarding thrust indication. First, Abbott (1990, 2000) has noted that the thrust indication shown is not a true thrust (i.e., not expressed in pounds of thrust), but uses other parameters that may be directly related to thrust: N1 and EPR. Abbott proposes deriving a true thrust index from a larger set of parameters. Some rare failure modes can significantly distort the relationship between these displayed parameters and true thrust. One example is offered by an accident in which the displayed thrust indication, EPR, may have misled the flight crew. Due to an iced pressure probe, EPR indications did not represent actual thrust and led the flight crew to believe they had sufficient takeoff thrust (though they did not). Although airplane performance provided some potential cues to the flight crew, they did not integrate them fully and see the complete picture. The airplane failed to climb, stalled, and crashed shortly after liftoff. A more direct indication of thrust might have aided the crew in seeing the discrepancy between indicated EPR and actual thrust.

Another benefit Abbott believes would be created by a change to true thrust is that thrust can always be normalized so that the flight crew sees the current thrust value in reference to 100% of maximum available thrust (no matter where the thrust reference value is set). When this is done, the maximum thrust level is always indicated at the same place on the round dial. Abbott believes that this consistency could aid flight crews in assessing the current thrust value. This is a case where the evolution of indications has provided this feature. The presentation of EPR in certain Boeing aircraft uses a normalized scale and achieves the benefit of a consistent position of maximum thrust value.

A second issue is the placement of, or integration of, the thrust indication. N1 or EPR are placed on the upper EICAS, away from the PFD. However, in some cases, a manual thrust setting is used to meet flight control targets (airspeed, altitude, or path). Ideally, thrust might be better integrated into the PFD to facilitate execution of flight control tasks; for example, to provide the pilot direct feedback on whether the current commanded thrust will allow him/her to achieve the desired target. Note, however, that the actual thrust value may not be the ideal piece of information to support these flight control tasks. Instead, the pilot may need something like potential gamma (as provided on some head-up displays), which is more of a direct indication of acceleration.

One example of linking thrust setting to a flight target is the use of the green arc on the ND. The green arc appears on the ND as a predictor for the location at which the airplane will reach the altitude target set on the MCP. Pilots, when climbing or descending to a target altitude at a waypoint, can adjust the thrust levers until the green arc intersects the waypoint, which ensures they will reach that altitude at that point. This integration provides a direct link between a flight target and the thrust-setting task.

4.3.3.4 Accident/Incident Literature.

Another important source for identifying safety concerns associated with the monitoring of engine indications are the recorded accidents and incidents involving UCRs to PSMs. A recently completed review of a PSM incident database (section 4.2 of Clark and Winters) analyzed 81 cases of UCR, including LOC, SDGE, RTO at a speed greater than V1, and other events that mainly involve failure to select or complete the appropriate nonnormal procedure. Consistent contributing factors in these incidents were the failures to detect a malfunction in a timely way, diagnose, and correctly respond to the PSM.

Overall, Clark and Winters estimate that the likelihood of a PSM—specifically, a PSM that occurs during the flight phases where the occurrence of a UCR is a safety concern—is on the order of 1 in every 20,000 flights. The PSMs most likely to occur are surge, oil system exceedances, powerloss, and high vibration. Further, they found

- Unannounced engine malfunctions, such as Powerloss, Surge, and Failed Fixed Thrust, are the most likely to involve UCR.
- Oil system malfunctions, although one of the most likely to occur, are one of the least likely to involve UCR. Oil system malfunctions are unambiguously announced through EICAS and generally do not develop rapidly (i.e., involve short timelines or time-critical scenarios).
- The likelihood of a PSM-related UCR is estimated to be 2.6E-07, or approximately one event in every 3.8 million flights.
- The likelihood of hull loss due to PSM-related UCR is estimated to be 7.5E-08, or approximately one event in every 13.3 million flights.

Thus, Clark and Winters show that the combination of a PSM and UCR rarely leads to a serious accident. It appears that even though crews may fail to detect or understand what is happening when a PSM occurs, the flight crew response is unlikely to lead to more serious problems, such as LOC. In fact, the Shontz study demonstrated just this fact. It showed that although only 3 of 18 subjects knew there was a surge, all responded in an acceptably safe, albeit incorrect, manner. However, three subjects unnecessarily shutdown an engine, and two others left an engine running at idle when it could have provided normal thrust. These are situations that can be managed quite safely.

While the very low engine malfunction and UCR accident rates are somewhat reassuring, there is still value in ensuring that crews detect in a timely manner, correctly interpret, and fully understand PSMs and their implications in terms of the state of the propulsion and higher-level airplane systems and mission. In fact, ideally, the flight deck interface design and associated procedures should be as foolproof as possible in aiding flight crews to move from a PSM to an appropriate response.

4.3.4 Role of the Flight Deck Interface in Propulsion System Management.

Given the range of flight crew tasks that are required and the above considerations, the following sections discuss how the flight deck interface should support propulsion system management (from a human performance perspective). The following also offers design guidance, at a high level, for the flight deck interface design.

4.3.4.1 Supporting Performance Monitoring.

The flight deck interface must support the flight crew in monitoring and controlling propulsion system performance, specifically, the fuel system and engines. An important step in interface design is defining the types of feedback the flight crew needs in system management.

Feedback first comes from showing the commanded value, which shows the flight crew what parameter target has been set (by them or by the automated agent). To assess performance, the parameter's actual value needs to be shown along with the commanded value. These two together tell the flight crew how well the system is meeting the target set for an individual parameter.

Then, the interface needs to provide feedback at a higher level of system description. First, it is important for the flight crew to know how the physical system (in this case, the fuel system) is configured and operating. This information supports flight crew assessment of, and changes to, the configuration. Also, the crew needs to know (at some level of description) fuel quantity and location, whether fuel is being distributed from the tanks to the engines, and fuel consumption or fuel flow rate to the engines. This information allows the crew to construct a situation model (see appendix B for a discussion of the situation model) and answer questions that may arise, such as

- Am I drawing fuel from a tank with fuel in it?
- Am I balancing fuel in my fuel tanks?

- Am I configuring pumps to get the fuel to the engines?
- Is there a fuel leak somewhere in the system?

In addition to feedback on how the physical system is functioning (i.e., configured and operating), the flight crew needs feedback on how well the fuel system and engines are achieving the objectives needed for the mission. This can also be referred to as airplane effects or mission-level effects. This feedback tells the flight crew what effects the fuel system and engines are having on airplane-level functions and the mission objectives. Examples of these are

- Range Objectives: Can we make it to the intended destination? What airports can we reach?
- Aviate Objectives: What limitations are there on maneuvering? What limitations are there on landing?

A more formal version of this multiple-level feedback scheme was developed by Rasmussen (1985), who established the abstraction hierarchy (AH) framework for supporting system management. Vicente (1999) has elaborated on the AH framework and worked through several detailed examples in his book. The AH provides system descriptions that allow designers and operators to consider the system from different perspectives; the levels are as follows:

- Physical form—this level describes equipment layout and the physical appearance and condition of the system.
- Physical function—this level describes the state of the physical components (e.g., settings on pumps or valves) and how components are connected and configured for operation.
- Generalized function—the functions that the system is designed to achieve (e.g., flow or storage of fuel, compression, and combustion) and the state of system functions (independent of the state of the equipment that creates those functions).
- Abstract function—first principles-type description of system performance (mass, energy, or information flows).
- Functional purpose—overall system purpose (What is the system doing for the airplane and its mission?)

Generally, AH levels move from physical properties of the system (lower levels) to functional properties/purpose (higher levels). Understanding and addressing problems at one level often can require understanding system actions at the next lower level. That is, physical components can be configured to achieve system functions, and combining system functions is required to achieve the overall system function. Vicente demonstrates how these levels are linked and, especially, how system representations can be used to support knowledge-based performance (reasoning through the system) (see the discussion in section 4.3.5.1 of Dinadis and Vicente's engine display developed from an AH analysis; also see section C.2 in appendix C for a discussion of knowledge-based performance). For now, one must carry forward the simpler

notion that system operators can benefit from representations of both the physical system and the system function (purpose). Such benefits may include increased situation awareness and, ultimately, better decision-making and action.

4.3.4.2 Supporting Monitoring Engine Health and Managing Nonnormals.

The interface must also support the flight crew in a very different way for monitoring engine health and then managing nonnormals when they occur. There are three general functions that the interface must provide:

- Monitoring/alerting/orienting
- Understanding
- Guiding to appropriate action

4.3.4.2.1 Monitoring/Alerting/Orienting.

The airplane senses and displays many parameter values, and these values change over time as the airplane progresses through its mission. Some parameter changes are more meaningful because they indicate that the airplane has transitioned into a nonnormal operating regime; for example, a component fails and airplane system functions are degraded or lost. It is important that the flight crew be aware of these meaningful changes. Because it is not possible for a flight crew to monitor all indications all of the time, systems have been designed that can, at least partially, monitor and alert the flight crew automatically when a meaningful change occurs.

Effective alerting requires that meaningful changes attract (grab) the flight crew's attention. Placing alert indications where the crew is likely to be looking and making them salient (e.g., accompanied by loud aural, bright, flashing, colorful) are important for effectiveness. Placing alerting messages in a central alerting area (e.g., EICAS) can also be effective. Thus, initially, the interface's primary role is to alert the flight crew to the change. However, it is useful if the alerting function can simultaneously convey the following additional information: the nature of the change (i.e., What system or component, and how has it changed?), the severity of the change (i.e., How greatly will it affect airplane performance? How rapidly is a response required?), and where they can get further information on the change (this is the orienting element).

4.3.4.2.2 Understanding.

After they are alerted to a meaningful condition, the flight crew needs to understand how this condition affects airplane operation. This should happen at two levels: the physical system and airplane effects (i.e., functional level). For the physical system, the flight crew needs to understand how the system configuration and state of operating components has changed. If there are automatic system control actions when a failure occurs, the crew should be able to see how those actions have changed the configuration (e.g., Is a different fuel pump working to replace the failed one? Is fuel being drawn from a different tank? Is some automatic process now initiated to compensate for the failure?). More important, at the level of airplane effects, the flight crew needs to understand how airplane performance is affected (e.g., Am I unable to reach the original destination? Will I have less fuel reserves?). Note that some judgment is required in

determining how much detail and depth is needed to ensure the flight crew understands the change that has occurred. In particular, the designer needs to decide the level at which system components should be represented and how those components should be represented.

4.3.4.2.3 Guiding Crew Actions/Response.

Finally, the flight crew must be guided to the set of appropriate actions that need to be taken, either immediately or at a later time. Often, a nonnormal checklist is used to inform and guide actions. These checklists are linked to an EICAS message or to lighted alerting messages on or around the interface. Immediate actions may be taken, or there may be other decisions or actions required at a later time—for example, a procedure may need to be adapted due to a failure in a critical system, or there may be limitations on maneuvering at the time of landing. Somehow, the interface must support the flight crew in making sound decisions and in taking appropriate actions.

In other cases, there is no discrete indication such as an EICAS message that directs the flight crew to an appropriate nonnormal checklist. Instead, there are unannounced checklists that the crew must initiate on their own. The flight crew needs to remember that a relevant nonnormal checklist exists (e.g., engine surge) and retrieve it. Thus, in these cases, the flight deck interface does not provide guidance to the crew because this level of describing engine state is not available; they are on their own to recognize the need and seek it out. This approach demands more of the flight crew and can lead to ICR.

4.3.5 Designing for Engine-Related Tasks.

In the previous sections, how the interface should support engine-related performance- and health-monitoring tasks were described (at a high level). In this section, motivated by this conception, alternatives to the current engine parameter indications are considered. To establish a reference point, the current indications can be characterized in the following way:

- Engine representation:
 - The indications represent individual engine parameters for each engine.
- Alerting scheme:
 - For some exceedances, an EICAS alert message is provided (in airplanes with EICAS); this is a centralized alerting scheme.
 - For other exceedances, the flight crew must detect a change in the indication; this is an indication-based alerting scheme. An example of indication change is a color change.
- Interpretation/understanding:
 - In some cases EICAS messages identify a specific engine state, e.g., engine fail.

- In some cases, the flight crew is required to assess the state of the fuel system and engine from individual parameters, such as N1, EGT, oil pressure, oil temperature.
- Response guidance:
 - In some cases, EICAS messages are provided to identify the appropriate nonnormal procedure.
 - In the cases where there is an absence of a specific malfunction indication or alert, there is a reliance on crew training to interpret correctly and determine the appropriate response, e.g., fuel leak, surge, or severe engine damage.

In the following consideration of alternative approaches to this scheme, two issues were discussed: level of representation and level of support from the interface.

4.3.5.1 Level of Representation.

Level of representation refers to the representation of an airplane system, such as an engine. At the lowest level, the engine is represented only by individual sensor-based parameters, which is the situation in today's flight decks. The flight deck interface presents each parameter directly and does not provide any higher-level representation of the state of the engine or fuel system. There are a few EICAS messages that provide higher-level descriptions of the engine state (e.g., engine fail and engine fire), but in terms of how the flight crew monitors each engine, it is viewed solely as individual parameters.

A small shift away from this approach would lead to indicating derived indices, such as true thrust (see Abbott, 2000), that may be more closely aligned with supporting flight crew tasks. More dramatic shifts lead to displays that show a more integrated engine status. For example, one could indicate whether the engine is good, meaning that all indications are within the normal range. One could also indicate the presence of faults or performance shifts, such as surge or fail fixed (or even degraded conditions within the normal range).

In the context of military aviation, Dinadis and Vicente (1999) reviewed engine indications in a Lockheed Hercules C-130. They began by applying an AH analysis and found that only the upper and lower levels of the AH were represented in the flight deck interface. They then went on to develop interface tools to support each level of the AH and proposed an engine/fuel system display with six regions, each having different representations of the engine and fuel system (see figure 4-13). Note that this display is quite different from the engine indications on today's commercial airplanes.

At the functional purpose level of the AH, they proposed a display related to the overall purpose of the engine and fuel systems, which is to reach a desired destination. This display (the upper left area of figure 4-13) focuses on airplane range based on variables such as fuel level, engine efficiencies, airspeeds, outside air temperature, and altitudes. The outcome of this computation is represented as minimum and maximum ranges from current position on a map display.

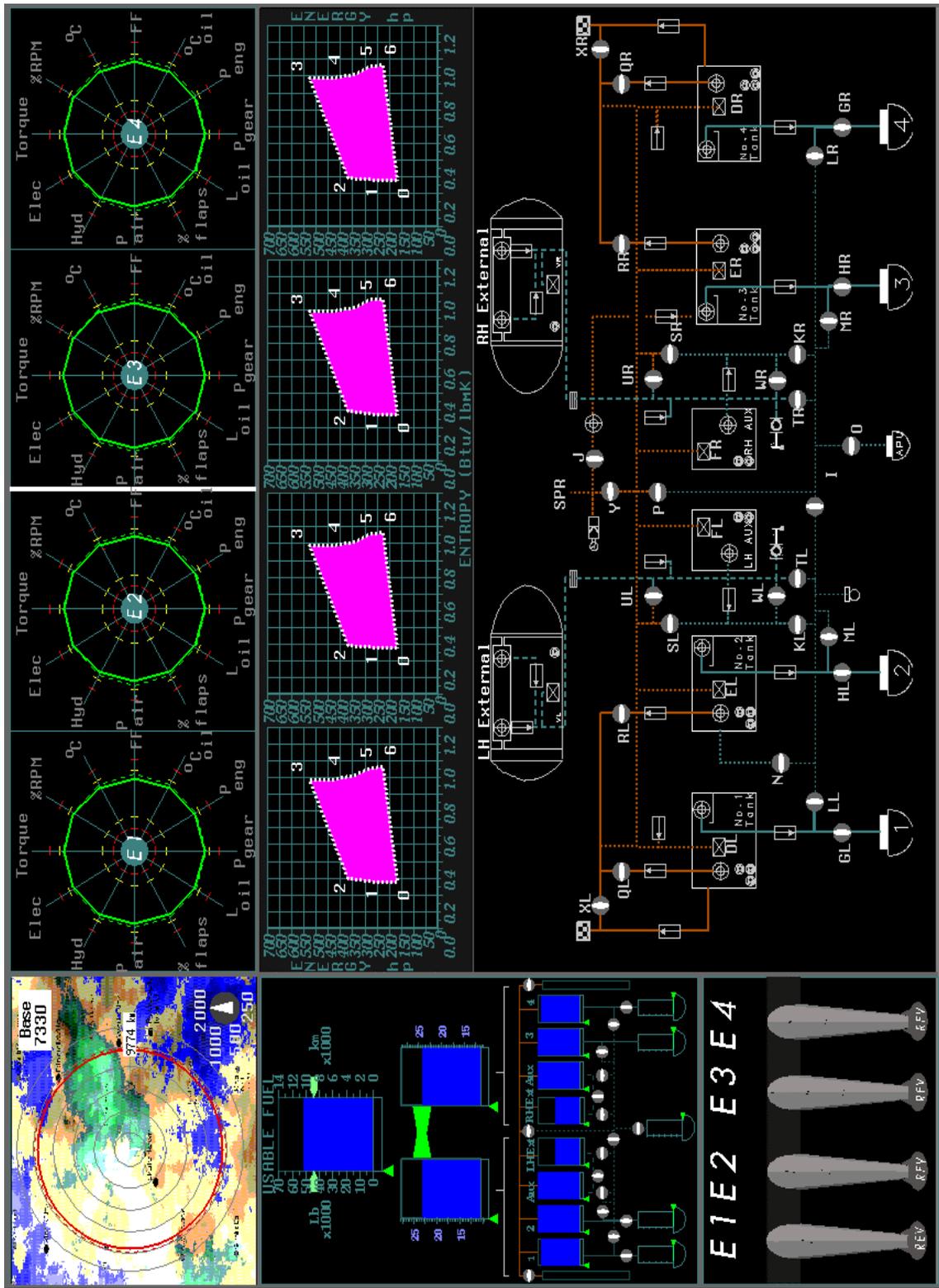


FIGURE 4-13. ENGINE/FUEL DISPLAY FOR A C-130 (Dinadis and Vicente, 1999)

The next level of the AH addresses each engine's purpose, which is to perform effectively and efficiently and to produce thrust. This area of the display (upper center and right areas of figure 4-13) provides an overview of each engine by showing 12 individual parameters organized into a polygon display. Each of the 12 parameters is normalized across engine power level. If there is a deviation on any parameter, the polygon changes from its regular shape (see figure 4-14). There are also caution and warning boundaries on each parameter that lead to a color change when the actual value crosses the threshold.

The next level of the AH shows the fuel system's purpose and functions. Similar to current synoptics, it shows fuel flow to each engine, tank fuel levels and flow indications, and information to support leak detection, including predicted fuel amounts (left center area of figure 4-13). The level below this one is a system display that provides a schematic representation of the physical fuel system and engines (lower right area of figure 4-13). This display element allows the flight crew to see the configuration of tanks, pumps, valves, etc., (with their current settings) that make up the system.

The final display component is an area that Dinadis and Vicente call systems information; this is meant to facilitate movement between the overview displays and the more detailed system displays. The first is an engine state diagram (energy x entropy) that shows both the expected behavior of each engine along with its current state (center right area of figure 4-13). A pilot can use these displays to get to a trend display (not shown) on various engine parameters.

There are several points to make regarding how this display applies to commercial aviation. First, the display uses too much interface real estate, and it would be difficult to keep it displayed full-time on the interface. All or part of it may work as a selectable display that can be called up when needed. Second, this display is meant to support knowledge-based (KB) performance as well as rule-based performance (see appendix C, section C.2 for further discussion of these concepts). Current commercial flight decks may not have the same mission to support KB performance, although as mentioned earlier, there needs to be some tools on the flight deck to support unanticipated scenarios requiring KB performance (the need for KB performance is guaranteed to occur at some point). Third, this display makes a major leap forward in presenting the fuel system and engine state at higher levels of description. Although it may not survive in its current form, it is worth exploring these ideas on how to communicate functional information regarding the propulsion system.

4.3.5.2 Level of Support From the Flight Deck Interface.

In this section, a distinction will be made between what the flight crew is responsible for and what the interface (automation) does for the crew. Section 4.3.4.2 described three necessary functions for managing nonnormals: monitoring/alerting, interpreting/ understanding, and guidance to an appropriate action. Interestingly, the few major research projects on engine indications have targeted the monitoring/alerting function (probably due to the FAA specification of the engine information that must be provided).

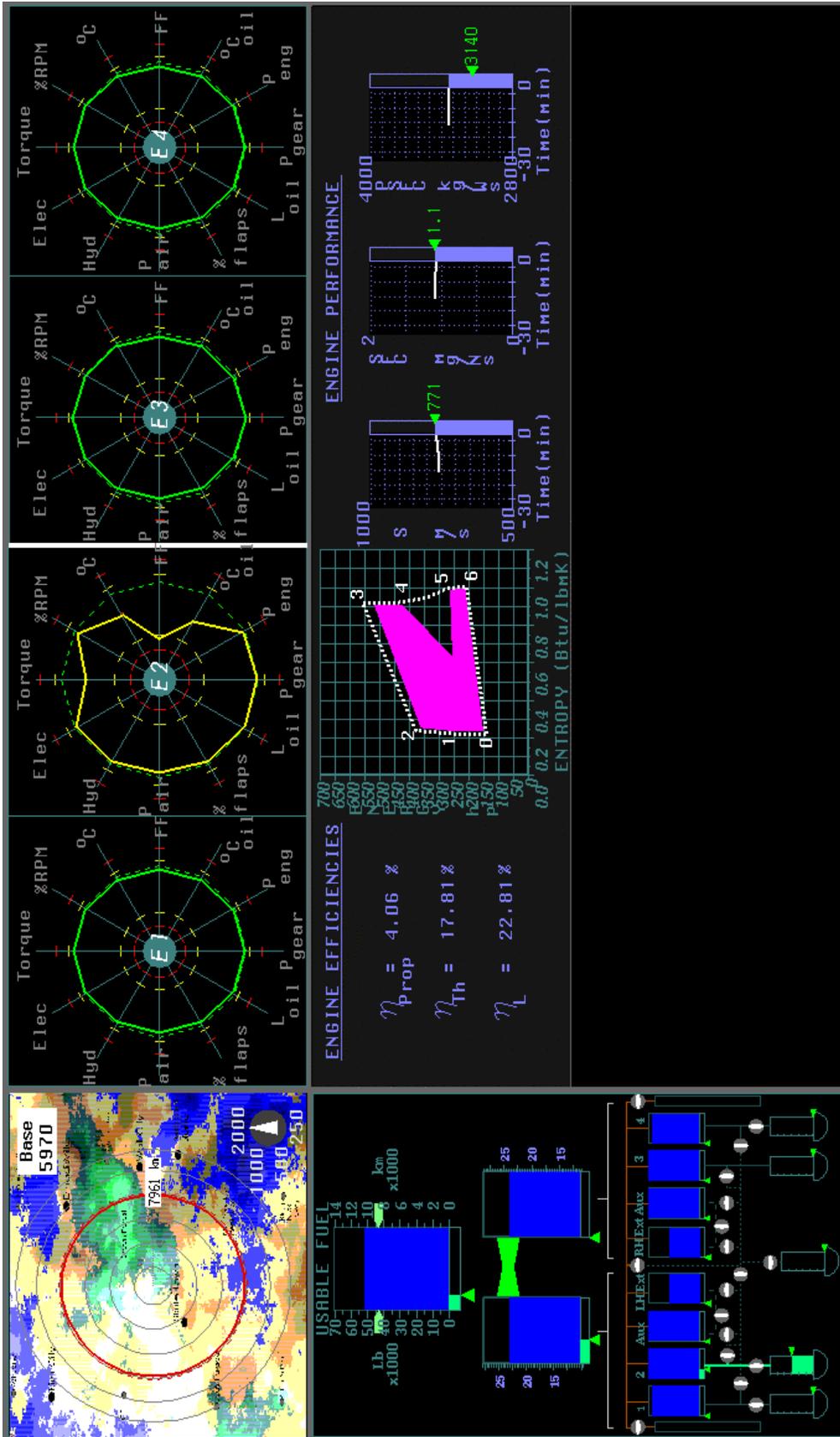


FIGURE 4-14. C-130 ENGINE/FUEL DISPLAY WITH SYSTEM FAULT (Dinadis and Vicente, 1999)

4.3.5.2.1 Research Findings.

4.3.5.2.1.1 Abbott Study.

Abbott (1990, 2000) focused primarily on supporting pilot health monitoring by converting each indication to a column deviation graph (see figure 4-15), called the Engine Monitoring and Control System (E-MACS) display. This graphical format focuses on two issues: easier detection of any deviation and, in particular, detection of deviations from the expected parameter value. Abbott claims that in addition to deviations that cross caution and warning thresholds, pilots care about deviations from the expected value of each parameter since this deviation may indicate a degraded level of performance (although it is short of being out of the normal range). In E-MACS, expected values come from a model of the system, and each parameter is then compared to that expected value. If the actual parameter value is the same as the expected value, the deviation graph will show zero deviation. The deviation graph also shows where the amber (caution) and red (warning) thresholds are. As figure 4-15 shows, Abbott normalized all parameters to have these thresholds lineup.

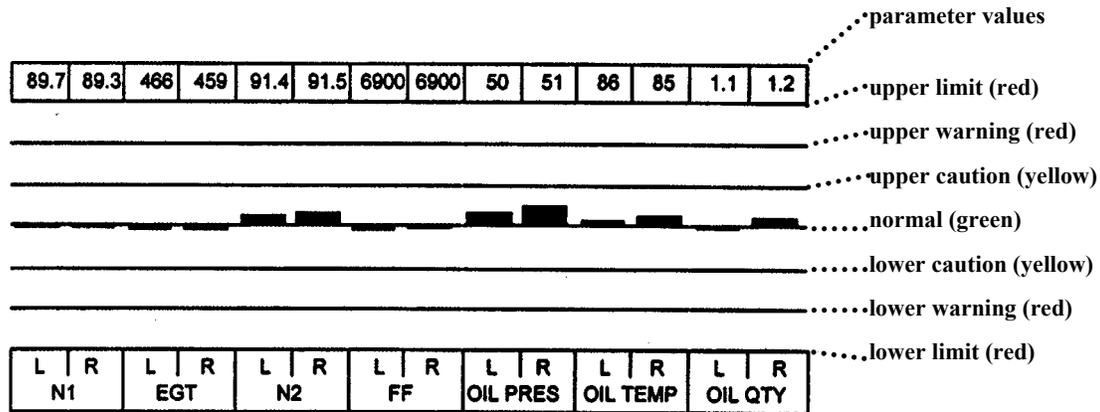
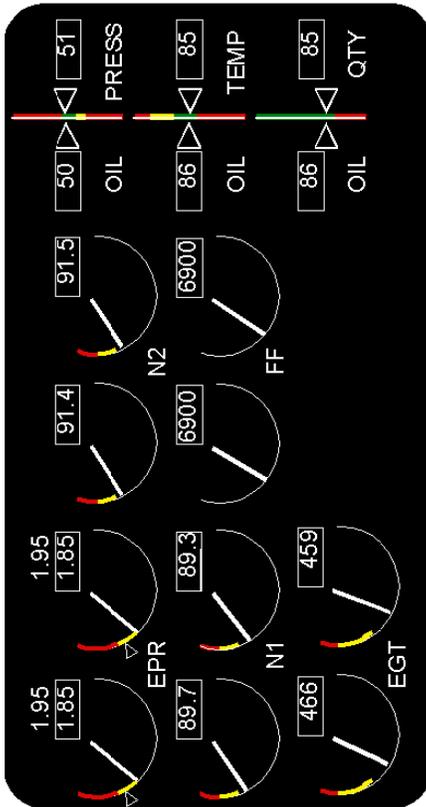


FIGURE 4-15. THE E-MACS DISPLAY (Abbott, 2000)

Figure 4-16 shows several comparisons of the E-MACS display to a standard engine display. The EMACS is slightly modified from the display shown in figure 4-15. In addition to the deviation scales, Abbott developed an alternative thrust indication (on the left side). Also, the parameters are grouped separately for each engine. Figure 4-16a compares a conventional engine display and the E-MACS concept for a normal, power-up condition. Figure 4-16b compares the two display schemes for a nonnormal condition. The E-MACS display shows erroneously high power information (the yellow bars on the left side). However, the E-MACS display also shows that both EGT and fuel flow are much too low for the amount of power the engine is supposedly producing.

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E-MACS

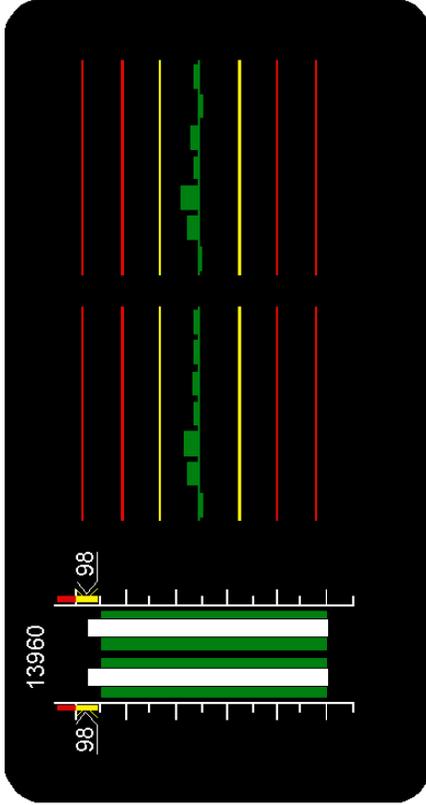
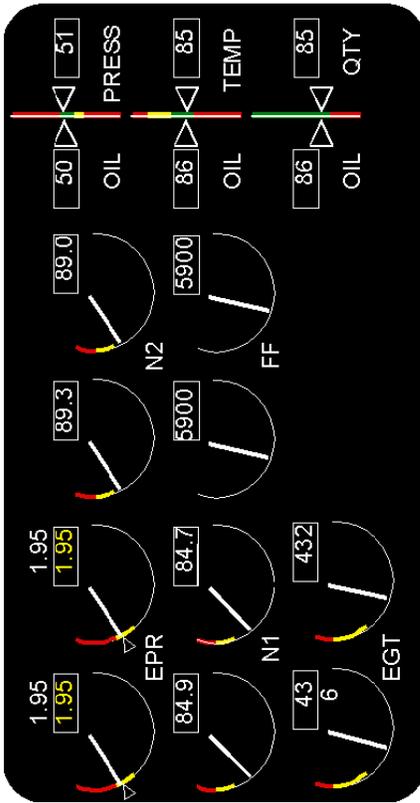


FIGURE 4-16a. THE E-MACS AND TRADITIONAL ENGINE INDICATIONS—NORMAL POWER-UP (NASA LANGLEY)

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E-MACS

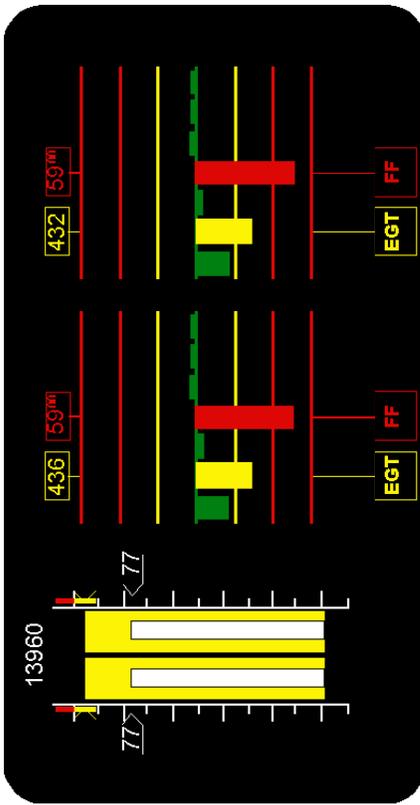


FIGURE 4-16b. THE E-MACS AND TRADITIONAL STANDARD ENGINE INDICATIONS (NASA LANGLEY)

Abbott ran a study to compare the E-MACS display to the traditional engine display. Abbot put 16 pilot subjects in a fixed-base simulator and ran them through several scenarios, once with the E-MACS display and once with the traditional display. The subjects were required to detect exceedances (without the support of EICAS alerting). Abbot found that with the E-MACS display, all 32 exceedances were detected. However, the subjects failed to detect 14 of the 32 exceedances with the traditional engine display. Also, a questionnaire showed that the pilots preferred the E-MACS display to the traditional display.

4.3.5.2.1.2 Hornsby Study.

Hornsby (1992) also conducted a simulator study that manipulated engine indications. In this case, Hornsby maintained the traditional Boeing engine indications but enhanced them in various ways:

- Added an EICAS message whenever any engine indication exceeded caution or warning thresholds.
- Added a green band to the parameter indication to show its nominal range (based on an engine model). The display changes color when the current value exceeds this range.
- Added an EICAS message, saying “monitor parameter,” whenever the current value exceeds the nominal range (but the nominal range is not shown).

Five engine indication conditions were created by using these enhancements alone and in combination (with the traditional engine display as condition 1). Hornsby had 10 pilot subjects fly multiple scenarios with each of these engine displays to compare performance (time to detect and the accuracy of identifying the problem). Hornsby found that detection time was decreased significantly by adding EICAS messages. The monitor parameter messages were also effective in decreasing detection time. Further, the enhancement of EICAS alerting messages (for exceeding caution and warning limits) was most preferred by the subjects. The green bands did not aid detection time and were not preferred by the subjects.

In terms of accuracy of identifying the fault, interestingly, the monitor parameter message hurt performance. This message decreased detection time but was insufficient for the subject to describe what the problem was. Then, the more informative message that followed (the EICAS alert) was often removed (artificially) by the time the subject looked there. Note that in a rating task, the subjects rated the display with all the enhancements as the easiest to interpret.

4.3.5.2.1.3 Summers Study.

In the other large study on engine indications (Summers, 1993), enhanced engine displays again showed superior performance. Summers compared the traditional MD-11 engine display with the E-MACS display and an approach that did automatic alerting. The traditional display used vertical bars to represent current values on engine parameters. The E-MACS display converted those to the column deviation format. The third engine display used a design-by-exception rule (DBE) that uses the engine model to monitor engine parameters automatically. Whenever an engine parameter differs significantly from the expected value, the crew is alerted through the

central alerting system (like EICAS) and can then bring up the traditional engine indications (otherwise, engine indications were not displayed).

Summers ran 12 pilot subjects through several scenarios with each engine display to compare performance. For detection of faults, the traditional display was the worst with 10 of 96 faults going undetected. All faults were detected with the newer (E-MACS and DBE) displays. Generally, the E-MACS and DBE displays also led to faster fault detections. However, there were problems in the accuracy of interpreting the fault for all displays. The newer displays did not seem to help the flight crews make sense of the nonnormals. (Note, however, that the grouping scheme used (by parameter, not by engine) may have diminished the interpretability in this study.)

4.3.5.2.1.4 Conclusions.

These three simulator studies show that monitoring/alerting enhancements can improve the likelihood of detection as well as time to detect an exceedance. The column deviation format makes deviations more easily detected, and certainly, the use of an alert message (EICAS) is a salient cue that a change has occurred. What is interesting, though, is that the identification of the fault (understanding) is not always enhanced through these new indications (although it is probably no worse than with current displays). Perhaps this outcome is due to the focus of these studies being on detection, not understanding.

There are two larger points here. First, these new schemes maintained individual engine parameters; there was no integration into higher-level engine descriptions. The authors seem to be focusing solely on detection concerns with the traditional scheme of individual parameters. It should not be surprising that an EICAS message (an automated alert) is more effective at getting the pilot's attention than is unaided monitoring. However, the lack of anymore integrated display means that flight crews will still have trouble with understanding the meaning of variation on the individual parameters, such as in cases like engine surge.

The second point is that these displays were developed to enhance detection of deviations and may not be suited to performance monitoring and control tasks. The primary element of E-MACS display (the column deviation graph), in particular, is optimized for detecting deviations. Other elements are needed to support thrust-setting tasks. The point is that multiple display elements will be needed to support both performance and health monitoring (as also shown by Dinadis and Vicente, 1999).

4.3.5.2.2 Alternative Schemes for Engine Indications.

In considering alternative engine indications schemes, there are a few key questions that should guide design. For monitoring/alerting, the primary question is:

How does the interface attract the flight crew's attention that a meaningful change has occurred?

For some PSMs, the crew will be alerted by unmediated indications—noises, smells, smoke, aircraft yaw. The occurrence of these may orient the flight crew to the engine display when they

associate that cue with the engines. If changes occur only at the engine indication (e.g., color change, text message) on the upper EICAS display and it is critical that the flight crew be aware of the change immediately, then the interface designer needs to ensure that this change has sufficient salience to attract the flight crew's attention. Generally, the designer needs to consider that this area is peripheral to where the crew's eyes are likely to be focused (PFD/ND or out the window), and some orienting cue will be necessary to attract attention (e.g., aural, glareshield light, flashing, etc.).

In the Abbott study, it was possible to enhance detection with an indication that more clearly showed deviations from the expected (the E-MACS display), but even that display requires that someone look at it. The most straightforward method to get attention is to announce the change on the EICAS, which is the central-alerting display. Again, the studies reviewed above showed that an EICAS message reduces detection time.

For interpreting/understanding, there are three questions to consider initially:

- What information types are needed to support the flight crew in assessing the fuel system and engines?
- How should the interface describe the new state of the engine or fuel system?
- What remains working that can be used?

The first question invites thinking about the types of information that might be provided. In today's aircraft, the engine indications provide only the current parameter value. With these indications, values that have existed prior to right now are lost, and there is no facility for seeing parameter history. Therefore, the first issue is—given an individual parameter representation—should trend information be added to the actual value for individual parameters to capture behavior over time?

One form of trend information is predicted behavior over short intervals (e.g., 5 seconds). For example, airspeed has a predictive trend vector on it that shows where airspeed is headed. Similarly, engine indications could show predicted behavior, but if this is useful, it may only apply to a few of the engine parameters—perhaps oil quantity and EGT. The other form is a historical trend, which could be a separate display that allows the flight crew to see the parameter trend (or behavior) over any selected time period. Or, it could show a continuously updated x-second trend, e.g., range over the last 5 seconds. This type of trend information could make it possible to retrieve transient changes that are no longer present, as in the case of a surge.

The second question is concerned with the level of representation of the engine and fuel system. Current engine displays rely on individual parameters. Several higher-level representations, notably in the Dinadis and Vicente (1999) work, were reviewed. It seems that some set of higher-level descriptions may be useful to make more clear to crews the state of the engine and any limits on its operation. Therefore, the flight deck could have interpretation capabilities built in to move from showing the current value on individual parameters to the current operational status of the engine.

The third, but related, question, “What remains working?,” is also a critical part of the system description. While it is important to aid the flight crew in taking action on failed systems, it is also important to ensure they do not take inappropriate actions on working components. Section 4.1 of Clark and Winters describes cases in which flight crews shutdown the functioning engine. Note that the quiet, dark philosophy common to flight deck design might be interpreted to exclude showing status of components that are working as expected. However, in trying to guide flight crew response, it may sometimes be beneficial to explicitly indicate normal system state or what capabilities are available.

Representation of systems (such as the fuel system) must also be considered. There is a trend toward increasing the automation of system management such that certain system failures (such as component failures) are managed without the need for crew input. As the flight deck automation takes on more of the role of interpreting nonnormal variation in indications and, perhaps in reconfiguring systems, one issue arises: handoffs back to the crew.

Research on expert systems (Roth, Bennett, and Woods; 1987) has shown that if an expert system reaches an impasse (e.g., cannot work through the interpretation), the partial solution and remaining problem gets handed back to the human operator (or the flight crew is told nothing about the actions of the automated agent). In this situation, it is desirable to support the human operator in completing the work (e.g., understanding engine state). The machine’s prior reasoning should be shared with the pilot in a concise summary. That is, the automation should communicate what it was looking at, what partial solutions it developed, and what remains to be understood (or where the uncertainty remains). In the current case, this may mean that if the automation cannot complete an interpretation of engine state, it should have a way to hand the task off to the flight crew so they can benefit from the partial solution. This may mean providing a meaningful display for monitoring that effectively characterizes the nonnormal variation of the engines.

For guidance in responding, the primary question is:

How does the interface lead the flight crew to take appropriate actions?

This guidance should make clear, first, what control/controller should be acted on. There are a small number of crew actions that are possible with the engine, primarily, reduce throttles or shut it down. Fuel system interactions can be more complex. The display that supports understanding should also reveal what should be acted on, i.e., which control is relevant. There may also be a benefit in guiding the flight crew to a procedure; for example, EICAS messages, typically, link to a procedure.

A second consideration is that the flight crew should get feedback on the actions they are taking to indicate that they are fixing the problem. Ideally, at the functional level, the crew can determine if propulsion-related airplane capabilities have been restored (and to what extent they have been restored).

4.3.5.3 Allocation Guidelines: Human Processor Strengths and Weaknesses.

The preceding guidelines are tied to the nature of propulsion system tasks. It is also worthwhile considering allocation (between humans and automation) guidelines tied to basic human performance issues.

Within the history of human factors, there has been a strong desire to understand how to allocate functions to humans and to machines. The development of human-operated technology has taken the approach that humans are best suited for some tasks and machines are best suited for other tasks. An early version was the Fitts list (1951). Fitts determined that humans should be allocated tasks that involved the ability to

- detect small amounts of visual or acoustic energy.
- perceive visual or auditory patterns.
- improvise and use flexible patterns.
- recall relevant facts at the appropriate time.
- reason inductively.
- exercise judgment.

Machines, on the other hand, were best suited to tasks that involved the ability to

- respond quickly to control signals.
- apply great force smoothly and precisely.
- Perform repetitive, routine tasks.
- store information briefly and then to erase it completely.
- reason deductively (from many cases to one rule), including computational ability.
- do many different things at once.

This list shows that humans and machines are very different types of processors. Humans are adept at seeing complex patterns, at generalizing from a few cases (but are sometimes fooled), at assessing the full context/situation and responding appropriately, and at behaving flexibly. Machines do not tire, can store and process great amounts of information, and handle multiple computationally complex or repetitive tasks simultaneously and quickly, as long as the situation does not change to make the actions inappropriate.

Not much has changed since 1951 to alter these lists of strengths and weaknesses; humans and computers are still essentially the same. However, what has evolved is the notion of how designers should create technology. Instead of allocating functions as though the two processors (human and machine) were independent, there has been subtle but important shift to focusing on the human as the central processor in the system and creating technology that supports the human's ability to serve this role. The current notion is that technology should be created to support and extend the human processor operating the system.

4.3.5.3.1 Guidelines for Automation's Role.

The following sections discuss areas where automation/technology should support human processors (pilots) to enhance flight operations.

Technology should be used to monitor for infrequent or subtle changes. Many years of research have shown that humans are poor at extended vigilance tasks (e.g., Broadbent, 1971). Specifically, when humans are asked to monitor a display to detect subtle or infrequent changes, they are not effective for very long (about 30 minutes, when there are no other tasks and they are highly motivated). Flight crews are rarely required to engage in sustained monitoring, but instead use periodic monitoring. Periodic monitoring in an operational setting is a different task than vigilance and is more driven by the conscious direction of attention and expectations about where meaningful information will be presented.

On the flight deck, monitoring of engine and other system indications is a secondary, or lower-order, task. Pilots are typically flying the airplane manually or engaged in some other activity (e.g., map reading, radio transmissions, flight management computer inputs, and visual search for threats) that requires their full attention. The pilot flying (PF) spends most of his/her time monitoring the PFD and ND during flight. In fact, several studies of pilots' visual fixations during routine flight (Heuttig, et al., 1999; Mumaw, et al., 2000; and Wickens, 2000) showed that pilots spend roughly 60% of their time monitoring the PFD/ND in a routine flight. Further, Mumaw, et al. found that only about 1%-2% of total monitoring time was spent on the upper EICAS display, where engine indications and EICAS alert messages are presented.

The role of technology is to carry out monitoring for the small, meaningful changes that lead to the need for pilot awareness or action. In most cases, the system designers (e.g., propulsion engineers) can identify the events that are defined as the meaningful changes pilots should notice. The interface then needs to turn these subtle changes in salient changes through the use of alerting schemes (e.g., visual and/or aural alerts). If the designer's objective is to rely on a pilot to monitor for these changes, then the indications need to be located in the areas where pilot attention is usually dedicated.

Technology should be used to integrate sensor information (data). Humans have limited storage and reasoning (processing) ability; there are limits on how many separate items can be considered or manipulated (Simon, 1957). Therefore, humans are limited in taking separate bits of data or information (e.g., variation in individual parameters) and integrating them to understand a larger truth (e.g., operational status of a system).

Engine indications are presented as a set of individual parameters to be monitored, and it is easiest for pilots to see changes in each parameter with this scheme. Technology can be used to integrate separate indications to show larger effects or trends (if there are meaningful integrations). It is the role of the interface designer to understand the information that the flight crew needs and then pull together indications from sensors and controls to support crew awareness and understanding. A number of researchers, working in other industrial applications, have developed techniques for integrating individual parameters into higher-level descriptions of system performance that may be applicable to the flight deck (for example, see Christoferson, et al., 1996; Vicente, et al., 1996; Woods, Wise, and Hanes, 1982).

Technology should be used to prevent recognition biases. As identified by Fitts (1951), humans are skilled at perceiving patterns and at inductive reasoning. More specifically, humans generalize quickly as expertise develops, learning to recognize meaningful events that are occurring. While this skill is often exploited to improve performance—to quickly see what is occurring and then react appropriately—humans also can over-generalize. That is, humans can see a few elements of some event and jump too quickly to the conclusion that the event is occurring (e.g., a loud bang from a surge is mistaken for a blown tire on rotation and the crew inappropriately rejects takeoff, or a loud bang from a blown tire is mistaken for a surge and the crew inappropriately reduces engine thrust). This is sometimes referred to as a garden path solution because the person was led down a garden path by a few familiar cues. The outcome is a significant misunderstanding of what is happening, which can bias decisions and actions taken subsequently. Further, one's understanding of the current situation can lead to a confirmation bias mindset (see Evans, 1989) in which only confirmatory information is sought.

The interface designer can reduce the likelihood of incorrect interpretations by providing higher-level representations of the system's (or airplane's) performance; these may include graphical depictions or simple textual messages about the system. If the pilot must rely on low-level indications of engine performance, it is easier to selectively attend to indications that can be misleading (or may not form a complete picture of the situation).

Technology should be used to determine consequences and reason about machine behavior. There has been a great deal of study of mental models (e.g., Gentner and Stevens, 1983; Oakhill and Garnham, 1996) in systems operation. A mental model is a person's mental representation of a system or device that allows him/her to reason about how it will behave or respond to inputs. Thus, if one has a mental model of the fuel system and engines (or some other airplane system), one can be told of a fault and use the mental model to step through the system effects. The outcome is an understanding about how well the system can perform and how the airplane mission may be affected (e.g., cannot make intended destination).

Unfortunately, as mentioned earlier, humans have limits in their capacities for this type of reasoning. Mental models are, therefore, limited and often inaccurate in some way. Further, the reduced emphasis on systems training in the last 10 years has left pilots with less well-developed mental models of airplane systems. There are numerous examples where pilots apparently made significant errors in understanding faults and anticipating outcomes. These cases suggest that humans should be supported in thinking through from faults/failures/reconfigurations to consequences for flight operations.

Electronic checklist systems collect notes from all executed nonnormal checklists to give the flight crew a compiled set of effects in the appropriate (approach/before landing) normal checklist. A potentially useful enhancement would be to integrate these consequences around mission-related capabilities, e.g., areas such as maneuvering, range, or landing. In this way, the computational power of the automation can aid the flight crew in understanding how their mission is affected, and the relevant information gets accessed by the crew when they need it.

Technology should be used to track goals and support task management. A number of accidents and incidents have demonstrated that flight crews sometimes fail to manage tasks well. There are many compelling historical examples of poor flight crew resource management. Typically,

in these cases, flight crews lose sight of the big picture (sometimes referred to as losing situation awareness) and inappropriately spend their resources on lower-level tasks when more critical tasks require attention. Certainly, CRM training is one approach to making crews better at managing with the big picture in mind. However, the flight deck interface might take on more of this role as well by providing enhanced representations of current status.

The flight crew needs to see clearly what problems exist and be able to assign priorities accordingly. As before, the interface needs to show system status effectively (e.g., engines or the fuel system) and its effects on mission completion. Flight crews should not have to generate these higher-level accounts on their own; it is time-consuming, error-prone, and a poor allocation of human effort.

Technology should be used to identify and locate appropriate procedures. After the flight crew is aware of a problem and understands the nature of the problem, the next thing needed is quick and reliable access to the appropriate guidance—that is, the nonnormal procedure. In Boeing's recent discussions with airlines, it was found that flight crews sometimes have difficulty getting the correct checklist when working with paper checklists (e.g., because of the organization of the document; note that the B777 Electronic Checklist has removed this concern). The organization of the paper checklists and the link between alert messages and checklists is important to getting appropriate/desired crew response. Boeing continues to focus efforts in this area. The point here is that technology (through interface design) offers more powerful means for guiding flight crews to the appropriate procedure/response.

Technology should be used to guide detailed sets of actions. Most flight deck procedures are driven by checklists, which is a rule-based form of performance (Rasmussen, 1986). The advantage of a rule-based approach, in which guidance is written down in detail to be followed by the flight crew, is that Boeing pilots and system engineers have already thought through the types of failures that can occur and the appropriate response to each. Many actions need to be performed exactly as specified, and the order of actions can be important. It is not possible for pilots to carry such detailed guidance in their heads and reproduce it consistently and accurately.

The appropriate role of technology in supporting the flight crew is to provide the detailed guidance (since it cannot be remembered accurately) and to aid the crew in adapting that guidance to the current conditions. The problem with developing a rule-based approach is that the people who write the procedure cannot anticipate all potential situations that might arise. The role of the pilot is to take the guidance and ensure it is applied appropriately for the situation. Technology can support this adaptation by making clear the intent of each step of the procedure and by showing the intended system, airplane, and mission consequences of the procedure.

Technology should be used to convey intent of the agents. On modern flight decks, there are typically three agents who can control the airplane and its systems: captain, first officer, and the automation (autopilot, autothrottle, and automated system logic). Each agent can have the authority to make virtually all control inputs. It is then the role of the other agents to monitor the controlling agent—PF or automated agent flying—and ensure that it is performing as expected. An important shift in flight crew training is that the PNF is referred to as the pilot monitoring (PM) (Helmreich, Klinect, and Wilhelm, 1999). It is the PM's role to understand what the PF is

intending to do and monitor for deviations or errors in executing that intent. The argument is that it is easier for the PM to detect and correct inadvertent errors than the pilot who made those errors, the PF. This applies equally well to cases where the automation is flying, i.e., the appropriate role of the human crew is PM.

In this framework, it is critical that the PM

- know and understand the controlling agent's intent and
- understand how to monitor the execution.

In the case of the automated agent (autopilot), there is evidence that the flight crew can fail on both accounts: they may fail to get, or be unable to get, sufficient feedback from the flight deck interface regarding what it intends to do (e.g., Sarter and Woods, 1997) and fail to monitor, or be unable to monitor, effectively, even when the intent is understood (Mumaw, et al., 2000).

In current flight decks, it is the responsibility of the flight crew to convey intent through briefings, formal callouts/procedures, or more casual communications. If the PF fails to convey intent, the task of the PM becomes much harder. Flight deck technology might be used to convey intent. In the case of the automated agent, the flight deck interface could convey what tactical targets it is using (i.e., altitude or airspeed) and how it will achieve those targets (e.g., Hutchins, 1993). Or when automated system control processes are initiated and it is important for the crew to have an awareness of those changes (e.g., changes that might suggest a fuel leak is occurring), the interface could make those processes more visible. Similarly, there may be ways for the interface to reveal the intent of the human PF in tactical flying or in systems management.

Technology should be used to support smooth task completion. Flight operations is often reactive to the needs of others, and flight crews can be distracted or interrupted by ATC, the airlines operation center, or the cabin staff. These interruptions can come while the flight crew is trying to accomplish some procedure, and the crew is responsible for successfully returning to and completing the interrupted task. Recent research (Dismukes, Young, and Sumwalt, 1998) has described how crews can fail to overcome these distractions. Checklist steps can be skipped, entire checklists can be forgotten, or other pilot actions can be lost (e.g., setting altimeter).

Flight deck technology can reduce the potential effects of this failure in prospective memory by helping the flight crew track what is being done or by alerting items that are not done. The B777 Electronic Checklist provides certain useful features in place keeping and tracking completed checklists. Airplanes also have the takeoff configuration warning system that alerts the crew when the airplane is not properly configured for takeoff. Ideally, these types of features can be implemented more broadly to help crews ensure that tasks and procedures are completed successfully.

Technology should be structured to support effective and efficient execution of common tasks. Currently, a number of flight operations tasks require the flight crew to pull together information

from a number of sources; an example is diversion planning where flight crews need to consult FMC performance data, get information from their airline operations center, assess airplane capabilities, etc. There can be a significant workload in gathering and integrating data to support this type of decision-making. Flight deck technology can better support performance by bringing all of the relevant information together to support these types of critical tasks.

As flight deck technology progresses, it will become more possible to bring data together around tasks instead of relying on the flight crew to integrate and interpret information from multiple sources. The result will be lower workload and better-informed decisions.

4.3.5.3.2 Overview of the Role of Humans and Machines.

The foregoing was intended to provide an overview of the types of activities that humans do poorly. Generally, humans

- have limited attention and working memory. They focus on a small set of items where they expect useful information to be. Attention becomes more focused when stress increases, and they can only keep a handful of items in mind at any one time. New information can bump other information out.
- can be overloaded in one modality. The visual system can only focus in a small area and information is more likely to be perceived when it comes through a different modality, such as aural or tactile.
- have limited reasoning abilities. Their understanding of complex systems is flawed, incomplete, and contains misconceptions. They can only make limited manipulations in working memory.
- can overgeneralize and leap to incorrect conclusions. Further, a pilot's current understanding can bias him/her to seek only confirmatory evidence from the set of indications available. They can become fixated on a problem that may be minor in the larger scheme.
- have limits on the detail that can be recalled from long-term memory. Precise instructions can be forgotten, and it is better to rely on written down instructions.

Technology—if one hopes to preserve the human as the primary authority on the flight deck—can be used to extend human capabilities and support flight crews in achieving mission objectives. Generally, the role of technology should be:

- Monitoring for meaningful changes in system and airplane performance and making those changes known to the flight crew.
- Guiding attention through either salient information in the field of view or attracting (or directing) attention to an area where important information can be found.

- Reducing workload by reducing the need for mental integration and manipulation by organizing data around meaningful events and system descriptions (not simply presenting data from individual sensors), by tracking individual system faults through to airplane effects, and by organizing data around important flight operations tasks and decisions.
- Support priority setting and task management by providing higher-level descriptions of airplane systems and functions (airplane capabilities) so that flight crews can identify the most important issues quickly and track how well those are being managed. Further, these high-level descriptions can potentially prevent incorrect interpretations of the current situation.
- Guiding flight crews from awareness through to understanding the problem to prescribed actions (procedure) for that problem.
- Capturing and conveying intent so that the pilot(s) who are not controlling the airplane or airplane systems can monitor execution more effectively and coordinate their own activities better. This reduces the need for explicit communication between agents, which may not always be done well, given the potential distractions and pitfalls in the environment.

The focus in the use of technology should not just be in reducing errors (either through eliminating them or making them more easily detected) and reducing workload. It is equally or more important to understand the flight crew's tasks and support the skillful and efficient execution of those tasks.

4.3.5.3.3 Data Versus Information: A General Guideline.

In the development of indications, an important distinction must be made between data and information. The two terms are defined as follows.

Data refers to a reading from an airplane sensor or control, e.g., airspeed, altitude, thrust lever position, and flap position. Note that the value may be processed in some way after being sensed.

Information, on the other hand, places data in context to support a task; that is, data are integrated with other data tied to a task. Context can include reference values (e.g., thrust reference limit, V_1 or V_R), thresholds (e.g., red-line limit or operating limit, flap placard speed), expected values (e.g., expected EPR for current conditions), or other parameters that change an expected value (e.g., appropriate configuration of systems is contingent on whether it is prior to or after engine start).

Thus, information is created by placing data in context; however, information is not useful unless it supports some flight crew task. A primary goal of interface design is to integrate data and appropriate context to guide pilots in decision-making and control actions (flight control or airplane system control). Another possibility is that the interface supports better understanding

of the current state of the airplane or an airplane system, which eventually supports decision-making and control tasks.

Broader design guidelines are presented in appendix C, which provides a description of pilot-centered design principles and also discusses Rasmussen's performance classification scheme (skill-, rule-, and knowledge-based).

4.3.6 Indication Ideas.

The foregoing has identified several considerations regarding engine indications. They typically

- are located in an area where the flight crew may not notice subtle changes and malfunctions, therefore, require either a salient presentation or an alert from the EICAS to be reliably detected.
- are at the level of individual parameters only.
- show only the current value (when behavior over time may be of interest).

If these indications remain as they are (individual engine parameters on the upper EICAS), there are two areas where enhancements could be considered: trend information could be added to capture behavior over time and differences between engines could be made more salient.

For the first issue, behavior over time, there are two reasons to add this type of information. First, sometimes changes are transient and may not be fully observed. Because the flight crew is not monitoring the engine indications continuously, transient fluctuations may be missed. If those transient variations can be captured within the indication, the flight crew can extract information that would otherwise be lost. Second, the pattern of the behavior may reveal something about the nature of the malfunction. Further analysis and validation is required to determine whether this type of information is valuable enough to include in the design of indications.

Figures 4-17 and 4-18 offer some ideas on how trend/history information might be added to the current indications. Figure 4-17(a) shows a traditional trend display that might be used in a process control setting. It shows current value with the diamond along the scale, and shows the parameter history over the previous 3 minutes. Figures 4-17(b) and 4-17(c) show variations on that indication style that summarize the trend over a time period. Figure 4-17(b) uses a bracket to indicate the range and minimum and maximum values of the parameter's variation over the previous 3 minutes. Figure 4-17(c) captures the same information but also indicates the percentage of time spent in a range of values. The rectangle indicates the range that the parameter has been in most of the previous 10 minutes, but the T on the top and the bottom indicate that there have been transient spikes outside of that range. Therefore, this indication separates the full range of variation over the 10-minute period from the range that better characterizes its value during that time. This type of display also helps show how stable the parameter has been.

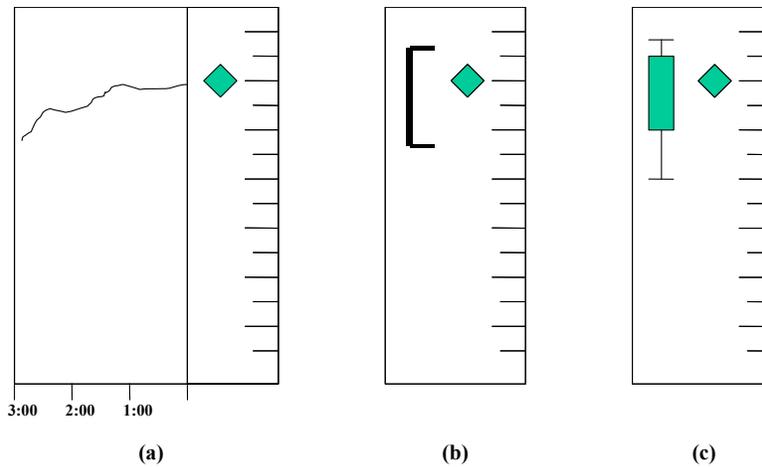


FIGURE 4-17. EXAMPLES OF PARAMETER INDICATIONS SHOWING HISTORY

Figure 4-18 shows how these concepts might work in the round-dial format. Figures 4-18(a) and 4-18(b) show a method for laying the range of parameter variation on top of the current indication, either as a shadowy pie wedge or as an arc well inside the edge of the round dial. It is important that neither indicator interferes with the ability to see the current value for the parameter.

Regarding the latter area of consideration, current engine indications appear to be optimized more for getting information about each engine than about comparing the values across engines. As mentioned, a major contributor to health monitoring is comparing parameter values or behaviors across engines. There are currently no data on how well pilots can detect differences across engines.

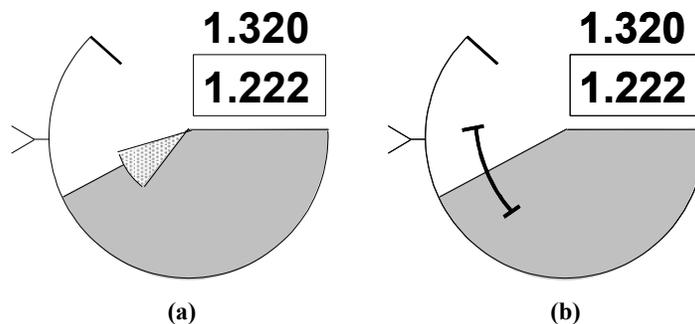


FIGURE 4-18. PARAMETER INDICATIONS SHOWING HISTORY WITH THE ROUND-DIAL FORMAT

Figures 4-19, 4-20, and 4-21 offer three ideas on how indications might be modified to make differences across engines more easily detected by showing the difference directly. Figures 4-19 and 4-20 show a vertical format, and figure 4-21 uses a horizontal format. In each case, the supplemental indication shows that the left engine is at a higher setting than the right engine. In figure 4-19, the amber band extends beyond the first threshold, which is there because not all

differences are meaningful. Figure 4-20 uses a similar idea, but with arrow indicators. The difference would have to be above the first threshold to be important. A second threshold is shown above that would turn red when exceeded. An L is placed above the engine difference bar to make more clear which engine is operating at a higher value. This provides guidance to the pilot for taking action on the left thrust lever. Further analysis and validation is required to determine whether this type of information is of benefit, and if so, how to best implement it in indications design.

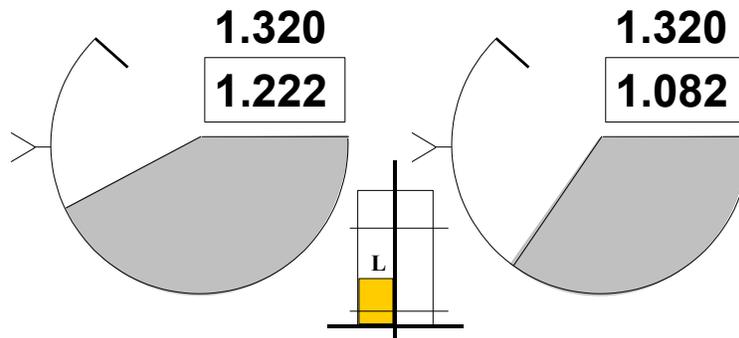


FIGURE 4-19. EXAMPLE OF A DIFFERENCE INDICATION, VERTICAL BAR FORMAT

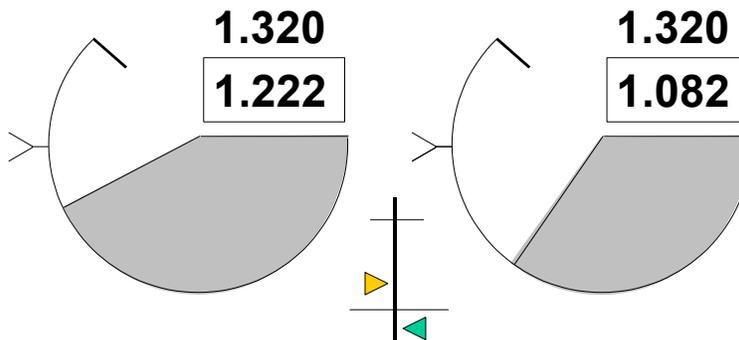


FIGURE 4-20. EXAMPLE OF A DIFFERENCE INDICATION, VERTICAL ARROW FORMAT

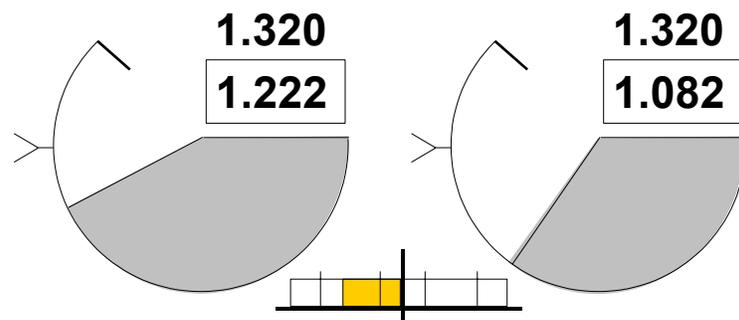


FIGURE 4-21. EXAMPLE OF A DIFFERENCE INDICATION, HORIZONTAL FORMAT

4.3.7 Summary and Recommendations.

This review of existing and alternative engine indication concepts has described known issues, research on specific issues, and broader human factors design principles. The following are findings that can be extracted from this work.

1. Current engine indications:

- The primary method for providing information to the flight crew about the engines is through indications that represent individual, sensed parameters. This is due to the evolutionary nature of flight deck interface design, earlier technology limitations (which may no longer apply), and FAA requirements.
- Engine indications are used to support engine performance monitoring and health monitoring (which includes managing nonnormals).
- Primary engine indications are continuously displayed and are part of routine scanning (by procedure). Secondary indications may be on selectable displays (not always displayed) and are not part of a pilot's routine scan (by procedure).
- The fuel system is represented by either a system synoptic on a display or by a control layout synoptic on the overhead panel. Through these, the flight crew gets feedback about the system configuration and component (e.g., pump and tank) status.
- Some engine indications use EICAS messages (or equivalent alerting) when an exceedance occurs; for the others, a pilot must detect a change to the indication (e.g., a change in color) when an exceedance occurs. In all cases, variation from the expected value that does not cross a parameter threshold (but may suggest degradation) is not accompanied by any salient change in the indication and is difficult to detect.

2. Detecting deviations:

- The following issues regarding detection were identified using the current engine indications:
 - Because EICAS messages are not used for all engine parameter exceedances, pilots must rely in some cases on detecting changes in the appearance of engine indications.
 - Research suggests that pilots spend only 1%-2% of their time monitoring the upper EICAS display and, therefore, may not see changes to engine indications.

- Other changes, such as a thrust asymmetry, can be difficult to detect because they may be masked by automation (that is, it may be clear that an asymmetry exists but the cause of the asymmetry may be difficult to determine). Also, indications may change in more subtle ways.
- Changes within the normal range (i.e., not exceeding the threshold) can indicate slow degradation in engine performance but are difficult to detect.
- Several researchers have proposed indications designed to make deviations more easily detected for some PSMs. This work relates to (for some parameters) the potential difficulty of detecting (in a timely way) deviations around the expected value, even when that deviation exceeds a threshold.
- In research on engine indications, the primary means for enhancing the detection of parameter deviations have been
 - using EICAS alerting messages and
 - building indications that show deviation from an expected parameter value (based on an engine model).

3. Understanding engine malfunctions:

- While a number of researchers have focused on solutions to improve detection of parameter exceedances, the larger issue is that flight crews may have difficulty interpreting these indications to arrive at a correct understanding of the engine state. For example, flight crews can have difficulty knowing when conditions such as engine surge versus severe engine damage exist, or flight crews may not know what type of action to take in response to conditions such as engine degradation or engine vibration.
- Even when engine state is not well understood, flight crews usually take an action that maintains a sufficient level of safety; a failure to detect in a timely way and correctly diagnose rarely leads to a UCR and a bad outcome. The PSM+UCR analysis suggests that accidents and incidents might be further reduced by addressing this issue.
- Only one researcher has put forward new ideas on the level of engine representation.
- Improving the flight crew's understanding may require representing engine state at a higher level than individual parameters.

4. Guidance to a response:

- For some malfunctions, crews are guided to a nonnormal checklist that provides a clear prescription for understanding the PSM and responding. For others,

guidance may be difficult to find because there is not a clear or simple cue that refers to a response (or there may not be sufficient time to interpret the indications correctly and respond). Specifically, the flight crew has to determine that an unannounced checklist should be executed.

- For potential benefit, the indication of engine state could also make clear if an engine is good (or indicate what level of functioning it has) to prevent pilots from taking an inappropriate action on a good engine. This would require an explicit indication of engine state.

5. Human factors guidelines:

- Several levels of human factors guidance have been identified and described:
 - High level—for organizing flight deck interface support for engine-related tasks.
 - Mid level—for identifying the types of support the flight deck interface should provide to the flight crew.
 - Low level—for developing effective indications.
- Indication enhancements should address both performance-monitoring tasks and health-monitoring tasks (including managing nonnormals).

The following recommendations are broken out into short-term, long-term, and research and development (R&D).

1. Short-term recommendations (current fleet enhancements):

- For cases where the propulsion engineers can reliably detect PSMs with existing sensors, create a method for alerting the crew to the PSM, then for improving flight crew understanding.
 - Either indications that are more closely related to revealing engine state changes or
 - Directly announce engine state changes.

In both cases, these announcements or indication changes should also be supported by linking them to a central alerting function such as EICAS.

- Evaluate how well flight crews can detect differences across engines, and assess the value of indication enhancements to make cross-engine differences more salient.

- Assess the value of methods for informing the flight crew when an engine is a good engine to prevent the flight crew from taking actions on the wrong engine.
2. Long-term recommendations (future fleet improvements):
- Assess the value of more integrated engine displays for future flight decks. Assess an approach that moves beyond indications tied to individual parameters in order to support more automated health monitoring. If possible, get FAA support to use interface real estate for presenting a more integrated view of the engine instead of engine parameters.
 - Determine if there is an operational benefit to specific indications that
 - better reveal dynamic behavior/trending/history and
 - serve as task-oriented displays (and for which tasks).
3. R&D recommendations (over the next 2 years):
- Work with the propulsion system engineers to characterize engine malfunctions—that is, understand how the current available parameters behave during known PSMs. Focus on engine states for which flight crew actions are needed (actions may be immediate or tied to deferred decision making).
 - When the propulsion engineers identify areas where they are unable to reliably detect a PSM, but there may be benefit to awareness that engine performance is degrading, develop a method for informing and involving the crew. Specifically, develop a monitoring aid that allows the crew to monitor engine performance more closely when engine behavior is suspect/uncertain. Further, develop procedures for guiding flight crew actions when there is uncertainty.

4.4 NONCOMMERCIAL AIRCRAFT TECHNOLOGY SURVEY (TASK 6.1).

Under task 6.1, Boeing surveyed noncommercial aircraft engine display and indication implementations, and documented noncommercial aircraft PSM indications and annunciations. The objective was to identify existing noncommercial indication and annunciation/alert implementations with potential for commercial aircraft flight deck application to address UCR to certain PSM.

4.4.1 Task 6.1 Objective and Goal.

The principal research objective was to evaluate PSM+ICR events, identify contributing factors, assess the detection and prevention potential of PSM annunciations, and establish a framework for understanding UCR to PSMs. The principal goal was to promote understanding of these events and develop recommendations pertaining to propulsion system sensing and flight deck indication in general, and PSM detection and flight deck annunciation in particular. It was intended that the recommendations transcend specific aircraft models, design, and operational philosophies to the maximum extent possible and practicable. As part of this overall research

effort, a noncommercial technology survey of propulsion indications, annunciations, and alerts was conducted to identify existing engine indication and PSM annunciation precedents and supporting technology of potential value and application. This report describes that effort and documents the results.

4.4.2 Task 6.1 Overview/Background and Methodology.

The noncommercial technology survey consisted of a survey of in-service and developmental noncommercial turbine engine-powered aircraft. The survey objective was to identify existing precedents and potential concept and technology transfer in the following areas:

- Engine indications and malfunction annunciations
- Flight crew actions and procedures
- Automated engine monitoring and control functions

From a candidate list of approximately 24 noncommercial turbine engine platforms, eight aircraft were selected for in-depth review and are listed below. The aircraft selected for the survey represent a cross section of current generation aircraft types, which are predominately military aircraft. This is particularly relevant to the issue of PSM+ICR because military aircraft missions impose unique and additional crew workload requirements. Mission-specific tasks add to the basic workload associated with primary aircraft control, navigation, and communication. The military mission is often a single pilot, high workload, and time-critical environment. This environment allows little time for basic airplane systems operation or accommodation and is typical of PSM+ICR events. In both the military mission and commercial environments, airplane system malfunctions in general, and propulsion system malfunctions in particular, must be quickly and correctly identified, understood, and accommodated.

- F15E
- F18E/F
- F22
- AV8B
- C17
- V22
- AH64D
- Gulfstream V

Airplane system, flight operation, and procedure manuals were reviewed for each aircraft. These reviews were supplemented with additional information provided by system engineering, flight operations engineering, and pilot contacts.

In general, for each aircraft, the engine controls, indications, annunciations/alerts, and normal and nonnormal operating procedures were reviewed. In particular, the survey sought to:

- identify the parameter(s) and means by which engine thrust/power is normally controlled. This included the Head Up Display, Head Down Display, and mechanical gage indicators.

- focus on Engine Fail/Subidle, Surge, Stuck Throttle, High Vibration, and Thrust Asymmetry PSMs and symptoms. Emphasis was placed on the differences and potential technology transfer in these areas and associated nonnormal indications, annunciations/alerts, and procedures.

Each aircraft review produced the following:

- A top level description of aircraft and engine type
 - Aircraft description transport (fighter, business, etc.), sector (military, civilian, etc.), status (design, prototype, testing, in service), and generation (old /new)
 - Engine description, e.g., number, location, engine type, controller type (FADEC, Non-FADEC, supervisory)
- An overview/description of normal engine instruments/indications and controls
 - Type (mechanical, LCD, display, etc.)
 - Engine Parameters
 - Specific parameters available full- versus part-time, e.g., N1, EPR, EGT, N2, N3, fuel flow, oil pressure, oil temperature, vibration, other
 - Any unique or unusual parameters or concepts
- Primary Thrust Control
 - What parameter(s) used and how used
 - What control devices used and how used
 - What thrust control parameter features, e.g., limits indications, commanded versus actual indications, graphical versus digital, unique or unusual.

An overview/summary of the aircraft alerting system, and the nonnormal annunciations (indications and alerts) and procedures follows:

- Engine Fail Low (flameout or subidle)
- Surge
- Stuck Throttle (i.e., throttle or thrust split)
- Engine Failed Fixed Thrust
 - Thrust Shortfall (actual thrust less than commanded thrust)
 - Overthrust (actual thrust greater than commanded thrust)

- High Vibration
- Thrust Asymmetry
- Engine Fail High (speed or other parameter exceedance)
- Any unique or unusual annunciation or procedure relevant to Powerloss, Surge, or Thrust Asymmetry.

The following sections describe the aircraft and engines surveyed, the survey results, and document survey conclusions and recommendations. Because of the potentially sensitive and proprietary nature of the aircraft and information involved, the detail aircraft write-ups are not included in this report. In addition, the tabular summaries of Engine Parameters, Annunciations/Alerts, and Potential Transfers of Precedence and Technology are not airplane-specific.

4.4.3 Aircraft and Engine Descriptions.

The following paragraphs describe the aircraft and engines surveyed.

4.4.3.1 F15E.

The F15E is a twin-engine United States Air Force (USAF) military single- or dual-seat, high-performance, supersonic, all-weather fighter. The current model is fourth generation and is currently in service.

The engines are P&W F100-PW-229 turbofan engines with afterburners. The -229 engine is controlled by a Digital Electronic Engine Control. The engines are internally mounted with side-mounted air inlets.

The primary and secondary engine indications are display-based, and the aircraft has a display-based centralized alerting system. A master caution light is provided. Aural alert tones and voices are provided.

4.4.3.2 F18E/F.

The F18F is a twin-engine U.S. Navy military single- or dual-seat, carrier-based strike fighter. The model is later generation and is currently in service.

The engines are GE F414-GE-400 low by-pass, axial-flow, twin-spool turbofans with afterburner (AB). The three-stage fan low-pressure (LP) compressor and the seven-stage high-pressure (HP) compressor are each driven by a single-stage turbine. Engine operation is controlled by a FADEC. The engines are internally mounted with side-mounted air inlets.

The primary and secondary engine indications are display-based, and the aircraft has a display-based centralized alerting system. A master caution light and aural are provided. Aural alert tones and voices are provided.

4.4.3.3 F22.

The F-22A Raptor is a twin-engine USAF military single-seat, all-weather tactical fighter. The current model is new generation and is currently in testing.

The engines are F119-PW-100 twin-spool, counter-rotating, afterburning engines equipped with two-dimensional convergent/divergent nozzles. The engines provide thrust levels sufficient to achieve supersonic flight without use of afterburners. The engines are internally mounted with side-mounted air inlets.

Each engine is controlled by two FADECs. The FADECs control engine operation from engine start to maximum AB power with protection for critical limits. Each engine also incorporates a comprehensive engine diagnostic unit to perform engine diagnostics and health management.

The primary and secondary engine indications are display-based, and the aircraft has a display-based centralized alerting system. TBV: master warning/caution lights and aural alert tones and voice are provided.

4.4.3.4 AV8B.

The AV-8B Harrier is a single-engine United States Marine Corp (USMC) military single-seat, transonic attack aircraft. The vertical/short takeoff and landing aircraft is currently in service.

The engine is a Rolls-Royce F402-RR-406A, F402-RR-406B, F402-RR-408, F402-RR-408A, or F402-RR-408B dual-spool, axial-flow, turbofan engine with thrust-vectoring exhaust nozzles. One of the spools is a three-stage, low-pressure compressor (fan) driven by a two-stage, low-pressure turbine, and the other is an eight-stage, high-pressure compressor driven by a two-stage, high-pressure turbine. Each spool is independent of the other, but they are coaxial and, to minimize gyroscopic effect, they counter-rotate.

The engine is controlled by a Digital Engine Control System (DECS). DECS is a full authority digital engine control system. The DECS provides engine control throughout the engine operating range in response to throttle position, altitude, airspeed, angle of attack, inlet air temperature, and aircraft configuration. The four main components of the DECS are a Pilot Lever Angle Assembly, two identical Digital Electronic Control Units, and a Fuel Metering Unit.

The primary engine indications are dedicated mechanical instruments. Secondary engine indications are display-based. Aircraft alerting is provided by discrete warning and caution panel annunciators. A master caution light and aural alert tones are provided.

4.4.3.5 C17.

The C17 Globemaster is a four-engine USAF military long-range transport aircraft. The aircraft is new generation and is currently in service.

The engines are P&W F117-PW-100 fly-by-wire turbofan engines. The F117-PW-100 is a dual-spool, single-stage fan, high by-pass ratio turbofan engine. The engine nacelles are mounted on underwing pylons. The low-speed rotor, designated N1, consists of one fan stage, four compressor stages, and five low-pressure turbine stages. The high-speed rotor, designated N2, consists of 12 high-pressure compressor stages and 2 high-pressure turbine stages. The 6-through 10-stage stator vanes are variable angle vanes that are used to improve starting characteristics and prevent compressor surge. The combustion section of the engine is comprised of a single-annular burner with 24 injectors for rapid combustion. The engine inlet is a fixed geometry inlet.

Engine operation is controlled by a dual-channel EEC, an electromechanical fuel control, a throttle, and a fuel shutoff valve. The EEC provides a full authority thrust management system, which has the following features: repeatable thrust settings, thrust rating control, engine limit protection, reverser control, continuous oil system, and engine component monitoring for built-in test and annunciation.

The primary and secondary engine indications are display-based, and the aircraft has a centralized alerting system. Master warning/caution lights and aural alert tones and voices are provided.

4.4.3.6 V22.

The V-22 Osprey is a two-engine USMC military tilt-rotor, multipurpose transport aircraft. The aircraft is new generation and is currently in testing.

The aircraft is powered by two Rolls-Royce Allison AE1107C turboshaft engines. An engine is mounted in each wingtip nacelle. Each engine consists of four major assemblies:

- Torquemeter assembly, which transmits engine output power to the Proprotor Gearbox (PRGB)
- Gas generator assembly, consisting of the compressor assembly, the combustor assembly, and the gas generator turbine
- Power turbine assembly, which converts gas energy into shaft power to drive the PRGBs
- Accessory drive gearbox, which drives the Fuel Pump Metering Unit (FPMU), engine oil pump and regulator assembly, and a Permanent Magnet Alternator

Each engine is controlled by a separate power control system consisting of two FADECs and an FPMU.

The engine indications are display-based, and the aircraft has a centralized alerting system. Master warning/caution lights and aural alert tones and voices are provided.

4.4.3.7 AH64D.

The AH64D Apache is a two-engine, tandem seat U.S. Army military four-blade, single-rotor helicopter. The aircraft is new generation and is currently in service.

The aircraft is powered by two T700-GE-701 turboshaft engines mounted in engine nacelles on each side of the fuselage. Each engine is controlled by a DEC and has a conventional fuel control system.

The primary and secondary engine indications are display-based, and the aircraft has a centralized alerting system. Master warning/caution lights and aural alert tones and voices are provided. An electronic checklist for nonnormal engine conditions is provided.

4.4.3.8 Gulfstream V.

The Gulfstream V is a two-engine General Aviation Business long-range, high-altitude aircraft. The aircraft is new generation and is currently in service.

The engines are Rolls-Royce BR 700 turbofan engines. The BR 700 is a two-spool, single-stage fan, ten-stage compressor, two-stage HP and LP turbine, high by-pass ratio turbofan engine. The engines are aft fuselage-mounted.

Engine operation is controlled by an FADEC. The FADEC provides the necessary engine control functions and operates in association with appropriate aircraft subsystems. The dual-channel EEC is the major part of the FADEC interfacing between the aircraft and the engine, and provides a means of controlling the engine.

The primary and secondary engine indications are display-based, and the aircraft has a centralized alerting system. TBV: master warning/caution lights and aural alert tones are provided.

4.4.4 Summary of Survey Results.

Tables 4-38 and 4-39 summarize the cross-aircraft survey of engine indications, parameters, and annunciations (on indications and as alerts).

4.4.5 Potential Precedent and Technology Transfers.

The following sections summarize the cross-airplane potential for transfer of noncommercial precedence and technology. The summary is not airplane-specific. Seven general categories were identified and specific implementation precedents and technologies within each category are listed.

TABLE 4-38. SURVEY AIRCRAFT NORMAL ENGINE PARAMETER INDICATIONS SUMMARY

NI and/or Rotor	EPR	EGT	N2	Oil P	Oil T	Fuel Flow	Vibration	Other
F-Digital and Graphic P-Digital and Graphic	N/A	F-Digital and Graphic P-Digital and Graphic	F-Digital and Graphic	F-Digital P-Digital	P-Digital	P-Digital	N/A	P-Graphical Oil Qty
P-Digital and Graphic	F-Digital and Graphic P-Digital	P-Digital and Graphic F-Digital and Time if >MCT	P-Digital and Graphic	P-Digital and Graphic	P-Digital and Graphic	F-Digital Total P-Digital (each eng)	N/A	F-Commanded EPR F-Standby Digital display of N2, EPR, EGT and NI
F-Digital and Graphic	N/A	F-Digital and Graphic	P-Digital	F-Digital P-Digital	P-Digital	P-Digital	N/A	
P-Digital	N/A	F-Digital	F-Digital P-Digital	F-Digital	P-Digital	F-Digital	P-Digital	P-Digital Engine Status P Digital Thrust (%Takeoff) P-Digital Vibration for Fan and Core P-Digital Compressor discharge pressure and pressure ratio P-Digital Throttle Lever Angle
P-Digital	N/A	F-Digital P-Digital and Graphic	F-Digital P-Digital and Graphic	P-Digital and Graphic	N/A	P-Digital	P-Digital	F-Graphical and Digital THRUST Indication P-Digital Turbine Blade Temp P-Digital Burner Pressure P-Digital ENG Airflow P-Digital Inlet Air Temp P-Digital Oil Qty Auto Display of Part-Time Engine Indications for Engine Malfunction
F-Digital	N/A	F-Digital	F-Digital	N/A	N/A	F-Digital	N/A	
N/A	N/A	F-Digital P-Digital	F-Digital P-Digital	F-Digital P-Digital	N/A	F-Digital P-Digital	N/A	
F-Digital and Graphic	F-Digital and Graphic	F-Digital and Graphic	F-Digital and Graphic	F-Digital	F-Digital	F-Digital and Graphic	F-Digital NI & N2	

F = Full-Time. P = Part-Time

TABLE 4-39. SURVEY AIRCRAFT NONNORMAL ANNUNCIATIONS SUMMARY—INDICATIONS AND ALERTS

Engine Fail Low (Subidle/Flameout)	Thrust Shortfall	Engine Surge/Stall	Over-Thrust	Engine Fail High (Exceedance)	Thrust Asymmetry	High Vibration	High EGT	Other
A-Flameout A-Shutdown I-Subidle rpm amber		A-Stall		I-Red analog and digital rpm		I-Digital	I-Red analog and digital EGT	A-Degraded Eng Op A-Loss of Eng Ctrl
A-Eng rpm I-Thrust loss ann. I-Subidle amber analog and digital N1	I-Thrust loss ann.			A-Eng rpm I-Amber analog and digital EPR and N1	A-Eng rpm I-Thrust loss ann.		A-Eng Temp I-Amber and red analog and digital EGT	A-Eng Stability (Bleed valve fault)
A-Flameout A-Subidle or Shutdown I-Highlight and Red digital rpm	A-Shortfall or Slow Response I-Highlight and Red digital rpm	A-Stall		A-Overspeed I- Highlight and Red digital rpm		A-Vibration I-Highlight and Red digital Vib	A-Eng EGT Highlight and Red digital EGT	
				A-Eng Exceedance		A-Eng Exceedance	A-Eng Temp	
I-Red analog N2				I-Amber and red analog and digital N1 and N2. A-Eng Exceedance		I-Amber digital	I-Amber and red analog and digital EGT A-Eng Exceedance	
A-Eng Fail	A-Low rpm	A-Eng Surge		A-N2 Overspeed or Limiting A-High rpm			I-Amber and red analog and digital EGT	
				I-Amber digital rpm			A-Eng Temp I-Amber digital EGT	
A-Eng Fail				A-Eng Fail I-Amber and red analog and digital % rpm		A-Vibration	I-Amber and red analog and digital EGT	

I = Engine Indication or Dedicated Annunciation
A = Alert Annunciation

4.4.5.1 Engine Indication Concepts.

- Engine Status Annunciation on ENG Display (e.g., NORM, THRUST, IDLE, SHUTDOWN, etc.). Research suggests such status could be provided there or in other more visible locations, e.g., on primary display.
- Normal full-time color coding of rpm arc—yellow below minimum idle, green operating range, and red above maximum operating limit.
- Display of acceleration time for applicable engine rpm range (e.g., idle to medium, medium to maximum).
- EPR thrust limit/rating label display—MAX, INT, MCT, DRT, MAN, NO RATING displayed with digital EPR limit.
- FADEC Unit and Channel control status—indication of which is in control.
- Display-based fuel flow vertical indication collocated between fuel flow round-dial indicators. Has potential application to other parameters where quick view comparison of engine parameters is desired.

4.4.5.2 Propulsion System Malfunction Indication Annunciations.

- Nonnormal Runaway (red) and subidle (amber) rpm gage color coding.
- Nonnormal Thrust gage color coding for any graphical round-dial gage nonnormals that color the dials red or amber.
 - Display of Time (a) at/over maximum thrust or (b) time remaining at/over maximum thrust.
 - EPR tape fill and digital indication turn amber when EPR exceeds displayed limit.
 - N1 and N2 digital and graphic displays turn red when parameter exceeds limit, turn amber when parameter is below low limit.

4.4.5.3 Propulsion System Malfunction Alert Annunciations.

- Voice alert implementation concepts, (e.g., engine voice alert accompanies overspeed, high EGT, flameout, stall, high vibration, and other propulsion system malfunctions).
- Time voice alert (e.g., FIFTEEN SECONDS FIFTEEN SECONDS) for critical time at overtemp.
- Voice alert provided in conjunction with various fuel system configuration or nonnormal condition caution alerts (e.g., FUEL CONTROL FUEL CONTROL or CAUTION CAUTION).

- Slow Throttle response alert (e.g., commanded and actual thrust delta).
- Engine-specific Stall/Surge alerts.
- Engine-specific alert for multiple different conditions—engine control, thrust loss/limited, fail to idle, auto shutdown.
- Engine-specific Flameout alerts.
- Engine-specific High Vibration alerts.
- Engine-specific Overspeed alerts.
- Thrust Loss caution indication in primary view of each pilot—a delta EPR (higher or lower) than a calculated average EPR.

4.4.5.4 Display Management Concepts.

- Display-based and facilitated pilot-selectable links to relevant system information.
- Pilot-selectable display management link/connection from nonnormal alert to applicable system page.
- Auto display of part-time or secondary engine parameters.

4.4.5.5 Airplane-Level Information Display.

- Airplane Level Information Display. Cruise data display on part-time/secondary engine page (e.g., range, time, etc.).
- Bingo fuel annunciation on primary display (commercial equivalent concept(s)).
- Total fuel flow and total fuel used calculation and display.

4.4.5.6 Health Monitoring and Control.

- FADEC Health Monitoring for engine surge, failure, and other malfunctions.
- FADEC Auto Shutdown to prevent catastrophic engine failure.
- FADEC auto stall recovery (engine will not respond to throttle commands (except OFF) until stall is cleared).

4.4.5.7 Airplane Flight Control or Control Function.

- Asymmetric Thrust Departure Prevention System. Under certain nonnormal engine conditions, engine thrust is automatically and temporarily equalized.

- Normal OFF Throttle control and finger lift interlock/guard.
- Throttle control finger lift interlock and alternative pilot force override force for maximum thrust. RE MD11 implementation of emergency overboost feature which allows the pilot to override the maximum rated thrust stop by exerting a force of about 33 pounds (15 kilograms) to the throttle levers. This overrides the FADEC into a mode where thrust is limited only by burner pressure or rotor speed limits.

4.4.6 Task 6.2 Conclusions.

The implementation precedents, technologies, and crew interface concepts and strategies used in the noncommercial aircraft surveyed have practical application to commercial aircraft operations in the pursuit of increased safety through improved crew airplane system awareness, understanding, and response associated with PSM+ICR events.

There is potential transfer of implementation concepts and supporting technologies in the following areas:

- Engine Indication Concepts
- PSM Indication Annunciations
- PSM Alert Annunciations
- Display Management Concepts
- Airplane-Level Information Display
- Health Monitoring and Control
- Airplane Flight Control or Control Function

4.4.7 Task 6.2 Recommendations.

In general, it is recommended that the implementation precedents, crew interface concepts and strategies, and supporting technologies identified by this survey be investigated further for their potential application and use in commercial transport aircraft designs and operations.

It is specifically recommended that the investigation focus on further assessing the potential application and use of:

- automatic and manual display management strategies,
- airplane-level display of engine status, thrust malfunction, and fuel information,
- annunciation of engine subidle and other malfunctions on the associated engine parameter indications,
- alert annunciations (nonvoice and voice) for engine surge, high EGT, high vibration, thrust shortfall, and overthrust conditions, and
- health monitoring and engine control concepts.

5. TECHNICAL FEASIBILITY ASSESSMENT.

This section provides a summary of technical opinion on the feasibility of detecting various PSM on future airplane models. The analysis of tasks 2.1, 5.1, and 5.2 were used to identify specific PSM to assess detection methods. Specifically, technical feasibility of detections methods of PSM to support annunciation concepts designed to reduce ICR, referred to as undesired outcomes herein, to the PSM on existing aircraft and in new designs were addressed. Analysis thus far suggest means to detect Surge and Engine Fail Low (including Nonrecoverable Surge and Powerloss) PSM events will provide the greatest opportunity to reduce the risk of undesired outcomes or ICR. An important qualifier is identified from the analysis thus far in that performing the detection of these PSM in a time-critical part of the flight profile will not significantly reduce the risk of undesired outcomes.

The work performed via subcontract for task 5.2 resulted in a detection algorithm for both Surge and Recoverability (Recoverable/Nonrecoverable Surge). The subcontractor concluded that the capture rate data for a detection algorithm must be on the same order or faster than the frame rate of the engine control outer control loop. Details of the engineering analysis are reported in appendix E.

Technical opinions were solicited from experts in the aerospace gas turbine engine community on means to detect these PSM events. These opinions include informal correspondence with technical experts from Boeing and from two aeroengine OEMs. In general, technical experts agree that detection of surge is feasible. These experts question the value of an annunciation of every surge detected. The value identified for surge annunciation is to:

- associate a surge PSM with the aural characteristic (the bang) of a surge.
- identify which engine has experienced the surge.

Further reliable and accurate detection of surge on future models will likely require improved sensors, in agreement with the subcontractor work described previously.

Technical opinion on the detection of recoverability is not conclusive. When the qualification that this detection scheme should not be applied to a time-critical portion of the flight, the experts believe a reliable system is more likely. The work performed by the subcontractor for task 5.2 supports this position. Boeing experts identify the response rate of existing sensor suites as an impediment to developing robust detection systems.

A PSM detection scheme related to the recoverability subject is the comparison of actual thrust to commanded thrust. The primary difficulty with this scheme is its reliance on a model of the engine to determine thrust. The problem is that the existing engine models are designed to validate minimum thrust for a nonmalfunctioning engine. The reliability of these models is not compatible with the ability to certify a system for determination of thrust in malfunctioning engines.

Detecting Surge PSM events is considered feasible by experts in the aerospace gas turbine engine field. These experts are concerned with the validity of annunciating all detected surges to the crew. Great care must be taken in developing a highly robust system to detect Nonrecoverable Engine Fail Low PSM events. Robust algorithms will likely require large empirical databases for development and validation. Once implemented, the system will rely on real-time tuning with current empirical data (both fleet and individual asset).

Further, as stated above, the reliable detection of a Surge (recoverable or nonrecoverable) is considered feasible. This is borne out in the implementation of surge recovery logic in the engine controls of modern turbojet and turbofan engines.

5.1 PROPULSION SYSTEM MALFUNCTION CHARACTERIZATION.

Incidents from the AIA PSM+ICR report were identified that contain representative PSMs to provide a basis for characterization and study of detection potential. The PSM characterizations were established to support discussion and assessment of detection potential and development of indication and annunciation strategies designed to reduce UCRs to PSMs and thereby enhance safety by mitigating the risk associated with such events. The representative events span the major categories of PSMs recommended for characterization and study:

- Recoverable and Nonrecoverable Engine Failure (low, fixed, and high power)
- Recoverable and Nonrecoverable Powerloss
- Recoverable and Nonrecoverable Surge

These categories are collector symptom categories that do not necessarily describe a root-cause PSM. These generalized categories provide a means to group and characterize different root-cause PSMs, to assess detection potential, and to assess the likelihood that annunciation will result in desired crew response.

- Recoverable versus Nonrecoverable: The distinction between a Recoverable and a Nonrecoverable PSM event is whether or not the engine is able to achieve the requested or commanded power (typically thrust) through either engine control or crew intervention after the PSM.
- Engine Fail: Engine Fail PSMs are generally characterized by either a lack of engine response to power lever movement or the inability to move a power lever. Definitions for Engine Fail PSMs are further refined into Failed Fixed, Fail High, and Fail Low categories. The ability of the engine system architecture and control logic or some crew initiated procedure to accommodate the root cause determines whether an Engine Fail PSM is Recoverable or Nonrecoverable.
- Failed Fixed: The inability to move a power lever is categorized as a Engine Failed Fixed PSM event. Additionally, an engine that does not respond to power lever movements is said to be failed fixed.

- Fail High: An Engine Fail High PSM is generally characterized by nonrequested increases in engine spool speeds, pressures, and temperatures. The rate and magnitude of these changes is dependent on the power setting required for the flight condition at the time of the PSM.
- Fail Low: An Engine Fail Low PSM is generally characterized by decaying spool speed(s) and engine temperatures. The rate and magnitude of these changes is dependent on the power setting required for the flight condition at the time of the PSM.
- Powerloss: A Powerloss PSM is generally characterized by decaying spool speed(s) and engine temperatures. The rate and magnitude of these changes is dependent on the power setting required for the flight condition at the time of the PSM. In the Engine Fail and Powerloss PSM categories, thrust asymmetry may be experienced as the engine with the PSM runs down while the other engine(s) produce thrust at a significantly different level. The thrust asymmetry will generally include an engine-to-engine difference in displayed parameters (EPR, N1, N2, EGT, etc.) and may include an offset or split in thrust lever position.
- Surge: A Surge PSM is generally characterized by an instantaneous noise, flame visible at the engine inlet, and a transient variation in engine parameter indications (EPR, N1, N2, EGT, etc.). Depending on the power setting, a Surge event may exhibit a transient, perceptible vibration and lateral acceleration. Recoverable versus Nonrecoverable Surge PSMs are generally differentiated by a sustained increase in vibration and the engine failing to a low/no power (wind-milling).

This section provides the supporting data that result in a precise definition of these categories of PSM events. PSM events categorized as LOC, Other, or SDTGE were identified as being linked with increased hazard risk. Specifically, Powerloss is the term used for 19 events and Surge is used to describe 18 of the events in the PSM+ICR report. Further, some of the Surge events are associated with a Powerloss condition. The following terms are used:

- Category: A grouping of PSMs that produce a similar propulsion system or airplane system-level response.
- Definition: A more detailed description of a PSM category. The definitions may break the PSM category into subcategories.
- Characterization: A listing of specific parametric attributes of a PSM. This is the most detailed description of a PSM category or subcategory.

The following observations were made:

- 73% of the PSM+ICR data falls into the Nonrecoverable Engine Fail Low, Nonrecoverable Powerloss or Surge (Recoverable or Nonrecoverable) categories.

- Powerloss and Engine Fail Low events are typically associated with the hard failure of some component that causes the powerloss. This being the case, Powerloss and Engine Fail Low events will normally be Nonrecoverable.
- Some Surge events are also associated with powerloss.
- A Surge event can be severe enough to cause collateral damage, or conversely, some source of engine damage may be the cause of a surge. The loss of power in either of these cases could typically be considered the equivalent of a Engine Fail Low state.
- Engine damage that makes a Surge PSM similar to a Engine Fail Low assigns it to the Nonrecoverable category. Data indicates that if an engine that has sustained a Nonrecoverable Surge produces power (thrust), it will be at a minimal level (idle or lower). Thus, it may be reasonable to consider including Nonrecoverable Powerloss (Nonsurge) and Nonrecoverable Surge events as subcategories of Failed Engine Low events.

The Simulator Issues Group (SIG) that was established in response to AIA PSM+ICR report recommendations documented investigations undertaken to make recommendations to improve PSM simulations. The SIG report provides definitions of PSM events. Although these definitions were developed on the basis of identifying means to improve flight simulators for training purposes, they align with the definitions and findings herein. The SIG reported three types of compressor surge malfunctions as having major shortfalls in cueing noise and tactile (thrust pulse and vibration) response.

- Compressor surge—self-recoverable (type 1)
- Compressor surge—multiple, recoverable with pilot action (type 2)
- Severe engine damage with compressor surge (type 3)

5.1.1 Propulsion System Malfunction Categories From Existing Data.

Data from IFSD and 2000-2001 PSM events was grouped into specific categories. One of these categories is Surge. If the events from this category and several others, directly attributable to the engine, are added together (e.g., Flame-Out, Disintegration), the sum accounts for 53% of the total events. Categories excluded are related to failures in ancillary engine systems (e.g., hydraulic, pneumatic, and oil systems). Of the events in the Surge, Flame-Out, Disintegration subgroup, approximately two-thirds are surge-related. This is the same percentage as seen in the PSM+ICR events.

5.1.1.1 Characterization of PSM Events Resulting in ICR.

The general PSM categories previously defined are qualified by PSM characteristics. These characterizations often describe symptoms and not a root cause of the PSM. Thus, the characterizations provided herein can be considered primarily as symptomatic descriptions of root-cause PSMs.

Subsequent analysis and data reviewed support the conclusion that PSM events that most frequently result in ICR are Nonrecoverable Engine Failed Low, Nonrecoverable Powerloss, and Surge (Recoverable and Nonrecoverable) events. Further, it may be possible to include the Nonrecoverable Powerloss and Nonrecoverable Surge events as a subcategory of Engine Failed Low events (Note: the use of subcategories implies the existence of a Engine Failed Low (Nonsurge) subcategory). Because these PSMs are the greatest contributors to ICR, additional characterization of these PSMs categories was pursued.

Determining that a malfunction of the propulsion system has occurred is based on an examination of indications or symptoms resulting from the malfunction, e.g., specified pressures or temperatures or required control inputs are not matching expectation. There are regions in the operating envelope where reliable detection from examining indications is impaired by uncertainty (from variations in measurements, configuration, deterioration, etc.). A potential means to overcome this uncertainty is the use of some type of procedure that challenges the propulsion system for conditions other than the current power setting. However, using such a procedure imposes a risk of inducing additional system damage.

5.1.1.2 Characterization of Indicated and Monitored Parameters.

This section is provided to further refine the parametric characterizations provided above. These refinements are stated for various classes of engine and various parts of the operating envelope. Definitions of engine classes are as follows:

- HBPR, $7 < BPR < 10$
- Medium By-Pass Ratio (MBPR), $3 < BPR < 7$
- LBPR $1 < BPR < 3$
- Hi Fn, High Power (Thrust) Capability, $70,000 < F_n \text{ (lbf)} < 100,000+$
- Med Fn, Medium Power (Thrust) Capability, $35,000 < F_n \text{ (lbf)} < 70,000$
- Low Fn, Low Power (Thrust) Capability, $15,000 < F_n \text{ (lbf)} < 35,000$

The engine spool-down characteristic is dependent on the moment of inertia of the spool (table 5-1) and the speed (Mach number) the engine is traveling through the air. A basic equation to define the time to reach wind-milling speed is as follows:

$$\Delta t = (I/\alpha) * \{(\omega_i^{(-n+1)} / (-n+1)) - (\omega_w^{(-n+1)} / (-n+1))\}$$

Where I = Moment of inertia of the spool
 α = Rotational speed decay coefficient
 ω_i = Initial rotational speed
 ω_w = Wind-milling rotational speed
 n = Some integer greater than 1

Values for the rotational speed decay coefficient are derived using the moments of inertia in the equation above with empirical data available. Representative coefficients for several engine types at different conditions are provided in table 5-2.

TABLE 5-1. MOMENTS OF INERTIA FOR ENGINE CLASSES

Spool	I - Moments of Inertia (lb ft ²)				
	Two Spool		Three Spool		
	L	H	L	I	H
HBPR Hi Fn	16950	1455	8400	1400	470
HBPR Med Fn	NA	NA	NA	NA	NA
MBPR Med Fn	5770	595	3100	1100	410
MBPR Low Fn	950-1123	230-690			
LBPR Med Fn	NA	NA	NA	NA	NA
LBPR Low Fn	NA	NA	NA	NA	NA

TABLE 5-2. REPRESENTATIVE ENGINE COEFFICIENTS

	Condition		α - Decay Coef	n
HBPR Hi Fn 2 Spool	35k ft/M~.7	L	3319.36	5.0
		H	228558	4.5
HBPR Med Fn 2 Spool		L		
		H		
HBPR Hi Fn 3 Spool	35k ft/M~.8	L	2116320	7.0
		I	0.4161183	2.5
		H	0.4761628	2.0
LBPR Med Fn 2 Spool	9k ft/M~.5	L	2.86578	2.5
		H	39201.5	3.5

The coefficient is variable with flight condition. A means to create a matrix of coefficients for various flight conditions would be to obtain data from a flight simulator with an engine shutdown induced at the desired conditions. This data would then be correlated to the service data provided above.

Indicated pressures will exhibit a decay characteristic that tracks the spool speed associated with that pressure. For example, if an EPR is displayed, the decay will track the low-pressure spool, as the pressures in the ratio are associated with that spool.

For an Engine Fail Low event, there is no engine temperature characteristic that can be used to reliably key on. The engine temperature is primarily dependent on whether the combustion process continues in the failed state. If combustion ceases, (fuel cutoff, flame-out) the engine temperature characteristic will be that of a Powerloss event.

5.1.1.2.1 Powerloss.

For a Powerloss event, the engine spool speeds will decay in the same manner as an Engine Fail Low event. A means to model this decay was provided in section 5.1.1.2. Again, any pressure

indications will track the decay in spool speed. The Temperature, EGT, for a Powerloss event will exhibit a given characteristic. The EGT will typically rise by approximately 5% of the engine temperature at the time of the event and then begin to decay toward ambient temperature. The temperature rise will peak after 5-7 seconds. The temperature decay is dependent on the ambient temperature and the speed (Mach number) at which the engine is traveling through the air.

5.1.1.2.2 Surge.

Again, referring to the SIG report, characteristics of a Surge event include the following:

- A motion effect, associated with a max power surge, which is simulated by a lateral sine wave input of 0.5 g with a time period of 0.75 second or less
- A vibration effect, similar to an airframe buffet, that fades out linearly over 2 to 4 seconds
- An aural effect that is dependent on the engine cycle and power setting.

The audible indication, for high-power conditions, has been described as a sharp pop for a low by-pass ratio fan or turbojet engine, while a large high by-pass engine will be a highly energetic boom. The intensity of this aural effect (i.e., volume) is weakly dependent on the power setting—the sound is louder at high power than at low power but not necessarily significantly. Finally, the report listed engine parameter effects of a compressor surge as a rapid decrease in rotor speeds, pressures, and fuel flow, and typically an increase in EGT. Some ranges of variation of these engine parameters are as follows:

- EPR/Burner Pressure 60%-90% drop to coincide with bang sound
- N1 15%-40% drop to coincide with bang sound
- N2 or N3 5%-10% drop to coincide with bang sound
- EGT 10-20 deg/sec rise

These ranges are developed from data for surges at a high power setting tabulated in Appendix A of the SIG report. The variations of pressure and spool speed are percentages of the initial value. The parameters will fluctuate in these ranges for 1 to 3 seconds. The pressure and spool speed ranges can be considered valid for a surge at any power setting, realizing that the initial values will be smaller. The duration of fluctuation will typically be shorter for a lower power setting. The characteristics of a surge at low power are typically very subtle. Recent reports, not included in the SIG report, indicate that for surges that occur at cruise conditions, the intensity of the aural indication is low enough to go undetected on the flight deck. The following is an excerpt from an airline report on a flight in which low power surges were experienced.

“The pilots in the cockpit heard nothing. They felt shaking, which they thought at first was clear air turbulence. There was absolutely no yaw. Left EGT was within limits, slightly higher than the opposite engine, but rpms looked like idle. When they listened for it, they were able to hear a faint, periodic rumble.”

The EGT fluctuation characteristic for a high power surge may or may not be present in a low power surge. This is likely due to the time period of the Surge event itself. For a high power surge, the cycle disturbance lasts longer than the sensor lag.

5.1.1.3 Nonrecoverable Surge.

This type of PSM is more fully described by combining characterizations provided above. First, a surge characteristic is experienced. Then, depending on the nonrecoverable failure mode, additional surges are experienced until power setting is reduced or the engine exhibits an Engine Fail Low characteristic. Again, the Nonrecoverable identifier says that the engine does not run event-free at all possible power settings.

5.1.2 Propulsion System Malfunction Event Characterization Data.

Queries of data bases available to Boeing were conducted to determine what data was available for PSM event characterization and analysis. Table 5-3 lists the data sets available for various PSM categories.

TABLE 5-3. EVENT DATA FOR ANALYSIS

	Recoverable Surge	Nonrecoverable Surge	Recoverable Engine Failed Low	Nonrecoverable Engine Failed Low
PSM+ICR Events	94/MWB/4/I 93/EWB/2/I	89/MNB/2/HF 93/MNB/2/I 91/MNB/2/H		

As is reflected in table 5-3, no data is available from the AIA PSM+ICR report to support characterizations provided herein for Recoverable and Nonrecoverable Engine Failed Low events.

The applicable events from the AIA PSM+ICR report are analyzed to develop in-service experience characterizations. Plots of parametric data available from a subset of the PSM+ICR events are provided in appendix D. The principal investigators identified five events for which data is plotted (table 5-4).

TABLE 5-4. THE PSM+ICR EVENTS WITH DATA PLOTS

PSM	ICR	Data Set	Plot
Recoverable Surge	Shutdown Good Engine	94/MWB/4/I 93/EWB/2/I	Figure D-1 Figure D-2, 3
Nonrecoverable Surge	Shutdown Good Engine	89/MNB/2/HF 93/MNB/2/I 91/MNB/2/H	Figure D-4, 5 Figure D-6 Figure D-7
Recoverable Fail Low			
Nonrecoverable Fail Low			

As shown in table 5-4, items 89/MNB/2/HF, 93/MNB/2/I, and 70/2ND/2/H from the list of events provided in appendix D apply to the Nonrecoverable Surge category. Items 95/2ND/2/H and 96/MWB/4/I from appendix A are applicable to the Nonrecoverable Engine Fail Low (Nonsurge) category.

5.1.3 Data Sets Used for Analysis of PSM Surge Events.

Proprietary data was provided to a subcontractor for analysis. The data is available at high capture rates for various parameters. Data for various parameters was provided at 1, 2, 4, 16, and 50 Hz. The parameters and capture rates are not consistent across the data.

The results of the subcontractor analysis are provided in appendix E. Key excerpts from the summary section are provided as follows.

5.1.3.1 Required Parameters.

Figure 5-1 shows practical set of parameters that have been identified for enabling enhanced surge awareness and surge recoverability. The first seven categories of parameters should be made available at greater than or equal to 2-Hz sampling rates. The essential set of parameters are denoted and are those required for the Surge Detection and Recoverability Algorithm developed under this program and discussed next. It should be noted that this set only applies to high-bypass turbofan engines with FADECs. Different parameters and sampling rates may be best for other engine types with or without FADECs.

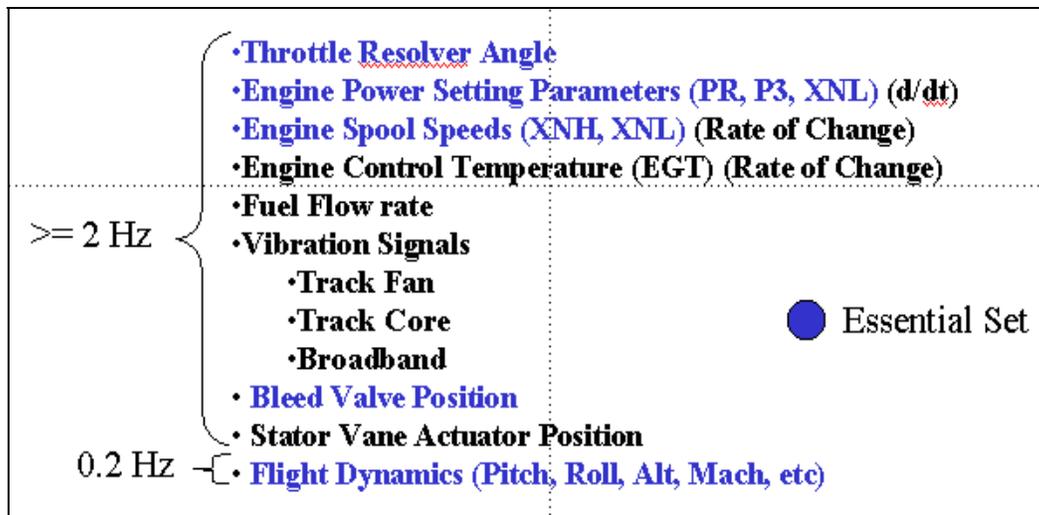


FIGURE 5-1. ENGINE ANALYSIS PARAMETER SET

5.1.3.2 Surge Detection and Recoverability.

Subcontractor team members developed a Matlab/Simulink program to analyze surge detection and recoverability determination. The premise is that key parameters/features such as XNH DOT (the derivative of core speed) and P25DOT, P3DOT should normally lag throttle position (TRA)

and gas path bleeds. Since in a Surge event a compressor is in an unstable dynamic state, changes to the key parameters are expected to lead TRA or bleeds and be uncorrelated to them within a certain time buffer. Hence, two surge detection modules were created in the generic Matlab/Simulink program called SEDRA (Surge Event Detection and Recovery Analysis); the results of which are fused together. The first module independently considers limit exceedances of XNHDOT and P25DOT, P3DOT, depending on the available data. The second module considers a zero lag cross correlation between the aforementioned parameters.

5.2 FEASIBILITY ASSESSMENT OF DETECTION METHODS.

The previous discussion defines the constrained categories of PSM for which detection concepts are required. Feedback was solicited for these constrained PSM categories from Boeing experts and from engine OEMs. This feedback is summarized as feasibility assessments for detection herein.

The question of feasibility of detection for some PSMs is somewhat obsolete. The current generation of commercial airplane engines already includes algorithms to detect numerous malfunction conditions, including some of the PSM under consideration here. The more pertinent question may be how accurate or robust these algorithms are (no missed detects, no false detects).

Some engine controls include a surge bit as part of the monitoring output. A Surge PSM is symptomatic in nature. Restated, a surge occurs as a result of some other engine damage, deterioration, or a (drastic) change in ambient conditions. This suggests that what really needs to be detected is the damage or deterioration. However, when considering the reduction of the risk of an undesired outcome to a PSM, some form of indication of a surge may be valid. The purpose of this indication is to accommodate the Association Ground Rule, which:

- puts a positive linkage between a Surge event and its aural characteristic (the bang).
- identifies which engine the surge came from.

One airplane model produces an Engine Fail indication. This is, in essence, what is referred to herein as a Nonrecoverable PSM. Refining and expanding the capabilities of these algorithms will be the focus of ongoing development. This development will occur regardless of nonmarket impetus.

5.2.1 Feasibility Assessment Technical Expert Feedback.

Technical experts from Boeing agree that from a first principles standpoint, the engine burner pressure is the primary indicative parameter for surge. The engine exhaust gas temperature is an additional indicator for surge. Using these parameters on existing airplanes is problematic in the response of the sensors used to measure them. In the case of the burner pressure, the sensors need to be able to produce accurate pressure, with a rapid response, in a range from 15 to 450 psi. The transient nature of a Surge event is damped by the responsiveness of the thermocouples or other temperature-measuring devices used to capture engine exhaust temperature.

The determination of recoverability is less apparent to Boeing. The current flight operations procedure for a surge is to reduce power, check for normal operation at idle, and then reapply power to check for normal operation at high power. The technical experts believe that a well-trained crew using this procedure will produce results as reliable as a logic designed to determine normal operation. Still, an algorithm that uses burner pressure, engine exhaust temperature, and engine rotational speeds is considered possible. Caveats to this perception include

- the need for better response from parameter sensors.
- the need to collect empirical data from individual engines, and the ability to create a generalized model from that data.
- changing the engine power setting during algorithm execution would likely be required.

The lack of confidence in a system because of false alarms (or missed detects) makes the implementation somewhat dubious.

A PSM detection scheme related to the Recoverability subject is the comparison of Actual Thrust to Commanded Thrust. This scheme suggests the engine is back in control, which follows the logic of the subcontractor work described below. This scheme is suggested as a means to identify Engine Fail (Low, High, Fixed) and Powerloss. As stated above, the Engine Fail Low state is closely related to the Recoverability issue.

This method is used in some production airplanes to identify the existence of Thrust Asymmetry and is constrained to a PSM resulting in a thrust shortfall. A thrust shortfall is identified by comparison of both commanded and actual thrust from an engine model. Commanded thrust is determined from the power-setting input, whereas actual thrust is calculated using the power-setting and engine parametric data. Identification of an actual thrust, some prescribed amount lower than the commanded thrust, would be identified as a thrust shortfall. For example, existing applications use a prescribed difference in commanded to actual thrust of approximately 10% to activate Engine Failure and Thrust Loss logic.

The risk of false or missed detects using this method lies in the current method to measure thrust. In reality, thrust is not measured on-wing. What is measured is a parameter that is used to indicate that an assumed thrust has been obtained. This method has been certified through the development of a model of the test stand and/or instrumented airplane's measured thrust and the indication parameter. This model is developed to ensure that a minimum thrust is attained. The thrust may be higher due to, in varying degrees, engine configuration, engine-to-engine variation, engine age, etc. Additionally, the model is not developed to provide a thrust indication during a transient. Most importantly, the model does not include an indication/thrust relationship for a damaged engine (i.e., if the engine is damaged, the thrust to indication parameter relationship is unknown). The risks in using this method increase as the commanded thrust decreases (i.e., the determination of actual thrust, from parametric data, to compare to a commanded thrust is more difficult at low power settings). This is because the inaccuracies of the thrust to indication parameter model becomes more pronounced at low power. The increased risk of missed detection during a transient or low power settings may lead to inhibiting the

detection algorithm in these operational states. This inhibit leaves open the operational risk of missed detection at low power, leading to the crew being unaware that higher power will not be obtained from the failed engine if commanded. The detection method would provide a valid result only when the higher power is commanded, at which time the crew would be alerted.

As stated, the current thrust models were developed to certify the thrust to indicating parameter relationship for minimum thrust of a nonmalfunctioning engine. Significant development is required to produce models of thrust deviation for all possible PSM modes. The reliability of current models is not compatible with the ability to certify a system for determination of thrust in malfunctioning engines.

5.2.2 Feasibility Assessment From Engine OEM Technical Expert Feedback.

Coordination memos were sent to two engine OEMs. A formal response from one engine OEM has been received. Lacking time to fully interpret this response and a complimentary response from the other OEM, it is inappropriate to report on informal responses received.

5.2.3 Feasibility Assessment From Task 5.2 Analysis.

Task 5.2 shown in appendix E is entitled “Data Acquisition and Detection Methods.” The purpose of this task was to assess the data available for potential methods of detecting a given PSM. The focus of the study was surge PSM because the analysis thus far identifies surge as a contributor to a significant number (<70%) of undesired outcomes. The objective of the task was to analyze high-fidelity data collected when a surge occurred to:

- identify any precursors.
- investigate means of determining recoverability.
- assess the adequacy of available data or need for additional parameters.

The subcontractors for this task, Impact Technologies LLC, produced an algorithm that identifies a Surge event and provides an indication of recoverability. Appendix E provides a detailed description of the task results. Some important conclusions are provided herein to meet the objectives of this report.

Appendix E concluded that a means to more reliably detect a surge is possible with data available from a FADEC-controlled engine with at least one qualifier. Most health management data capture is performed at 1 Hz. This data capture rate leaves detection methods vulnerable to the engine control logic attempting to adapt to the PSM. Impact Technologies recommends a capture rate of 50 ms or less.

The detection scheme developed employs a derivative limit for various parameters combined with a cross correlation of those parameters. The derivative functions are based on engine component performance maps derived empirically from the data. This algorithm successfully detected the surges identified in the data provided. In addition, the data contains what are agreed to be false detects of a Surge event. The subcontractor’s algorithm was successful in avoiding false detects on this data.

Impact Technology fused the results of the surge detection algorithm with a tool to determine whether the engine would recover from the surge or not. It is important to provide a definition of recoverability in context of this contract work. A surge that will recover (Recoverable Surge) is a PSM after which the engine will respond to engine control (automatic or crew intervention) to provide any requested power setting/thrust. Conversely, a Nonrecoverable Surge is a PSM after which the engine, although it may run surge-free at some power settings, is not able to produce the requested thrust at all possible power settings. Again, the Time Lag Ground Rule, detection is not to be a time-critical function (e.g., $RTO > V1$), applies to concepts for determining recoverability.

The task 5.2 report states that the recoverability detection scheme "... operates in much the same fashion as the surge detection except that it waits for ... [engine parameters] ... to respond normally to TRA and Bleed, meaning that the engine is back in control." This scheme was successful in determining whether an engine would recover from a Surge event or not. The time required was on the order of 3 to 5 seconds. Impact Technology states that the addition of a vibration monitor to the aforementioned could improve the robustness (no missed detects, no false positives) of the surge detection/recoverability scheme.

The subcontractor stresses the fact that claims of success are based on a single data point in the case of Nonrecoverable Surge. With this qualifier, the research performed by Impact Technologies is promising.

5.3 SIMULATOR EVALUATION AND REQUIREMENTS.

The principal objective of the overall research effort was to evaluate PSM+ICR events, identify contributing factors, assess the detection and prevention potential of PSM annunciations, and establish a framework for understanding UCR to PSMs. The principal goal was to promote understanding of these events and develop recommendations pertaining to Propulsion System sensing and Flight Deck indication in general, and PSM detection and Flight Deck annunciation in particular.

5.3.1 Overview.

As part of this overall research effort, Task 6.3, Development of Simulator Research Evaluation Requirements, was accomplished. The objective of the task was to document a plan for development and refinement and test and validation of the report PSM annunciations recommended in the tasks 1.2 and 1.3 reports. This plan is provided as proposed future effort.

5.3.2 Task 6.3 Background and Methodology.

Task 6.3 consisted of the development of simulator research/evaluation requirements and a preliminary plan for simulator demonstration and evaluation of engine failure, surge, and thrust asymmetry for their effectiveness in preventing or reducing ICR to these PSMs. The development of these requirements was based on research, analysis, and recommendations from other task reports and on past practical simulator study/evaluation experience.

5.3.3 The PSM Annunciation Simulator Research Evaluation Requirements.

The following sections document a preliminary top-level simulator research PSM annunciation evaluation plan.

5.3.4 Research Issues/Questions.

- What is the appropriate means of Flight Deck PSM annunciation of Powerloss (Engine Subidle and Thrust Shortfall), Surge, and Stuck Thrust (Thrust Shortfall and Overthrust)?
- What is the effectiveness and the operational performance effects of Flight Deck PSM annunciation of Powerloss (Engine Subidle and Thrust Shortfall), Surge, and Stuck Thrust (Thrust Shortfall and Overthrust)?
- What is the operational acceptability of Flight Deck PSM annunciation of Powerloss (Engine Subidle and Thrust Shortfall), Surge, and Stuck Thrust (Thrust Shortfall and Overthrust)?
- Should Thrust Asymmetry, Stuck Throttle, and High Vibration annunciations be provided, and if so, how?

5.3.5 Test Objectives.

- Develop and refine PSM annunciation implementations for Powerloss (Engine Subidle and Thrust Shortfall), Surge, and Stuck Thrust (Thrust Shortfall and Overthrust).
- Objectively and subjectively test and validate PSM annunciation implementation concepts for Powerloss (Engine Subidle and Thrust Shortfall), Surge, and Stuck Thrust (Thrust Shortfall and Overthrust).
- Define and document Powerloss (Engine Subidle and Thrust Shortfall), Surge, and Stuck Thrust (Thrust Shortfall and Overthrust) implementation requirements.

5.3.6 Test Experimenter(s) and Facility.

- Multidisciplinary Boeing Company Experimenter Engineering Team: Flight Deck Crew Operations, Propulsion Systems, Human Factors, and other group review support.
- Boeing Company Integrated Airplane Systems Laboratory (IASL) engineering simulator(s). Engineering Cab TBD: B777 (figure 5-2), Motion-Cab, and/or Other (B737, B757, B767, or B747-400)



FIGURE 5-2. B777 ENGINEERING CAB

5.3.7 Malfunctions.

- Powerloss—Engine Subidle and Thrust Shortfall.
- Surge—Self Recoverable, Recoverable only with Crew Action, and Nonrecoverable.
- Stuck Thrust—Thrust Shortfall and Overthrust. Stuck Throttle, High Vibration and Thrust Asymmetry testing and evaluation TBD.

5.3.8 Propulsion System Malfunction Annunciation Test Concepts.

Engine indication annunciation and EICAS alert annunciation concepts are in development and will be reported as part of Task 6.4, Engine Malfunction Annunciations Demo. Concepts in development for Engine Indication annunciation and EICAS Alert annunciation for:

- Powerloss (Engine Subidle and Thrust Shortfall)
- Surge
- Stuck Thrust (Thrust Shortfall and Overthrust)
- Engine Status—Including Normal/Good Engine Concepts

5.3.9 Pilot Test Subjects/Evaluators.

- Initial Testing: Minimum 12 Boeing pilot test subjects/evaluators—typically half Flight Test Engineering and half Flight Training.
- Follow-on Testing: Customer line, training, and engineering/management pilots. FAA FAR Part 25 Certification and FAR Part 121 Operations pilots.

5.3.10 Preliminary Experimental Design.

- Objective between subject blind test design—different pilots tested for nonannunciation and annunciation concept performance.
- Subjective between blind and follow-up within nonblind subject test design—different pilot subjects were tested for annunciation and nonannunciation performance and, subsequently, provided subjective assessments. After the initial testing and debrief, subjects are briefed on the true nature of the test evaluation. The nonannunciation subjects then flew annunciation concepts and provided subjective comments and assessments; annunciation pilots flew nonannunciation scenarios and provided subjective comments and assessments.
- The presentation of scenarios and concepts was typically mixed/balanced to minimize the potential for learning transfer and/or practice effects. Table 5-5 shows a PSM annunciation test concept versus a malfunction matrix, which will be used to develop detail test plans.

TABLE 5-5. THE PSM ANNUNCIATION TEST CONCEPT VERSUS MALFUNCTION MATRIX

No Annunciation ¹	Engine Indication Annunciation Only ²	EICAS Alert Annunciation Only ³	Engine Indication and EICAS Alert Annunciations Combined ³
Normal—No Malfunction	N/A	N/A	N/A
Engine Failure (subidle)	X	X	X
Engine Surge	X	X	X
Thrust Shortfall	X	X	X
Overthrust	X	X	X

1. Pilot Engine Indication Monitoring and PSM Detection and Interpretation. Unannounced/Unlinked Nonnormal Procedure.
2. Automated Monitoring and Detection, Explicit PSM Engine Indication Annunciation Unannounced/Unlinked Nonnormal Procedure.
3. Automated Monitoring and Detection, Explicit PSM Alert Annunciation. Linked Nonnormal Procedure.

5.3.11 Malfunction Test Scenario Matrix.

Table 5-6 shows a phase of flight versus propulsion system malfunction matrix, which will be used to develop detail test plans.

TABLE 5-6. FLIGHT PHASE VERSUS PROPULSION SYSTEM MALFUNCTION MATRIX

Flight Phase*	Propulsion System Malfunction				
	None	Engine Failure	Surge	Thrust Shortfall	Overthrust
Takeoff Ground Roll					
Takeoff Climb					
Cruise to Descent					
Descent Level Off					
Approach and Landing/Go Around					

* Instrument Meteorological Conditions and Night Visual Meteorological Conditions.

To ensure an adequate workload level and to assess the level of system awareness provided by each concept, various operational tasks and additional system misconfigurations and failures are typically used. A balanced presentation of concepts will minimize the opportunity for transfer and/or practice effects.

5.3.12 Data Collection, Analysis, and Reporting.

5.3.12.1 Objective Data Collection, Analysis, and Reporting.

- Time Stamped 250 millisecond frame rate Simulation Data: Multiaxis Accelerations, Airspeed, Altitude, Attitude (Pitch and Bank), Heading, Vertical Speed, Flight Mode Annunciations, Throttle Lever Angle, Flight Control Inputs, Primary and Secondary Flight Control Surface and Gear Positions, Fuel Control Switch state, Fire Handle state, Engine Parameter Indications (EPR, N1, EGT, N2, Vibration, Fuel Flow, Oil Pressure (P) and Temperature, Autothrottle and Autopilot engagement, Engine Indication Annunciations, Alert Annunciations, Electronic Checklist Selections, etc.
- Video and Audio Recording
- Flight/Operational Performance, Response Time, Error Recording, etc.
- Objective Data Reporting—Reduction (e.g., Analysis of Variance (ANOVA) and other data analyses for statistical significance), Data and Results Discussion

5.3.12.2 Subjective Data Collection, Analyses, and Reporting.

- Workload
- PSM Awareness Level
- PSM Understanding Level
- Overall PSM Awareness and Interpretation Effort
- PSM Annunciation Concept Usability
- PSM Annunciation Concept Assessment

- PSM Annunciation Concept Rankings
- Subjective Data Discussion and Reporting

5.3.12.3 Test Data Analysis.

Typically, a normal baseline performance for each phase of flight to be tested was established for each pilot test subject as part of warmup and familiarization. This baseline allowed a relative within subject assessment of normal versus nonnormal pilot operational performance, response times, and errors.

The pilot test subjects who flew the nonannunciation concept scenarios collectively establish a baseline objective performance average against which objective performance with annunciation concepts were analyzed for statistically significant differences. Similar analysis was accomplished using the subjective data collected. Objective and subjective data were correlated for trends and significance.

The following are examples of typical performance measures:

- Time-to-initiate action—typically measured from some initial condition (e.g., malfunction insertion) and from the appearance of an annunciation to the first clear compensatory control or corrective action taken. This is predominately objective data.
- Time-to-complete actions—typically measured from the first compensatory control or corrective action taken to the last switch activation or cursor click for each task. This is predominately objective data.

Errors were typically identified by recording deviations from the expected/accepted levels of flight performance, appropriate selection of nonnormal procedure, and appropriate sequence of related compensatory control or corrective actions. This is predominately objective data.

Workload, both mental (subjective) and physical (objective), was typically evaluated as reported, observed, or recorded. This is typically a mix of objective and subjective data.

Malfunction detection/awareness of system state/configuration and of confederate pilot errors was typically evaluated. This is typically a mix of objective and subjective data.

Malfunction interpretation/understanding of system state/configuration and of confederate pilot errors was evaluated. This is typically a mix of objective (response) and subjective (reported) data.

When collected, video, audio, and simulator data were typically collected continuously. For each scenario, simulation variables were automatically recorded and time stamped by computer simulation monitoring. Subjective data were typically collected immediately after each concept/scenario, and at the end of each significant debrief. A questionnaire collected additional overall opinions and comments after the final session debrief.

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APPENDIX A—PROPULSION SYSTEM MALFUNCTION AND INAPPROPRIATE CREW
RESPONSE DATA ANALYSIS SUMMARY

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	ID Number	Event Class	PSM+ICR Category	ICR Appears Intentional (Y/N/U)	PSM Symptom	ICR Cause	Eng Ind/Ann Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Contributing Factor (Y/N/U)	Potential Fit Deck PSM Annunciations (Indications and/or Alerts)
85	44	85/EWB/4/H	H	LOSS OF CONTROL	N/A	THRUST REVERSER FAIL TO DEPLOY & Full Fwd Thrust on Eng	No Awareness/Annunciation of T/R Fail. Directional Control. Thrust Asymmetry.	U	Y	N	N	Thrust Reverser x Fail. Thrust Asymmetry.
73	10	73/1ST/2/HF	HF	LOSS OF CONTROL	N/A	POWERLOSS	Attitude/Airspeed Control	U	Y	U	U	Eng x Fail - Thrust Shortfall/Subside. Thrust Asymmetry?
83	34	83/1ST/2/HF	HF	LOSS OF CONTROL	N/A	POWERLOSS	Airspeed Control. Rushed downwind approach. CFIT.	U	U	U	U	Eng x Fail - Thrust Shortfall. Thrust Asymmetry?
85	43	*85/2ND/2/H F	HF	LOSS OF CONTROL	N/A	POWERLOSS/Surge	Attitude/Airspeed Control	U	Y	U	U	Eng x Fail - Thrust Shortfall. Surge. Thrust Asymmetry?
82	61	*92/MNB/2/H F	HF	LOSS OF CONTROL	N/A	STUCK THROTTLE - @ Idle Power	Attitude Control. No Awareness/Annunciation of Stuck Throttle and Thrust Asymmetry.	U	Y	Y	Y	Throttle Split. Thrust Asymmetry.
95	74	*95/EWB/2/H F	HF	LOSS OF CONTROL	N/A	STUCK THROTTLE - @ Climb Power	Attitude Control. No Awareness of Stuck Throttle and Thrust Asymmetry.	U	Y	N	Y	Throttle Split?-A310. Thrust Asymmetry. Thrust Overthrust.
95	77	95/2ND/2/HF	HF	LOSS OF CONTROL	N/A	POWERLOSS	Attitude/Airspeed Control	U	Y	U	U	Eng x Fail - Thrust Shortfall/Subside. Surge? Thrust Asymmetry?
85	39	*85/EWB/4/S	S	LOSS OF CONTROL	N/A	POWERLOSS	No Awareness/Annunciation of Subside and Thrust Asymmetry. Attitude/Directional Control	U	Y	Y	Y	Eng x Fail - Thrust Shortfall/Subside. Thrust Asymmetry.
83	37	83/1ST/4/HF	HF	LOSS OF CONTROL	N/A	POWERLOSS SUSPECTED	Attitude/Directional Control	U	U	U	U	Eng x Fail - Thrust Shortfall. Surge? Thrust Asymmetry?
88	50	88/EWB/3/I	I	LOSS OF CONTROL	N/A	THRUST REVERSER FAIL TO DEPLOY	No T/R Fail Awareness. Directional Control. Thrust Asymmetry.	U	Y	N	N	Thrust Reverser x Fail. Thrust Asymmetry.
71	6	71/1ST/4/H	H	LOSS OF CONTROL-TRAINING	N/A	POWERLOSS + V1 Throttle Cut	Attitude/Directional Control	N	Y	U	U	Eng x Fail - Thrust Shortfall. Thrust Asymmetry?
81	27	81/1ST/4/I	I	OTHER - ATB and R/W Excursion; UNCORD APPR & LANDING/OFFSIDE - PILOTING SKILL	Y	Powerloss/Surge. Eng Fire.	Rushed downwind approach. Landed 25 kts fast.	U	N	N	N	
82	32	82/EWB/4/I	I	OTHER - CREW FAILED TO SECURE/Shutdown Eng Per Emergency Procedure	U	Surge Vibration	Unknown why crew did not follow emergency procedure. Lack of compelling non-normal annunciation? Crew choice?	U	N	N	N	Excess Vibration. Eng Surge?
96	81	96/1ST/4/HF	HF	OTHER - Failed to RTO for Powerloss < V1.	Y	Powerloss/Surge.	No Awareness/Annunciation of PSM?	U	U	U	U	Eng Fail - Thrust Shortfall/Subside. Thrust Asymmetry?
83	35	83/1ST/2/H	H	OTHER - FAILURE TO COMPLETE Eng SHUTDOWN PROCEDURES Following RTO	U	Powerloss/Surge.	Unknown why crew did not follow emergency procedure. Lack of adequate/compelling non-normal annunciation? Crew choice?	U	N	N	N	Eng Fail - Thrust Shortfall/Subside. Surge?
91	57	91/2ND/3/I	I	OTHER - MIS-IDENTIFIED MALFUNCTION	N	Surge Vibration (Airframe)	ICR? No Awareness/Annunciation of PSM.	N	N	N	N	Excess Vibration. Eng Surge.
94	68	94/2ND/3/I	I	OTHER - SHUTDOWN GOOD ENGINE	Y	Surge Vibration (Airframe)	No Awareness/Annunciation of PSM location.	N	N	N	N	Surge. Excess Vibration. Eng Fail - Thrust Shortfall?
93	62	*93/MNB/2/I	I	OTHER - UNABLE TO ISOLATE/IDENTIFY WHICH ENGINE WAS SURGING	N	Surge Vibration/Shudder (Airframe)	N/A	N	N	N	N	Surge.

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	Recommended Propulsion Detection/Investigation/Study PSMs	Propulsion System Malfunction/Failure	PSM Recoverable (Y/N/U)	Eng Ind Avail (Y/N/U)	Eng Ind/Am Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	PSM Thrust Asym Awareness (Y/N/U)	A/P Engaged (Y/N/U)	A/P Contributing Factor (Y/N/U)	Engine Symptom	Annunciation Prevention Potential (Y/N/U)	Malfunction Detection Potential (Y/N/U)
85	44		THRRTL CABLE SEPARATED-RESULTING IN FULL FWD THRUST	N	Y	U	Y	Y	U	N	THRUST REVERSER (NO.1) DID NOT TRANSITION TO 'REV THRUST', YAW RIGHT, THRUST INCREASE TO FULL FWD THRUST, RIGHT YAW CONTINUED	N	Y
73	10	POWERLOSS - Thrust Shortfall/Subidle. Low to High Power event.	POWERLOSS	U - Did Not Recover	Y	U	Y	U	U	U	POWERLOSS	Y	Y
83	34	POWERLOSS/TURBINE BLADE FAILURE - Thrust Shortfall. High Power event.	TURBINE BLADE FAILURE	N	Y	U	U	Y	U	U	POWERLOSS (UNRECOVERABLE)	N	Y
85	43	POWERLOSS/Surge/ - Thrust Shortfall/DISINTEGRATION. High Power event.	DISINTEGRATION - COMPRESSOR SPACER FAILURE	N	Y	U	Y	U	U	U	COMPRESSOR SURGE, AND POWERLOSS	U	Y
92	61		THROTTLE STUCK	Y	Y	U	Y	N	Y	Y	STUCK THROTTLE	Y	Y
95	74		THROTTLE STUCK	Y	Y	U	Y	N	N	Y	NO RESPONSE TO COMMANDED POWER	Y	Y
95	77	POWERLOSS/Surge - Thrust Shortfall/Subidle/FAN BLADE FRACTURE. Low to High Power event.	FAN BLADE FRACTURE	N	Y	U	Y	U	U	U	SURGE-LOW POWER, VIBRATION & BANG, THRUST LOSS	Y	Y
85	39	POWERLOSS - Thrust Shortfall/Subidle. Low to High Power event.	RUNDOWN BELOW SUB-IDLE	Y	Y	U	Y	N	Y	Y	POWERLOSS (NO.4)	Y	Y
83	37	POWERLOSS/Surge - Thrust Shortfall. High Power event.	POWERLOSS SUSPECTED	U	U	U	U	U	U	U	POWERLOSS SUSPECTED	U	U
88	50		THRUST REVERSER SYSTEM BINDING	N	U	U	Y	Y	U	N	THRUST REVERSER TO UNLOCK POSITION	N	Y
71	6	POWERLOSS - Thrust Shortfall. High Power event.	TRAINING - V1 THROTTLE CUT & POWERLOSS NO.3	U	Y	N	Y	Y	U	U	POWERLOSS	Y	Y
81	27		POWERLOSS	N	U	U	N	Y	N	N	COMPRESSOR SURGE	N	Y
82	32	Eng Fail/Vibration/LP LOCATION BEARING FAILURE. Surge? High Power.	LP LOCATION BEARING FAILURE	N	Y	U	N	Y	U	N	EXCESSIVE A/YM WARNING LIGHT, VIBRATION, COMPRESSOR SURGE	Y	Y
96	81	Powerloss - Thrust Shortfall/Subidle. High Power.	POWERLOSS	U	U	U	U	U	U	U	COMPRESSOR SURGE - POWERLOSS	U	U
83	35	Eng Fail - Thrust Shortfall/Subidle/Fail Of. Surge? DISINTEGRATION. High Power.	DISINTEGRATION	N	Y	U	N	U	N	N	COMPRESSOR SURGE	U	U
91	57	Eng Fail/Surge - Vibration, Fan Blade Damage. High Power.	NOSE SPINNER SEPARATION	N	Y	N	N	N	N	N	HEAVY NOISE AND VIBRATION, COMPRESSOR SURGE	Y	Y
94	68	Surge - Fan Blade Fracture and Turbine Blade Melt. Powerloss - Thrust Shortfall? High Power.	FAN BLADE FRACTURE	N	Y	N	N	N	N	N	COMPRESSOR SURGE	Y	Y
93	62	Surge - Damaged/Missing Compressor Blades. High Power.	BMOD	N	Y	N	N	Y	Y	N	COMPRESSOR SURGE	Y	Y

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	ID Number	Event Class	PSM+ICR Category	ICR Appears Intentional (Y/N/U)	PSM Symptom	ICR Cause	Eng Indi/Ann Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Contributing Factor (Y/N/U)	Potential Fit Deck PSM Annunciations (Indications and/or Alerts)
88	51	88/2ND/2/HF	HF	OTHER (ICR?) OTHER-DUAL ENG POWERLOSS;CONTINUOUS SURGING ENGS on two eng aircraft. Increased power on engines.	Y	Surge Power Loss/Eng Fail - Dual Eng.	ICR? Low Altitude Takeoff Power Loss - EPR Reduction.	Y	N	N	N	Surge. Eng Fail - Thrust Shortfall/Subidle.
92	59	92/MWB/2/I	I	OTHER- Fail to detect Eng Fail and ASYMMETRIC THRUST	N	Eng Fail Fixed Low - Fail To Respond.	ICR? No awareness of Eng Fail to Respond and Thrust Asymmetry.	N	Y	Y	Y	Eng Fail - Thrust Shortfall/Subidle. Thrust Asymmetry.
81	30	81/1ST/4/H	H	OTHER-ATB & R/W Excursion; UNCOORD APPR&LNDG-LOC-ASYM REV THRUST- BELOW Vmcg	Y	Eng Oil Qty Loss	Airmanship/Pilot Judgement.	N	Y	N	N	Thrust Asymmetry.
91	58	91/MNB/2/H	H	OTHER-DUAL ENG POWERLOSS;CONTINUOUS SURGING ENGS on two eng aircraft. Did not reduce power on suiting engine #2.	Y	Surge Powerloss/Fail (BOTH ENGINES SEQUENTIAL)	ICR? Low Altitude Takeoff Power Loss.	U	N	N	N	Surge. Eng Fail - Thrust Shortfall/Subidle.
88	47	88/EWB/4/I	I	OTHER-EXCESSIVE PITCH ATTITUDE (22 deg) and Stickshaker @ Liftoff	N	Powerloss/Surge.	Altitude Control. Power Loss. Thrust Asymmetry. Adverse Wind.	U	U	N	N	Eng Fail - Thrust Shortfall. Surge. Thrust Asymmetry?
68	1	68/1ST/4/HF	HF	OTHER-PYLON S/O VALVE NOT SECURED UNCONTROLLED FIRE	U	Engine Fail/Fire	Unknown why crew did not follow emergency procedure. Lack of non-normal annunciation? Crew choice?	U	N	N	N	Eng Fire. Eng Fail - Thrust Shortfall/Subidle/Fell Off.
96	78	*96/EWB/3/H	HF	RTO > V1 (Alter Liftoff)	Y	Surge/Powerloss.	Powerloss. No positive rate of climb. Airspeed loss. Captain did not believe aircraft had lifted off. No Awareness/Annunciation of PSM (Engine Surge) or affected Engine(s).	N	N	N	N	Eng x Surge. Eng x Fail - Thrust Shortfall/Subidle.
69	3	69/1ST/4/S	S	RTO@V1. ICR = Braking Delay and Technique. A/C Fuel Overload.	RTO - Y. Braking - U.	Surge/powerloss eng #2. Bird ingestion on engines 1, 2, and 3.	Unknown for Braking. Surge related noise and powerloss for RTO.	Y - RTO. U - Braking.	N	N	N	Annunciation of PSM would not have affected ICR (Braking Technique)
81	29	*81/EWB/4/S	S	RTO<V1. ICR = Braking Technique/STOP PROCEDURE.	RTO - Y. Braking - U.	Surge. Aircraft Shudder. EGT Exceedance.	Unknown for Braking. EGT Warning light and FE Eng Fire callout for RTO.	Y - RTO. U - Braking.	N	N	N	Inhibit Warning annunciation and/or associated lights and aural. Note: annunciation of PSM would not have affected ICR (Braking Technique)
90	54	90/1ST/4/H	H	RTO<V1. ICR = Braking Technique	RTO - Y. Braking - U.	Surge.	Unknown for Braking. Surge effects for RTO.	U	N	N	N	Annunciation of PSM would not have affected ICR (Braking Technique)
78	19	78/2ND/2/H	H	RTO>V1	Y-PF. N-PIC	Powerloss	Crew coordination - PF braking with PIC attempting takeoff. Training related event. Fire Warning	U	N	N	N	Eng x Fail - Thrust Shortfall/Subidle?
85	40	85/1ST/4/H	H	RTO>V1	Y	Fire Warning		Y	N	N	N	Inhibit Warning annunciation and/or associated lights and aural.
77	16	*77/EWB/3/I	I	RTO>V1	Y	Surge	Engine Failure annunciation.	Y	N	N	N	Inhibit failure annunciation and/or any associated lights and aural.
78	22	78/EWB/3/I-2	I-2	RTO>V1	Y	Powerloss	Engine Failure annunciation.	Y	N	N	N	Inhibit failure annunciation and/or any associated lights and aural.
85	38	85/EWB/4/I-1	I-1	RTO>V1	Y	Surge	Surge Effects.	U	N	N	N	Eng x Surge.
86	45	86/2ND/2/I	I	RTO>V1	Y	Surge/Powerloss/Flameout	Surge/Powerloss	U	N	N	N	Eng x Surge. Eng x Fail - Thrust Shortfall/Subidle.
88	48	88/2ND/2/I	I	RTO>V1	Y	Powerloss/Surge	Engine Power Loss Indication	Y	N	N	N	Eng x Surge?

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	Recommended Propulsion Detection/Investigation/Study PSMs	Propulsion System Malfunction/Failure	PSM Recoverable (Y/N/U)	Eng Ind Avail (Y/N/U)	Eng Ind/Am Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	PSM Thrust Asym Awareness (Y/N/U)	A/P Engaged (Y/N/U)	A/P Contributing Factor (Y/N/U)	Engine Symptom	Annunciation Prevention Potential (Y/N/U)	Malfuction Detection Potential (Y/N/U)
88	51	Surge - Compressor Blade Separation and Turbine Blade Melt. Powerloss - Thrust Shortfall/Subidle. High Power.	MULTIPLE BIRD INGESTION	N	Y	Y	N		U	N	COMPRESSOR SURGES	Y	Y
92	59	Eng Fail - Thrust Shortfall/Subidle. Low Power.	THROTTLE STUCK	N	Y	N	Y		Y	Y	NO RESPONE TO COMMANDED POWER	Y	Y
81	30		OIL LOSS	N	Y	N	Y		N	N	LOW OIL QUANTITY	N	Y
91	58	Surge - Compressor Blade Separation and Turbine Blade Melt. Powerloss - Thrust Shortfall/Subidle. High Power.	FOD INGESTION (WING ICE)	N	Y	U	N		U	N	CONTINUOUS COMPRESSOR SURGES (BOTH ENGINES SEQUENTIAL)	Y	Y
88	47	Powerloss - Thrust Shortfall. Surge. High Power.	POWERLOSS	U	Y	U	U		N	N	COMPRESSOR SURGE	N	Y
68	1	Eng Fail - Thrust Shortfall/Subidle/Fail Off. DISINTEGRATION - COMPRESSOR DISK FAILURE.	DISINTEGRATION - COMPRESSOR DISK FAILURE	N	Y	U	N		U	N	COMPRESSOR SURGE	U	U
96	78	Surge, Powerloss - HP Turbine blade failure. High (Takeoff Power)	Turbine blade failure (high pressure)	N	Y	N	N		N	N	LOUD BANG (COMPRESSOR SURGE) & POWERLOSS	U	Y
69	3	Surge/Powerloss - Birdstrike. POWERLOSS	BIRDSTRIKE - POWERLOSS	U	Y	U	N		N	N	COMPRESSOR SURGE	N	Y
81	29		COMPRESSOR SURGE	N	Y	Y	N		N	N	COMPRESSOR SURGE, AIRPLANE SHUDDER, FLASH OF LIGHT	N	Y
90	54		COMPRESSOR SURGE	U	Y	U	N		N	N	COMPRESSOR SURGE + VISUAL SIGHTING OF BIRDS, SURGES ON NO.2&3 ENGINES	N	Y
78	19	Powerloss - Bird ingestion. High (Takeoff Power).	POWERLOSS (BIRD INGESTION)	U	Y	U	N		N	N	POWERLOSS	N	U
85	40		FIRE WARNING	N	Y	Y	N		N	N	FIRE WARNING	N	Y
77	16	Surge/Compressor Stall - CIT SENSOR COLDSHIFT. High (Takeoff Power).	CIT SENSOR COLDSHIFT, CAUSED STALL	N	Y	Y	N		N	N	COMPRESSOR SURGE	N	Y
78	22		POWERLOSS - INTERNAL DISTRESS (SEIZED N2)	N	Y	Y	N		N	N	POWERLOSS	N	Y
85	38	Surge - Birdstrike/Compressor Stall. High (Takeoff Power).	BIRD INGESTION	Y	Y	U	N		N	N	COMPRESSOR SURGE	U	U
86	45	Surge/Powerloss - Bird ingestion. High (Takeoff Power).	BIRD INGESTION - POWERLOSS	U	Y	U	N		N	N	COMPRESSOR SURGE	U	Y
88	48	Surge/Powerloss - Bird ingestion. High (Takeoff Power).	BIRD INGESTION - POWERLOSS	U	Y	Y	N		N	N	COMPRESSOR SURGE	N	Y

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	ID Number	Event Class	PSM+ICR Category	ICR Appears Intentional (Y/N/U)	PSM Symptom	ICR Cause	Eng Indi/Ann Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Contributing Factor (Y/N/U)	Potential Fit Deck PSM Annunciations (Indications and/or Alerts)
	91	55	91/EWB/2/I	I	RTO>V1	Y	Vibration - severe. Powerloss?	Severe Vibration.	Unable (severe vib)	N	N	Eng x Vibration. Eng x Fail - Thrust Shortfall.
	92	60	92/EWB/4/I	I	RTO>V1	Y	Surge/Overtemp	Surge Effects.	U	N	N	Eng x Surge.
	93	64	93/EWB/4/I-2/I	I	RTO>V1	Y	Surge.	Surge Effects.	U	N	N	Eng x Surge.
	95	75	95/MWB/2/I-1	I	RTO>V1	Y	Thrust Reverser Unlock Annunciation	ICR? (Decision @V1). Thrust Reverser Unlock Annunciation.	U	N	N	Inhibit Thrust Reverser Unlock Annunciation?
	96	80	96/MWB/4/I	I	RTO>V1	Y	Powerloss/Decel Stall Surge.	Powerloss/Decel Stall Surge - Sense line leaking/open.	U	N	N	Eng x Fail - Thrust Shortfall/Subidle.
	72	8	72/2ND/2/S	S	RTO>V1	Y	Powerloss	Powerloss	U	N	N	Eng x Fail - Thrust Subidle. Eng x Fail - Thrust Shortfall?
	75	12	75/2ND/3/S	S	RTO>V1	Y	Powerloss (Perceived)/Airplane Decel	Powerloss perceived/interfered from aircraft decel.	U	N	N	Eng x Fail - Thrust Shortfall.
	78	21	*78/EWB/4/S	S	RTO>V1	U	Surge. Powerloss?	Surge related effect(s). Unknown if Awareness/Annunciation of PSM (Engine Surge) or affected Engine(s) causal.	U	N	N	Eng x Surge? Eng x Fail - Thrust Shortfall/Subidle?
	83	36	*83/EWB/4/S	S	RTO>V1	Y	EGT Exceedance.	EGT Exceedance.	Y	N	N	Inhibit exceedance announcement and/or any associated lights and aural.
	88	49	*88/EWB/4/S	S	RTO>V1	Y	Vibration. Powerloss?	Fire Warning and lack of adequate Crew Coordination/Communication.	U	N	N	Inhibit Warning announcement and/or associated lights and aural.
	76	14	76/EWB/3/I	I	RTO>V1 (@ Rotation)	Y	Surge	Surge Effects.	U	N	N	Eng x Surge.
	77	17	77/2ND/3/I	I	RTO>V1 (@ Rotation)	Y	Surge/Powerloss. Vibration. Eng Fail indication.	Surge related noise and powerloss. Engine Failure announcement.	U	N	N	Inhibit failure announcement and/or any associated lights and aural.
	91	56	91/MNB/2/I	I	RTO>V1 (@ Rotation)	Y	Surge.	Surge related noise and yaw.	U	N	N	Eng x Surge?
	81	28	*81/2ND/3/S	S	RTO>V1 (@ Rotation)	Y	Surge/Powerloss.	Surge related noise and decreasing engine power indications. No Awareness/Annunciation of severity of PSM (Engine Surge). Multiple circumstantial and experiential factors in pilot decision.	Y	N	N	Eng x Surge? Eng x Fail - Thrust Shortfall/Subidle?
	88	52	*88/MNB/2/S	S	RTO>V1 (@ Rotation)	Y	Surge. Powerloss?	Surge related noise - misidentified failure (Fire vs Eng). No Awareness/Annunciation of PSM (Engine Surge) or affected Engine(s).	N - (All Normal)	N	N	Eng x Surge?
	95	76	*95/EWB/3/S	S	RTO>V1 (@ Rotation)	Y	Surge/Powerloss. Vibration and Airframe Shudder.	Surge related noise and vibration-misidentified failure? No Awareness/Annunciation of PSM (Engine Surge & Powerloss) or affected Engine(s).	U	N	N	Eng x Surge. Eng x Fail - Thrust Shortfall/Subidle.
	70	4	70/2ND/2/H	H	RTO>V1 (After Liftoff)	Y	Surge/Powerloss.	Misread normal unaffected eng indications. Thought both engines failed? No Awareness/Annunciation of PSM (Engine Surge)/Affected Engine(s).	Y	Y	N	Eng x Surge. Eng x Fail - Thrust Shortfall/Subidle.
	86	46	*86/EWB/2/H	H	RTO>V1 (After Liftoff)	Y	Surge. Powerloss. Heavy Vibration.	Unknown - Bang? No Awareness/Annunciation of PSM (Engine Surge) or Affected Engine(s)?	N	N	N	Eng x Surge. Eng x Fail - Thrust Shortfall/Subidle.
	93	65	93/MWB/3/I	I	RTO>V1 Attempted. F/O attempted RTO/throttled engines. Captain intervened and continued takeoff.	Y	Surge. Vibration.	Surge Effects. Vibration.	U	N	N	Eng x Surge.

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	Recommended Propulsion Detection/Investigation/Study PSMs	Propulsion System Malfunction/Failure	PSM Recoverable (Y/N/U)	Eng Ind Avail (Y/N/U)	Eng Ind/Am Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	PSM Thrust Asym Awareness (Y/N/U)	A/P Engaged (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Engaged (Y/N/U)	A/T Contributing Factor (Y/N/U)	Engine Symptom	Annunciation Prevention Potential (Y/N/U)	Malfunction Detection Potential (Y/N/U)
	91	Vibration/Powerloss - Tire ingestion. High (Takeoff Power).	TIRE TREAD INGESTION	N	Y	Unable (severe vib)	N	N	N	N	U	N	SEVERE VIBRATIONS & PERCEIVED POWERLOSS	N	Y
	92	Surge - FAN BLADE FRACTURES (BIRD STRIKE). High (Takeoff Power).	BIRD INGESTION	U	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	U	Y
	93	Surge - BIRD STRIKE. High (Takeoff Power).	FAN BLADE FRACTURES (BIRD STRIKE)	N	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	U	Y
	95		THRUST REVERSER UNSTOW INDICATION	U	Y	U	N	N	N	N	U	N	THRUST REVERSER "REV UNLK" LIGHT ON	N	Y
	96	Powerloss/Decel Stall Surge High (Takeoff Power)	CONTROL SYSTEM FAULT	N	U	U	N	N	N	N	U	N	POWERLOSS + DECEL STALL/SURGE	U	Y
	72		TEMPORARY POWER LOSS THEN RECOVERED FULLY	Y	Y	U	N	N	N	N	U	N	TEMPORARY POWERLOSS DUE TO STANDING WATER INGESTION DURING T/O	U	Y
	75		NONE	Y	Y	U	N	N	N	N	U	N	SUPECTED POWER LOSS DUE TO AIRCRAFT DECELERATION	U	Y
	78	Surge. High (Takeoff Power).	TIRE TREAD INGESTION	U	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	N	Y
	83		TURBINE BLADE RETAINER FAILURE	N	Y	Y	N	N	N	N	U	N	EGT WARNING (AMBER AND RED)	N	Y
	88		CASE RUPTURE	N	Y	U	N	N	N	N	U	N	FIRE WARNING	N	Y
	76	Surge/Compressor Stall. High (Takeoff Power).	COMPRESSOR SURGE	U	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	U	Y
	77	Surge (Compressor stall)/Powerloss - DETERIORATION. High (Takeoff Power)	DETERIORATION	N	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	N	Y
	91	Surge - COMPRESSOR LINER DISTRESS. High (Takeoff Power)	COMPRESSOR LINER DISTRESS	N	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	N	Y
	81	Surge - Recoverable. High (Takeoff Power).	POWERLOSS - REPORTED AS PARTIAL	Y	Y	Y	N	Y	N	N	U	N	COMPRESSOR SURGE	N	Y
	88	Surge - TURBINE BLADE FAILURE. High (Takeoff Power).	TURBINE BLADE FAILURE	N	Y	N - (All Normal)	N	N	N	N	U	N	COMPRESSOR SURGE	U	Y
	95	Surge. Powerloss - HPC BLADE SEPARATION. High (Takeoff Power)	HPC BLADE SEPARATION RESULTING FROM FOD	N	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	U	Y
	70	Surge. Powerloss - Turbine blade failure. High (Takeoff Power)	POWERLOSS - TURBINE BLADE FAILURE	N	Y	Y	Y	Y	N	N	U	N	COMPRESSOR SURGE	Y	Y
	86	Surge. Powerloss - Fan blade fracture/Bird ingestion. High (Takeoff Power).	FAN BLADE FRACTURE - BIRD INGESTION	N	Y	N	N	N	N	N	U	N	COMPRESSOR SURGE (POWERLOSS)	N	Y
	93	Surge. High (Takeoff Power).	COMPRESSOR SURGE	Y	Y	U	N	N	N	N	U	N	COMPRESSOR SURGE	N	U

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	ID Number	Event Class	PSM+ICR Category	ICR Appears Intentional (Y/N/U)	PSM Symptom	ICR Cause	Eng Ind/Ann Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Contributing Factor (Y/N/U)	Potential Fit Deck PSM Annunciations (Indications and/or Alerts)
89	53	*89/MNB/2/H F	HF	SHUTDOWN GOOD ENGINE	Y	Surge Vibration (Airframe).	No Awareness/Annunciation of PSM (Engine Surge) or Affected Engine.	N	N	N	N	Engine x Excess Vibration. Engine x Surge.
70	5	70/EWB/4/I	I	SHUTDOWN GOOD ENGINE	N	Fire Warning	Unintended Fuel Control/Mgmt Error.	U	N	N	N	
72	7	72/EWB/4/-1 I	I	SHUTDOWN GOOD ENGINE	N	Fire Warning	Unintended FE Fuel Control/Mgmt Error.	U	N	N	N	
72	9	72/EWB/4/-2 I	I	SHUTDOWN GOOD ENGINE	Y	Powerloss/Surge	Crew misinterpreted rising EGT. No Awareness/Annunciation of PSM (Engine Surge) or Affected Engine(s).	Y	Y	N	N	Engine x Surge.
75	11	75/EWB/4/-1 I	I	SHUTDOWN GOOD ENGINE	U	Surge/EGT Rising	Eng #3 N1 decreasing. No Awareness/Annunciation of PSM (Engine Surge) Affected Engine.	Y	N	N	N	Engine x Surge.
75	13	75/EWB/4/-2 I	I	SHUTDOWN GOOD ENGINE	U	Surge.	Unknown. Pilot error or FE fuel mgmt error?	N	N	N	N	
77	15	77/EWB/4/I	I	SHUTDOWN GOOD ENGINE	U	Surge/Powerloss/Quit Running.	No Awareness/Annunciation of PSM (Engine Surge) or Affected Engine. ICR Suspected.	U	N	N	N	Engine x Surge. Eng x Fail - Thrust Shortfall/Subidle?
78	18	78/2ND/3/-1 I	I	SHUTDOWN GOOD ENGINE	U	Powerloss/Fail-Quit #3	Unknown. Crew error during restart procedure suspected. ICR Suspected.	U	N	N	N	Eng x Fail - Thrust Shortfall/Subidle?
78	20	78/EWB/4/I	I	SHUTDOWN GOOD ENGINE	N	Powerloss	Unintended FE? Error - S/D wrong/good engine during restart.	N	N	N	N	
79	23	79/EWB/4/-1 I	I	SHUTDOWN GOOD ENGINE	N	Surge/EGT Exceedance.	Unintended FE Error - Fuel Heat misgmt.	N	N	N	N	
79	24	79/2ND/2/S I	I	SHUTDOWN GOOD ENGINE	Y	Surge/DISINTEGRATION. Cabin Depressurization.	No Awareness/Annunciation of PSM (Engine Surge) or Affected Engine. Loss/zeroing of indications.	U	N	N	N	Engine x Surge. Eng x Fail - Thrust Shortfall/Subidle? Thrust Asymmetry?
80	25	80/EWB/3/I	I	SHUTDOWN GOOD ENGINE	U	Fail/Subidle. NO RESPONSE TO THROTTLE	Unknown.	N	N	N	N	
81	26	81/2ND/2/I	I	SHUTDOWN GOOD ENGINE	U	Powerloss	Unknown. ICR Suspected.	U	U	N	N	Eng x Fail - Thrust Shortfall/Subidle?
81	31	81/EWB/4/I	I	SHUTDOWN GOOD ENGINE	U	Powerloss	Crew Error.	U	N	N	N	Eng x Fail - Thrust Shortfall/Subidle?
82	33	82/EWB/4/I	I	SHUTDOWN GOOD ENGINE	N	Vibration. AVM and Vibration Alert Eng #2	Unintended FE Error - Pulled wrong fire handle - eng #1.	N	N	N	N	
85	41	85/EWB/4/-2 I	I	SHUTDOWN GOOD ENGINE	Y	Surge.	Crew misinterpreted fuel flow drop due to throttle cut on good engine - TWO-ENG OUT. Crew Coordination/communication.	Y	N	N	U	Engine x Surge. Eng x Fail - Thrust Shortfall/Subidle.
85	42	85/MWB/2/I	I	SHUTDOWN GOOD ENGINE	Y	Surge Vibration (Airframe).	No Awareness/Annunciation of PSM (Engine Surge) or Affected Engine.	U	N	N	N	Engine x Excess Vibration. Engine x Surge.
93	63	93/EWB/4/-1 I	I	SHUTDOWN GOOD ENGINE	Y	Surge/EGT Exceedances.	ICR? - ICR Assumed. EGT Exceedances.	Y	N	N	N	Engine x Surge/Inlet cone liberation. Engine x Surge/Fan Blade Damage from metal particle ingestion. High Throttle Split. Eng x Fail - Subidle.
93	66	*93/MNB/2/I	I	SHUTDOWN GOOD ENGINE	Y	STUCK THROTTLE - @ Medium (Approach) Power	No Awareness/Annunciation of Stuck Throttle. Crew misinterpreted idle eng as flameout.	Y	U	N	Y	Engine x Surge. Eng x Fail - Thrust Shortfall/Subidle.
94	71	*94/MWB/4/I	I	SHUTDOWN GOOD ENGINE	Y	Powerloss/Surge (Crew induced)	Crew misinterpreted failing engine indications as Failure.	Y	N	N	N	Engine x Surge. Eng x Fail - Thrust Shortfall/Subidle.

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	Recommended Propulsion Detector/Investigation/Study PSMs	Propulsion System Malfunction/Failure	PSM Recoverable (Y/N/U)	Eng Ind Avail (Y/N/U)	Eng Ind/Am Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	PSM Thrust Asym Awareness (Y/N/U)	A/P Engaged (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Engaged (Y/N/U)	A/T Contributing Factor (Y/N/U)	Engine Symptom	Annunciation Prevention Potential (Y/N/U)	Malfunction Detection Potential (Y/N/U)
89	53	Surge/FAN BLADE FRACTURE. Vibration. Medium to Low (Cruise, Descent, & Approach) Power.	FAN BLADE FRACTURE	N	Y	N	N		U	N	U	N	COMPRESSOR SURGE, MODERATE TO SEVERE VIBRATION, BURNING SMELL, AND SOME VISIBLE SMOKE IN CABIN	Y	Y
70	5		PNEUMATIC BLEED DUCT RUPTURE	N	Y	U	N		U	N	U	N	FIRE WARNING	N	Y
72	7		NACELLE FIRE - FUEL LEAK FROM W/ TRANSMITTER	N	U	U	N		U	N	U	N	FIRE WARNING	N	Y
72	9	Surge/Airflow Related. Cruise Power.	HPT BLADE FAILURE	N	Y	Y	Y		U	N	U	N	COMPRESSOR SURGE	U	Y
75	11	Engine x Surge/COMPRESSOR DETERIORATION. Medium (Cruise) Power.	COMPRESSOR DETERIORATION	Y	Y	Y	N		U	N	U	N	COMPRESSOR SURGE	Y	Y
75	13		NO CAUSE FOUND, ENGINES CHECKED OK	Y	Y	N	N		U	N	U	N	HI STAGE BLEED LIGHT, COMPRESSOR SURGE	U	Y
77	15	Surge/Internal Eng Damage. Surge/Airflow Related. Climb Power.	COMPRESSOR SURGE	N	Y	U	N		U	N	U	N	COMPRESSOR SURGE	Y	Y
78	18	Powerloss/GEAR SHAFT FAILURE. High (Climb) Power.	GEAR SHAFT FAILURE	N	Y	U	N		U	N	U	N	POWERLOSS	N	Y
78	20		POWERLOSS (HPC HUB FAILURE)	N	Y	N	N		U	N	U	N	COMPRESSOR SURGE	N	Y
79	23		POWERLOSS	Y	Y	N	N		U	N	U	N	COMPRESSOR SURGE AND OVERTEMP	U	Y
79	24	Surge/HPC DISINTEGRATION. Powerloss - Thrust Shortfall/Subidle? Medium (Cruise) Power - event/DISINTEGRATION - HPC DISK	DISINTEGRATION - HPC DISK	N	Y - Missing - all zero except EGT.	U	N		U	N	U	N	COMPRESSOR SURGE	U	U
80	25		ROLLED BACK SUB-IDLE	N	Y	N	N		Y	N	U	N	NO RESPONSE TO THROTTLE	U	Y
81	26	Eng Fail - Thrust Shortfall/Subidle. High Power	FUEL PUMP SHAFT FAILURE	N	Y	U	U		N	N	U	N	POWERLOSS	U	Y
81	31	Powerloss? Medium (Cruise) Power.	POWERLOSS	U	U	U	N		U	N	U	N	POWERLOSS	U	Y
82	33		POWERLOSS - LP LOCATION BEARING FAILURE	N	Y	N	N		U	N	N	N	COMPRESSOR SURGE	N	Y
85	41	Surge/Metal In Tailpipe Damage. Highw (Climb) Power.	COMPRESSOR SURGE - MITP	N	Y	Y	N		U	N	U	U	COMPRESSOR SURGE	Y	Y
85	42	Surge/HPC Damage. Vibration. Medium to Low (Cruise and Descent) Power.	HIGH PRESSURE COMPRESSOR FOD	Y	U	U	N		U	N	U	N	COMPRESSOR SURGE	Y	Y
93	63		NOSE SPINNER SEPARATION	U	Y	Y	N		U	N	U	N	COMPRESSOR SURGE	U	Y
93	66		THROTTLE STUCK	Y	Y	Y	U		U	N	Y	Y	STUCK THROTTLE	Y	Y
94	71	Surge/Stator Vane Hysteresis. High Power.	COMPRESSOR SURGE	Y	Y	Y	N		U	N	Y	N	COMPRESSOR SURGE	Y	Y

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	ID Number	Event Class	PSM+ICR Category	ICR Appears Intentional (Y/N/U)	PSM Symptom	ICR Cause	Eng Indi/Ann Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Contributing Factor (Y/N/U)	Potential Fit Deck PSM Annunciations (Indications and/or Alerts)
95	73	*95/MWB/2/I-2	I	SHUTDOWN GOOD ENGINE	Y	STUCK THROTTLE - @ High (94%) Power	No Awareness/Annunciation of Stuck Throttle. Crew misinterpreted vibration, decreasing eng parameters, and idle eng as failure.	Y	Y	N	Y	Throttle Split (A300)? Eng x Fail - Subidle.
96	79	96/MNB/2/I	I	SHUTDOWN GOOD ENGINE	Y	STUCK THROTTLE - @ Idle Power	No Awareness/Annunciation of Stuck Throttle. Crew misinterpreted thrust asymmetry and idle eng as flameout.	U	Y	N	Y	Throttle Split. Eng Fail - Subidle.
93	67	*93/EWB/2/I	I	THROTTLED GOOD ENGINE	U	Surge.	Unknown - Could not determine which engine was surging?	U	U-Possible	N	TBD	Engine x Surge.
94	69	*93/MWB/2/I-3	I	THROTTLED GOOD ENGINE	Y	Surge.	Unknown - Could not determine which engine was surging?	U	U-Possible	N	TBD	Engine x Surge.
94	70	94/MWB/2/I-2	I	THROTTLED GOOD ENGINE	U	Surge.	Unknown - Could not determine which engine was surging?	U	U-Possible	N	TBD	Engine x Surge.
94	72	94/MWB/2/I-1	I	THROTTLED GOOD ENGINE	Y	Surge.	Unknown - Could not determine which engine was surging?	U	U-Possible	N	TBD	Engine x Surge.
69	2	69/2ND/2/H	H	THROTTLED GOOD ENGINE - FORCED LANDING	Y	Surge.	Could not determine which engine was surging.	U	N	N	N	Engine x Surge.

TABLE A-1. INDICATIONS OF PROPULSION SYSTEM MALFUNCTIONS

Year	Event #	Recommended Propulsion Detector/Investigation/Study PSMs	Propulsion System Malfunction/Failure	PSM Recoverable (Y/N/U)	Eng Ind Avail (Y/N/U)	Eng Ind/Am Use Contributing Factor (Y/N/U)	Thrust Asym Contributing Factor (Y/N/U)	PSM Thrust Asym Awareness (Y/N/U)	A/P Engaged (Y/N/U)	A/P Contributing Factor (Y/N/U)	A/T Engaged (Y/N/U)	A/T Contributing Factor (Y/N/U)	Engine Symptom	Annunciation Prevention Potential (Y/N/U)	Malfunction Detection Potential (Y/N/U)
95	73		THROTTLE STUCK/JAMMED	N	Y	Y	Y		Y	N	Y	Y	STUCK THROTTLE	Y	U
96	79		STUCK THROTTLE	Y	Y	U	Y	Y	Y	N	Y	Y	STUCK THROTTLE	Y	Y
93	67	Surge. High (Takeoff) Power.	COMPRESSOR SURGE	Y	Y	U	U-Possible		U	N	U	TBD	COMPRESSOR SURGE	U	Y
94	69	Surge. High (Takeoff) Power.	COMPRESSOR SURGE	Y	Y	U	U-Possible		U	N	U	TBD	COMPRESSOR SURGE	U	Y
94	70	Surge. High (Takeoff) Power.	COMPRESSOR SURGE	U	Y	U	U-Possible		N	N	U	TBD	COMPRESSOR SURGE	U	Y
94	72	Surge. High (Takeoff) Power.	COMPRESSOR SURGE	Y	Y	U	U-Possible		U	N	U	TBD	COMPRESSOR SURGE	U	Y
69	2	Surge/HP TURBINE SEAL FAILURE. High (Takeoff) Power.	HP TURBINE SEAL FAILURE	N	Y	U	N		U	N	U	N	COMPRESSOR SURGE	Y	Y

APPENDIX B—HUMAN FACTORS MONITORING FRAMEWORK

Appendix B: Monitoring Framework

Indications (in addition to controls) are key elements of the interface and support a range of flight crew tasks. Because the flight deck interface offers more information than a flight crew can see at one time, they must allocate their attention to the various elements of the interface in an appropriate and efficient way. Flight crew training and operational policy provide guidance concerning which indications to monitor at what times, but the days of the simple, basic “T” are gone—much more information is available on the interface—and monitoring is a complex task. The following sections offer a framework for describing flight crew monitoring—more specifically, to describe where a crew is likely to be looking and to ensure that monitoring processes are supported.

In the following, we do not indicate which pilot is the one monitoring. Generally, we are assuming a two-person crew with a pilot flying (PF) and pilot not flying (PNF). The PF is the pilot primarily involved in performance monitoring, and the PNF is more involved in the periodic scanning related to health monitoring.

B.1 Primary Monitoring Drivers

There are three primary initiators of flight crew monitoring:

- Task requirements (from a crew-initiated task)
- Routine scan
- Detecting a change

Task requirements. The flight crew is often engaged in control activities that require feedback through the interface, which is performance monitoring. For example, if a pilot is flying the airplane manually or to flight director (FD) guidance, he/she needs to monitor attitude, altitude, airspeed, heading, path, and thrust setting to ensure that flight targets are being achieved. The primary flight display (PFD) in modern “glass cockpits” brings together most but not all of these indications so the pilot can get immediate feedback on how well he/she is controlling. Or, a pilot may be conducting an engine start and seeking feedback on engine response. At these times, then, monitoring (attention) is directed to a specific area of the interface and a specific set of indications, which are a small subset of available indications.

Routine scan. Pilots scan a wide range of indications periodically to ensure that the state of the airplane is as expected; this may serve either performance or health monitoring. For example, even when flying and focused on the PFD and ND, a pilot must also periodically glance at the engine indications and at the EICAS area to ensure that no important changes have occurred in those areas. At other times, pilots conduct routine scans (or flows) through a set of controls and indications before or after taking certain actions, such as thrust setting or engine start. Thus, pilots are directing attention to a set of indications and/or controls in succession.

Detect change. In the first two cases, pilots are consciously directing their attention to indications. In this third case, salient changes “attract” attention; the flight crew “detects” a change. Changes in interface alerting devices (e.g., master warning light), or message areas (e.g., EICAS message popping up), color changes or flashing (e.g., an indication changing to red), or “pop up” display of indications can attract attention and orient monitoring to a new set of indications. This is tied to health monitoring.

B.2 The Situation Model

The conscious direction of attention (task requirements and routine scan) is driven by a model in the pilot’s mind. That is, a pilot has expectations about how each system—and, therefore, each indication—will behave. The overarching model driving these expectations is called a situation model (ref, 19xx); this model represents the pilot’s current understanding of the state of the airplane and the environment it is operating in. More specifically, the pilot has some level of expectation about the current state of the weather, the terrain, the airplane systems, airplane health, the current role of autoflight and the flight plan, etc.

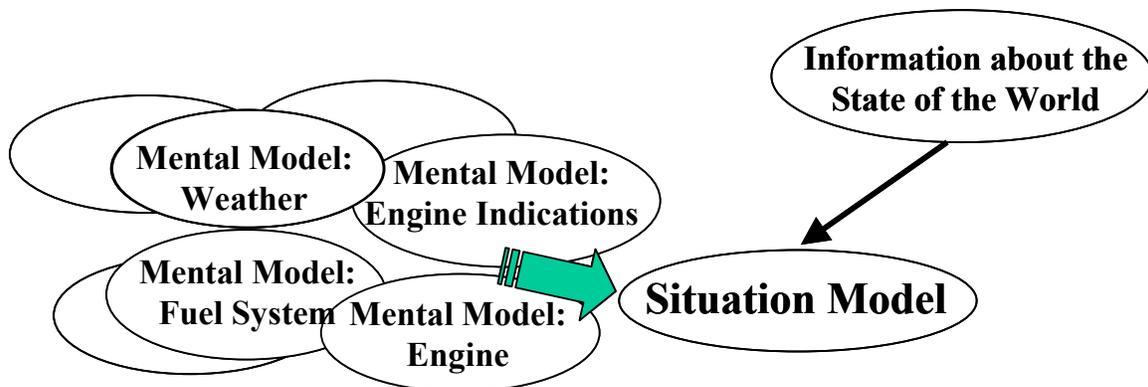


Figure B1. Situation model and supporting mental models (and inputs from the world)

As Figure B1 shows, the situation model depends on the pilot’s understanding of each system, as characterized by mental models (a sample of possible mental models is shown). A mental model is a person’s mental representation of a system or device that allows them to reason about how it will behave or respond to inputs given its current state. For example, if a flight control action is taken, a pilot can reason about how the airplane will change attitude, altitude, speed, direction, etc. Note that typically a person’s mental model is not a perfect representation of the system; it is typically a simplification that can contain misconceptions and factual flaws. As this figure also shows, there needs to be input about the current state of the world. Pilot monitoring of the world brings in this information (this element is implied in the remaining figures).

The pilot develops these mental models over time through training and experience with the systems, through study, or through discussing the system with others. As the pilot

flies, he/she creates a situation model using his/her current understanding of the environment, the actions taken on the system, and system responses as inputs to the mental models. Thus, as mentioned, the situation model also depends on information about the current state of world (through monitoring, which is deliberate, and detection, which is more passive). The situation model is updated as new information accrues, and the pilot maintains an awareness of airplane state. Obviously, the situation model doesn't capture all elements of the world, and no pilot has complete awareness (and complete awareness is not desirable).

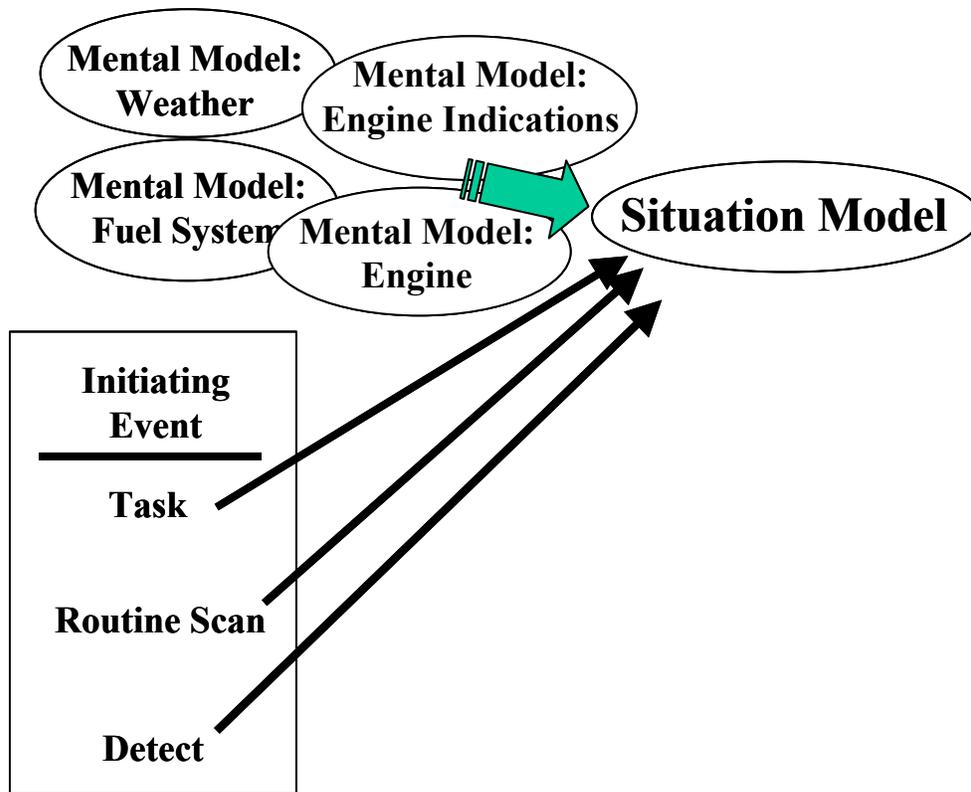


Figure B2. Monitoring uses the situation model to generate expectations about indications.

The point is that this situation model drives expectations about what should be happening. For example, from the situation model, the pilot will expect N2 to increase after the engine start sequence has been initiated, and then will expect fuel flow and EGT to rise after the fuel control switch is selected on. To confirm that engine start is progressing smoothly, the pilot will direct attention to (i.e., monitor) relevant parameters expecting to see them behave in expected ways. Figure B2 shows that monitoring, no matter how it is initiated, first uses the situation model to develop expectations about what indication behavior is expected.

B.3 Monitoring Processes

Figure B3 and B4 show the range of specific monitoring processes that need to be considered, starting with those tied to crew-initiated tasks in Figure B3. The following describe monitoring processes M1 through M5.

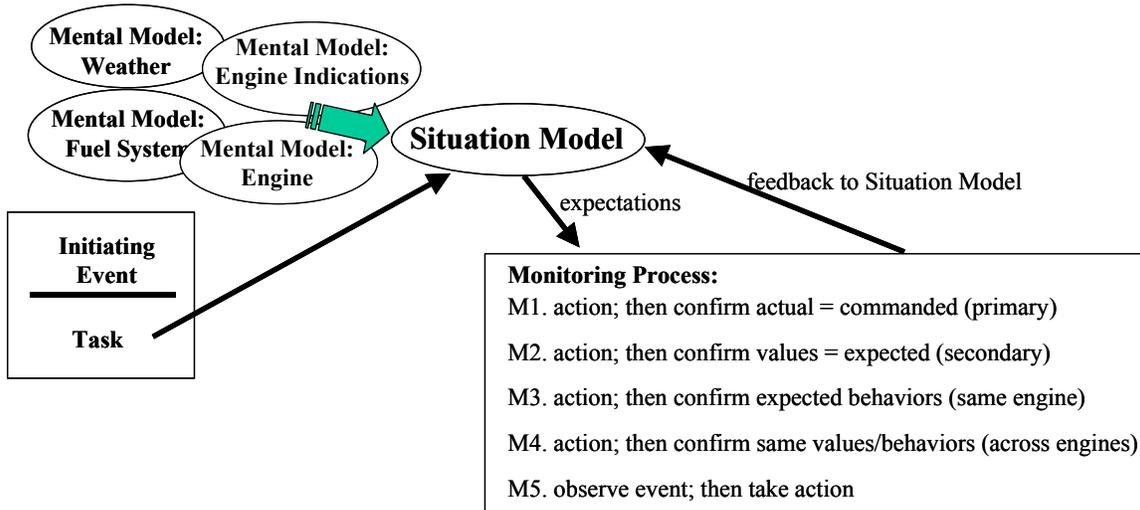


Figure B3. Monitoring processes tied to flight crew tasks.

- *M1: action; then confirm actual = commanded (primary)*
The pilot takes an action to directly affect some parameter. Specifically, the pilot sets a commanded value. The pilot then monitors to confirm that the actual parameter value goes to the commanded value in the expected period of time. The pilot will have a general expectation, and may have a detailed understanding of how the actual parameter will change to meet the command. For example, the pilot commands a thrust setting with the thrust levers, and monitors to confirm that N1 increases to meet that value, or the pilot selects fuel control switch on for start and monitors that fuel flow occurs.
- *M2: action; then confirm values = expected (secondary)*
The pilot takes an action and has expectations about how that action will influence secondary indications (indications that he/she is not attempting to control directly). The pilot then monitors to confirm that these parameter values are as expected. For example, the pilot selects fuel control switch off for shutdown and monitors that some engine indications fall to zero.
- *M3: action; then confirm expected behaviors (same engine)*
In some cases, the pilot is not monitoring for a specific value but is looking for an indication (or set of indications on the same engine) to behave in a certain way

(e.g., increase rapidly, remain stable, increase and then level off). Monitoring is directed toward confirming that these behaviors occur.

For example, the pilot starts the engine doing a manual start procedure, selects fuel control switch on and monitors that EGT, oil pressure, oil temperature, and N2 increase and stabilize. Monitoring serves to confirm that a set of parameters on the same engine respond in expected ways.

- *M4: action; then confirm same values/ behaviors (across engines)*

Generally, both (all) engines should either change in unison or one should converge to the other(s). Thrust levers are typically set to the same value and engine performance should be symmetrical. In this case, the pilot takes an action and monitors to confirm that the two engines behave the same way.

For example, the pilot sets the thrust levers to a higher or lower value and monitors that N1 or EPR values are close in value. Or, during engine start, the pilot monitors that parameters on the starting engine converge to those of the already running and stable engine.

- *M5: observe event; then take action*

The pilot knows that as tasks are being conducted, certain actions are triggered by indications (more generally, events). During normal or non-normal operations, there are pilot actions that are triggered by a parameter reaching a stable value or crossing a threshold. As a pilot is conducting a task, he/she is aware of how indications can reveal that a problem has occurred. In either case, monitoring serves to identify the event that triggers a required pilot action.

For example, during a manual start, as an engine start is proceeding, the pilot monitors engine speed to select fuel flow on at the appropriate point, and monitors EGT since abnormally high EGT indicates a hot start and the need for a pilot action.

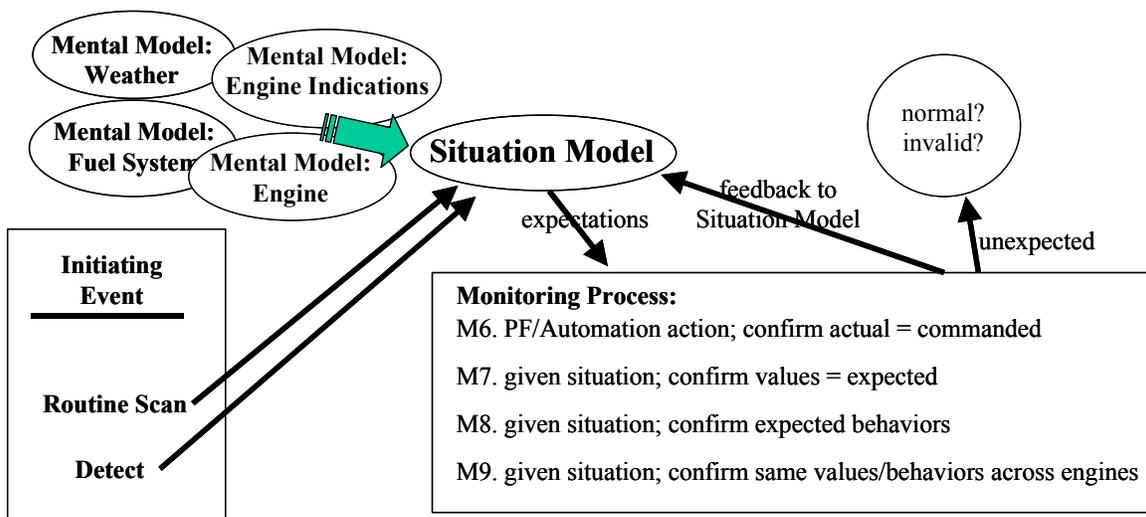


Figure B4. Monitoring processes tied to routine scan and detection.

Figure B4 shows the specific monitoring processes tied to routine scanning and detection of change. The following describe monitoring processes M6 through M9.

- *M6: PF/Automation action; confirm actual = commanded*
Another agent (pilot flying or autopilot) takes an action, and the pilot monitors to confirm that the actual value goes to the commanded value. Monitoring is not part of the control task since the pilot is not controlling, but a check on whether the airplane is responding appropriately in the current situation.
For example, the autothrottle commands a thrust increase to climb from a level segment, and the pilot monitors to confirm that N1 increases to meet the commanded value.

- *M7: given situation, confirm values = expected*
As a routine flight proceeds, the pilot generates expectations about the specific value of one or more airplane indications. Monitoring routinely will check current values against these expectations.
For example, the pilot will have expectations concerning altitude, airspeed, stable and symmetric engine thrust and no non-normal indications being “pushed to the pilot.”

- *M8: given situation, confirm expected behaviors*
In some cases, the pilot’s expectations for a situation are about the behavior of one or more indications. Monitoring is used as a routine check to confirm that parameters are trending as expected.
For example, as the flight progresses, thrust and fuel flow for a given airspeed will decrease as weight decreases, airplane CG will shift, oil quantity may decrease, etc. Other parameters are expected to remain constant/unchanging. Routine monitoring is used to check that these values are behaving as expected.

- *M9: given situation, confirm same values/behaviors across engines*
As mentioned above, generally both (all) engines should behave in parallel. In this case, the pilot has expectations that the engines will behave similarly, and the routine scan monitoring is used to ensure that parameters are consistent across engines.
For example, a routine scan may reveal that oil pressure is significantly higher on engine 1 than on engine 2, which is unexpected and leads the pilot to try to understand why this might be the case.

As mentioned above, generally both (all) engines should behave symmetrically. In this case, the pilot has expectations that the engines will behave similarly, and the routine scan monitoring is used to ensure that parameters are consistent across engines. For example, a routine scan may reveal that EGT is significantly higher on engine 1 than on engine 2, which is unexpected and leads the pilot to try to understand why, and then assess the potential system, airplane, and mission effects.

Notice that Figure B4 also considers the possibility that monitoring uncovers an unexpected indication (bubble in the upper right corner). In this case, the pilot must determine if this outcome is really normal (what he/she should have expected) or invalid (due to some failure, such as a sensor failure). These possibilities create the need for two additional initiators of monitoring (see Figure B5).

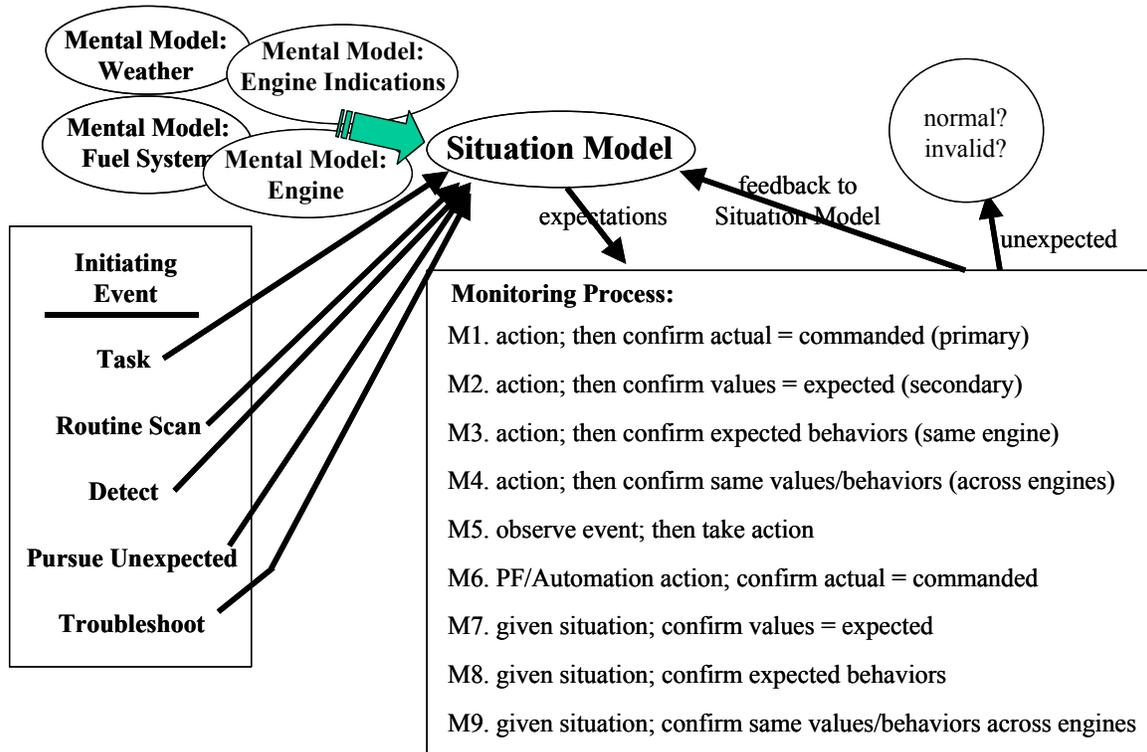


Figure B5. Other initiating events for monitoring

Pursue unexpected findings. In the case that monitoring reveals an unexpected indication, the pilot must determine what is happening with the airplane; this finding, therefore, may initiate new monitoring. From the initial unexpected indication, hypotheses are generated (using the mental models) about what might be happening. These hypotheses are further used to generate expectations about other indications, and monitoring commences to determine the actual values of other indications. This monitoring activity can either reveal a problem (e.g., failure) that is causing the unexpected indications, or it may suggest that the initial unexpected indication is not a valid indication. Note that, due to inaccurate or incomplete mental models, the flight crew may reach an incorrect conclusion.

Troubleshoot. An alternative approach—which may be rarely used—when confronted with unexpected indications (or concerns about airplane performance) is to engage in troubleshooting activities. In this case, the pilot has a concern about a system and takes control actions with known effects (determined from the mental models). Monitoring is used to confirm that the system responds as expected to the control actions. Through this type of experimentation and confirmation, the pilot attempts to learn something about the

nature of the unexpected indication. Again, due to inaccurate or incomplete mental models, the flight crew may reach an incorrect conclusion.

B.4 Example Monitoring Cases

Case 1: Thrust setting. Figure B6 offers an example of how this monitoring framework allows one to trace and describe pilot behavior. The red boxes and arrows illustrate pilot behavior in the case of thrust setting. At box 1, “initiate new thrust setting,” the pilot initiates a task of commanding to a new thrust target. This action, through the situation model, generates expectations (box 2) about what indications will change and how they will change. From these expectations, the pilot monitors the N1 indication to confirm that the actual N1 value meets the commanded value (box 3). The expected result occurs, and the situation model is updated with the new thrust value (box 4).

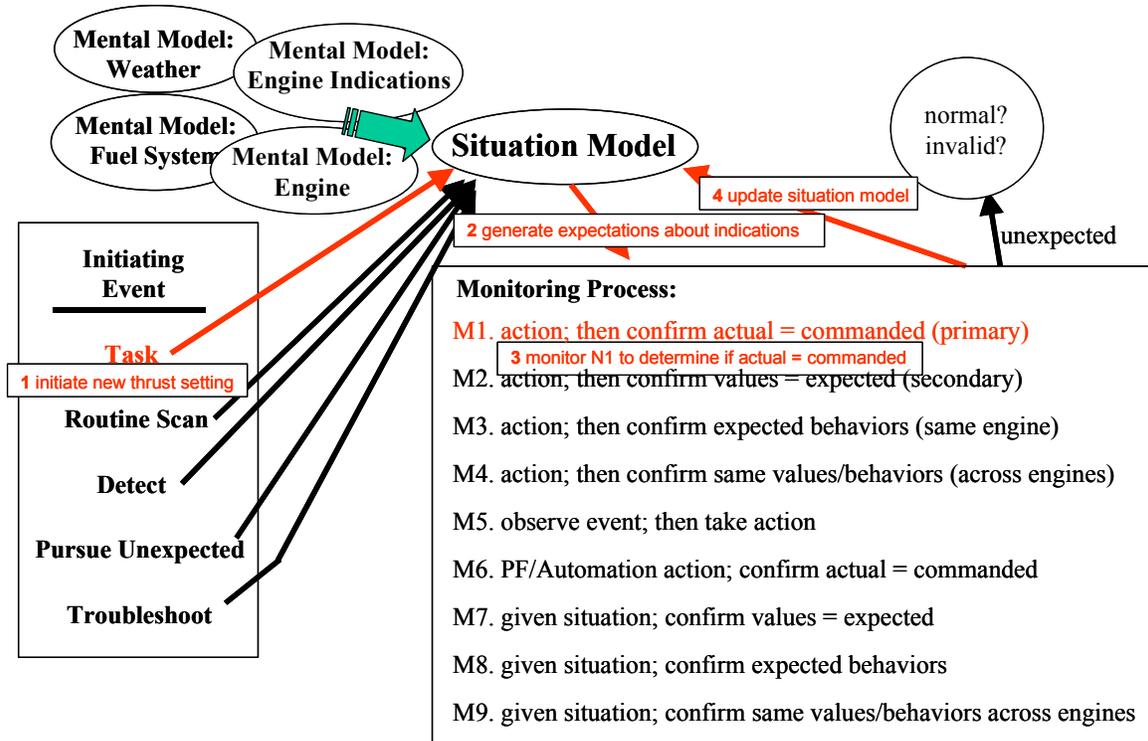


Figure B6. Case 1: Thrust setting.

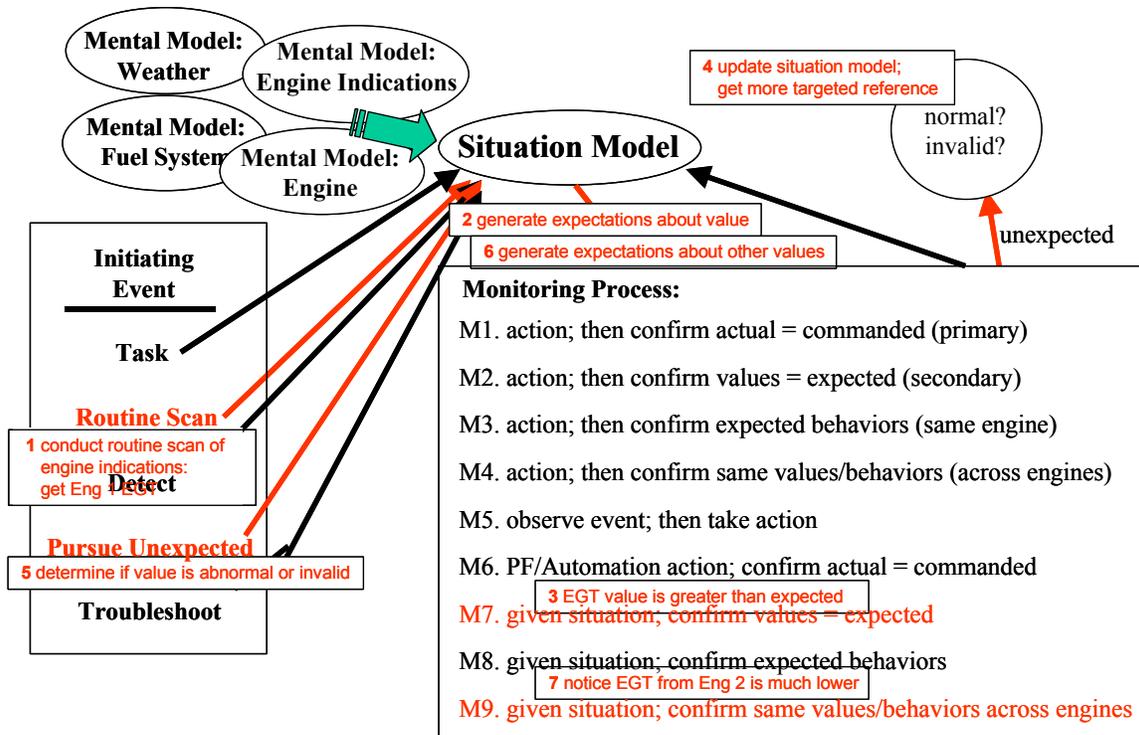


Figure B7. Case 2: Notice deviation in oil pressure.

Case 2: Notice deviation in EGT. Figure B7 takes a more complex case. As part of a routine scan of engine indications (box 1), the pilot monitors the EGT value on engine 1. Using the situation model (which is unaware of any problems), the pilot generates an expectation about the EGT value (box 2). The pilot then notices that the observed EGT value is greater than expected (from the situation model) (box 3). The unexpected observation (box 4) leads the pilot to pursue it by monitoring in a more focused way (box 5). Using the situation model, a determination is made to look at the same indication on engine 2 as a comparison (box 6). Finally (box 7), monitoring engine 2 reveals that there is a significant discrepancy between the EGT values on the two engines. This may prompt crew action.

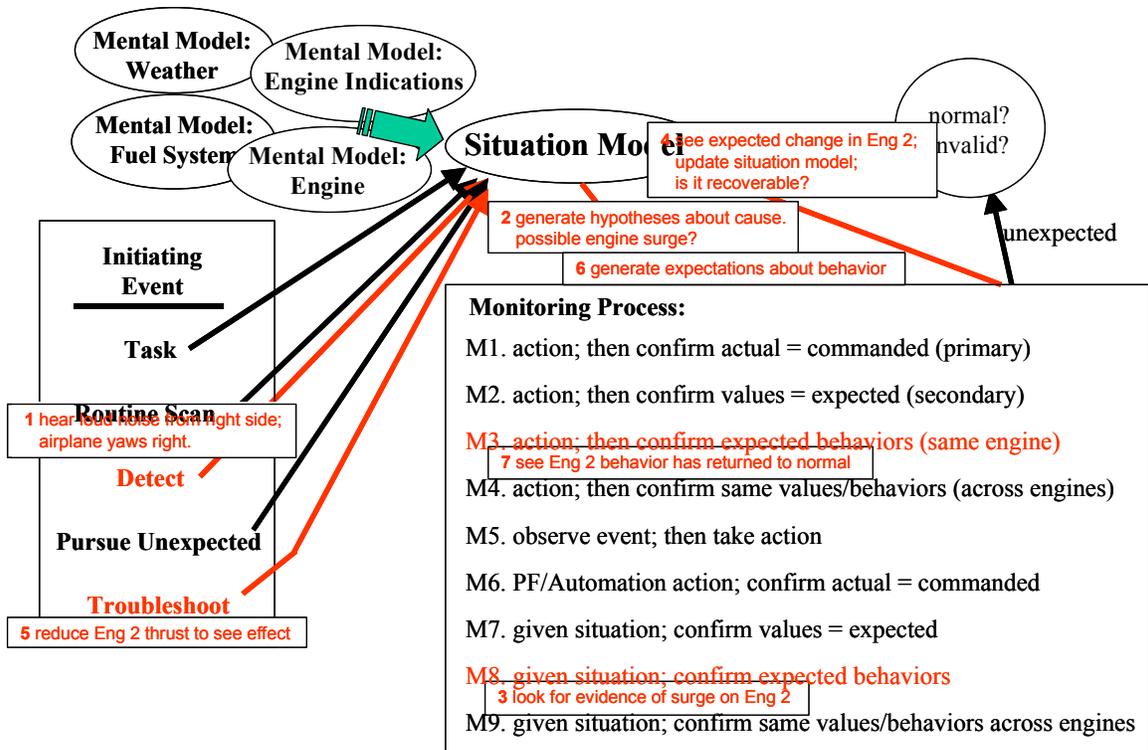


Figure B8. Case 3: Respond to a loud noise.

Case 3: Respond to loud noise. Figure B8 illustrates a case in which monitoring is initiated by the detection of a change. The pilot hears a loud noise from the right side of the airplane, and the airplane yaws right (box 1). Because this noise was unexpected, the pilot must use the situation model to generate hypotheses about what may have happened (box 2). The primary candidate is that an engine surge occurred, which generates expectations about changes on the right engine. Monitoring reveals that right engine thrust is fluctuating significantly, EGT is rising, and engine vibrations are high (box 3). This confirms the hypothesis that an engine surge is occurring (box 4). Depending on past experience, circumstances, training, SOPs, and other factors, the crew may elect to shut the engine down. To further confirm surge and determine if it is recoverable, the pilot must take an action and then monitor the engine response (box 5). Reducing engine thrust leads to generating expectations about how engine 2 indications will behave (box 6). In box 7, the pilot monitors and confirms that the engine is, or is not, responding in the expected manner.

These three figures illustrate how monitoring is the pilot's conscious direction of attention to specific indications. Each time, the pilot uses his/her understanding of the airplane, its systems, and the environment around it to generate expectations about the behavior or value of specific indications. Monitoring then closes that loop, when expectations are confirmed, or can initiate another loop when an unexpected indication is observed.

The point of developing this framework is to aid in thinking about how indications can support the flight crew, how monitoring processes are influenced, where and how monitoring processes fail, and how they might be supported to better ensure the desired outcome—safe and efficient airplane missions.

APPENDIX C—HUMAN FACTORS GUIDANCE ON FLIGHT DECK DESIGN

Appendix C: Human Factors Guidance on Flight Deck Design

The following two sections provide some background on flight deck design guidance. The first section discusses pilot-centered (human-centered) design. The second section describes Rasmussen's concept of skill-based, rule-based, and knowledge-based performance, which was referred to earlier in this report.

C.1 Pilot-Centered Design

The notion of human-centered design (or pilot-centered design in the case of airplanes) has come out of the discipline of cognitive engineering, which strives to design systems that are compatible with the cognitive requirements of systems operation (e.g., Norman, 1986). Pilot-centered design has the following basic steps:

1. define/describe operational tasks
2. define the desired role of the pilot
3. define the set of displays and controls (required information) needed to support pilots

The first two steps go almost hand-in-hand as the designer defines the scope of operations: What tasks need to be accomplished for safe and efficient completion of the mission? This analysis might start with thinking about general functions that must be achieved. For example, for a flight crew to manage airplane systems, they must be able to

- monitor the current state of relevant airplane and airplane system parameters
- monitor the current values of each system parameter (perhaps with some exceptions)
- detect "meaningful" changes in the state of each system or parameter
- locate guidance for managing system faults
- change a system's state or configuration through component controls

These are examples of the types of functions that need to be achieved. More specific task analysis would be required to specify fully a task list.

The second step is to define the role of the pilot/flight crew. The designer needs to determine how the human operators will coordinate activities with the automated agents to carry out tasks. In particular, the designer needs to think about how the human resources will be spent and what the humans need to be engaged in.

Some activities are very demanding for humans—for example, constant monitoring of parameter values requires a high level of vigilance, and humans are not very effective in this task. If humans are asked to monitor for subtle changes in a parameter, their attention is unavailable for other activities. Another consideration is what the automation hides. If the automation takes over processes completely, the flight crew is likely to be

unaware of what is happening with those processes. For example, if the automation identifies a fault and then reconfigures a system to eliminate that fault, the human may have no knowledge of the change in that system. Thus, the designer needs to determine how the limited flight crew resources are going to be spent: What should they be engaged in? and What should they be aware of?

C.2 Skill-Based, Rule-Based, and Knowledge-Based Performance

Rasmussen (1986), in the context of a general model of human performance, described three levels: skill-based, rule-based, and knowledge-based. Figure C1 illustrates each of these.

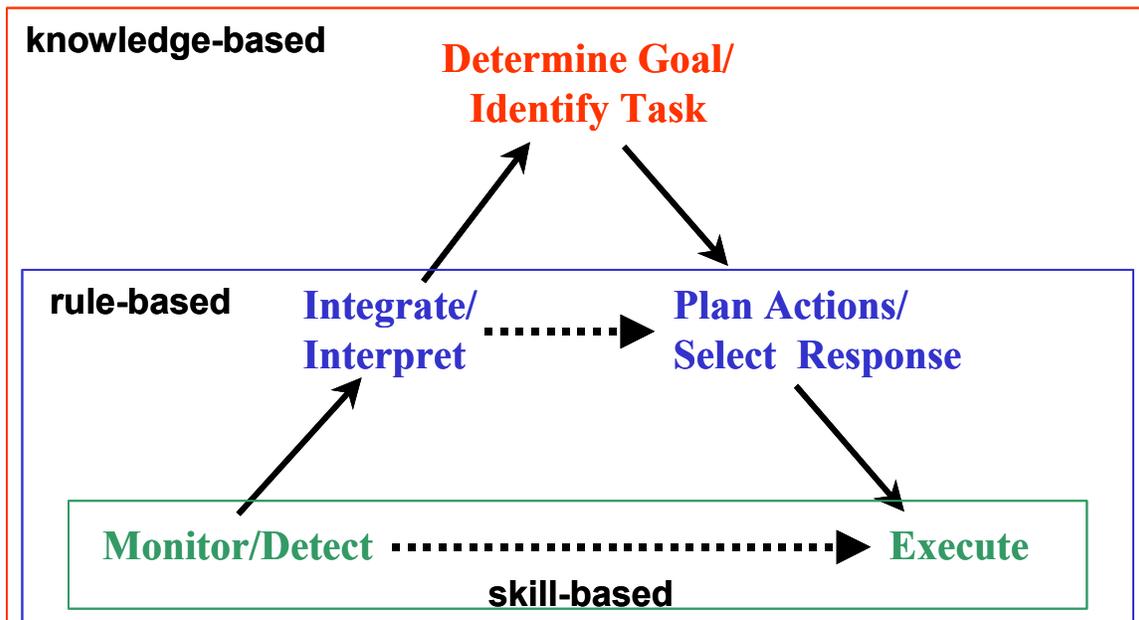


Figure C1. Skill-Based, Rule-Based, Knowledge-Based Performance.

Generally, Figure C1 captures Rasmussen's performance model. Starting at the lower left, Figure C1 shows that task performance is composed of a series of cycles each of which involves elements of monitor, interpret, set goals, plan actions, and execute. More specifically, monitoring allows the gathering of data about a system's components, which is integrated and interpreted in terms of a system description (or system fault). From this system description, the pilot must determine what goal needs to be addressed first (e.g., maintain altitude), and develop a response plan to meet this goal. The response plan is finally executed. Feedback from that execution, as well as continued monitoring of the system leads into the next cycle. This performance model makes a number of simplifying assumptions but serves as a useful organizing framework for discussing performance, from awareness to understanding to response.

Figure C1 also breaks out Rasmussen's three levels. In the lower green box are the components of skill-based performance. Skill-based performance is performance that takes place without conscious control; it involves smooth, automated, and highly

integrated patterns of behavior. Simple examples can be taken from sports (catch a ball, volley a tennis ball), driving (steering a car through a curve), or flying (using rudders to steer the centerline during the take-off roll). The green box shows this performance as a direct link from monitoring to execution (or, get an input and respond).

The blue box in Figure C1 shows rule-based performance, which is performance that is consciously controlled by a procedure or set of rules. Although individual behaviors may be skill-based, their performance is structured by a set of rules, which are often documented in a formal manner (e.g., checklist or procedure). The set of rules also captures the purpose or goal of performance (e.g., the procedure title). In Figure C1 monitoring is followed by integration and interpretation (or understanding). Understanding leads to the selection of the appropriate set of action items, which are already defined, followed by execution of those actions.

Knowledge-based performance, in red in Figure C1, uses the entire cycle and is reserved for unfamiliar or previously unanalyzed situations, where performance is generated from the pilot's reasoning process. Often, the goal of the task must be determined from an understanding of the situation, and individual behaviors must be identified out of an analysis of the goal. These cases are rare in commercial aviation, and much is done to avoid the need for this type of performance. However, it is important to remember that it is not possible to anticipate every situation and develop a procedure for it. At some point a flight crew will be faced with the need for knowledge-based performance, and the flight deck interface should provide them tools to support it.

APPENDIX D—PROPULSION SYSTEM MALFUNCTION CHARACTERIZATION DATA

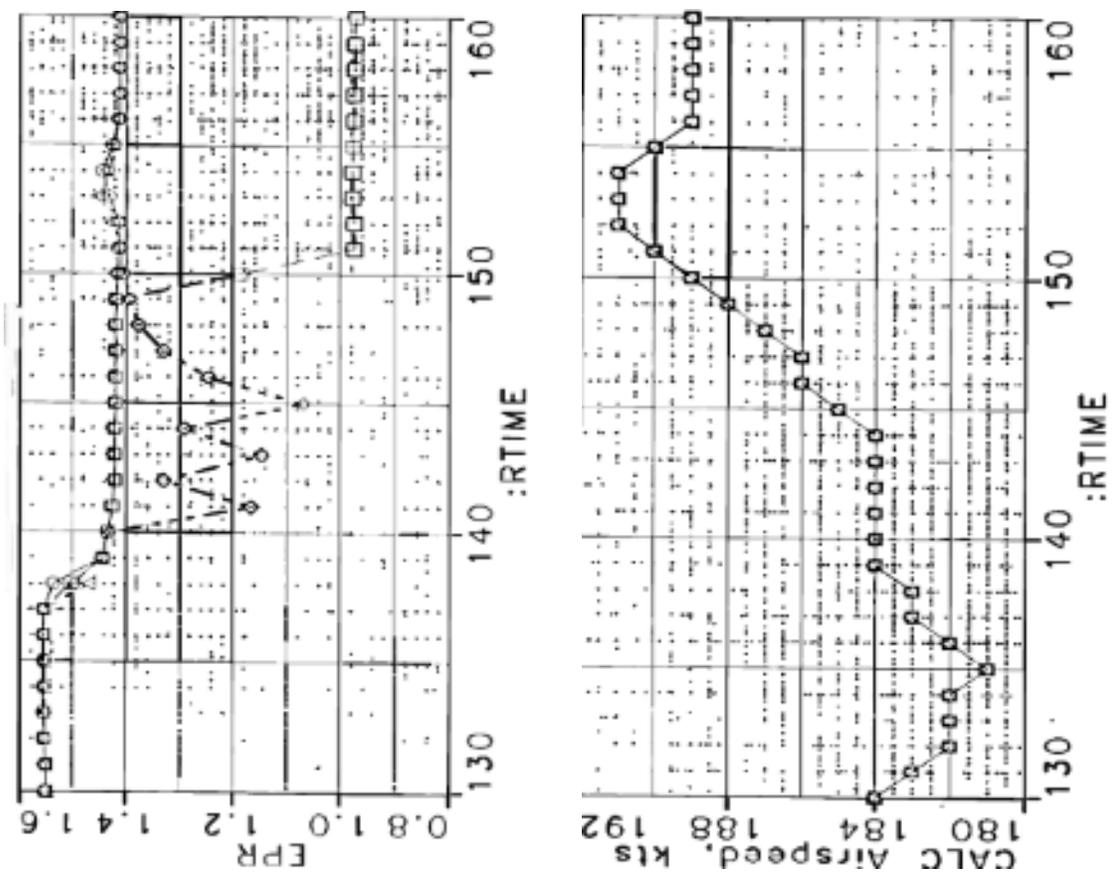
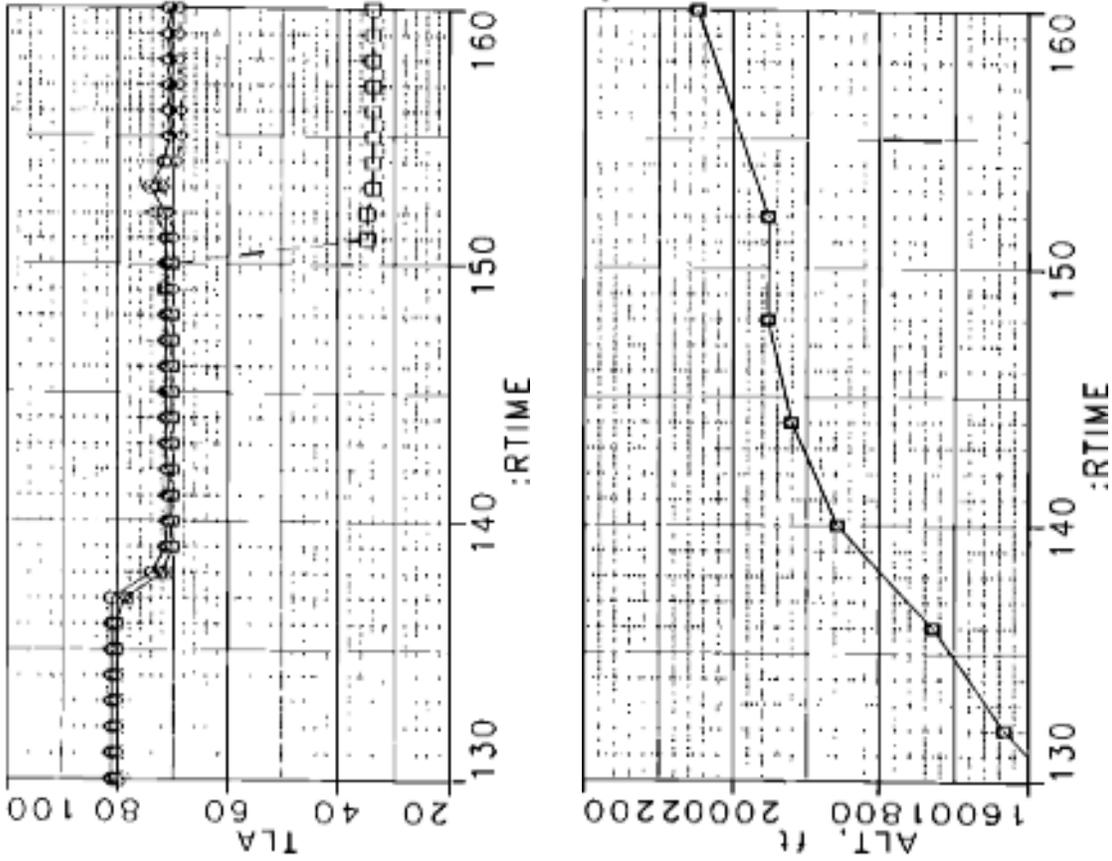


Figure D-1. PSM+ICR Event 94/MWB/4/1 (Recoverable Event)

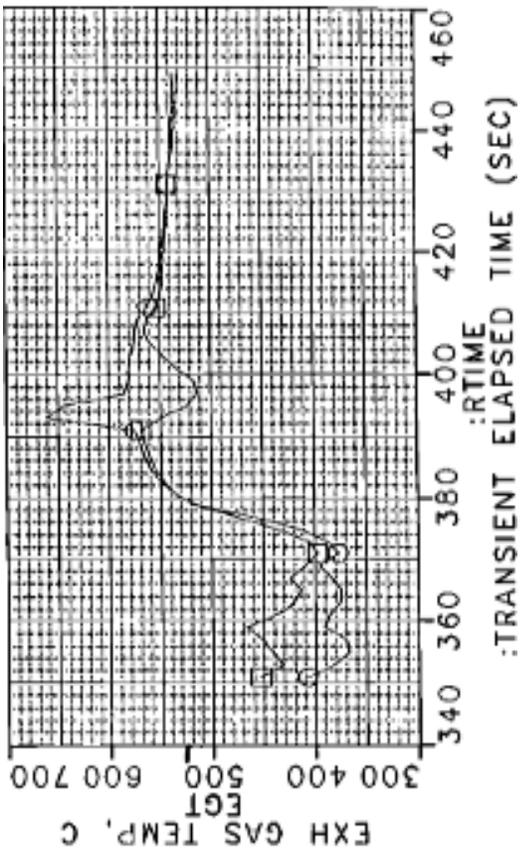
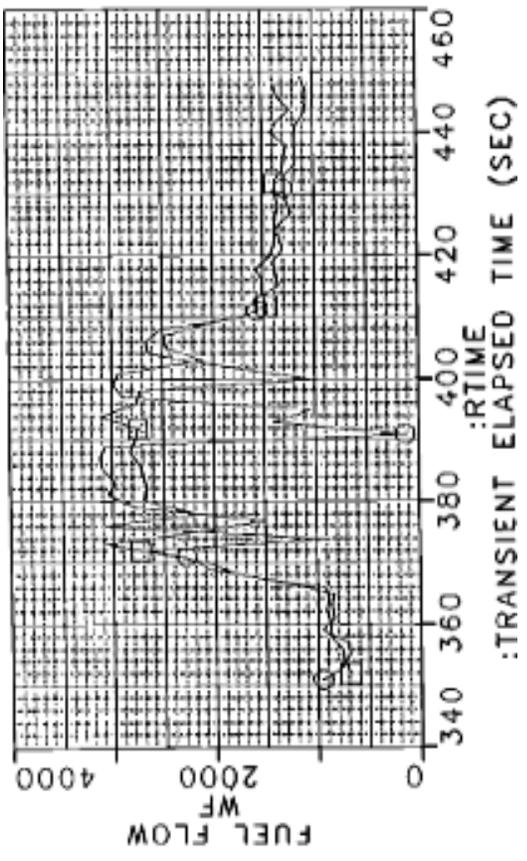
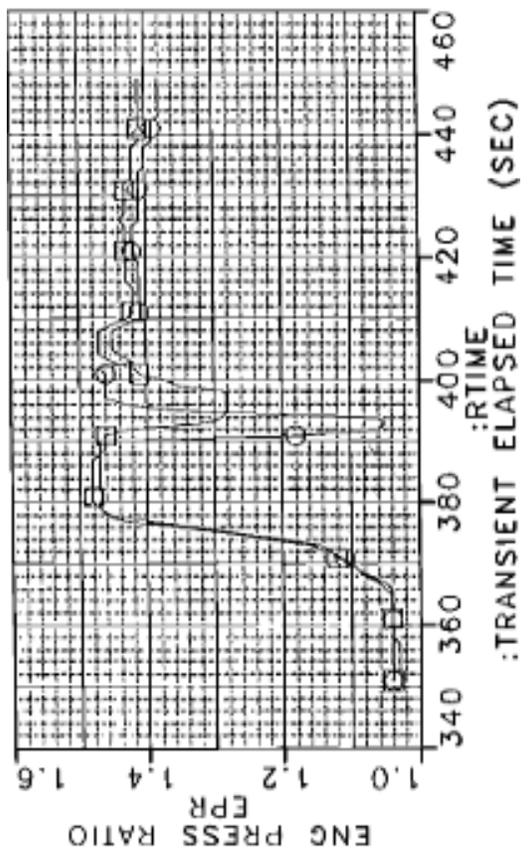
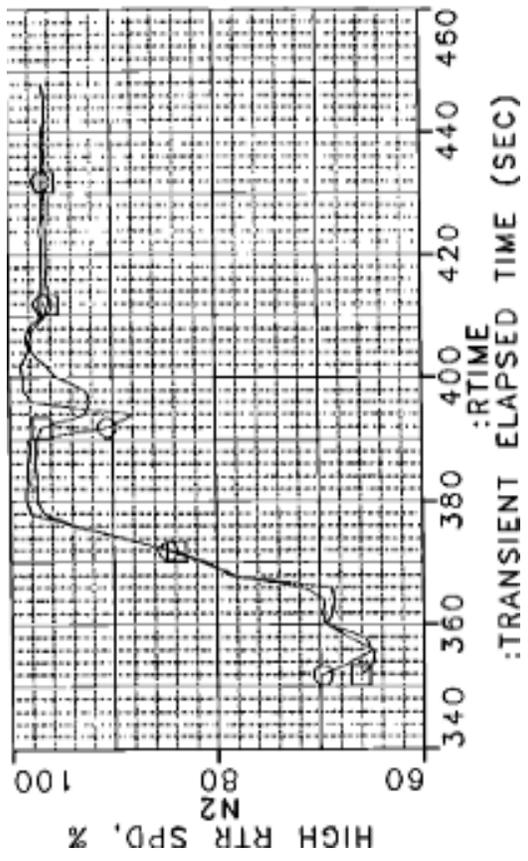


Figure D-2. PSM+ICR Event 93/EWB/2/1 - Parameters (Recoverable Event)

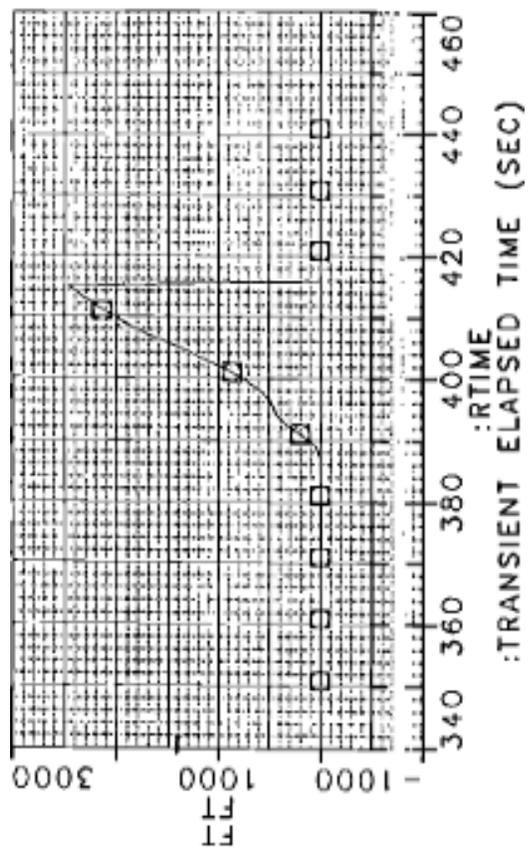
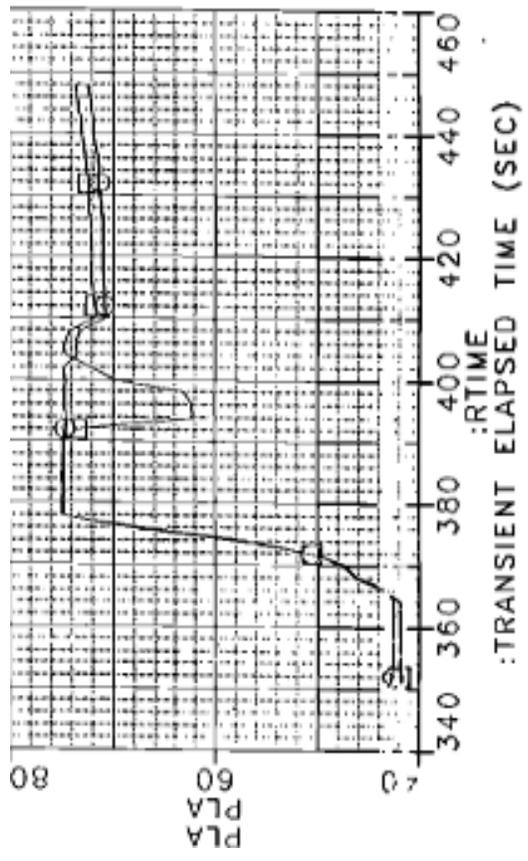


Figure D-3. PSM+ICR Event 93/EWB/2/1 - Conditions (Recoverable Event)

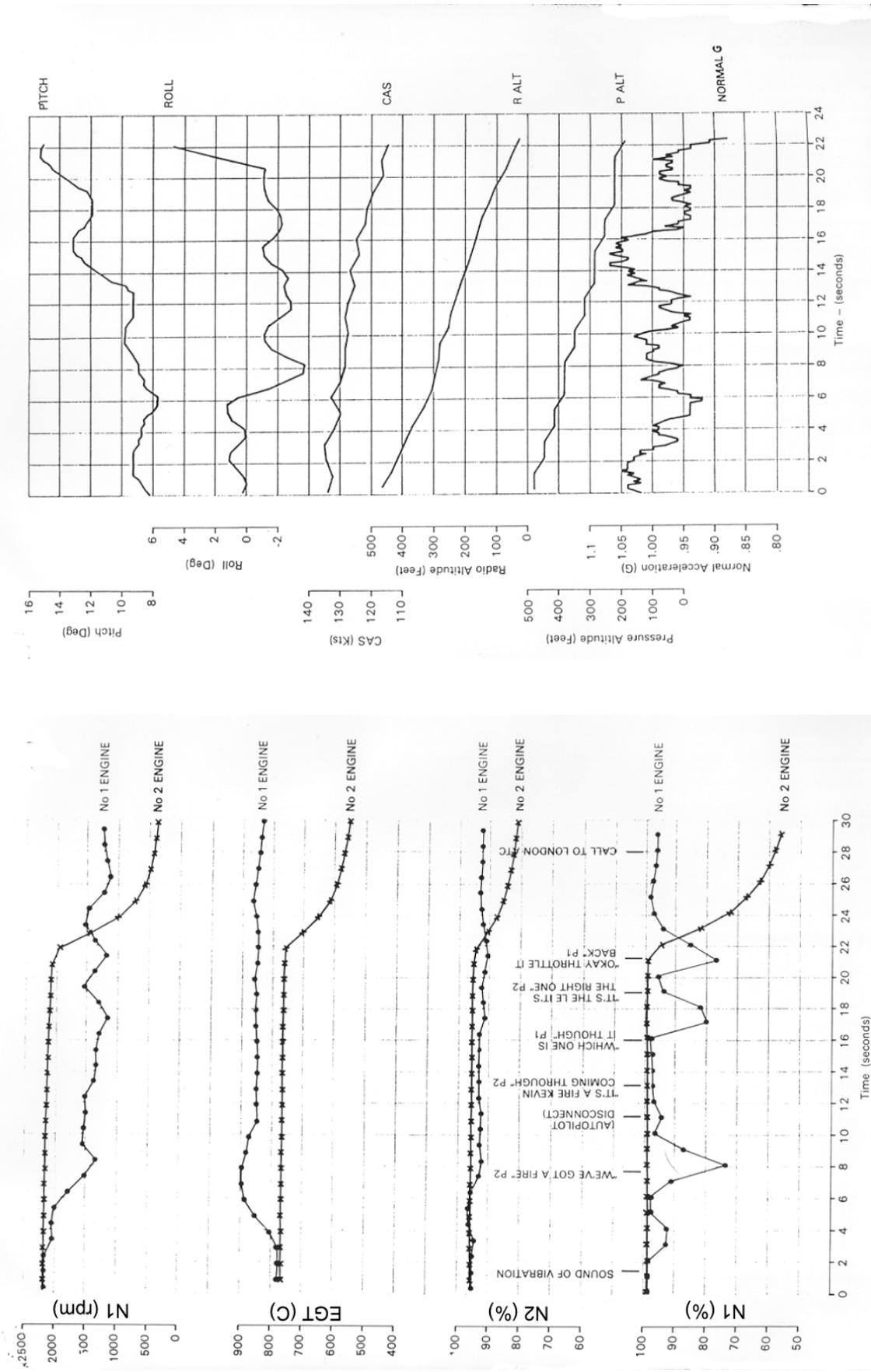


Figure D-4. PSM+ICR Event 89/MNB/2/HF (Non-Recoverable Event)

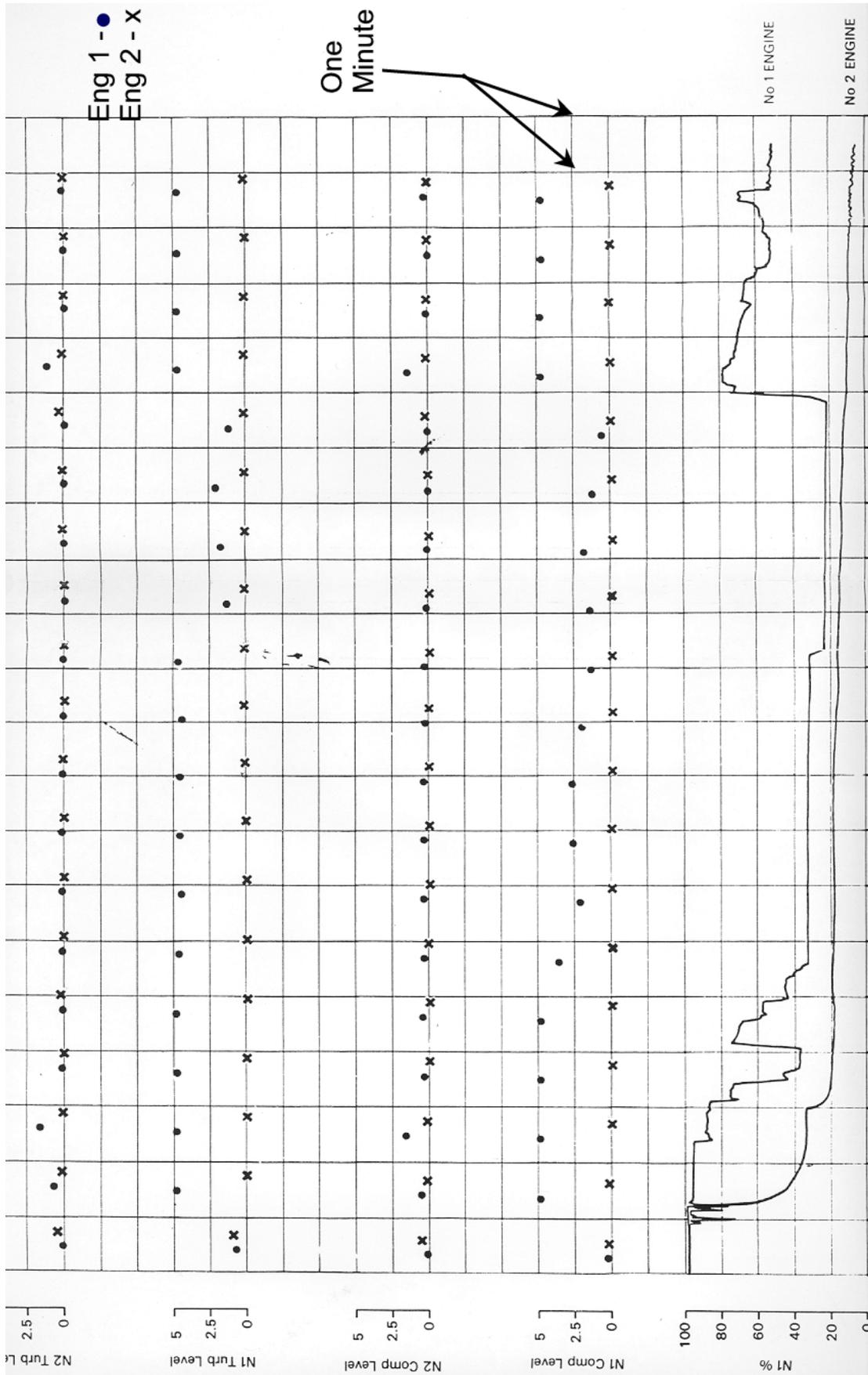


Figure D-5. PSM+ICR Event 89/MNB/2/HF (Non-Recoverable Event)

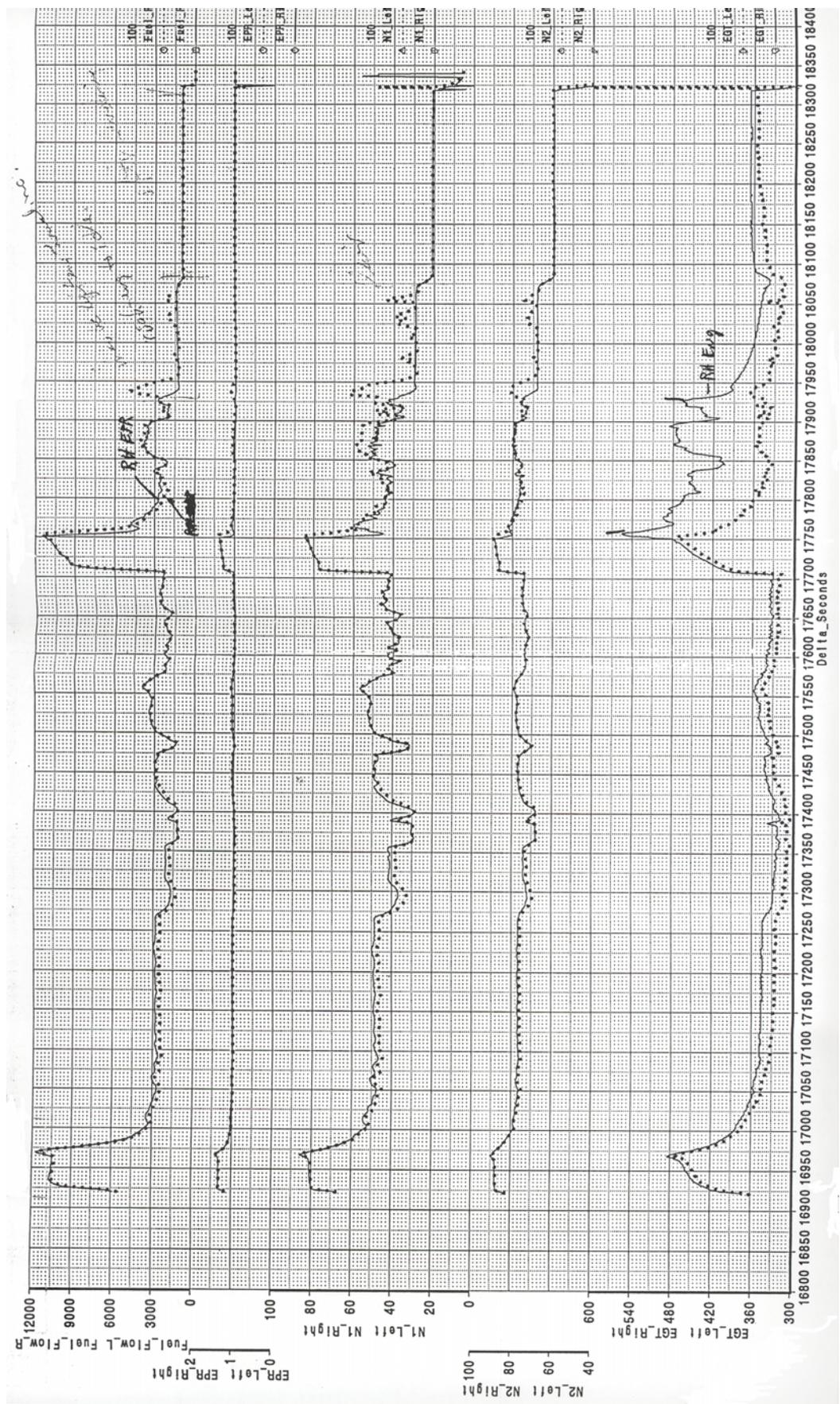


Figure D-6. PSM+ICR Event 89/MNB/2/HF (Non-Recoverable Event)

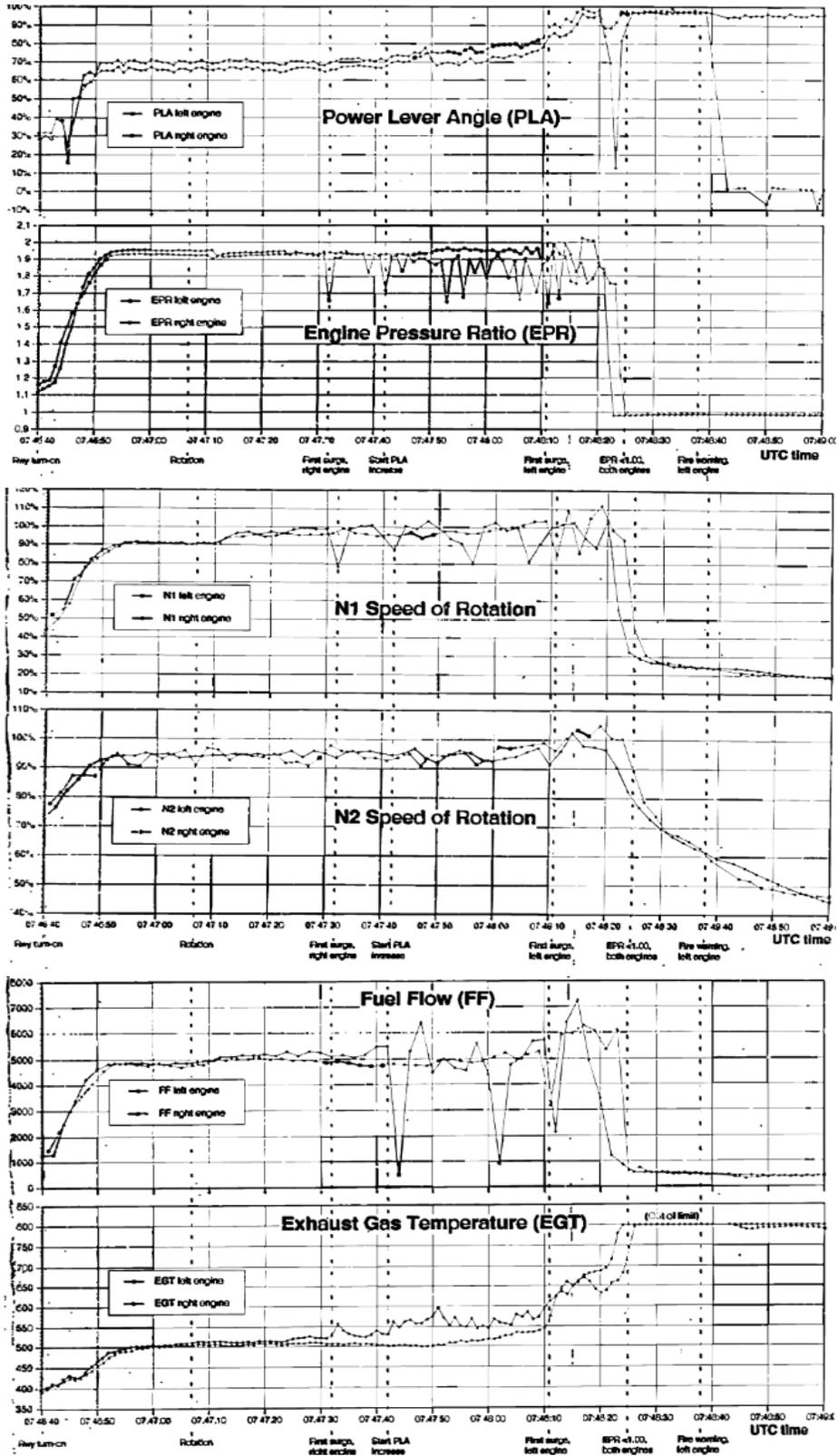


Figure D-7. PSM+ICR Event 91/MNB/2/H (Non-Recoverable Event)

Analysis Type	Analysis Priority	Event #	ID Number	Event Class	Hazard Level	PSM+ICR Category
Data. Ops.	High	53	*89/MNB/2/HF	HF	5	SHUTDOWN GOOD ENGINE
Data	High	42	85/MWB/2/I	I	1B	SHUTDOWN GOOD ENGINE
Data. Ops.	High	62	*93/MNB/2/I	I	1B	OTHER-COMPRESSOR SURGE; UNABLE TO ISOLATE WHICH ENGINE WAS AFFECTED
Data. Ops.	Med-Hi	77	95/2ND/2/HF	HF	5	LOSS OF CONTROL
Data. Ops.	Medium	56	91/MNB/2/I	I	1B	RTO
Data. Ops.	Medium	80	96/MWB/4/I	I	2G	RTO
Data. Ops.	Medium	71	*94/MWB/4/I	I	2F	SHUTDOWN GOOD ENGINE
Data. Ops.	Medium	52	*88/MNB/2/S	S	3B	RTO

Table D-1. PSM+ICR Events of Interest

APPENDIX E—TECHNICAL FEASIBILITY ENGINEERING STUDY

Note: This version of Impact Technologies' Technical Report has been edited by The Boeing Company to remove proprietary flight test data.

Technical Report No. P268-01-1

TASK 5.2 Final Report

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EXECUTIVE SUMMARY

Under FAA contract DTFA03-01-R-00019 “Indications of Propulsion System Malfunctions”, The Boeing Company was tasked with the overall objective of improving characterization of Propulsion System Malfunctions and Inappropriate Crew Responses (PSM+ICR) and address the potential of improved Fleck Deck annunciations/indication of PSM events. Impact Technologies LLC, was subcontracted to perform contract subtask 5.2 entitled “Data Acquisition and Detection Methods”, which specifically focused on performing detailed technical evaluations of data-rich engine surge events. The focus on surge events was motivated by the fact that, from the AIA PSM+ICR report and data, 73% of the PSM events in these categories can be identified as either Power Loss or Surge [1]. Task 5.2 objectives were identified as follows:

1. Analyze data representative of surge events
2. Characterize any engine surge precursors
3. Identify if and how recoverability of surge events can be determined
4. Identify enhanced parameters, technical issues and health management methodologies for achieving objectives 2 and 3.

Impact Technologies evaluated 5 sets of data. All of the data sets contained enhanced parameter sets at sampling frequencies of greater than or equal to 2Hz. The following accomplishments and generalizations were achieved as a result of detailed analysis of these data sets:

1. Identified parameter sets and sampling rates for potentially improving surge detection confidence.
2. Identified a methodology for quantifying surge risk initiated under design-limits surge subcategory.
3. Identified a potential methodology for assessing recoverability of a surge event/s (based on only one instance of non-recoverability)
4. Developed a Matlab/Simulink model for demonstrating the surge detection and recoverability algorithms derived from the data analysis.

Detailed descriptions of the data analysis methodologies and conclusions are provided herein.

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Event Precursors

Recoverability

First Engine Conclusions

SECOND ENGINE-T405

Event Identification and Description

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Second Engine Conclusions

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Event Identification and Description

Event Precursors

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REQUIRED PARAMETERS

SURGE DETECTION AND RECOVERABILITY

CONCLUSIONS

DISCUSSION

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Surge subcategories – Taken from Report 5.1

Characterizations of surge from PSM+ICR report – Taken from Report 5.1

SEDRA V1.0b Readme File

Background

Tasks 2.1 and 5.1 entitled “In-service Data Assessment” and “Physical Characterization” respectively supported task 5.2. Task 2.1 was aimed at “acquiring and reviewing appropriate service information and report relevant to engine surge, thrust asymmetry, and engine fail conditions. Safety data was reviewed to determine whether lack of (or availability of) annunciated information led to in-service events” [2]. Task 5.1 was focused on “defining the physical characteristics of propulsion system malfunctions of selected high priority safety concern scenarios identified through Task 2.1”[2].

Tasks 2.1 and 5.1 identified a group of incidents from the AIA PSM+ICR report [1] that are judged to have the greatest opportunity to provide meaningful, positive crew indication or alerts. This group of PSM events was placed into three high-level symptom identifier categories [2]:

Failed Commanded Pwr:	The engine is unable to obtain commanded power (thrust) under engine control logic or with crew intervention and has failed to a power level that is not the maximum or minimum.
Failed High Power:	The engine is unable to obtain commanded power (thrust) under engine control logic or with crew intervention and has failed to a state where it is producing maximum power (thrust) allowed by the engine control and/or fuel governor.
Failed Low Power:	The engine is unable to obtain commanded power (thrust) under engine control logic or with crew intervention and has failed to a state where it is producing minimum or no power (thrust), i.e. windmilling.

73% of all the PSM events in these categories were identified as either Power Loss (Failed Low Power) or Surge and some of the Surge events were associated with a loss of power. Hence, it was determined that a technical evaluation of enhanced flight deck annunciations relative to engine surge could prove most valuable. Furthermore, a method of distinction between recoverable and non-recoverable events for the power loss symptom identifier was identified as being potentially valuable in preventing ICR events. The definitions of recoverability related to surge from the 5.1 report are provided below. [2]

Recoverable Surge:	The engine is able to return to commanded power (thrust) with either the engine control logic or crew intervention
Non-Recoverable Surge:	An engine surge event, after which the engine is NOT able to return to commanded power (thrust) with either the engine control logic or crew intervention. Typically, the engine runs down to a state where it is producing minimum or no power (thrust), i.e. windmilling.

Report Organization

This report provides a description of the Matlab/Simlink surge detection and recovery algorithm is provided. In the final section of the report, generalizations, conclusions and recommendations based on all data sets are made. Appendices, categorized by engine type, will contain supporting plots not directly relevant to the main body content.

Required Parameters

The following is a practical set of parameters that have been identified for enabling enhanced surge awareness and surge recoverability. The first seven categories of parameters should be made available at greater than or equal to 2 Hz sampling rates. The essential set of parameters are denoted and are those required for the Surge Detection and Recoverability Algorithm developed under this program and discussed next. It should be noted that this set only applies to high-bypass turbofan engines with FADECs. Different parameters and sampling rates may be best for other engine types with or without FADECs.

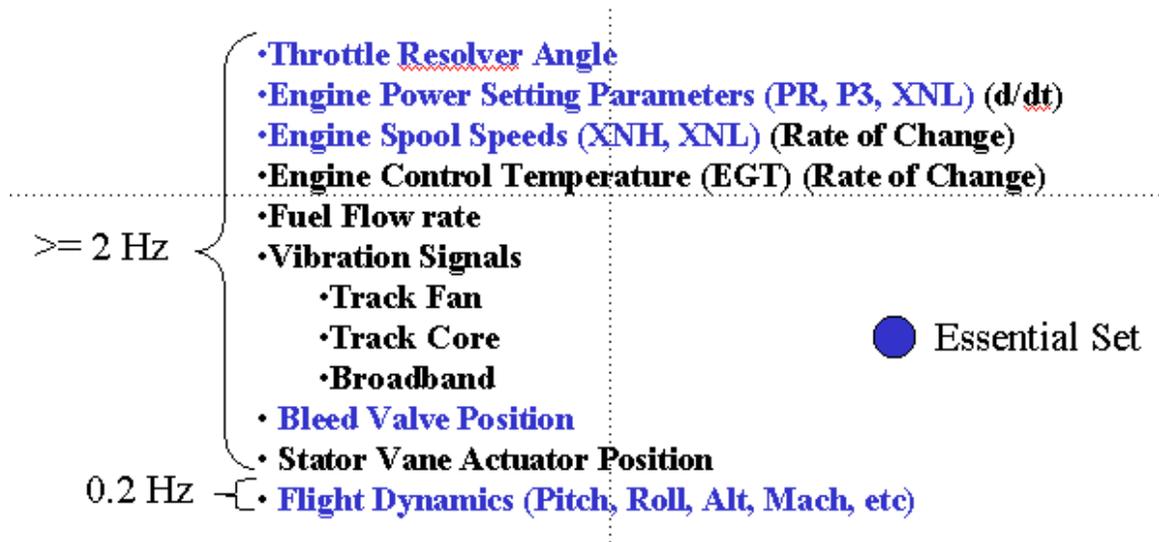


Figure 1 – Parameter set

Surge Detection and Recoverability

A Matlab/Simulink program was created to embody the general premise for enhanced surge detection and recoverability determination developed under this study. This premise is that key parameters/features such as XNH DOT (the derivative of core speed) and P25 DOT, P3 DOT should normally lag TRA and gas path bleeds. Since in a surge event a compressor is in an unstable dynamic state, changes to the key parameters are expected to lead TRA or bleeds and be uncorrelated to them within a certain time buffer. Hence, two surge detection modules were created in the generic Matlab/Simulink program called SEDRA (Surge Event Detection and Recovery Analysis) the results of which are fused together. The first module independently considers limit exceedences of XNH DOT and P25 DOT, P3 DOT depending on the available data. The second module considers a zero lag cross correlation between the aforementioned parameters where the cross correlation function is defined as:

$$C(m) = E[A(n+m) \cdot \text{conj}(B(n))] = E[A(n) \cdot \text{conj}(B(n-m))]$$

Where:

$C(m)$ is the cross correlation for lag m , E is the expected value operator, and A and B are the discrete signals. Postprocessing normalizes the sequence so the autocorrelations at zero lag are identically 1.0 forcing the zero lag cross correlation between 0 and 1.

One important aspect of the surge detection scheme is the use of time buffers in which a positive indication of during the buffer window is held on for fusion. A surge detection is only called out when

the limits and cross correlation “fire” in their respective time windows. A top-level view of the surge detection module is given in Figure 2.

The Recoverability module in the SEDRA program is triggered only if a surge is detected. It operates in much the same fashion as the surge detection except that it waits for XNHDOT and P3DOT, P2.5DOT to respond normally to TRA and Bleed meaning that the engine is back in control. In addition, the recoverability scheme looks for fail-low-power characteristics such as XNH being at sub-idle for TRA at the idle setting.

Because vibration was not included for all data sets and was not included in the SEDRA program. It is believed that vibration would add a further level of robustness to the module forming it into the framework shown in Figure3.

The Readme file for SEDRA is included in the Appendix of this report describing the usage of the program in detail. SEDRA V1.0b has been included as a deliverable with this final report.

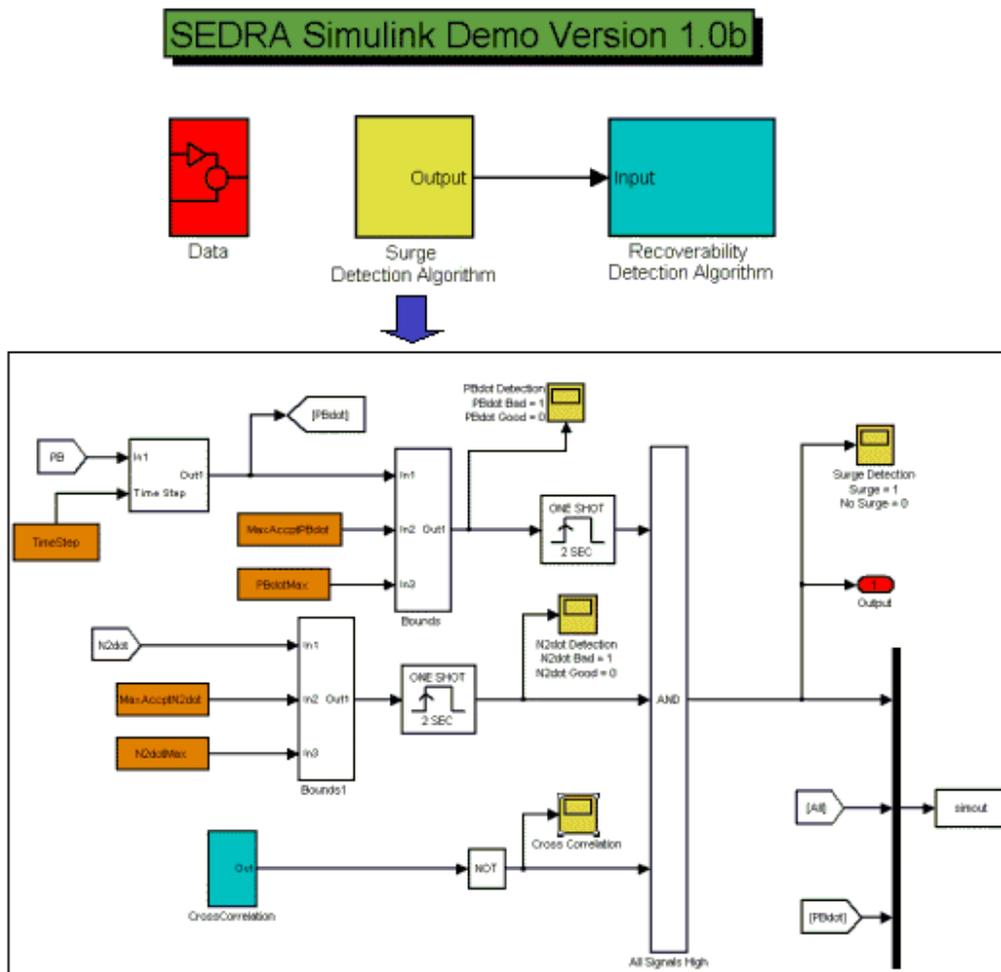


Figure 2 – Surge detection module

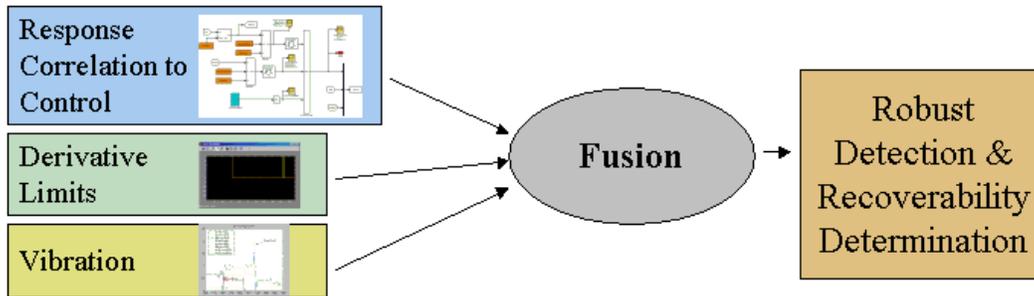


Figure 3 – Overall SEDRA scheme

SEDRA detected the surge events correctly for the first, second and third data sets, however, the limit settings had to be decreased for the third data set to detect the event. It is unclear as to the extent that decreasing this setting will yield false alarms over all possible normal operating conditions. The recoverability of the surge event was determined by SEDRA in 3-6 seconds and was correct in all three cases. It should be noted that validation on one non-recoverable surge event is not sufficient to validate the algorithm as a whole.

Conclusions

The following generalized conclusion were drawn from this study in accordance with the Task objectives:

- For high bypass turbofan engines with digital controls, existing surge detection schemes initiate TRA and bleed valve response in <0.25 seconds. This intervention diminishes observability of the engines natural response during a surge event and to some extent diminishes the observability of the underlying “health” of the engine.
- An algorithm for determining the recoverability of a surge event may be feasible but more recoverable/non-recoverable surges should be analyzed. Such an algorithm would require the parameter set given in the “Parameter Requirements” section of this report with a minimum of a 2 Hz sampling rate for the 1st eleven parameters. It would focus on the correlation of gas path parameters to TRA and bleeds.
- The confidence and false alarm rate of surge detection and recoverability algorithms could be improved by fusing lead/lag relationships and limits on broadband and tracked order vibration, P3, or P25, XNHDOT, TRA and bleed valve positions. This approach was demonstrated in the SEDRA program.
- There is currently no evidence that surge events can be predicted greater than a fraction of a second before it takes place with existing instrumentation (see discussion) based on data sets analyzed. However, the relative risk of surge for the subclass of surge events instigated by cycle deterioration or design limits may be determinable with a health management process for trending gas path features (EGT, PR vs. airflow etc.).

Discussion

The conclusions drawn from this analysis are based on a small sample of data sets that represent surge events and gas turbine theory. The general conclusions should be tested against a broader set of surge events that do not necessarily have to be data-rich before they should be implemented as premises for engine health management algorithms designed for providing potential flight deck annunciations. Data sets containing surge events on non-FADEC engines would also be valuable for characterizing the variability in surge events and observing raw engine response.

A significant body of research is available on compressor surge precursors and suppression with active control schemes [8,9,10]. One such precursor is high frequency P3 pressure waves coupled with a real-time lumped parameter state space compressor model. It is the authors' opinion that this technology is still relatively high risk and the robustness and cost/benefit of the sensor upgrades is suspect.

References

- 1) AIA/AECMA Project Report on Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR), Volume 2, 1 November 1998
- 2) Iverson, Mesick, Task 5.1 report
- 3) From correspondence with Gene Iverson, Jacob Mesick related to flight test logs
- 4) Impact report P223-01-2, "Stall/Surge Risk Assessment for the 777" 1/7/02
- 5) McKenzie, Axial Flow Fans and Compressors, 1997, Ipswitch Publishing Co.
- 6) Walsh, Gas Turbine Performance, 1998, ASME Press
- 7) Proakis, J., Digital Signal Processing, Principles, Algorithms and Applications, Prentice Hall 3rd edition
- 8) Willems, F., "Modeling and Bounded Feedback Stabilization of Centrifugal Compressors", Technische Universiteit Eindhoven, ISBN 90-386-2931-1
- 9) Yeung, "Non-linear control of Rotating stall and surge with Axisymmetric Bleed and Air Injection on Axial Flow Compressors", California Institute of Tech. 1999
- 10) Krichene, Prasad, et. al. "Stall and Surge Control of Compressors Using Real Time Precursor Identification", American Institute of Aeronautics and Astronautics, 2000

NOTES

Surge subcategories – Taken from Report 5.1

The first sub-category is a surge from cycle deterioration or more generally current cycle. This is a characterization that could be put on an engine that has been in service for some time and is deteriorated to the point where the stall margin is no longer sufficient to continue operating without surging. However, a relatively new engine may fall into this category if, for example, it is a poor performer from the production line (low on the production acceptance chart) and it runs into enough unusual but not uncommon operating conditions that the stall margin is depleted

The second sub-category is hardware / software malfunction. This is easy in the case of hardware - some part broke. It is not as easy to define for software (and for some hardware failures) and leads to the possible third category - design limits.

The design limits sub-category would be for a cycle that is closer to its stall margin than expected because production variation affects the operating line more than expected, stator vane schedules are too demanding, stability bleed system mechanical performance varies, stator vanes are mis-rigged, bleed scheduling is over/under-active, etc.

Characterizations of surge from PSM+ICR report – Taken from Report 5.1

The report listed engine parameter effects of a compressor surge as a rapid decrease in rotor speeds, pressures, and fuel flow, and typically an increase in EGT. The report provides some ranges of variation of these engine parameters as follows.

EPR/Burner Pressure	60% - 90% drop to coincide with bang sound
XNL	15% - 40% drop to coincide with bang sound
XNH	5% - 10% drop to coincide with bang sound
EGT	10 – 20 deg/sec rise

SEDRA V1.0b Readme File

SEDRA is Matlab/Simulink/Stateflow program for evaluating flight test data files for surge events and determining if the surge event was recoverable or not.

The program is split into 2 main sections 1) Surge Event Detection and 2) Recoverability determination. Surge detection is basically performed by looking at the behavior of HPC pressure, and XNH (plus their derivatives) with respect to TRA and Bleed valve positions or flows over a time buffer. If a surge event is detected, the recoverability algorithm becomes activated and observes the response of HPC pressure and speed to FADEC or crew intervention to the event over a time buffer. Currently, it specifically focuses on failure to low power.

To run the program:

- 1) Open Matlab 6.1 R12 or greater with Simulink and Stateflow
- 2) Run SurgeInit_a.m (This program will load up all constants, selects a data file, and sets the available parameters and sampling rates) The m-file is configured to load the data from third engine flight test which contained a non-recoverable surge event.
- 3) Open SurgeDetection040402.mdl
- 4) Double click into “Surge Detection Algorithm” and click on the “run” arrow
- 5) Open any or all of the scopes provided to see intermediate results.
- 6) Open the “Result” scope to see the final surge detection result.
- 7) Open the “Recoverability Detection Algorithm” and inspect the scope on the far right to see that the program determined that surge was non-recoverable (value of 1).
- 8) To see a contrasting case, open the SurgeInit_a.m file and change line 30 from “load DataE3” to “load DataE2”, save and run
- 9) Note that even though this is a very similar operational event no surge is detected.

APPENDIX F—AIRPLANE ENGINE INDICATIONS

Appendix F. Airplane Engine Indications

737-200

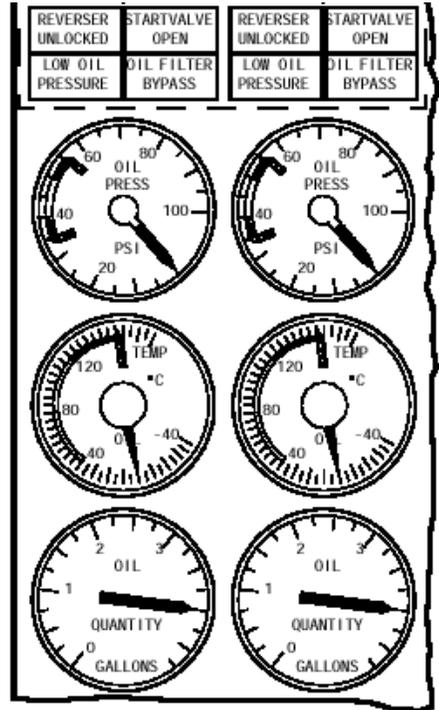
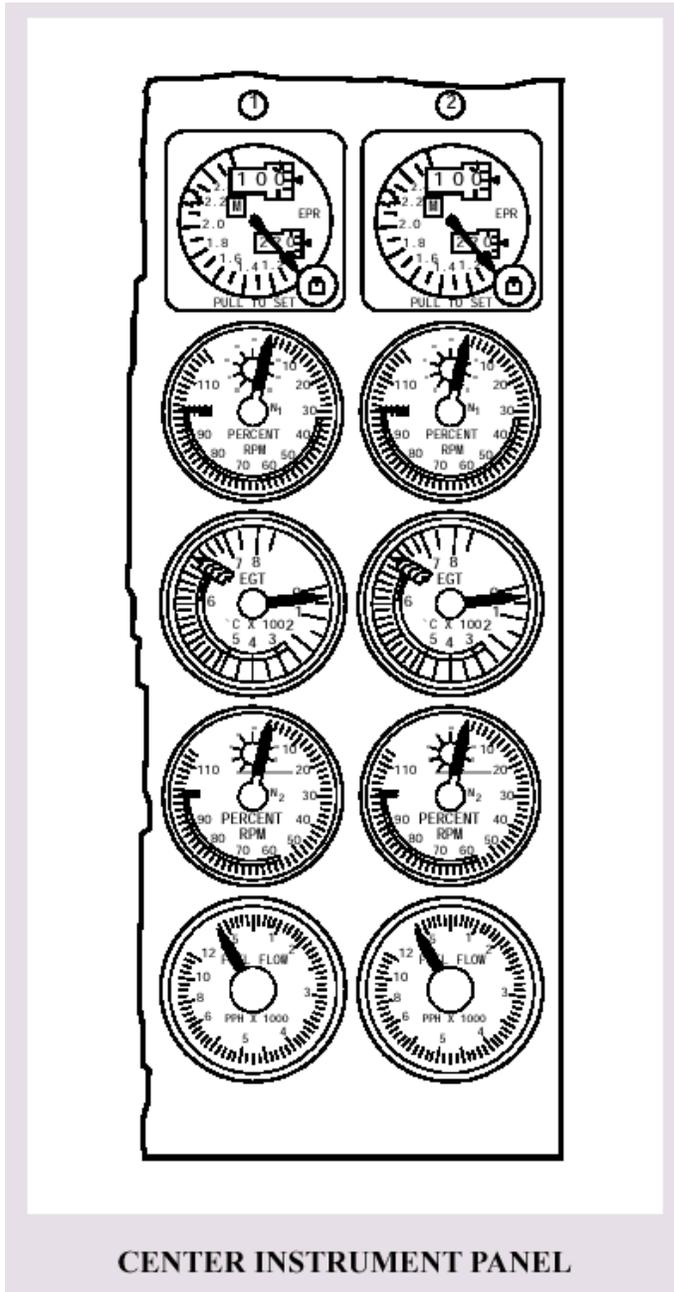


Figure F-1. Discrete/Dedicated Mechanical Engine Instruments - Boeing 737-200

737-300/400/500

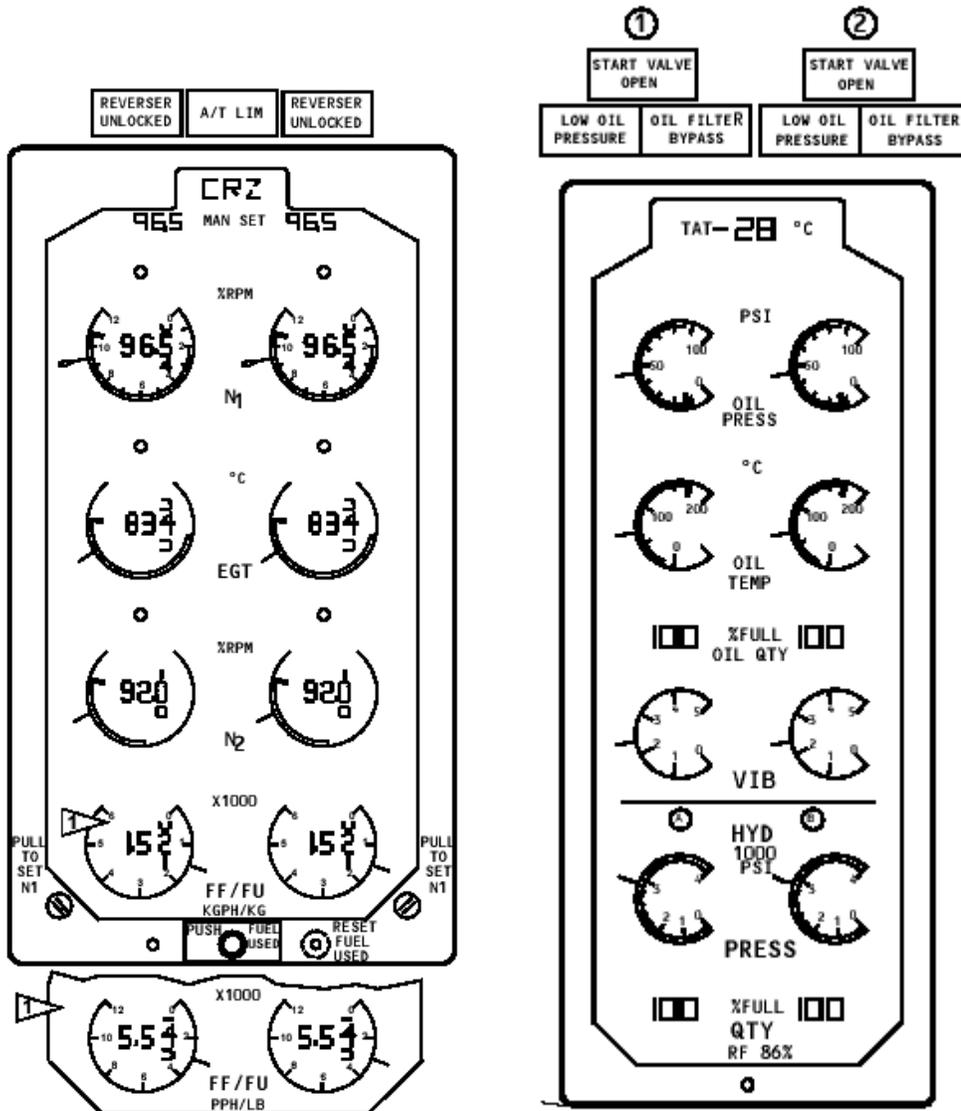


Figure F-2. Liquid Crystal Display (LCD) Engine Indications - Boeing 737-300/400/500

737-600/700/800/900

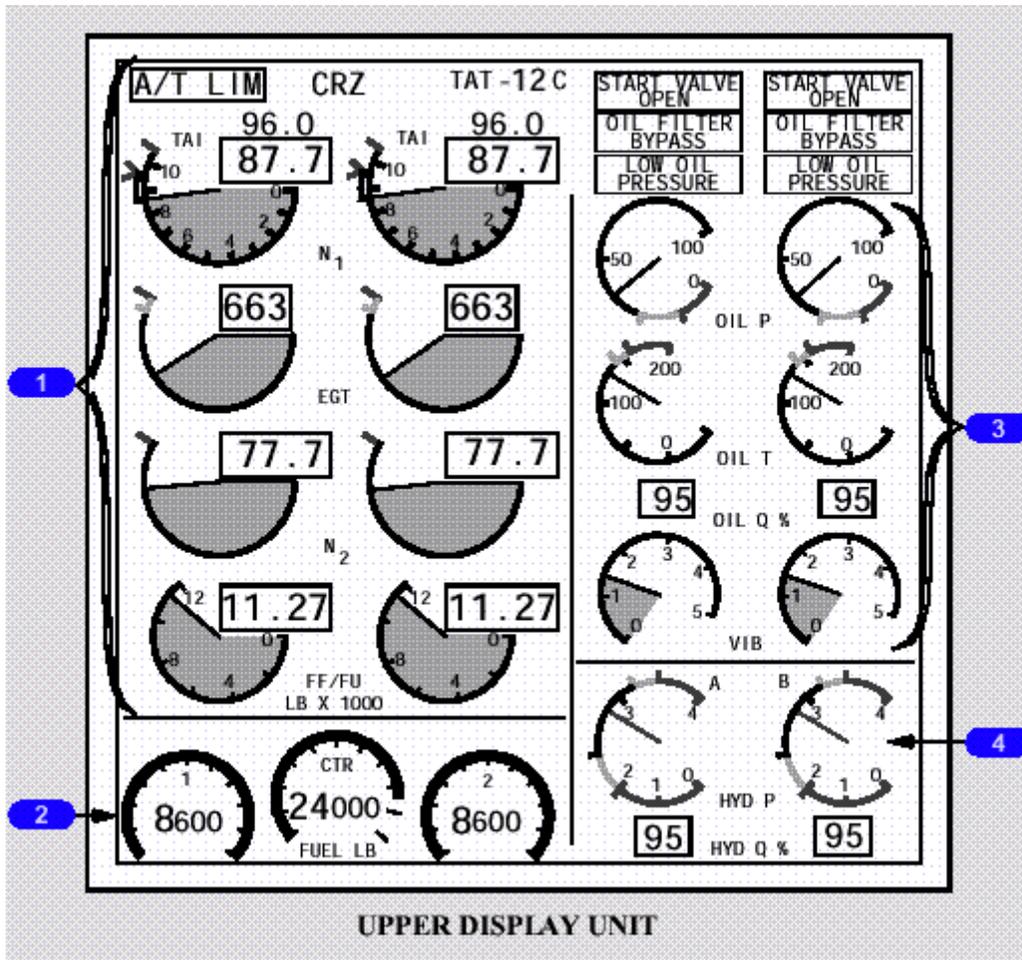
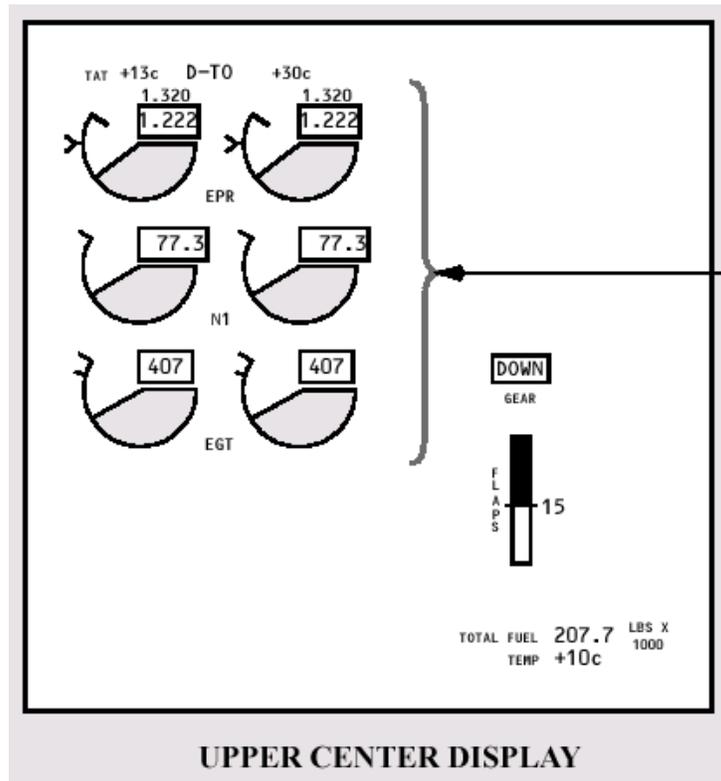


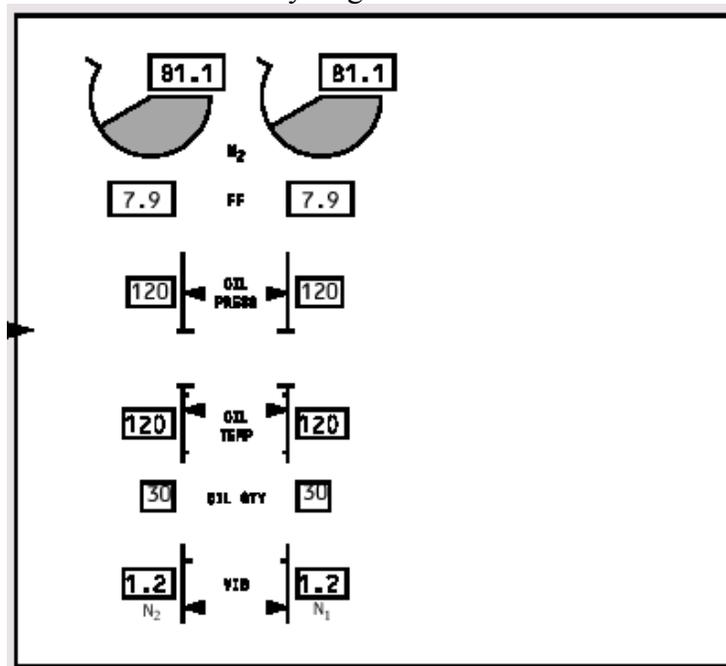
Figure F-3. Display Based Engine Indications - Boeing 737-600/700/800/900

Figure 5 illustrates 737 Next Generation Primary Engine Indications (1), Fuel Quantity Indications (2), Secondary Engine Indications (3), and Hydraulic Indications (4) displayed on the upper center engine indications display. Two main configurations are possible: 1) The side-by-side configuration shown in Figure 3, and 2) An Over-Under configuration similar to the EICAS airplane implementations on 747-400, 757, 767, and 777 models.



UPPER CENTER DISPLAY

Primary Engine Indications



Secondary Engine Indications

Figure F-4. Display Based Engine Indications - Boeing 777-200/300

Indication Features/Enhancements and Annunciations

Engine indication features or enhancements are provided to reduce crew integration activity and thereby reduce crew workload. Features and enhancements generally involve collocation and presentation of related information (e.g., commanded and actual state information), presentation of control target and system limit indications, and other elements and implementations that integrate data into information. Engine indication annunciations are provided to support crew detection of non-normal conditions. Annunciations generally involve color coding, flashing, and other implementations that call attention to a particular indication or feature. Engine indication features, enhancements, and annunciations are designed to make it easier and quicker for the user to obtain relevant or necessary information.

737-200 Thrust Setting Parameter

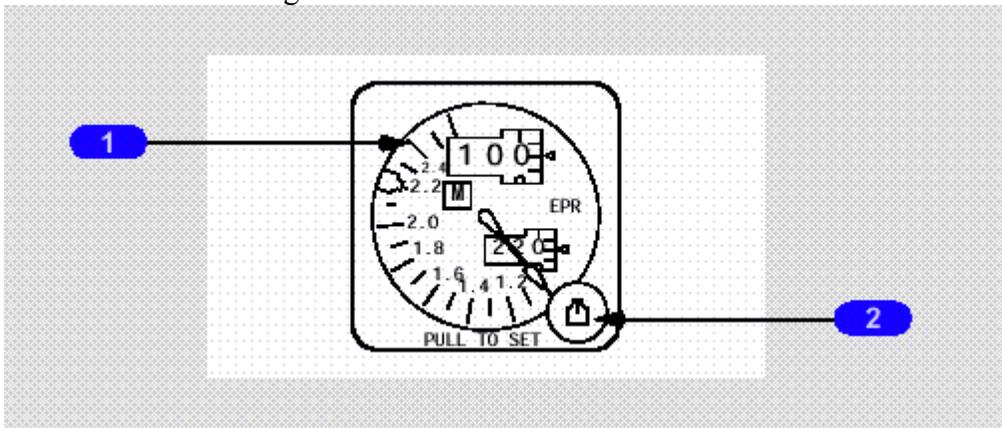


Figure F-5. 737-200 Engine Pressure Ratio (EPR) Indicator

Engine Pressure Ratio (EPR) is the primary thrust setting reference on 737-200. Figure 5 illustrates the 737-200 EPR Indicator. Flag 2 EPR Reference Selector. ROTATE – Positions the EPR reference “bug” and changes the reference EPR digital readout in the lower window correspondingly. When the reference selector is pushed in, the lower digital window and “bug” will be set by an input signal from the Performance Data Computer (PDC).

737-300/400/500 Thrust Setting Parameter

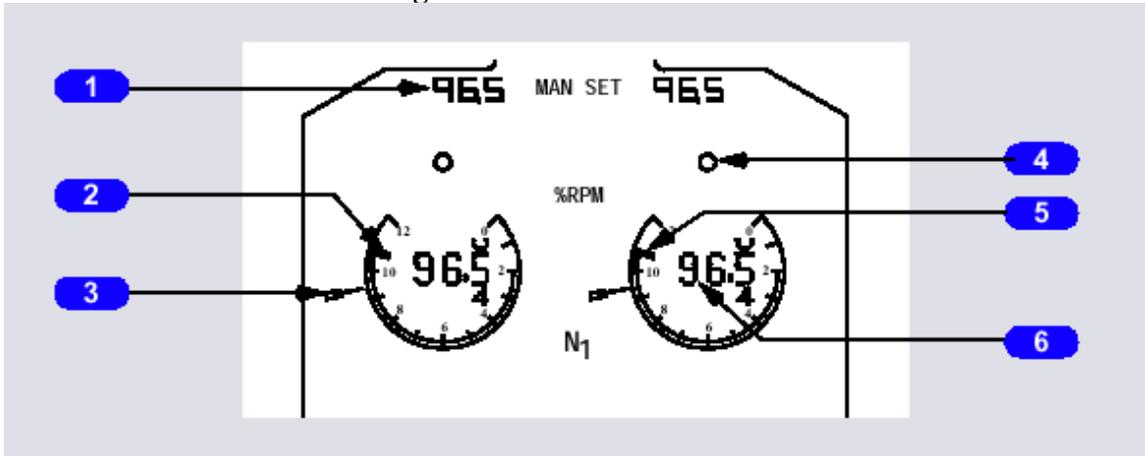


Figure F-6. 737-300/400/500 Engine Fan Speed (N1) Indicator

1 N1 Manual Set Indication. Set by N1 manual set knob. Blank when manual set knob is pushed in.

2 N1 RPM Indication (green). Displays N1 % RPM.

3 Reference N1 Bug (yellow). With N1 manual set knob pushed in it is positioned by FMC, based on N1 limit page and takeoff reference page, and displays active N1 limit for A/T operation.

With N1 manual set knob pulled out it displays crew selected N1 limit, and has no effect on A/T operation.

4 Warning Light. Illuminated (red) it indicates the N1 limit has been reached or exceeded, and remains illuminated until N1 is reduced below the limit.

5 N1 Red Radial. Shows N1 % RPM operating limit.

6 N1 RPM Readout (digital). Displays N1 % RPM.

737-600/700/800/900 Thrust Setting Parameter

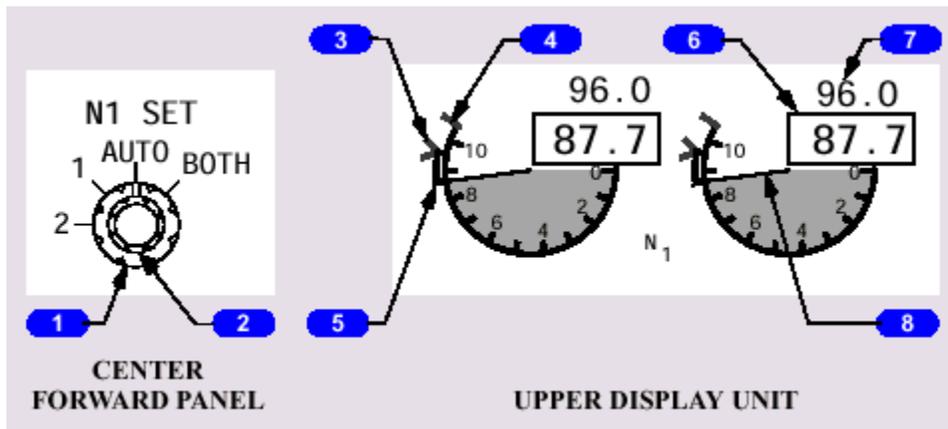


Figure F-7. 737-NG Engine Pressure Ratio (EPR) Indication

1 N1 SET Outer Knob

AUTO – Both reference N1 bugs set by FMC based on N1 limit page and takeoff reference page. Displays reference N1 bugs at active N1 limit for A/T.

BOTH – Both reference N1 bugs and readouts manually set by turning N1 SET inner knob. Has no effect on A/T operation.

1 or 2 – Respective N1 reference bug and readout manually set by turning N1 SET inner knob. Has no effect on A/T operation.

2 N1 SET Inner Knob (spring-loaded to center). Rotate – positions reference N1 bug(s) and readouts when N1 SET outer knob is set to BOTH, 1, or 2.

3 Reference N1 Bugs. Displayed (green) – with N1 SET outer knob in AUTO, 1, 2 or BOTH position.

4 N1 Redlines. Displayed (red) – N1% RPM operating limit

5 N1 Command Sectors. Displayed (white) – momentary difference between actual N1 and value commanded by thrust lever position.

6 N1 RPM Readouts (digital). Displayed (white) – normal operating range. Displayed (red):

- operating limit exceeded
- on ground after engine shutdown, red box indicates an inflight exceedance has occurred.

7 Reference N1 Readouts. Displayed (green) – manually set N1% RPM:

- set with N1 SET inner knob when N1 SET is in BOTH, 1, or 2 position
- blank when N1 SET outer knob in AUTO position
- – – – – when N1 SET outer knob in Auto and FMC source invalid.

8 N1 RPM Indications. Displays N1% RPM:

- displayed (white) – normal operating range
- displayed (red) – operating limit exceeded.

777 THRUST SETTING PARAMETER

Engine Pressure Ratio (EPR) is the primary thrust setting reference on 777 airplanes with PW and RR engines. On 777 PW and RR engines, N1 is the alternate thrust setting reference in certain Electronic Engine Control (EEC) modes of operation. Similar EPR and N1 indications are implemented on other EICAS airplanes. The following paragraphs describe EPR and N1 indications on 777 PW and RR engines.

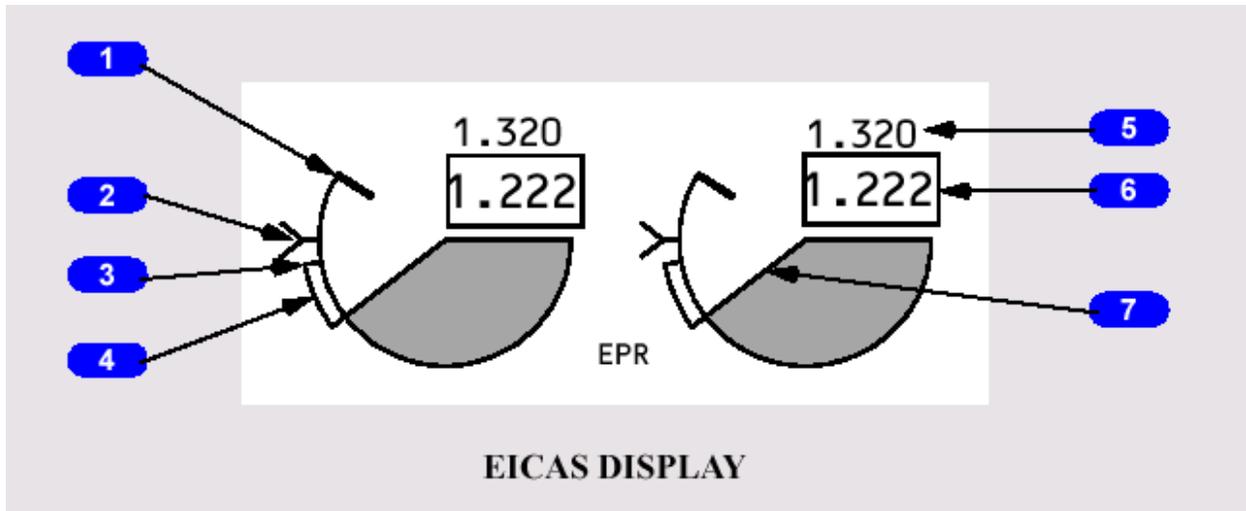


Figure F-8. 777 Engine Pressure Ratio (EPR) Indication [PW, RR Engines]

1 Maximum EPR Line. Displayed (amber).

2 Reference/Target EPR indication. Displayed (green) – reference EPR limit.
Displayed magenta – target FMC commanded EPR when VNAV is engaged and the autothrottle is engaged in THR or THR REF mode, or the autothrottle is not engaged.

3 Commanded EPR. Displayed (white).

4 Commanded EPR Sector. Displays momentary difference between engine EPR and EPR commanded by thrust lever position.

5 Reference EPR. Displayed (green).

6 Actual EPR. Displayed (white).

7 Actual EPR indication. Displayed (white). **Note:** When reverse thrust is activated, maximum EPR line, commanded EPR, reference/target EPR indication, and reference EPR are not displayed:

777 Fan Speed (N1) Parameter

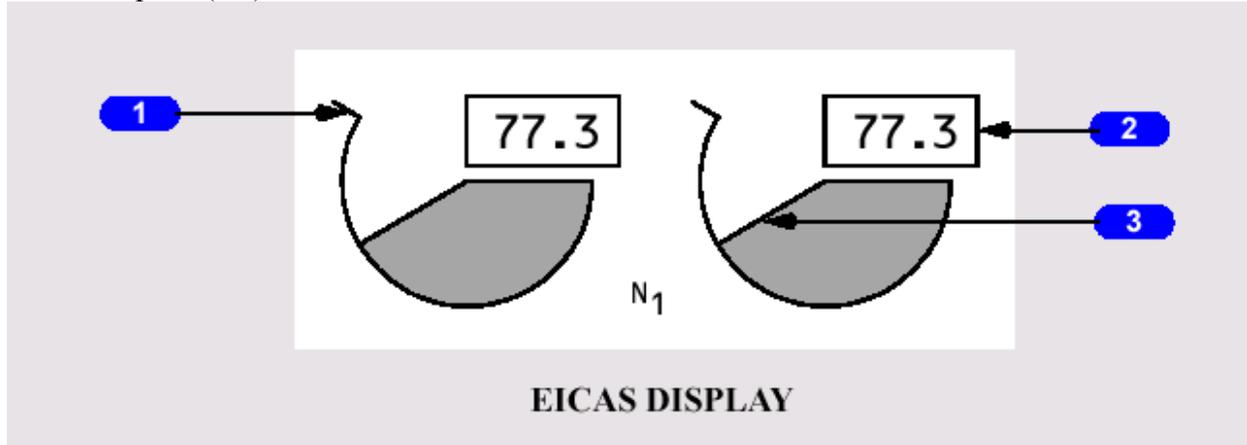


Figure F-9. 777 Engine Fan Speed (N1) Indication [PW, RR Engines]

- 1 N1 Red Line.** Displayed (red) – N1 RPM operating limit.
- 2 N1.** Digital N1 RPM (%), displayed: • (white) – normal operating range. • (red) – operating limit reached.
- 3 N1 Indication.** N1 RPM, displayed: • (white) – normal operating range. • (red) – operating limit reached.

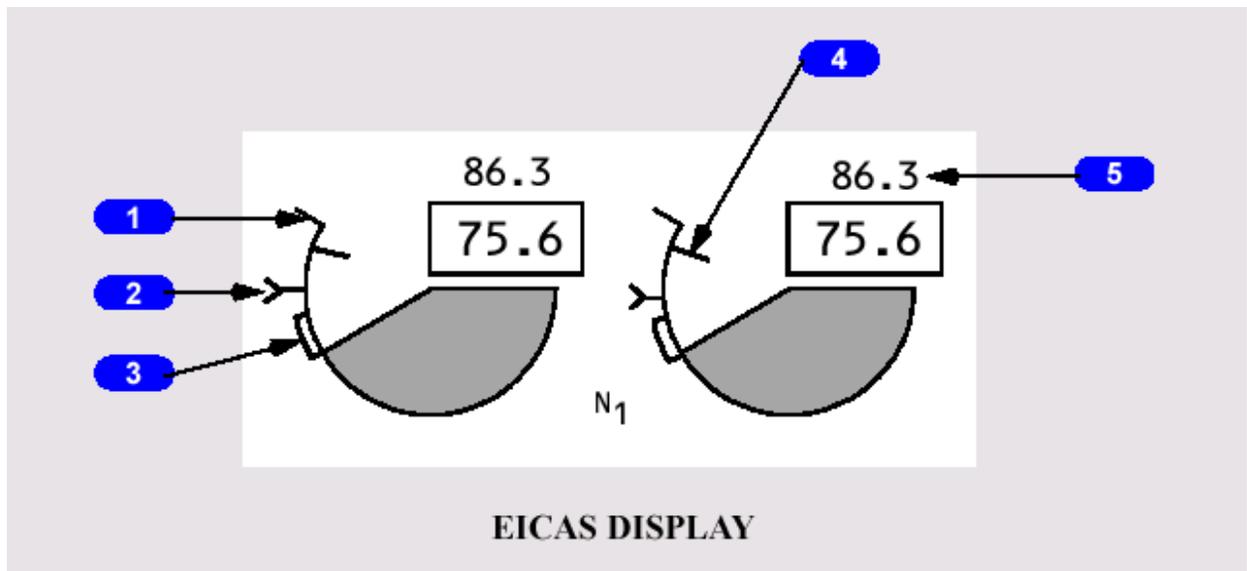


Figure F-10. 777 . Hard Alternate Mode Engine Fan Speed (N1) Indication. [PW, RR Engines]

- 1 N1 Red Line.** Displayed (red).
- 2 Reference/Target N1 Indication.** Displayed (green) – reference N1 limit. Displayed (magenta) – target FMC commanded N1 when VNAV is engaged and: • the autothrottle is engaged in THR or THR REF mode, or • the autothrottle is not engaged.

3 Commanded N1 Sector. Displays momentary difference between engine N1 and N1 commanded by thrust lever position.

4 Maximum N1 Line. Displayed (amber).

5 Reference N1. Displayed (green) – thrust reference calibrated for N1.

Note: When reverse thrust is activated, maximum N1 line, commanded N1, reference/target N1 indication, and reference N1 indications are not displayed.

Fan Speed (N1) is the primary thrust setting reference in all modes of operation on 777 airplanes with GE engines. Similar N1 indications are implemented on other EICAS airplanes. The following paragraphs describe N1 indications on 777 GE engines.

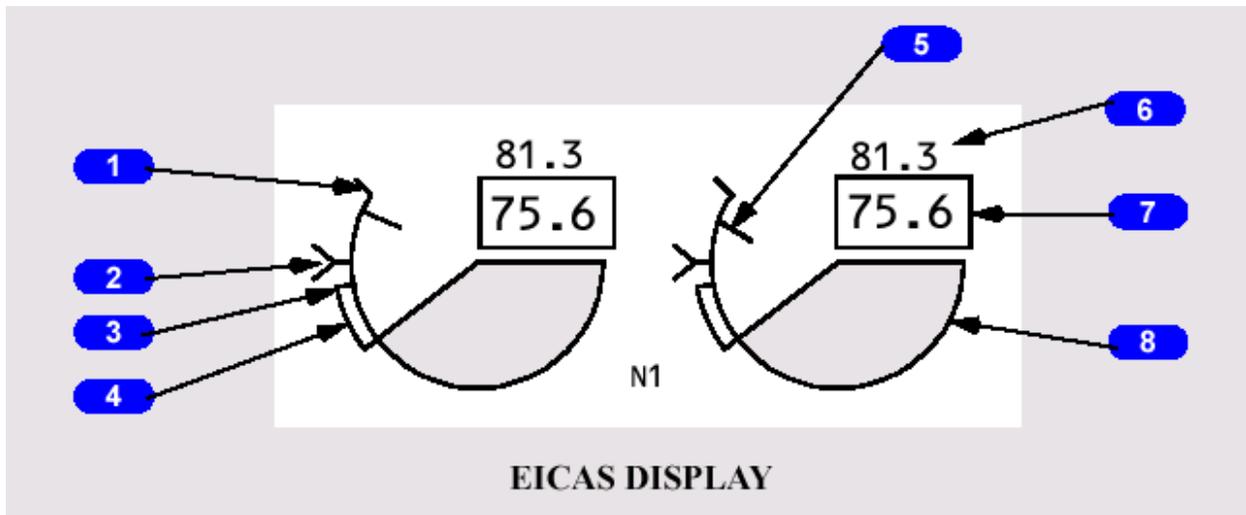


Figure F-11. 777 Engine Fan Speed (N1) Indication. [GE Engines]

1 N1 Red Line. Displayed (red) – N1 RPM operating limit.

2 Reference/Target N1. Displayed (green) – reference N1 limit. Displayed (magenta) – target FMC commanded N1 when VNAV is engaged and: • the autothrottle is engaged in THR or THR REF mode, or • the autothrottle is not engaged.

3 Commanded N1. Displayed (white).

4 Commanded N1 Sector. Displays momentary difference between engine N1 and N1 commanded by thrust lever position.

5 Maximum N1 Line. Displayed (amber).

6 Reference N1. Displayed (digital, green).

7 N1. Digital N1% RPM, displayed: • (white) – normal operating range, • (red) – operating limit reached.

8 N1 Indication. N1 RPM, displayed: • (white) – normal operating range, • (red) – operating limit reached.

Note: When reverse thrust is activated, maximum N1 line, commanded N1, reference/target N1 indication, and reference N1 indications are not displayed:

ENGINE INDICATION ANNUNCIATIONS

737-NG

N1 RPM Readouts (digital). Displayed (red): • operating limit exceeded, • on ground after engine shutdown, red box indicates an inflight exceedance has occurred.

N1 RPM Indications. displayed (red) – operating limit exceeded.

777 PW, RR, AND GE

N1. Digital N1 RPM (%), displayed: • (red) – operating limit reached.

N1 Indication. N1 RPM, displayed: • (red) – operating limit reached.

777 PW and RR: ?EPR. No exceedances or conditions currently annunciated or alerted.?

Thrust Reverser (REV) Indications

Figure 13 illustrates 737NG reverse thrust indications displayed on the primary engine indication display. REV is displayed in amber when the thrust reverser is moved from stowed position. REV REV is displayed in green when the thrust reverser is deployed. The 737 REV indications are representative of such indications on Boeing EICAS aircraft (747-400, 757, 767, and 777).

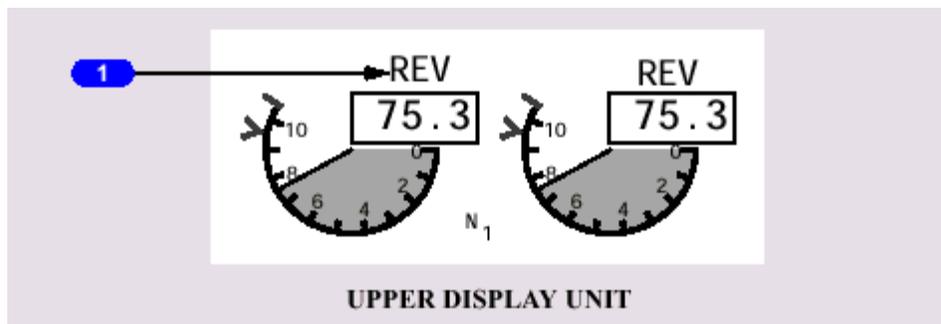


Figure F-12. 737 Reverse Thrust Indications

737NG Engine Fail (ENG FAIL) Alert

Displayed (amber): • engine operating below sustainable idle (less than 50% N2); and • engine start lever in IDLE position. Alert remains until: • engine recovers; or • start lever moved to CUTOFF; or • engine fire warning switch pulled. As previously noted 737 model aircraft do not have a display based centralized alerting system. 737 system failure indications are provided by discrete alert lamps and display indications.

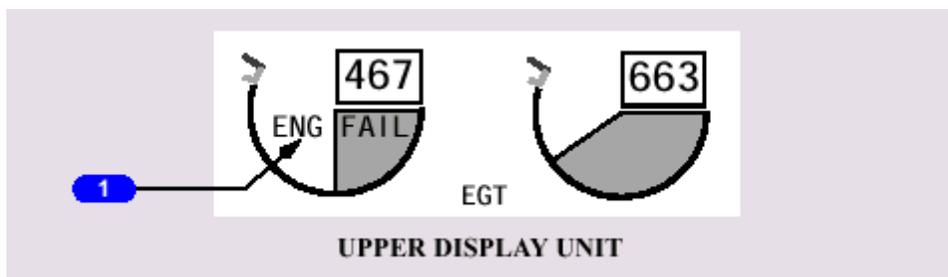


Figure F-13. ENG FAIL Indication

Automatic Display of Secondary Engine Indications

737 Secondary engine indications are automatically displayed when: • CDS initially receives power, • selected by the Multi-Function Display (MFD), • in flight when an engine start lever moved to CUTOFF, • in flight when an engine fails, or • when a secondary engine parameter exceeds normal operating range.

The 777 and other EICAS airplane secondary engine indications are automatically displayed when: • the displays initially receive electrical power, • a FUEL CONTROL switch is moved to CUTOFF in flight, • an engine fire switch is pulled in flight, • a secondary engine parameter is exceeded, or • engine N2 or N3 RPM is below idle in flight.

777

The oil temperature vertical indication has caution ranges displayed by amber bands. If oil temperature reaches the caution range, the digital readout, digital readout box, and pointer all change color to amber.

The oil temperature and oil pressure vertical indication has caution ranges displayed by amber bands. If oil temperature or oil pressure reaches the caution range, the digital readout, digital readout box, and pointer all change color to amber.

N1, N2, N3, EGT, oil pressure, and oil temperature indications have operating limits indicated by red lines. If one of these indications reaches the red line, the digital readout, box, and pointer change color to red for that indication. *Note: If an N1, N2, N3, or EGT red line is exceeded, the box enclosing the digital readout remains red after the exceeded limit returns to the normal range. The red box color can be canceled to white or recalled to red by pushing the cancel/recall switch on the display select panel. An indication changes color back to white when it returns to the normal operating range.*

The EGT indication has a maximum takeoff limit displayed by a red line. If EGT reaches the maximum takeoff limit, the digital indication, box, pointer and dial, all change color to red.

For low oil quantity, the oil quantity digital readout changes to black text on a white background. The white text LO is displayed adjacent to the readout.

For high engine vibration, the vibration digital readout changes to black text on a white background.

777 Compact Display Format

In compact format, primary and secondary engine indications are combined on the same display.

[PW Engines] The EPR and N1 displays are the same as the normal displays. All other indications change to digital readouts only. If an amber or red line parameter for a digital indication is exceeded, the digital indication changes color to amber or red (as does the box that appears around an EGT, or N2 indication for a red line exceedance). If the EGT or N2 red line is exceeded, the red color of the box around the digital indication can be returned to white (if the exceeded parameter has returned to normal) by pushing the display select panel CANCEL/RECALL switch.

[GE Engines] The N1 and EGT indications are displayed as they are normally (moving pointer/round dial and digital indications). All other indications change to digital readouts only, with the exception that the N2 digital readout is boxed if a parameter is exceeded. If an amber or red line parameter for a digital indication is exceeded, the digital indication changes color to amber or red (as does the box that appears around the N2 indication for a red line exceedance). If the N2 red line is exceeded, the red color of the box around the digital indication can be returned to white (if the exceeded parameter has returned to normal) by pushing the display select panel CANCEL/RECALL switch.

[RR Engines] The EPR and N1 displays are the same as the normal displays. All other indications change to digital readouts only. If an amber or red line parameter for a digital indication is exceeded, the digital indication changes color to amber or red (as does the box that appears around an EGT, N2, or N3 indication). If the N1, N2, N3, or EGT red line is exceeded, the red color of the box around the digital indication can be returned to white (if the exceeded parameter has returned to normal) by pushing the display select panel CANCEL/RECALL switch.

Primary and secondary engine indications are displayed on EICAS in compact format whenever:

- secondary engine display is automatically selected, and the lower multifunction display is failed, unpowered, or is occupied, or
- secondary engine display is manually selected to the lower center MFD and the lower MFD is failed, unpowered, or occupied with EICAS.

APPENDIX G—FLIGHT DECK DESIGN AND OPERATIONAL PHILOSOPHY

Appendix G. Applicable Flight Deck Design & Operational Philosophy, Requirements, & Guidelines

The following paragraphs document selected generalized Flight Deck design and operational philosophies, and interface design requirements and guidelines applicable to transport category commercial airplanes. These selected objectives, guidelines, and requirements, are applicable to the design and development of Flight Deck controls, indications, and annunciations in general, and engine related indications and annunciations in particular. The objectives, guidelines, and requirements are also relevant to the operational assessment of new indications and annunciations designed to prevent or reduce engine malfunction related undesired crew response, and are a basis for the conclusions and recommendations herein. The objectives, guidelines, and requirements are provided to aid in understanding how report conclusions and recommendations are reached.

Flight Deck Design & Operational Philosophy

The following paragraphs are selected generalized Flight Deck Design and Operational Philosophy. These excerpts, in the form of objectives and guidelines, are applicable to the design and development of engine indications and annunciations, are relevant to the operational assessment of new indications and annunciations, and are a basis for the conclusions and recommendations herein.

System designs should adhere to proven design concepts of simplicity, fault tolerance, error tolerance, and appropriate use of redundancy and automation.

Human engineering design principles should be used, and human factors considered, as part of the Flight Deck interface design process.

Human engineering principles should be used to provide a safe, efficient, and comfortable, working environment.

Systems design should correlate with Flight Crew Training philosophy.

System control and display information should be as simplified as possible.

Controls and displays should, to the extent possible, be co-located and grouped according to operational function.

Related display information should be integrated into a single consistent format compatible with operational usage.

For flight essential functions, supplemental information, which clarifies or reinforces the normal indications of functional operations, should be provided.

Minimization of the effect of crew errors should be an integral part of the design.

Quiet, Dark Flight Deck Philosophy - Alerting indications should not be presented for normal operation.

Alerting should be implemented based on a demonstrable need for crew awareness or action, and minimal risk of inappropriate or undesired crew distraction, response or desensitization.

Flight crews should be alerted to non-normal operational and system conditions according to the severity of the condition and the criticality of flight crew awareness and response time.

Alert presentations must not degrade flight operations.

System failure responses may be automated when the response is:

- Invariant regardless of circumstance
- Consistent or compatible with pilot expectations
- Reversible, and
- Has no consequential effects which directly interfere with other pilot tasks.

The operational hierarchy, listed in order of importance to Flight Safety is:

- **Flight path control**
- **Navigation/Guidance,**
- **Aircraft separation**
- **Communication, and**
- **System operation**

Flight Deck design should optimize pilot workload

- Design should allow pilots to focus on total flight operations rather than on subsystem monitoring, control, troubleshooting, or problem solving.
- Too little or too much workload should be avoided.
- Pilot memory requirements should be minimized
- The number, difficulty, and time allowed for tasks should be considered.
- Complex procedures should not be used to compensate for non-optimized systems design.
- Design should provide flexibility to allow pilots to manage workload across functions, flight phases, and individual differences.

Normal and non-normal procedures should encourage and facilitate crew coordination.

With respect to flight control and automation, the pilots should have final authority.

With respect to decision-making, the Captain has the final authority, but both pilots are responsible for the safe operation of the airplane.

Flight Deck Interface Design Guidelines and Requirements

The following paragraphs contain selected generalized Flight Deck interface design requirements and guidelines applicable to the development of engine indications and annunciations applicable to transport category commercial airplanes. These requirements and recommendations are also relevant to the operational assessment of new indications and annunciations, and are a basis for the conclusions and recommendations herein.

Primary flight and thrust controls must incorporate visual and tactile feedback to the flight crew

Systems controls and displays should be labeled according to their actual function within the system.

Controls and displays must be consistent in operation, information coding, operator feedback, and appearance.

Wherever possible, controls and displays must be equally accessible to both pilot locations such that either pilot may accomplish the Pilot Flying and the Pilot Not Flying duties, and carry out Captain and First Officer responsibilities.

Each pilot must be able to see and read all in-flight required non-duplicated instruments and control panels.

Switches, controls, and essential displays must be distinguishable under all probable cockpit lighting conditions, and must provide clear and unambiguous information or status.

Displays or annunciators presenting dynamically changing information required to be read for immediate understanding must have nomenclature which subtends a minimum of xx minutes of visual arc as measured from the Flight Deck Eye Reference Point (ERP).

Individual displays or annunciators presenting alerting or dynamic information must have nomenclature which subtends a minimum of xx minutes of visual arc as measured from the Flight Deck Eye Reference Point (ERP) unless it can be otherwise demonstrated that alternative means provide sufficient information.

The minimum visual angles specified can be reduced by xx% for electronic display symbols. Electronic display symbols must subtends at least of xx minutes of visual arc as measured from the Flight Deck Eye Reference Point (ERP).

Airplane retrofits should be implemented in a manner consistent with existing best practices, the certification basis of the airplane, and in a manner consistent or compatible with the specific airplane flight deck design and interface being retrofit. The feasibility of retrofit should be considered.

Alerting indications should not be presented for normal operation (Quiet, Dark Flight Deck).

The crew must be alerted to unsafe operating conditions to enable appropriate corrective action to be taken.

The consequences of false or nuisance alerting should be assessed, and the potential for false or nuisance alerting must be minimized.

The consequences of failure to alert must be assessed, and the potential for failure to alert should be minimized.

Alert presentations must provide combinations of visual, aural, or tactile elements to attract attention and define the alert condition sufficiently for appropriate crew action or awareness.

Alert conditions must be indicated on the forward panels such that determination of when to take action can be made by the pilot without further reference.

All non-voice aural alert annunciations must be accompanied by a visual annunciation which defines the alert condition.

Alert conditions should be presented as one of the following alert levels:

- Time Critical Warning – An operational condition which requires immediate pilot and immediate corrective or compensatory action to maintain safe flight
- Warning - An operational or aircraft system condition which requires immediate crew awareness and timely corrective or compensatory action.
- Caution - An operational or aircraft system condition which requires immediate crew awareness. Corrective or compensatory action may be required.
- Advisory- An operational or aircraft system condition which requires crew awareness. Corrective or compensatory action may be required.

A master aural annunciation unique to each alert level must be provided for all time critical warning, warning, and caution level alerts.

Alert annunciations must automatically clear when the alert condition no longer exists.

System controls, and associated monitoring and alerting, must be designed to minimize the probability of crew error which could create additional hazards following a failure.

System information should be automatically displayed, or readily available, when the information is required to assess a failure or take action.

Applicable Federal Aviation Regulations (FARs)

FAR 25-1305 Powerplant Instruments

FAR 25-1305 documents FARs applicable to Powerplant Instruments. The following applicable requirements are excerpted from 25-1305. The following FAR 25-1305 excerpts document required powerplant instruments applicable to this operational assessment:

25-1305 (a) For all airplanes. (1) A fuel pressure warning means for each engine, or a master warning means for all engines with provision for isolating the individual warning means from the master warning means.

25-1305 (c) For turbine engine-powered airplanes.

(1) A gas temperature indicator for each engine.

(2) A fuel flowmeter indicator for each engine.

(3) A tachometer (to indicate the speed of the rotors with established limiting speeds) for each engine.

25-1305 (d) For turbojet engine powered airplanes

(1) An indicator to indicate thrust, or a parameter that is directly related to thrust, to the pilot. The indication must be based on the direct measurement of thrust or of parameters that are directly related to thrust. The indicator must indicate a change in thrust resulting from any engine malfunction, damage, or deterioration.

(2) A position indicating means to indicate to the flight crew when the thrust reversing device is in the reverse thrust position, for each engine using a thrust reversing device.

(3) An indicator to indicate rotor system unbalance.

FAR 25.1309 Equipment, systems, and installations.

(a) The equipment, systems, and installations whose functioning is required by this subchapter, must be designed to ensure that they perform their intended functions under any foreseeable operating condition.

(b) The airplane systems and associated components, considered separately and in relation

to other systems, must be designed so that --

(1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and

(2) The occurrence of any other failure conditions which would reduce the capability of the

airplane or the ability of the crew to cope with adverse operating conditions is improbable.

(c) Warning information must be provided to alert the crew to unsafe system operating conditions, and to enable them to take appropriate corrective action. Systems, controls, and associated monitoring and warning means must be designed to minimize crew errors which could create additional hazards.

(d) Compliance with the requirements of paragraph (b) of this section must be shown by

analysis, and where necessary, by appropriate ground, flight, or simulator tests. The analysis must consider --

- (1) Possible modes of failure, including malfunctions and damage from external sources.
- (2) The probability of multiple failures and undetected failures.
- (3) The resulting effects on the airplane and occupants, considering the stage of flight and operating conditions, and
- (4) The crew warning cues, corrective action required, and the capability of detecting faults.

Advisory Circular Guidance

AC 20-88A provides guidelines on the marking of aircraft powerplant instruments and electronic displays (cathode ray tubes, etc.).

4. b. Powerplant instruments (displays) may be electromechanical, mechanical, or electronic indicators.
5. e. The color red indicates an operating condition beyond authorized limits and requires a specific action on the part of the flightcrew. The specific action to be taken should be described in detail in the Airplane/Rotorcraft Flight Manual.
5. f. The color green is used to indicate a normal condition for operation, both ground and flight.
5. g. The color yellow is used to indicate either a takeoff or cautionary range where limited operation is permissible as directed by the applicable Airplane/Rotorcraft Flight Manual.
6. d. The advent of the CRT display allows greater flexibility in the design of instrument marking schemes. A concept has been developed where normal engine operating conditions are not identified and only abnormal conditions are designated by colored markings. If all abnormal conditions are adequately indicated by specific design features, green markings are unnecessary based on a finding of equivalency. Yellow and red markings are used but may be subdued until the parameter being monitored reaches the caution or warning value. At that time the respective color is highlighted in some manner to alert the flightcrew.

AC 25-11 provides guidance for certification of cathode ray tube (CRT) based electronic display

systems used for guidance, control, or decision-making by the pilots of transport category airplanes. The AC states in paragraph 4.a. *“The use of electronic displays allows designers to integrate systems to a much higher degree than was practical with previous airplane flight deck components. With this integration can come much greater simplicity of operation of the airplane through automation of navigation, thrust, airplane control, and the related display systems.”*

4.a.3.ix. Propulsion, System Parameter Displays.

5. INFORMATION SEPARATION

- a. Color Standardization.
- b. Color Perception vs. Workload.
- c. Standard Symbology.
- d. Symbol Position.
- e. Clutter.

- f. Attention-Getting Requirements. (1) Some electronic display functions are intended to alert the pilot to changes: navigation sensor status changes (VOR flag), computed data status changes (flight director flag or command cue removal), and flight control system normal mode changes (annunciator changes from armed to engaged) are a few examples. For the displayed information to be effective as an attention-getter, some easily noticeable change must be evident. A legend change by itself is inadequate to annunciate automatic or uncommanded mode changes. Color changes may seem adequate in low light levels or during laboratory demonstrations but become much less effective at high ambient light levels. Motion is an excellent attention-getting device. Symbol shape changes are also effective, such as placing a box around freshly changed information. Short-term flashing symbols (approximately 10 seconds or flash until acknowledge) are effective attention-getters. A permanent or long-term flashing symbol that is noncancellable should not be used.

6. DISPLAY VISUAL CHARACTERISTICS. e. Dynamics.

7. INFORMATION DISPLAY. Display elements and symbology used in real-time "tactical" airplane control should be natural, intuitive, and not dependent on training or adaptation for correct interpretation.

h. Full-Time vs. Part-Time Displays.

10. INTEGRATED WARNING, CAUTION AND ADVISORY DISPLAYS.