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Indications of Propulsion System Malfunctions—Sustained Thrust Anomaly Study

May 2007

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16. Abstract

The feasibility of providing specific indications to flight crews when a propulsion system malfunction occurs was evaluated. The Boeing Phase 1 Report, Indications of Propulsion System Malfunctions, DOT/FAA/AR-03/72, reviewed and analyzed propulsion system malfunctions (PSM) plus inappropriate crew response (ICR) accident and incident events for the potential of PSM annunciations to prevent ICR. This Phase 2 work involved the development of PSM detection and annunciation strategies. The focus of Phase 2 work was placed on sustained thrust anomalies (STA) identified to be the most common factor and significant contributor in PSM+ICR events. This report documented the results of the Phase 2 study. The research included propulsion system malfunction detection criteria derived from: propulsion system operational criteria; crew operational criteria; and new indication concept criteria. The research also included sets of potential detection strategies to meet the established propulsion and crew operational criteria; technology risk assessment and down selection of strategies; and development, demonstration, and validation plan for the selected strategies.

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LIST OF ACRONYMS

A/T	Autothrottle
AD	Airworthiness Directive
AECMA	European Association of Aerospace Industries
AIA	The Aerospace Industries Association
ALTN	Alternate mode
BCA	Boeing Commercial Airplanes
DFDR	Digital flight data recorder
EEC	Electronic engine control
EGT	Exhaust gas temperature
EICAS	Engine indication and crew alerting system
EPR	Engine pressure ratio
FAA	Federal Aviation Administration
FADEC	Full authority digital engine controller
FF	Fuel flow
FPV	Flight path vector
GE	General Electric
H	Hull loss
HF	Hull loss fatal
HP	High pressure
HPC	High-pressure compressor
HPT	High-pressure turbine
HUD	Head up display
ICR	Inappropriate crew response
IFSD	In-flight shuddown
IP	Intermediate pressure
IPT	Intermediate-pressure turbine
LLP	Limited-life part
LOC	Loss of control
LP	Low pressure
LPC	Low-pressure compressor
LPT	Low-pressure turbine
N1	Fan/LPT speed
N2	Core/HPT speed (2-spool engines), IPT speed (3-spool engines)
N3	Core/HPT speed (3-spool engines)
NGV	Nozzle guide vane
NORM	Normal mode
NNP	Nonnormal procedures
NVM	Nonvolatile Memory
P	Pressure
P0	Ambient pressure
P2	Total pressure
PB	Burner pressure
PFD	Primary flight display
PPP	Procedure, practice, and policy
PSM	Propulsion system malfunction

PSM+ICR	Propulsion system malfunction and inappropriate crew response
PW	Pratt & Whitney
RTO	Rejected takeoff
SB	Service bulletin
SDGE	Shutdown good engine
SDTGE	Shutdown or throttled good engine
STA	Sustained thrust anomaly (longer than 5 seconds)
STA-PSM	Sustained thrust anomaly propulsion system malfunction
T	Temperature
T2	Total temperature
T25	Intercompressor stage temperature
T3	Compressor exit temperature
TOGA	Takeoff/go around
TRA	Thrust lever resolver angle
V1	Takeoff decision speed
VSV	Variable stator vane

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. The rate of occurrence per airplane departure for PSM+ICR accidents has remained essentially constant for many years. These accidents are still occurring despite the significant improvement in propulsion system reliability over the past 20 years, suggesting an increase in rate of ICR to propulsion system malfunctions.

In response to industry recommendations, the Federal Aviation Administration sponsored follow-on studies of PSM+ICR events. The Boeing Phase 1 Report, "Indications of Propulsion System Malfunctions", DOT/FAA/AR-03/72, reviewed and analyzed PSM+ICR accident and incident events for the potential of PSM annunciations to prevent ICR. The Phase 2 work involved the development of PSM detection and annunciation strategies. The focus of Phase 2 work was placed on sustained thrust anomalies (STA), which were identified to be the most common factor and significant contributor in PSM+ICR events. This bounded focus on STAs facilitated the development of detection and annunciation strategies that address the majority of PSM+ICR events. This report documented the results of the Phase 2 study.

In Phase 2, engine and operational PSM detection and annunciation criteria were developed from event data. Criteria included engine integrity, engine thrust recovery needs, malfunction symptoms, malfunction characterizations, flight phase, power, timing, annunciation reliability, and annunciation availability. Malfunction detection and annunciation strategies were defined and developed from the criteria. Detection strategy strengths, weaknesses, and technology risks were assessed.

Engine indication and annunciation-related best practices and principles and new possible engine malfunction detection and annunciation-related improvements were identified from nonnormal procedures review. High-level criteria (guidelines) for an information-based engine indication paradigm were developed from procedures, practices and policies review, operational design philosophy, and human factors considerations. In addition, specific engine indication and control-related information and automation opportunities were identified.

The relationships among engine malfunction detection and annunciation, engine system indications and controls, engine malfunction accommodation automation, pilot role, and procedures for normal and nonnormal operations were examined. Technology (capability and reliability) effects on engine system design and pilot role relative to potential detection and annunciation strategies and implementations were considered.

A strategy/concept technology development, demonstration, and validation plan was prepared for continuous/multiple surge detection and accommodation. In preparation for follow-on work, engine damage types were categorized by subcomponent and frequency of occurrence.

The focus of the research was on the technology and strategy development for detection and annunciation of sustained thrust anomalies. Current state-of-the-art glass cockpit capability and Full Authority Digital Engine Controller (FADEC) was assumed to be the baseline. The research identified opportunities for product improvements and further investigation.

A potential suite of engine malfunction annunciations derived from integrated propulsion system and crew operational criteria were identified and are documented in section 8. Section 6 assesses the technical risk of providing these messages with an estimated level of integrity.

Down Selection of Crew Annunciation Categories for Sustained Thrust Anomalies

Engine Malfunction Detection/Annunciation Categories	Procedure	Implementation and Development Technical Risk
Subidle (includes flameout and surge/nonrecoverable stall) [1]	Stall requires fuel cut to address malfunction. Flameout requires ignition. Subidle recovery may require starter or other assistance to recover to running (above idle).	Low (currently exists in many applications)
Continuous/multiple surge (multiple surges)	A fuel flow reduction, possibly to idle, needed to address engine malfunction. Thrust lever readvancement needed to recover from thrust loss and verify normal engine operation.	High (does not currently exist)
Alternate mode (actual thrust higher or lower than command due to failure of primary thrust sensed parameter	Reversion to alternate mode needed to address the engine system malfunction and recover sustained thrust loss	Low-Medium (exists in many applications, but an improvement to the current detection threshold increase the risk to medium)
Thrust Anomaly (other STAs not included in the other annunciation categories)	Awareness only annunciation - specific pilot action to address engine malfunction or recover thrust is context dependent and not procedurally specified.	Medium-High (portions exist in some applications, risk depends on specific anomaly, those anomalies which address PSM+ICR have medium risk)

[1] For the purpose of this report, single surge events that recover are not considered a STA.

This suite of annunciations provides operational benefit for sustained thrust anomaly propulsion system malfunctions (STA-PSM), and has prevention potential for a majority of PSM+ICR events. Individual or a selective subset of annunciations from this suite would also have operational benefits. However, detection and alert annunciation is not the only way to provide operational benefit. Other approaches such as malfunction recognition training, engine indications (which facilitate malfunction detection and minimize interpretation), airplane level annunciations (such as abnormal airspeed, attitude, and performance that guard against loss of control or performance), airplane level automation and compensation, proactive engine health management (to reduce the number of PSMs), improved crew procedures and practices, etc., can provide operational benefit. Where reliance is on crew awareness and response, an annunciation is the most effective way to provide crew awareness and ensure an appropriate response.

The Phase 2 research work concluded that new capability (algorithm development), not new technology (hardware), is needed in developing this suite of annunciations for airplanes with glass cockpits and engine FADEC systems.

A cost-benefit study is needed when considering the development and implementation feasibility of these detection and annunciation capabilities for modern or future airplane programs. The subidle condition has the lowest technical detection and annunciation risk and the highest potential benefit. Continuous/multiple surge condition has the highest technical detection and annunciation risk, due primarily to the lack of sufficient engine data to validate the reliability of a detection algorithm. The higher the technical risk and reliability requirements, the less likely a cost-effective benefit can be shown.

To modify or retrofit existing airplanes with new sustained thrust anomaly detection and annunciation capabilities is not presently considered feasible, because the cost-benefit trade-off for these additions is not likely to be favorable.

Several areas of follow-on research work supporting malfunction detection, malfunction accommodation, and engine operation were identified:

- Acquisition of continuous/multiple surge data
- Engine damage detection, annunciation, and procedure strategies
- Engine malfunction autoaccommodation indication, annunciation, and procedures
- Airplane level malfunction accommodation strategies
- Information-based engine display paradigms and displays

It is important to note that PSMs are a rare occurrence, and PSMs coupled with ICR are even more rare. Analysis indicates a potential benefit for annunciation of STA-PSM, but the benefit has not been quantified. Although an annunciation of a STA-PSM condition could be beneficial, the benefit is realized only if the annunciation is reliable. An unreliable annunciation could cause more problems than it resolves.

Although this study indicates that annunciation of STA-PSMs have the potential to reduce PSM+ICR, the feasibility (e.g., reliability, cost-benefit, etc.) of achieving those benefits through malfunction annunciation has not been established. Additionally, reliable relationships between

engine damage and engine thrust capability for all conditions have not been established, and as such, the intent of follow-on work would be to determine whether combining detection of mechanical malfunction with engine performance, engine parameter, or engine anomaly monitoring and detection (e.g., surge or significant parameter change) might be a reliable indication of the inability of an engine to make or sustain thrust. The technical, operational, and economic feasibility of any approach should be established before any regulatory, implementation, or other action is taken.

PSM annunciation was the only solution investigated in this study. Investigation and data analysis has provided sufficient understanding to state that PSM annunciation has the potential to reduce the rate of PSM+ICR. The extent to which PSM annunciation would reduce ICR has not been quantified. It is recognized that validation of the benefits of new annunciations is often difficult to obtain. PSM annunciation may or may not be the most feasible or preferred solution to PSM+ICR. It was not within the scope of this study to investigate alternative approaches to reducing PSM+ICR.

It is perhaps most important that the approach to reducing PSM and PSM+ICR events be data-driven and coordinated with other high-priority safety enhancements. The challenge is to emplace the most effective and efficient means of reducing fatal accident risk from all hazards.

1. BACKGROUND.

This Phase 2 project was awarded to The Boeing Company as follow-on to the Boeing Phase 1 research project. The purpose was to determine the feasibility and appropriateness of providing specific indication to flight crews of propulsion system malfunctions (PSM).

- The Aerospace Industries Association (AIA) and European Association of Aerospace Industries (AECMA) 1998 Project Report [1] assessed the causes and contributing factors in accidents and incidents where a single benign PSM occurred (which should have been a nonhazardous event) and the pilot(s) did not appropriately respond to the situation (inappropriate crew response (ICR)). This study was undertaken in response to a Federal Aviation Administration (FAA) letter of March 6, 1996, requesting the AIA use data from a previous AIA activity and a recent accident as a basis for initiating development of guidelines for an engine failure indications system. The AIA proposed that the initial focus of activity would be on assembling all the relevant facts and data associated with historical accidents and incidents, experience with various mitigation approaches, fixed-based and motion-based simulator capabilities and programs, and other relevant information appropriate for a thorough study of engine failures coupled with inappropriate crew response(s): PSM+ICR. The AIA wrote that they believed all parties would be best served by not prematurely focusing on a solution. Upon completion of this work, a decision gate would be applied before deciding how to proceed into additional phases that could suggest multiple paths and increased use of resources.

1.1 PHASE 1 SUMMARY.

The Boeing Phase 1 research project was a recommendation as part of the AIA/AECMA Project Report [2]. The study reviewed and analyzed 80+ in-service events related to PSM followed by ICR. These events ranged from hull loss and fatalities to benign incidents. The common thread was an engine malfunction with subsequent pilot action not appropriate to the condition (henceforth referred to as PSM+ICR). The PSM+ICR event data analysis, documented in reference 2, suggests, “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., the lack of a clear and explicit indication or annunciation that a PSM exists,” with “Surge and Powerloss [being] the major type PSMs associated with ICR.”

The research assessed four primary ICR categories:

- Rejected takeoff (RTO)above decision speed (RTO>V1)
- Loss of control (LOC)
- Shutdown or throttled good engine (SDTGE)
- Other (primarily procedurally related error)

The research concluded that PSM annunciations had ICR prevention potential in all but the RTO>V1 category. It was concluded that this ICR is most effectively addressed through training.

The Boeing Phase 1 Report suggested that historically the most significant PSM+ICR contributors are:

- Powerloss
- Surge
- Stuck thrust lever

It should be noted, however, that stuck thrust lever is a malfunction associated with older airplanes that use cables to control engine power setting. There are no known events of unannunciated stuck thrust lever failure conditions on modern airplanes with Full Authority Digital Engine Control (FADEC) engines.

The Boeing Phase 1 Report identified that prevention potential is associated with annunciation of PSM, identification of affected engine, and guidance to the appropriate procedure. It should be noted, however, that the prevention potential was not quantified.

The Boeing Phase 1 Report proposed follow-on work to assess the feasibility of detection and annunciation of the major malfunctions associated with PSM+ICR events. This resulted in the Phase 2 work package.

1.2 PHASE 2 SUMMARY.

The purpose of the Boeing Phase 2 research was to determine the feasibility and appropriateness of providing specific indications of PSMs to guide the pilot. The project was to include the development of criteria for engine malfunction detection and annunciation, including specific detection strategies and flight deck annunciations coupled with engine malfunction procedures.

This research project developed the term engine needs, which is referred to throughout this document. While the engine does not have needs that supercede the need for the pilot to fly the airplane first, the engine potentially has certain needs to clear or overcome the malfunction, and certain needs in order for thrust to be restored. This is consistent with the training video developed as a result of the reference 1 AIAAECMA Project Report.

For this study, engine needs were defined operationally as two categories:

- Integrity needs: What is required to prevent either damaging or increasing the damage to the engine?

- Thrust recovery needs: What is required to restore thrust?

1.3 STATEMENT OF WORK SUMMARY.

The Statement of Work for this contract involved six tasks. Figure 1-1 shows the interrelationships of these tasks. Task descriptions are provided below.

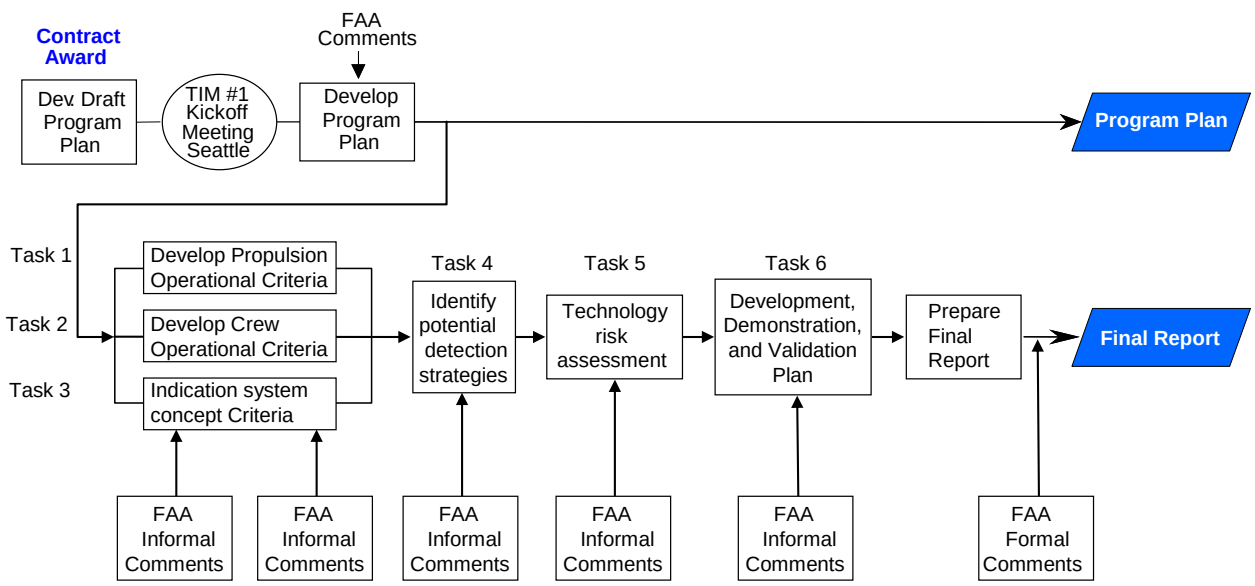


Figure 1-1. Task 1—Propulsion System Malfunction Detection Criteria Derived From Propulsion System Operational Criteria

1.3.1 Task 1—Propulsion System Malfunction Detection Criteria Derived From Propulsion System Operational Review.

The Boeing Team evaluated detection criteria related to operation of the engine during a PSM event. Items included in the consideration were malfunction characterizations, flight crew action required to maintain operation of the engine (e.g., what is needed to recover engine operation) or shut it down, information to the crew, timing of the information, ambiguity and reliability of the information, and flight phase dependencies.

The principal focus was sustained thrust anomaly (STA) PSMs and the propulsion FADEC control systems' ability to differentiate between failures to support crew awareness and responses (procedures).

The task involved coordination with two engine manufacturers in a supportive role: General Electric (GE) and Pratt & Whitney (PW).

1.3.2 Task 2—Propulsion System Malfunction Detection Criteria Derived From Crew Operational Review.

The Boeing Team developed a comprehensive, multidisciplinary, integrated approach to PSM annunciation based on desired crew awareness and action criteria. The team established PSM detection criteria and guidelines related to malfunction annunciation and operation of the airplane in the event of a sustained thrust anomaly based on

- review and summary of the supporting historical PSM+ICR event data analysis.
- review and evaluation of thrust-related nonnormal procedures.
- crew operational criteria (i.e., procedural practices and operational philosophy).

The assessment included:

- Which malfunction detection/annunciation is desired
- When detection/annunciation is desired (e.g., flight phase and power level)
- The detection time available to support, provide, and ensure meaningful annunciation and crew response
- The detection reliability desired (failure to alert and false alert)
- The envisioned flight deck indications and annunciations and the expected, desired, or possible crew response

1.3.3 Task 3—Propulsion System Malfunction Detection Criteria Derived From New Indication Concept Review.

With a focus that went beyond sustained thrust anomalies, the Boeing Team identified high-level operational and information criteria to provide a starting point for developing an information-based engine indication paradigm (in lieu of data parameters used today for crew awareness and response to nonnormal engine operation).

The information criteria were based on a high-level (e.g., crew procedures level) crew task and information analysis for a generic current or future generation airplane.

This analysis identified specific information and automation opportunities, issues that need to be resolved, and the technology and detection that need to be developed to enable an information-based engine display paradigm.

1.3.4 Task 4—Set of Potential Detection Strategies to Meet Criteria of Tasks 1, 2, and 3.

The Boeing Team identified a set of separate possible malfunction detection strategies from the information gathered in tasks 1, 2, and 3. The strategies were developed considering the systems and functionality available on modern FADEC systems as the baseline.

For each detection strategy, the parameter monitoring and sensing, hardware processing, software processing, supporting inputs, and resulting outputs were defined.

In addition, the strengths, weaknesses, limitations, and how well the detection strategy satisfied the operational and propulsion system criteria were assessed.

1.3.5 Task 5—Technology Risk Assessment and Down Selection of Strategies.

The Boeing Team conducted a technology feasibility and technology risk assessment of the set of the Task 4 candidate detection strategies relative to modern FADEC system capabilities.

The technology risk assessment, developed with GE and PW, identified potential technical hurdles, the technology readiness level of sensors, hardware, software, algorithms, and verification methods.

These technology risk assessments, in conjunction with the assessments of potential benefit, were used to guide a down selection of the strategies with a final recommendation on the strategy to pursue under Task 6.

1.3.6 Task 6—Development, Demonstration, and Validation Plan.

The Boeing Team prepared a plan for development, including demonstration and validation of technologies required for the propulsion malfunction detection and accommodation strategy selected in Task 5.

In preparation for identified follow-on research work, this task also categorized engine damage types by subcomponent and frequency of occurrence.

1.4 PHASE 2 CONCLUSIONS.

A suite of engine malfunction annunciations was developed that address STA-PSMs. The annunciations (table 1-1) have operational benefit for STA-PSMs, which were derived from the integrated propulsion system plus crew operational criteria, and provide prevention potential for a majority of the PSM+ICR events.

Table 1-1. Suite of STA-PSM Annunciations

Annunciation	Detected STA-PSMs	Pilot Procedure
Subidle	Includes flameout, surge/nonrecoverable stall*	Shutdown, restart (if no damage)
Continuous/multiple surges	An engine with repetitive surges	Retard thrust lever, readvance (if no damage)
Alternate mode	Failure of primary thrust parameter sensor	Select alternate mode operation
Other STA	Indicated thrust high or low, slow to respond	None (awareness only)

*The focus of this effort is STA, so an event where a surge occurs and recovers is not included.

In the process of assessing the implementation of these detection/annunciation capabilities for modern engines and airplanes, a cost-benefit study must be considered. The annunciation of technical highest risk is for continuous/multiple surge, due primarily to lack of sufficient engine data to validate the reliability of a detection algorithm. The higher the technical risk and reliability requirements, the less likely a cost-benefit can be shown. To reduce the technical risk, a program to modify a FADEC to capture high fidelity and high sample rate engine

continuous/multiple surge failure data in revenue service should be considered. This data is needed for the development of reliable detection algorithms.

The cost-benefit trade-off to retrofit only a suite of annunciations for existing airplanes or older engines is not likely to be favorable.

2. TASK 1—PROPULSION SYSTEM MALFUNCTION DETECTION CRITERIA DERIVED FROM PROPULSION SYSTEM OPERATIONAL REVIEW.

The Task 1 objective was to evaluate detection criteria related to operation of the engine during a PSM event. Considerations included PSM characterizations, annunciation to the pilot of the PSM (awareness), guidance on pilot procedure to address the malfunction and to recover thrust, timing of the information, ambiguity, and reliability of the information and flight phase dependencies.

The area of focus was STA engine malfunctions and the propulsion FADEC control system's ability to differentiate between failures to support crew awareness and action. This derived a complete suite of engine malfunction annunciations and strategies with potential operational benefit that could address the majority of the PSM+ICR events.

Although considered, the annunciation of engine damage, recoverable surges, or thrust lever splits were beyond the scope of this study. These conditions may warrant additional research.

Development of the Task 1 detection criteria required classifying engine failures into distinct categories with the root cause and PSM symptom as primary conditions. An engine failure database was developed and evaluated for flight dependence, timing, flight deck effect, engine needs, and FADEC action to recover, accommodate, mitigate, or annunciate. FADEC detection logic, frequency, and desired crew response were also evaluated. Nine symptom categories were identified and are shown in table 2-1.

Table 2-1. Engine STA-PSM Symptoms Categories

STA-PSM Symptom	Engine Characteristic	Recommended Pilot Action
Flameout	Quenching of combustor	Restart (if no apparent damage)
Surge/nonrecoverable stall	Sustained surge (hung, stalled)	Clear stall (retard thrust lever, shutoff fuel). Restart (if no apparent damage)
Continuous/multiple surge	Repetitive surging (surge, recover, surge, recover, and so on)	Clear surging (retard thrust lever). Operate engine normally or at a surge-free thrust level.
Thrust high or low (sensor)	Thrust shortfall or overthrust. Primary thrust set parameter sensor failure	Select ALTN operation
Thrust failed low (indicated)	Thrust shortfall. Thrust parameter is less than commanded thrust set parameter	Awareness (no specific procedure provided)
Thrust failed high (indicated)	Overthrust. Thrust parameter is higher than commanded thrust set parameter	Awareness (no specific procedure provided)
Engine slow to respond	Slow to accelerate or decelerate	Awareness (no specific procedure provided)
Thrust failed low (damage)	Thrust shortfall. Indicated thrust parameter is equal to commanded thrust parameter, but physical thrust is low (e.g., fan blade/area damage)	Awareness (no specific procedure provided)
Thrust oscillations	Thrust oscillations	Awareness (no specific procedure provided)

ALTN = Alternate mode

2.1 PROPULSION SYSTEM MALFUNCTION DATABASE DEVELOPMENT.

A database of all PSMs that could result in STAs was developed. The review was not limited to ICR-related malfunctions. Many engine malfunctions can result in the same or similar engine or flight deck symptoms or characteristics and may lend themselves to common annunciation. Based on a comprehensive review of the malfunctions database, malfunctions that cause the same symptoms were grouped for follow-on consideration of symptom annunciations.

The malfunctions in the database are drawn from Boeing Commercial Airplane (BCA)/GE/PW collective experience, as well as a review of Boeing internal database and significant fleet issues prior to May 2004.

For the review of the database, a thrust anomaly was considered sustained if it lasted for more than 5 seconds. Given this STA definition, the pop surge, or single recoverable surge, was not considered for this database analysis. However, for completeness and perspective, single surge events were evaluated as a part of this contract, and a summary is included in section 2.5.2.

The failure categories were based on gas path sources. Although lubrication system, bearing, and gearbox failures are major causes of engine removals (see section 7.3), these failures tend to result in pilot initiated shutdowns rather than STAs. Additionally, these do not directly cause STAs, but rather cause gas path conditions (such as blade failures) that can lead to thrust loss.

2.1.1 Terminology for PSM Database.

Different terms and definitions for propulsion malfunctions and symptoms (e.g., surge, stall, and rotating stall) are available within the industry. Therefore, the terminology, engine control systems, malfunction and symptom definitions used for this research and throughout this report are discussed in sections 2.1.1.1 through 2.1.1.2.

2.1.1.1 Turbofan Propulsion System Principle Control Components.

Figure 2-1 provides information on the turbofan propulsion system principal control components.

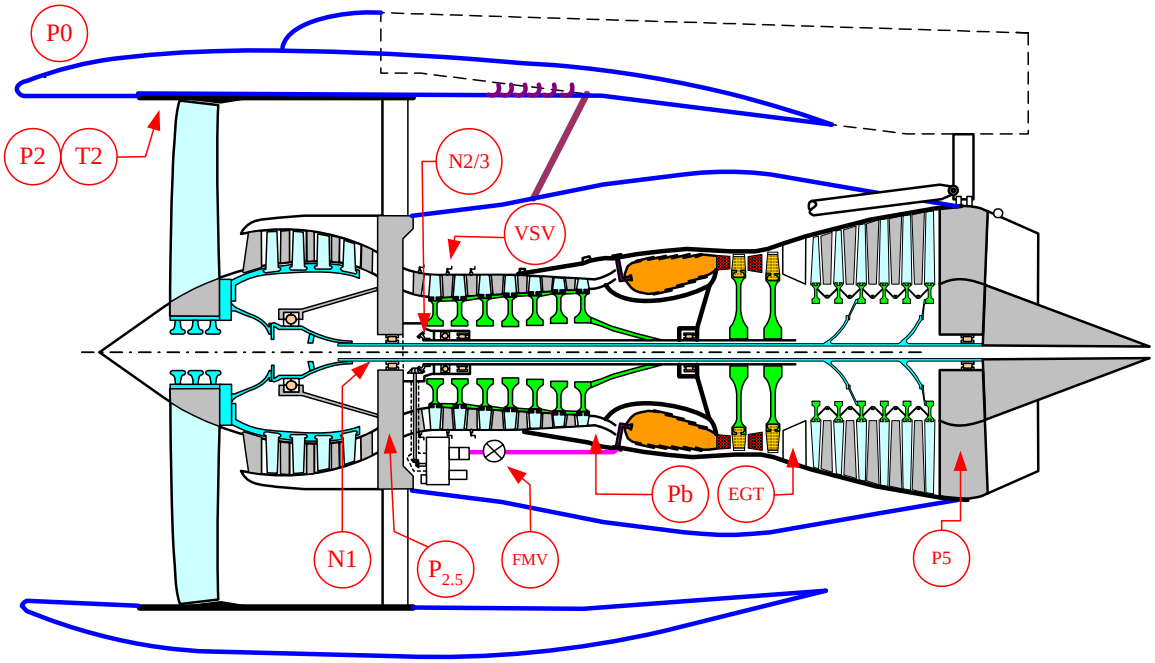


Figure 2-1. Turbofan Propulsion System Principal Control Components

Acronym	Control Component Description	Usage
N1	Fan /LPT Rotational Speed	Thrust Calculation
N2/N3	Core Rotational Speed	Fuel Scheduling, LPC, HPC Surge Margin Control
T2	Inlet Temperature	Fuel Scheduling, LPC, HPC Surge Margin Control
EGT	Exhaust Gas Temperature	Health Monitoring
P0	Ambient Pressure	Altitude Calculation
P2	Inlet Pressure	Fuel Scheduling, LPC, HPC Surge Margin Control
P2.5	HPC Inlet Pressure	LPC, HPC Surge Margin Control
PB/P30	Burner (HPC Discharge) Pressure	Fuel Scheduling, HPC Surge Margin Control
P5	Exhaust Pressure	Thrust Calculation
EPR	Engine Pressure Ratio (P5/P2)	Thrust Calculation
FMV	Fuel Metering Valve	Fuel Scheduling
VSV	Variable Stator Vanes	HPC Surge Margin Control
N1CMD	Commanded N1	Thrust Calculation
EPRCMD	Commanded EPR	Thrust Calculation

LPC = Low-pressure compressor
HPC = High-pressure compressor
LPT = Low pressure turbine

Figure 2-1. Turbofan Propulsion System Principal Control Components (Continued)

2.1.1.2 Recoverable Surge.

Surge refers to a condition where compressor airfoil flow separation has occurred. The term surge usually describes a transient phenomenon characterized by rapid flow separation and immediate reattachment. Surges audibly manifest themselves as pops or bangs depending on the degree of flow separation and compressor operating condition (pressure ratio and airflow). If the surge is violent enough, the attendant flow reversal can cause the combustion process to move forward out the inlet or aft out the tailpipe resulting in visible fireballs.

During a recoverable surge, as shown in figure 2-2, the airflow separates (resulting in a rapid compressor pressure drop) and then reattaches (resulting in the recovery to the original operating condition). A recoverable surge will complete the recovery cycle in a fraction of a second and regain the commanded thrust.

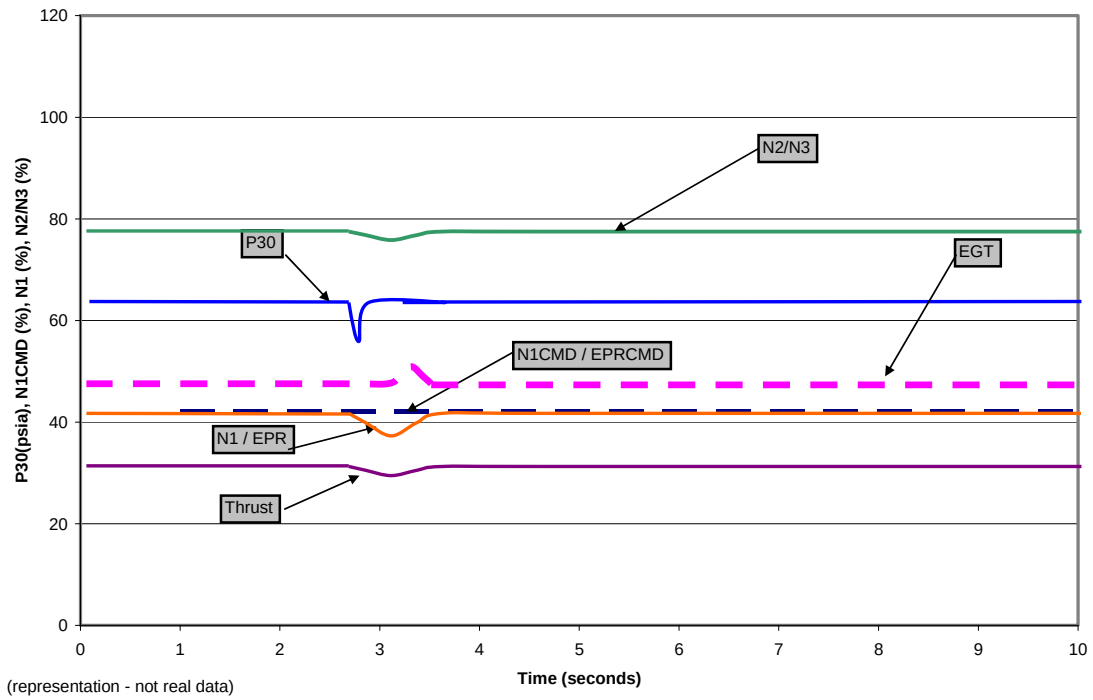


Figure 2-2. Recoverable Surge

2.1.1.3 Surge/Nonrecoverable Stall.

Surge followed by stall is the typical progression for a nonrecoverable surge: a sudden flow reversal, often but not always accompanied by flames out the front of the engine and noise, followed by the engine entering locked stall. Rotor speeds decay as airflow is reduced due to a stalled packet of blades rotating in the compressor. This resultant quasi-steady state condition, where one or more compressor stages have localized airflow separation on a sector of blades, is known as stall or locked stall. The combustor remains lit, and due to the lack of airflow, exhaust gas temperature (EGT) typically rises quickly (often exceeding limits) and the engine decelerates (usually below idle). Stalls are sometimes accompanied by audible engine rumble.

Note that the terms rotating stall, rollback, rundown, and locked stall have been used in the industry to mean the resultant condition of a nonrecoverable surge. In this document, the term surge/nonrecoverable stall is used for this condition. Figure 2-3 represents a surge/ nonrecoverable stall.

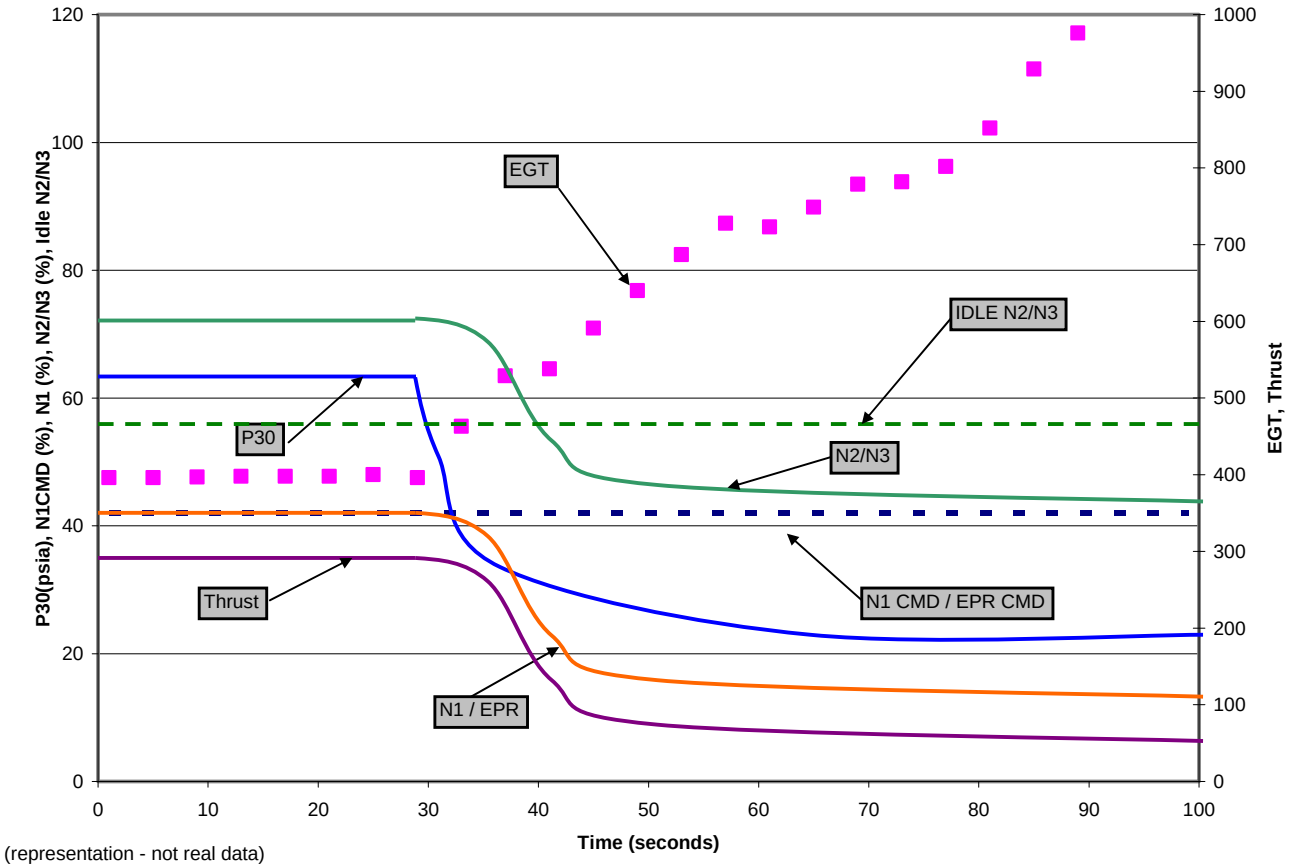


Figure 2-3. Surge/Nonrecoverable Stall

Surge can be followed by flameout if the surge is of a sufficient violence to extinguish the flame. In this case, the outcome of the event would be identical to a flameout. The thrust decay characteristic can be generalized as rapid.

2.1.1.4 Continuous/Multiple Surge.

A continuous multiple surge is characterized by two or more repetitions of a surge and recovery cycle (surge, recover, surge, recover, and so on).

The time interval and thrust decay characteristic of this malfunction is not quantifiable, since there are many failure conditions that could result in this symptom.

A single recoverable surge could have multiple subevents that can still be considered part of a single recoverable surge (i.e., there could be several distinct surges in the first ~0.5 second). The distinction between a single and a continuous/multiple surge is that a subsequent surge ~>0.5 seconds after the first is an indication that the engine is not able to recover and requires a reduction in fuel flow (FF) to clear the surges.

There also can be two surges separated by a long enough time (~>20 seconds) that they would be characterized as distinct recoverable surges. These are not characterized as continuous/multiple surges, since it is unlikely that a reduction in FF alone will clear the surging and allow the engine to recover thrust. It is more likely environmental (ambient conditions), transient engine control dependency, propagation of damage, or flight phase condition causing intermittent surging. Figure 2-4 represents a continuous/multiple surge.

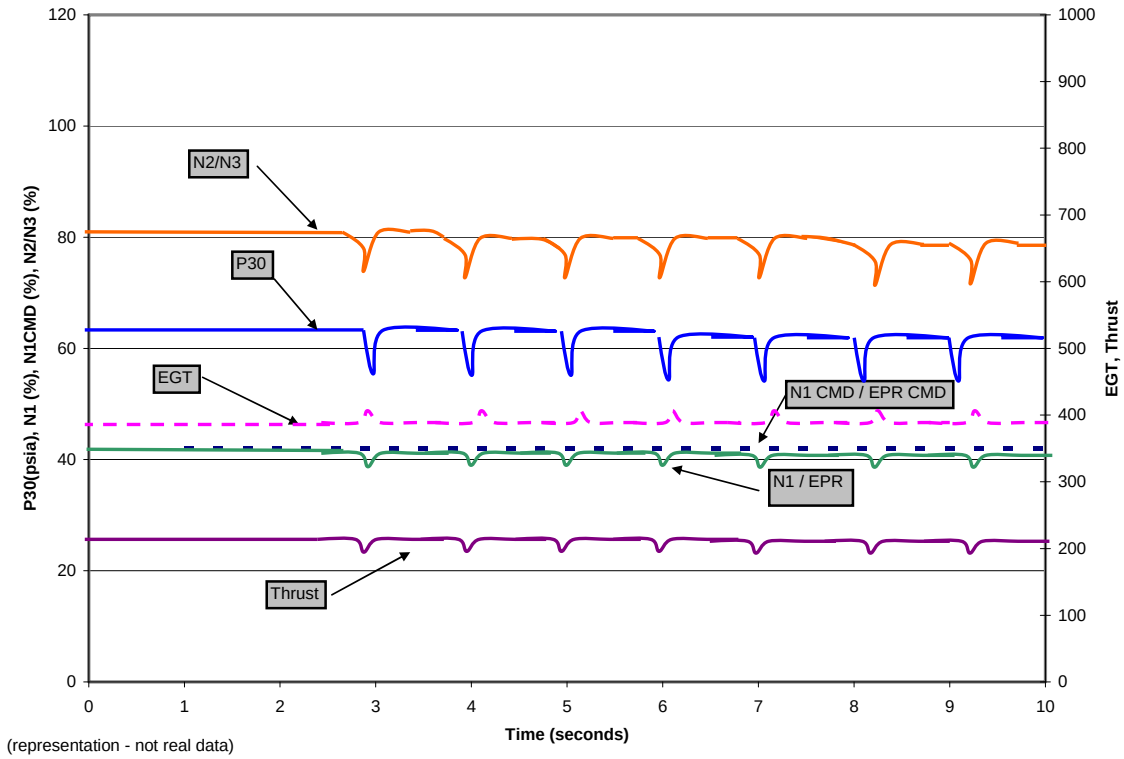


Figure 2-4. Continuous/Multiple Surge

2.1.1.5 Rotating Stall.

A rotating stall is a sector of stalled compressor blades. There are three types of rotating stalls: (1) fan rotating stall, (2) low-pressure/intermediate-pressure (LP/IP) compressor rotating stall, and (3) high-pressure (HP) compressor rotating stall. A rotating stall does not cause an operationally significant thrust loss unless it deteriorates to a surge/nonrecoverable stall. In the database reviewed for this study, the term rotating stall denotes only the occurrences that are not preceded by a surge. Rotating stalls that were preceded by a surge were counted as surge/nonrecoverable stall events.

- Fan rotating stall: a sector of stalled fan blades causing airflow blockage and loss of fan pumping capability. If the engine controls to engine pressure ration (EPR), the response to hold EPR causes the N1 to climb, possibly accompanied by an EGT climb. An N1 controlled engine will see the engine pressures and core speed drop. The loss of fan work can cause the low-pressure compressor (LPC) operating line to rise, and it is possible for a core surge to occur. There is likely to be a small thrust loss, but it is not likely to be

sustained or operationally significant. The thrust loss is less discernable when controlling to EPR.

- LP/IP compressor rotating stall: a sector of stalled compressor blades, typically not accompanied by noise. With this type of stall, engine airflow is disrupted, but parameters stay within limits with some EGT rise. An LP/IP compressor rotating stall tends toward a full stall quickly at high power and slowly at low power. Also, a rotating stall at low power will progress to a full stall with a commanded thrust increase. This condition can occur at mid-low power when the operating line meets the surge line on some compressors. There is not likely to be a discernable thrust loss. Figure 2-5 represents an LP/IP compressor rotating stall.

- HP compressor rotating stall: on rare occasions part span or localized HP compressor rotating stall can occur, but is unlikely to be detected without high-response pressure instrumentation. These instabilities are likely to result in full stall or disappear with thrust lever movement.

Note that the terms rotating stall, rollback, rundown, and locked stall have been used in the industry to mean the resultant condition of a nonrecoverable surge. In this document, the term Surge/nonrecoverable stall is used for this condition.

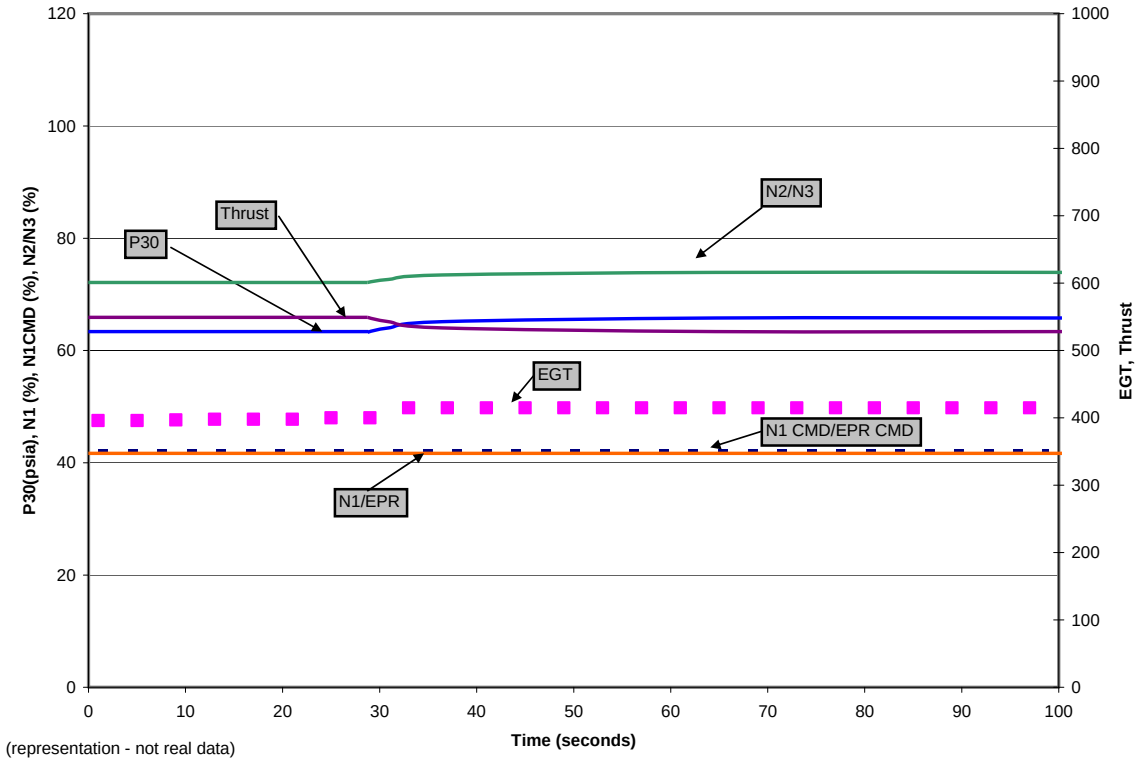


Figure 2-5. The LP/IP Compressor Rotating Stall

2.1.1.6 Flameout.

A flameout occurs when combustion is quenched, all engine parameters drop subidle, and EGT decays. The thrust decay characteristic can be generalized as rapid for a flameout. Figure 2-6 represents a flameout malfunction.

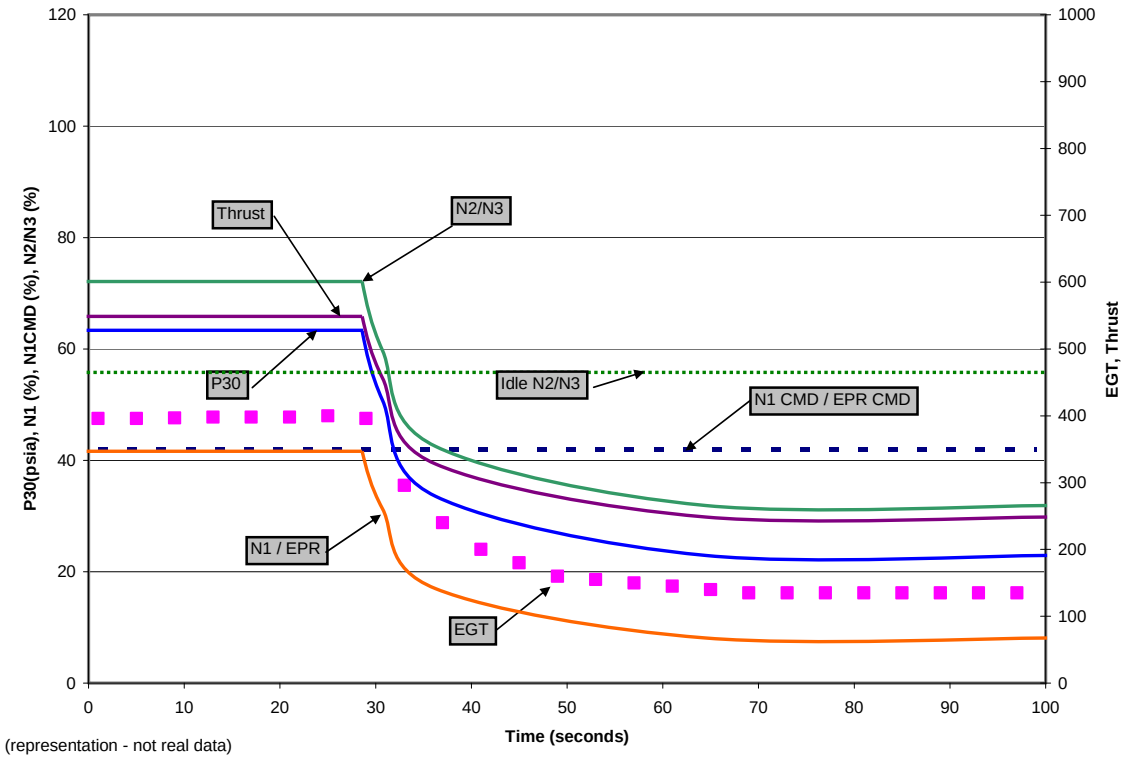


Figure 2-6. Flameout

2.1.1.7 Thrust Failed Low (Indicated).

The characterization of a thrust failed low (indicated) malfunction is when both actual and indicated thrust are less than commanded. This condition could be caused by either an engine losing thrust after power set (engine cannot maintain target thrust lever setting, rotor speeds, and FF drop) or not accelerating when command is increased (thrust lever is advanced).

One type of thrust failed low anomaly is rollback. A rollback is characterized as the condition where the engine cannot schedule enough fuel to maintain the commanded power setting (for example, due to airflow blockage or inclement weather) and the engine speed decays. This condition is included in the thrust failed low (indicated) category. Often a rollback progresses to the point where combustion can no longer be supported and a flameout occurs as covered in section 2.1.1.6.

Another type of anomaly is where the control is operating on a limiting function where FF is purposely being restricted to protect a limit, therefore, commanded thrust is not achievable.

The timing and thrust decay characteristic of this condition is not quantifiable because there are many failure conditions that could result in this symptom. Figure 2-7 represents a thrust failed low (indicated) malfunction.

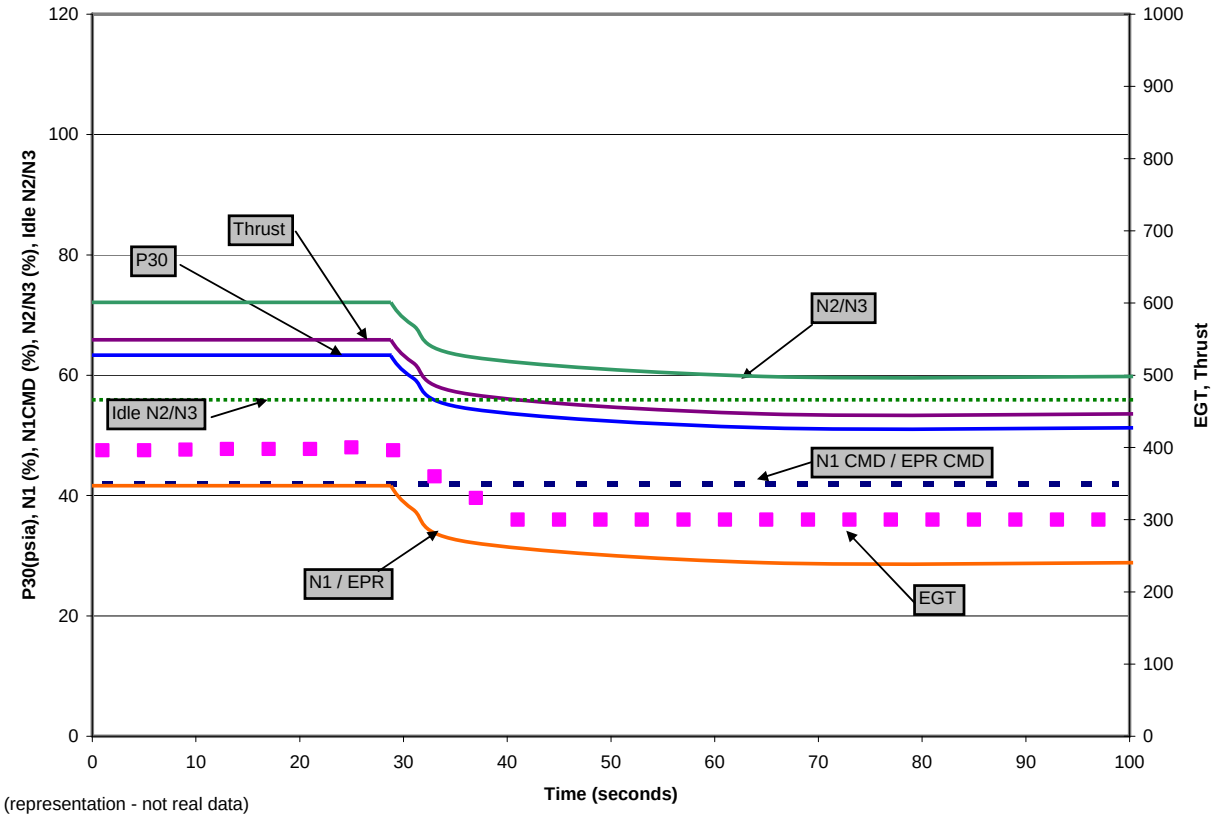


Figure 2-7. Thrust Failed Low (Indicated)

2.1.1.8 Thrust Failed Low (Damage).

The characterization of a thrust failed low (damage) malfunction is the indicated thrust that matches the target thrust, but thrust is physically lower. The most likely cause is engine damage (e.g., fan blade damage or nozzle damage, which results in open nozzle area).

The thrust loss would be more pronounced when controlling to N1. The thrust loss would be less pronounced when controlling to EPR.

The time and thrust decay characteristic of this condition is not quantifiable because there are many failure conditions that could result in this symptom. Figure 2-8 represents a thrust failed low (damage) malfunction.

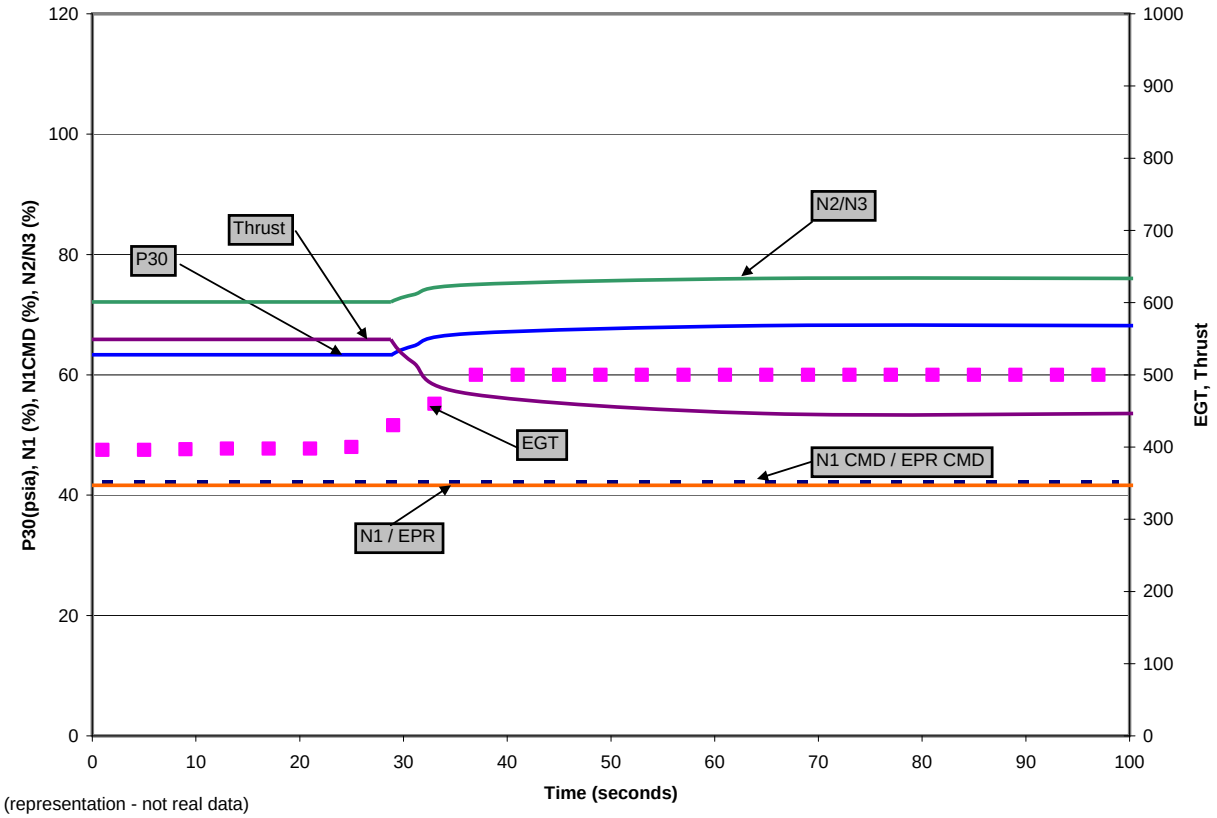


Figure 2-8. Thrust Failed Low (Damage)

2.1.1.9 Thrust Failed High (Indicated).

The characterization of a thrust failed high (indicated) condition is both actual and indicated thrust are greater than commanded. This condition could be either an engine increasing thrust from power setting or not decelerating when the command is decreased (thrust lever retarded).

The timing and thrust increase characteristic of this condition is not quantifiable because there are many failure conditions that could result in this symptom. Figure 2-9 represents a thrust failed high (indicated) malfunction.

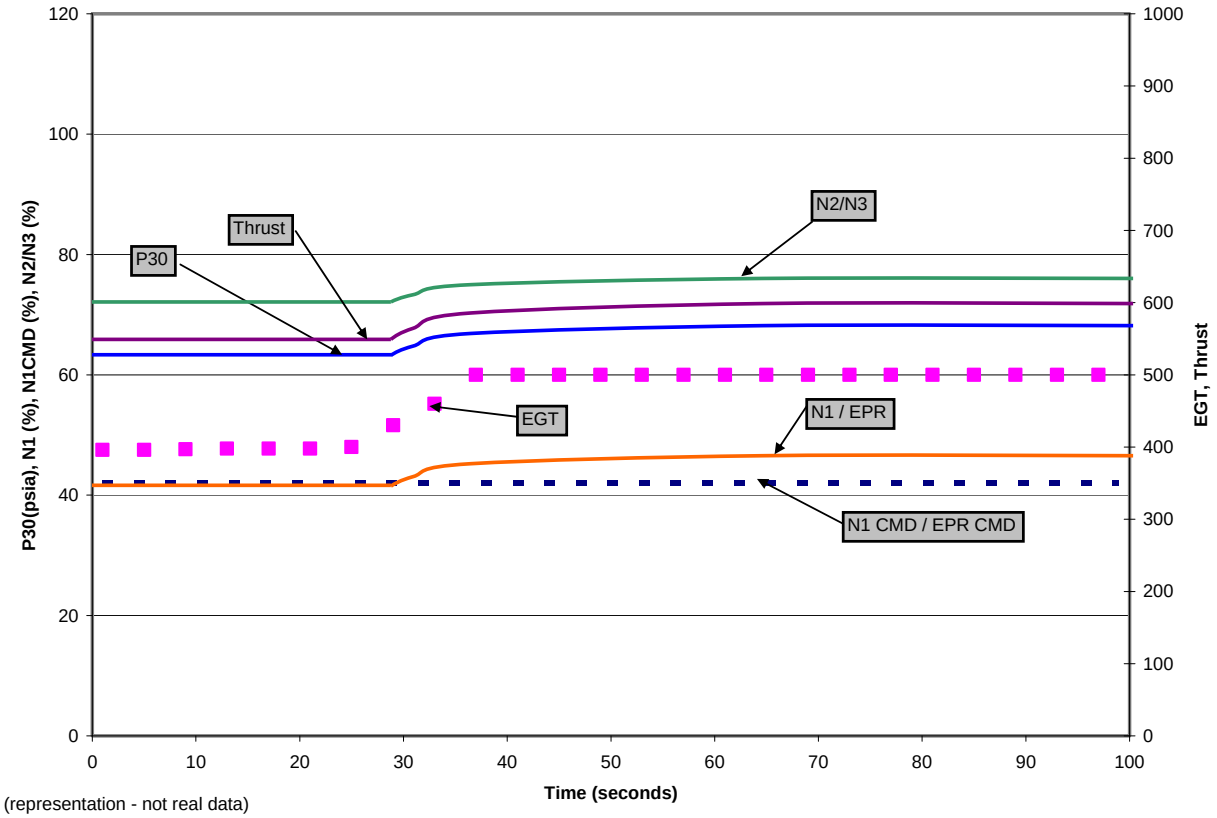


Figure 2-9. Thrust Failed High (Indicated)

2.1.1.10 Thrust Failed High (Sensor).

The characterization of a thrust failed high (sensor) malfunction is the indicated thrust that matches the commanded thrust, but the actual thrust is higher. This is primarily caused by a failure of the sensor used to measure thrust (e.g., EPR). In this case, the measurement is erroneously low so fuel is increased to bring the measured parameter to command increasing actual thrust. In this condition, symmetric thrust levers would produce asymmetric thrust. Selection of alternate mode (ALTN) is required to correct this condition. ALTN uses a simpler thrust setting schedule, allowing the pilot to achieve the desired thrust with symmetric thrust levers.

The timing and thrust increase characteristic of this condition is not quantifiable since there are many failure conditions that could result in this symptom. Figure 2-10 represents a thrust failed high (sensor) malfunction.

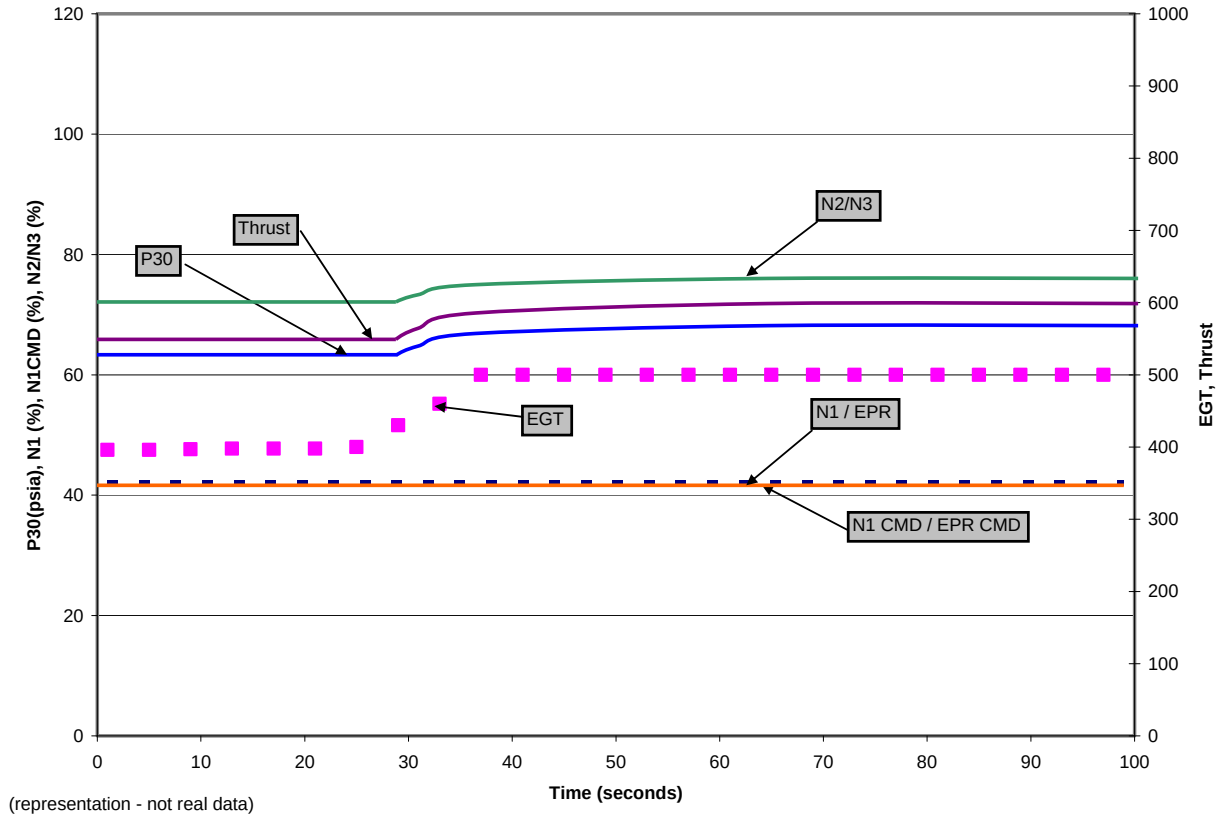


Figure 2-10. Thrust Failed High (Sensor)

2.1.1.11 Thrust Failed Low (Sensor).

The characterization of a thrust failed low (sensor) malfunction is the indicated thrust that matches the commanded thrust, but the actual thrust is physically lower. This failure is primarily caused by a failure of the sensor used to measure thrust (e.g., EPR, T2). In this case, the measurement is erroneously high; therefore, fuel flow should be decreased to bring the measured parameter to command, decreasing actual thrust. In this condition, symmetric thrust levers would produce asymmetric thrust. Selection of ALTN is required to correct this condition. ALTN uses a simpler thrust setting schedule, allowing the pilot to achieve the desired thrust with symmetric thrust levers.

The timing and thrust decay characteristics of this condition are not quantifiable because there are many failure conditions that could result in this symptom. Figure 2-11 represents a thrust failed low (sensor) malfunction.

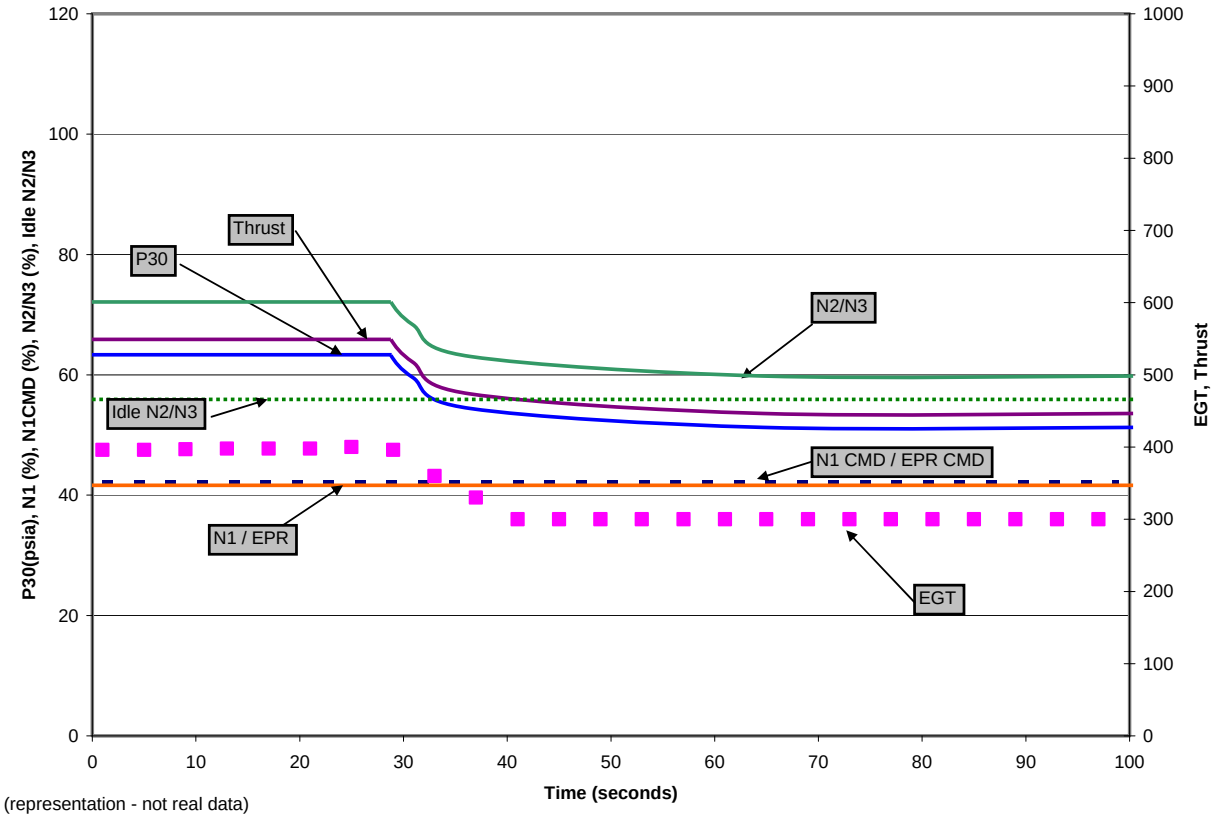


Figure 2-11. Thrust Failed Low (Sensor)

2.1.1.12 Engine Slow to Respond.

The characterization of an engine slow to respond malfunction is an engine that is slow to accelerate or decelerate to command. This condition can be considered an STA if the transient thrust characteristic differs significantly from the normal transient characteristic.

The timing and thrust characteristics of this condition is not quantifiable because there are many failure conditions that could result in this symptom. Figure 2-12 represents an engine slow to respond malfunction.

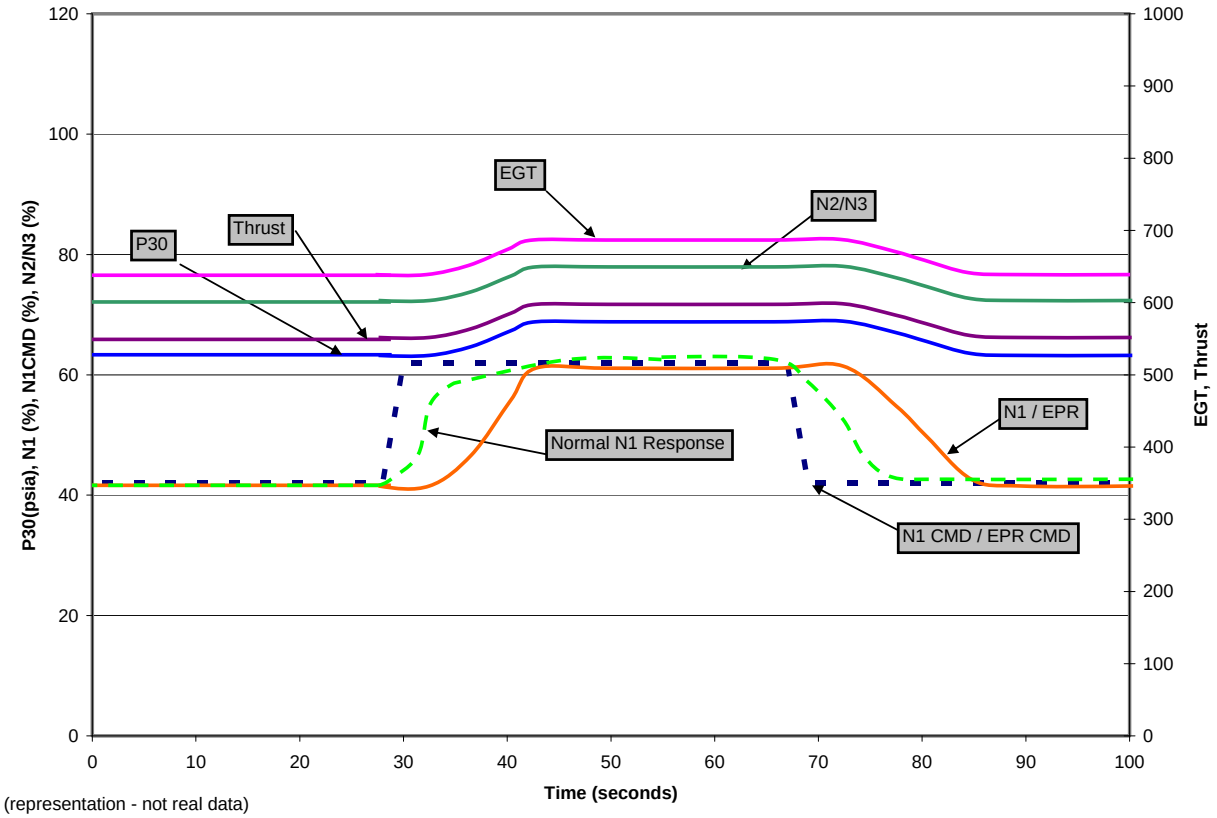


Figure 2-12. Engine Slow to Respond

2.1.1.13 Thrust Oscillations.

The characterization of a thrust oscillation malfunction is uncommanded thrust that increases and decreases from power set command.

In this report, thrust oscillations refer to oscillations having a mean thrust equal to the commanded thrust. Failures, which result in a change in the mean thrust (whether high or low), but also include oscillations, are categorized as thrust failed high or thrust failed low.

The timing and thrust characteristics of this condition are not quantifiable because there are many failure conditions that could result in this symptom. Figure 2-13 represents a thrust oscillation malfunction.

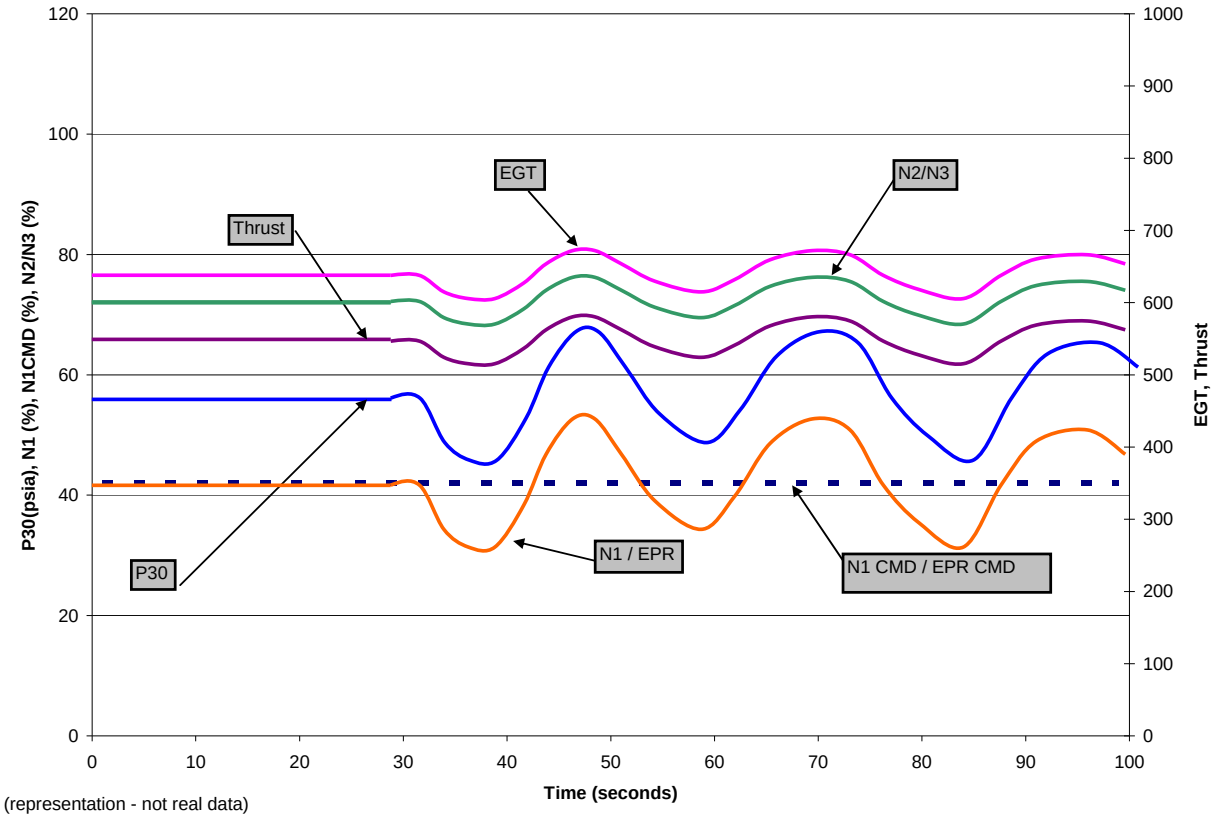


Figure 2-13. Thrust Oscillations

2.1.2 Propulsion System Malfunction Database Analysis.

The STA-PSMs were grouped both by gas path root cause and by symptom (if the other analysis categories were significantly affected, e.g., flight deck effects, etc.). Some root cause failures are not listed directly (e.g., a lube system, gearbox, bearing) because they are included indirectly. These components lead to an STA event because they cause a down stream effect on a gas path component (compressor or turbine damage).

The assessments of the engine control systems capability to detect, accommodate, and recover from the failure are based on a modern FADEC system. In many cases, the types of parameters and computing power required for detection are currently not available on older systems. Although the focus of this study was on FADEC engines, non-FADEC malfunctions were included for completeness to ensure all possible types of failure conditions and symptoms were compared and analyzed.

The STA-PSM categorization resulted in 33 distinct database entries. These entries are listed in table 2-2. The 33 STA-PSMs were analyzed using the characteristics of table 2-3. The results of this analysis are provided in tables 2-4 to 2-20.

Table 2-2. Sustained Thrust Anomaly PSM Database Entries

Failure No.	Root Cause	Sustained Thrust Anomaly
1	Fan damage	Loss of physical thrust
2	Inlet distortion	Surge/nonrecoverable stall
3	Inlet distortion	Thrust shortfall
4	Compressor damage	Surge/nonrecoverable stall
5	Compressor damage	Slow acceleration
6	Reduced compressor surge margin, deterioration	Surge/nonrecoverable stall
7	Reduced compressor surge margin, design issue	Surge/nonrecoverable stall
8	Reduced compressor surge margin, design issue	Surge/flameout
9	Reduced compressor surge margin, malfunction	Continuous/multiple surge
10	Reduced HP compressor surge margin	HP rotating stall
11	Reduced LP/IP compressor surge margin	LP rotating stall
12	Stability bleed failure	Surge/nonrecoverable stall
13	Stator vanes failed more open	Surge/nonrecoverable stall
14	Stator vanes failed more closed	Thrust shortfall
15	Stator vane damage	Slow acceleration
16	FOD	Surge/nonrecoverable stall
17	FOD	Flameout
18	Turbine blade damage	Surge/Nonrecoverable stall, flameout, continuous/ multiple surge
19	Turbine blade damage	Slow acceleration
20	Nozzle area failure	Thrust shortfall
21	Expanded tip clearance	Slow acceleration
22	Significant engine damage	Surge/nonrecoverable stall, surge/flameout
23	Thrust set parameter shift	Overthrust/thrust shortfall
24	PB loss	Thrust shortfall
25	PB shift high	Hung deceleration
26	PB shift low	Slow acceleration
27	Fuel leak	Flameout, thrust shortfall
28	Fuel metering valve failed open	Overthrust
29	Fuel metering valve failed closed	Flameout, thrust shortfall
30	ECS check valve failure	Surge/nonrecoverable stall
31	A/C bleed switching	Thrust oscillations
32	T2 sensor failure	Overthrust/thrust shortfall
33	Deceleration schedule margin loss	Hung deceleration

ECS = Environmental control system; PB = burner pressure; FOD = Foreign object damage

Table 2-3. Malfunction Database Analysis Characteristics Definitions

Engine problem causes and STA-PSM symptom	The root cause of the engine malfunction The STA symptom of the malfunction Notes: (1) multiple symptoms may result in separate database entries and (2) recoverable events are not considered in this analysis.
More details of the event	Examples of the event or the event causes
Flight phase	If the engine malfunction only occurs in specific phases of flight, it is noted here.
High or low power?	If the engine malfunction only occurs at one power level, it is noted here.
Flight deck effect	List of all possible flight deck effects, including sounds (though not all events will have all effects, e.g., a surge at low power may not be audible).
Engine integrity needs	The action that would be desirable from the standpoint of engine integrity (to prevent incurring damage), not necessarily to recover thrust. Single engine events were considered, since the engine integrity needs could then be evaluated independently from the airplane needs.
Typical of all engines?	Captures the case where specific engine designs were susceptible to this malfunction, or the design precluded the malfunction
Engine control action to recover	What is currently available on a modern airplane, or can be done in the future, to address root cause of PSM.
FADEC fault accommodation	What the control can do to detect the imminent onset of the malfunction, or make the outcome less severe (to prevent or mitigate).
FADEC detection logic	What characteristics of the malfunction can be used for annunciating the specific problem (to distinguish between different failures conditions).
Frequency of occurrence	Rare (has happened), Occasional (1-10 per year), Frequent (>10 per year). This category will help guide the value of detection and annunciation for each type of malfunction. (Based on engineering assessment.)
Desired crew response	What action could be taken by the pilot to recover thrust or prevent further damage to the engine. (This is referred to thrust recovery needs in the subsequent sections.)
Timing for engine integrity needs	If action has desired timing needs to prevent further damage or loss of engine integrity
Comments	If further data is needed to clarify the malfunction

Table 2-4. Malfunction Database Analysis, Numbers 1 and 2

Malfunction No.	1	2
Engine problem causes and STA-PSM Symptom	Fan damage Loss of physical thrust, fan stall, core surge is possible	Inlet distortion Fan stall, core surge/nonrecoverable stall
More details of the event	Example: bird ingestion	Examples: lighting, ice or water ingestion, for tail mounted engines: distortion from wing
Flight phase	Any	Takeoff—cross-or tailwind, high angle of attack
High or low power?	Most likely at high, could be any. At high power, most likely to incur damage	Any
Flight deck effect	Vibration (tactile and noise), smell. Potential increase in EGT due to loss of fan efficiency.	Fan growl, vibration, if severe, and core stalls, then bang, noise depends on power level (and subjectivity of pilot), EGT rising, parameters dropping
Engine integrity needs	Possible power adjustment due to vibration, depends on extent of damage	Shutdown, restart, avoid inlet distortion cause
Typical of all engines?	Yes	Yes
Engine control action to recover	None	Opening LPC bleeds may help recovery
FADEC fault accommodation	Prevent: annunciate health shift. Mitigate: surge recovery	Prevent: none (external influences) Mitigate: surge recovery
FADEC detection logic	Conceivable fan damage detection. Perhaps diagnostic monitoring of engine health would detect performance shift	Inlet pressure probes could detect distortion in conjunction with stall detection
Frequency of occurrence	Occasional	Rare
Desired crew response	Possible power adjustment due to vibes, depends on extent of damage	Increase airplane airspeed or reduce thrust
Timing for engine integrity needs	None, unless exceeding EGT or vibration limits	Timely/prompt response desired, due to stall
Comments	None	Likely that inlet distortion will be recoverable, and increased airspeed will correct

Table 2-5. Malfunction Database Analysis, Numbers 3 and 4

Malfunction No.	3	4
Engine problem causes and STA-PSM symptom	Inlet distortion Failure to achieve thrust (EPR)	Compressor blade damage Surge/Nonrecoverable stall
More details of the event	Ambient Pressure (P0) probe sees separated flow, low reading results in fuel reduction.	Examples: blade/vane failure, lining loss, open tip clearances, bearing failure
Flight phase	Takeoff—cross- or tailwind	Any
High or low power?	High	Any
Flight deck effect	Indicated engine EPR reads high, so FF reduced	Bang, noise depends on power level (and subjectivity of pilot), vibrations, EGT rising, parameters dropping
Engine integrity needs	Keep going—increase airspeed	Shutdown, depending on extent damage, restart, operate at full or reduced power, with caution
Typical of all engines?	Older EPR engines only (many fixed with control system changes or new probe location changes)	Yes
Engine control action to recover	Current: engine inlet pressure probe fault detection.	None
FADEC fault accommodation	Prevent/mitigate: logic to detect condition.	Prevent: annunciate health shift. Mitigate: surge recovery
FADEC detection logic	Inlet pressure probes could detect	Conceivable core damage detection, except for severe HP compressor blade damage (such as separation)
Frequency of occurrence	Rare	Occasional
Desired crew response	Increase airplane airspeed, or reduce thrust	Possible power adjustment due to vibrations, depends on extent of damage
Timing for engine integrity needs	None	Timely/prompt response desired (due to stall)
Comments	Likely that inlet distortion will be recoverable, and increased airspeed will correct	None

Table 2-6. Malfunction Database Analysis, Numbers 5 and 6

Malfunction No.	5	6
Engine problem causes and STA-PSM symptom	Compressor blade damage Slow engine acceleration, hung acceleration	Reduced compressor surge margin—no damage—deterioration surge/ nonrecoverable stall
More details of the event	Example: FOD ingestion	None
Flight phase	Any	Any
High or low power?	Any	Any
Flight deck effect	Parameter mismatch during acceleration, vibration	Bang, noise depends on power level (and subjectivity of pilot), EGT rising, parameters dropping.
Engine integrity needs	No imminent need. May need to monitor and potentially shutdown to avoid further damage.	Shutdown, restart, operate at lower power, minimize rapid thrust lever movements, refurbish engine
Typical of all engines?	Yes	Older engines only
Engine control action to recover	None	Current: If above idle: igniters and recovery bleeds. If below idle: auto-re-light/auto-start logic (fuel, igniters, bleeds)
FADEC fault accommodation	Prevent: annunciate health shift Mitigate: none	Very difficult to prevent initial event. More practical is to prevent engine from going subidle. Can then modify logic (fuel schedules) to slow down transient (reasonable for get-home mode only). Conceivable to annunciate to pilot for slow thrust lever movements to mitigate transient working line rise. Adding bleed may be helpful on some engines, and is dependent on which compressor is deteriorated. Difficult to distinguish surge due to deterioration from other destabilizing events such as distortion.

Table 2-6. Malfunction Database Analysis, Numbers 5 and 6 (Continued)

Malfunction No.	5	6
FADEC detection logic	Conceivable core damage detection. Perhaps diagnostic monitoring of engine health would detect performance shift.	Although conceptually conceivable to develop logic to detect compressor operating line relative to surge line, not practical to implement. Reasons: Surge line moves with deterioration, clearances, efficiencies; none of these are detectable. Compressor operating line shifts with deterioration, which is detectable. It is usually an external disturbance (wake/inlet) that ultimately causes the deteriorated engine's compressor operating line to reach the surge line.
Frequency of occurrence	Occasional (older engines)	Rare (most surges caused by deterioration self-recover)
Desired crew response	No imminent need. May need to monitor and potentially shutdown to avoid further damage.	Clear stall (cycle fuel switch)
Timing for engine integrity needs	None	Timely/prompt response desired due to stall
Comments	None	Hard to understand exactly what condition the engine is really in. Even in the test cell, usually takes several factors to show up at the same time—bleed, altitude effects, surge causing rubs. Automated accommodation not worth pursuing. Checklist for pilot more appropriate (to rule out other factors such as wake turbulence). Need significant amount of instrumentation. Deteriorated engines: deterioration occurs very slowly. An instability is most likely to self recover, so a STA from deterioration is rare.

Table 2-7. Malfunction Database Analysis, Numbers 7 and 8

Malfunction No.	7	8
Engine problem causes and STA-PSM symptom	Reduced compressor surge margin—no damage—design issue. Surge/nonrecoverable stall	Reduced compressor surge margin—no damage—design issue. Surge/flameout
More details of the event	Compressor designed without sufficient margin to accommodate all operating conditions or stability bleeds not scheduled to open at the required conditions	None
Flight phase	Any	Any
High or low power?	Any	Any
Flight deck effect	Bang, noise depends on power level (and subjectivity of pilot), EGT rising, parameters dropping	Bang, noise depends on power level and subjectivity of pilot, all parameters dropping, engine goes subidle
Engine integrity needs	Shutdown, restart, operate at full or reduced power with caution, minimize rapid thrust lever movements	Restart; operate at full or reduced power with caution, minimize rapid thrust lever movements
Typical of all engines?	Yes	Yes
Engine control action to recover	Current: If above idle: igniter and recovery bleeds. If below idle: clear stall (shutdown). Restart	Current: If above idle: igniter and recovery bleeds. If below idle: autostart/auto-re-light logic (fuel, igniters, bleeds).
FADEC fault accommodation	Prevent: too unique to prevent. Mitigate: surge recovery	Prevent: too unique to prevent. Mitigate: surge recovery
FADEC detection logic	Too unique to warrant effort to design detection logic	Too unique to warrant effort to design detection logic
Frequency of occurrence	Occasional on introduction of engine type. Rare after mature	Occasional on introduction of engine type. Rare after mature
Desired crew response	Clear stall (cycle fuel switch)	Pilot action depends on FADEC logic (modern engines have subidle automatic restart available)
Timing for engine integrity needs	Timely/prompt response desired (due to stall)	None
Comments	None	None

Table 2-8. Malfunction Database Analysis, Numbers 9 and 10

Malfunction No.	9	10
Engine problem causes and STA-PSM symptom	Reduced compressor surge margin—malfunction Continuous/multiple surges	Reduced HP compressor surge margin Localized HP rotating stall, no response to thrust lever
More details of the event	Example: compressor vane/blade failure, damage, design deficiency, control malfunction	Not preceded by a surge
Flight phase	Takeoff	Descent, starting (in-flight, on-ground), taxi operation
High or low power?	High	Typically lower, often associated with thrust lever transient
Flight deck effect	Multiple loud bangs, possible EGT and vibration variation, possible rotor speed variation	Typically not noticeable to crew until progresses to full stall. EGT rising, parameters dropping, goes subidle
Engine integrity needs	Retard thrust lever until engine stops surging. Continue operation cautiously. If engine does not stop surging at idle, shutdown.	Shutdown, if no damage, restart, operate at full or reduced power, with caution. Avoid adverse thrust lever movements.
Typical of all engines?	Yes	No, depends on subtle compressor design aspects, and where the idle floor is set.
Engine control action to recover	Future: sensing repeated drops in PB, deltas in EGT and vibrations, control could enhance detection	Future: high-response pressure sensors. Sense pressure rise across compressor inter-stages
FADEC fault accommodation	Prevent: monitoring tip clearance and blade efficiency is not currently feasible Mitigate: surge recovery	Prevent: monitoring tip clearance and blade efficiency not feasible. Is currently not feasible Mitigate: surge recovery when progresses to full stall

Table 2-8. Malfunction Database Analysis, Numbers 9 and 10 (Continued)

Malfunction No.	9	10
FADEC detection logic	Technology exists to develop detection logic (repeated events).	Commercial hardware technology exists (temp (EGT)/pressure(PB)/ speed) probes). Software development needs to develop robust algorithms. Distinguishing between HP/LP requires instrumenting both compressors. Smaller pressure disturbance magnitudes make detection more difficult. This may require high-response sensors, which currently have reliability issues.
Frequency of occurrence	Occasional	Rare (mostly with malfunction or damage)
Desired crew response	Retard thrust lever to idle	Shutdown engine
Timing for engine integrity needs	Timely/prompt response desired (due to surging)	Not desirable to allow condition to persist for durability reasons. Thrust may not be available on subsequent accelerate/decelerate
Comments	After stalling has been cleared, whether thrust lever can be advanced without stall depends on the cause.	Would become aware condition exists when thrust change is commanded. On thrust lever advance, will not increase in thrust or may stall. On thrust lever retard will go into full stall.

Table 2-9. Malfunction Database Analysis, Numbers 11 and 12

Malfunction No.	11	12
Engine problem causes and STA-PSM symptom	Reduced LP/IP compressor surge margin LP/IP rotating stall, no response to thrust lever	Stability bleed valve stuck in closed position. Fails to follow scheduled position. Surge/ nonrecoverable stall
More details of the event	Not preceded by surge	None
Flight phase	Descent, any time thrust lever is retarded	Takeoff power set, descent, any engine deceleration to mid-low power, any acceleration from low power
High or low power?	Typically lower, often associated with thrust lever transient	Mid-to-low power
Flight deck effect	Subtle parameter changes, thrust lever advance will result in HP rotating stall (go subidle)	Bang, noise depends on power level, parameters dropping
Engine integrity needs	Shutdown, if no damage, restart. Operate at full or reduced power, with caution. Avoid adverse thrust lever movements.	Shutdown, attempt restart, operate at idle
Typical of all engines?	No, depends on subtle compressor design aspects, and where the idle floor is set.	Yes
Engine control action to recover	Future: high response pressure sensors. Sense pressure rise across compressor interstages.	None (hardware failure)
FADEC fault accommodation	Prevent: monitoring tip clearance and blade efficiency not feasible in the near term. Mitigate: surge recovery when progresses to full stall	Prevent: Sense bleed valve positions and accommodate using other bleeds on detected failure (get home mode). Mitigate: Slow accelerate/decelerate
FADEC detection logic	Commercial hardware technology exists (temp (EGT)/pressure(PB)/ speed) probes). Software development needs to develop robust algorithms. Distinguishing between HP/LP requires instrumenting both compressors. Smaller pressure disturbance magnitudes make detection more difficult. This may require high-response sensors, which currently have reliability issues.	Bleed valve position sensors (not currently found to be economical. Sensors tend to be less reliable than systems they are sensing). Logic to track EGT rise on scheduled bleed valve command changes, operating line shifts

Table 2-9. Malfunction Database Analysis, Numbers 11 and 12 (Continued)

Malfunction No.	11	12
Frequency of occurrence	Rare	Occasional
Desired crew response	Shutdown engine	Restart, operate at idle
Timing for engine integrity needs	Desirable to clear condition, for durability reasons. Thrust may not be available on subsequent accelerate/ decelerate command.	Timely/prompt response desired (due to stall)
Comments	Would become aware condition exists when thrust change is commanded. On thrust lever advance, will not increase in thrust or may stall. On thrust lever retard will go into full stall.	None

Table 2-10. Malfunction Database Analysis, Numbers 13 and 14

Malfunction No.	13	14
Engine problem causes and STA-PSM symptom	VSV failed beyond schedule (more open) Surge/Nonrecoverable stall	VSV failed below schedule (more closed) Core speed, EGT high, possibly thrust shortfall. Surge/Nonrecoverable stall at low power possible
More details of the event	Typically VSV actuation system (including actuator jam), temperature measurement error, VSV sensor failure	Typically VSV actuation system (including actuator jam), temperature measurement error, VSV sensor failure
Flight phase	Any	Any
High or low power?	Typically mid to high power, aggravated by deceleration. Could occur at idle	More notable at high power
Flight deck effect	Bang, noise depends on power level, possible vibrations, possible EGT rise, parameters dropping	High EGT, N2, low N1
Engine integrity needs	Shutdown, almost no chance of successful restart. Restart not desired due to possibility of overheat.	Retard thrust lever
Typical of all engines?	Yes	Yes

Table 2-10. Malfunction Database Analysis, Numbers 13 and 14 (Continued)

Malfunction No.	13	14
Engine control action to recover	None (hardware failure), temperature fault detection (used in scheduling VSVs)	None (hardware failure), temperature fault detection (used in scheduling VSVs)
FADEC fault accommodation	Prevent: none Mitigate: use failed position to prevent auto-re-start and indicate that restart not advisable	Prevent: none Mitigate: FADEC command engine to idle and annunciate to pilot
FADEC detection logic	FADEC fault detection (tracking check) of the VSVs	FADEC fault detection (tracking check) of the VSVs
Frequency of occurrence	Hardware failure: occasional. Temperature error: rare	Hardware failure: occasional Temperature error: rare
Desired crew response	Shutdown engine	Restart, operate at idle
Timing for engine integrity needs	Timely/prompt response desired (due to stall)	Timely/prompt response desired (due to stall potential)
Comments	None	Operate at low power, may need to shutdown

VSV=variable stator vane

Table 2-11. Malfunction Database Analysis, Numbers 15 and 16

Malfunction No.	15	16
Engine problem causes and STA-PSM symptom	VSV damage Slow engine acceleration, hung acceleration	FOD ingestion into core Surge/Nonrecoverable stall
More details of the event	Results in vanes off schedule, excessive free-play, lever arm failure	Examples: bird, ice/hail, volcanic ash
Flight phase	Takeoff/go around	Any
High or low power?	High power	Any
Flight deck effect	Parameter mismatch during acceleration	Bang, noise depends on power level (and subjectivity of pilot), EGT rising, parameters dropping
Engine integrity needs	No imminent need. May need to monitor and potentially shutdown to avoid further damage	Shutdown, restart, if damaged operate at reduced power, minimize rapid thrust lever movements

Table 2-11. Malfunction Database Analysis, Numbers 15 and 16 (Continued)

Malfunction No.	15	16
Typical of all Engines?	Yes	Yes
Engine Control Action to Recover	None (hardware failure)	None (hardware failure)
FADEC fault accommodation	Prevent: none Mitigate: annunciate fault	Prevent: potential to annunciate health shift Mitigate: surge recovery.
FADEC detection logic	FADEC fault detection (tracking check) of the VSVs	Conceivable core damage detection. Perhaps diagnostic monitoring of engine health would detect performance shift before condition deteriorates.
Frequency of occurrence	Rare	Occasional
Desired crew response	Slow thrust lever movements	Shutdown, restart. If damaged, operate at reduced power. Minimize rapid thrust lever movements.
Timing for engine integrity needs	None	Timely/prompt response desired (due to stall)
Comments	None	None

VSV = variable stator vane
FOD = foreign object damage

Table 2-12. Malfunction Database Analysis, Numbers 17 and 18

Malfunction No.	17	18
Engine problem causes and STA-PSM symptom	FOD ingestion into core Flameout	Turbine blade failure/damage Surge/nonrecoverable stall, possibly followed by flameout, multiple surges
More details of the event	Example: ice, hail, or volcanic ash ingestion	Examples: blade/vane failure, tip clearance loss, bearing failure
Flight phase	Any	Any
High or low power?	Any, low power for ice	Any
Flight deck effect	All parameters dropping, engine goes subidle	Bang, noise depends on power level, all parameters drop rapidly
Engine integrity needs	Shutdown, restart. If damaged operate at reduced power.	Engine shutdown no restart
Typical of all engines?	Yes	Yes
Engine control action to recover	Flameout detection logic	None
FADEC fault accommodation	Prevent: future potential to annunciate health shift Mitigate: flameout recovery	Prevent: future: potential annunciate health shift Mitigate: surge recovery
FADEC detection logic	Perhaps diagnostic monitoring of engine health would detect performance shift before condition deteriorates.	Conceivable turbine damage detection. Perhaps diagnostic monitoring of engine health would detect performance shift.
Frequency of occurrence	Occasional	Occasional
Desired crew response	Shutdown, restart. If damaged, operate at reduced power. Minimize rapid thrust lever movements.	Shutdown engine
Timing for engine integrity needs	None	Timely/prompt response desired (due to stall or continuous surging)
Comments	None	None

FOD = foreign object damage

Table 2-13. Malfunction Database Analysis, Numbers 19 and 20

Malfunction No.	19	20
Engine problem causes and STA-PSM symptom	Turbine blade failure/damage Inability to reach power, slow engine acceleration, overtemperature	Thrust reverser failure/primary or fan nozzle failure Loss of thrust
More details of the event	Scenario: failure occurs and performance degraded. Could overtemperature when try to command high power.	Example: departure of parts with resultant open nozzle area
Flight phase	Any	Takeoff, climb, go around
High or low power?	More likely at high power	More likely at high power
Flight deck effect	EGT high, parameter mismatch during acceleration	Subtle N1, N2 changes, possible EGT changes
Engine integrity needs	Engine integrity needs depends on extent of damage. Pull back thrust lever for EGT exceedance. May need to monitor and potentially shutdown to avoid further damage.	Not imminent threat to engine. May fail fan outlet-guide-vanes if fan operating line low enough.
Typical of all Engines?	Yes	Yes
Engine control action to recover	None	None
FADEC fault accommodation	Prevent: detect health shift Mitigate: perhaps in the future, annunciate health shift	Prevent: none Mitigate: perhaps in the future, annunciate health shift
FADEC detection logic	Conceivable turbine damage detection. Perhaps diagnostic monitoring of engine health would detect performance shift.	Conceivable. Perhaps diagnostic monitoring of fan operating line would detect shift. Would need fan pressure sensing, but sensors could be damaged, too.
Frequency of occurrence	Occasional in older engines, rare in newer engine	Rare
Desired crew response	Depends on the extent of damage	Depends on the extent of damage
Timing for engine integrity needs	None, unless exceeding EGT limits	None
Comments	None	Can stress outlet-guide-vanes with significant operating line reduction or significant open area.

Table 2-14. Malfunction Database Analysis, Numbers 21 and 22

Malfunction No.	21	22
Engine problem causes and STA-PSM symptom	Deteriorated engine Slow acceleration	Significant engine damage Surge/nonrecoverable stall or surge/flameout
More details of the event	Expanded tip clearances, eroded airfoils, loss of turbine/compressor blade efficiency	Multiple blade/disk failure
Flight phase	Takeoff /go around	Takeoff /go around
High or low power?	High power	Likely at high power
Flight deck effect	Parameter mismatch during acceleration	Bang, high vibrations, fluctuating parameters or dropping parameters, EGT exceedance
Engine integrity needs	No imminent need. Needs overhaul	Shutdown
Typical of all engines?	Hydromechanical controls only	Yes
Engine control action to recover	None	None
FADEC fault accommodation	Prevent: annunciate health shift Mitigate: none	Prevent: none Mitigate: none
FADEC detection logic	FADEC can detect slow to acceleration. Conceivable to monitor health to identify cause.	Stall/flameout logic. Conceivable engine damage detection. Perhaps diagnostic monitoring of engine health would detect performance shift.
Frequency of occurrence	Rare	Occasional
Desired crew response	None	Shutoff fuel
Timing for engine integrity needs	None	None
Comments	None	None

Table 2-15. Malfunction Database Analysis, Numbers 23 and 24

Malfunction No.	23	24
Engine problem causes and STA-PSM symptom	Sensing for power setting parameter (EPR: inlet or other pressure probe error (P2, P5, P0)) Thrust high or low	PB measurement loss Thrust low
More details of the event	Most notable at high power. N1 in-range failures not very likely.	Examples: PB line failure, blockage
Flight phase	Any	Any
High or low power?	More notable at high power	Any
Flight deck effect	Subtle, nonthrust setting parameters differ with other engine	Likely will go subidle
Engine integrity needs	Revert to ALTN (automatic or manual)	If above idle can operate at part power. If subidle, shutdown. Can attempt restart, but it may not be successful.
Typical of all engines?	EPR engines only	Compensation logic has been used to prevent roll back.
Engine control action to recover	ALTN	Fault accommodation
FADEC fault accommodation	Prevent: sensor fault detection/accommodation Mitigate: ALTN	Prevent: model PB accurately and use in logic Mitigate: use modeled PB in control logic
FADEC detection logic	Pressure sensor fault detection	Pressure sensor fault detection
Frequency of occurrence	Occasional	Occasional
Desired crew response	Operate with both engines in ALTN	With fault detection: none. Without fault detection: If above idle, can operate at part power. If subidle, shutdown. Can attempt restart, but it may not be successful.
Timing for engine integrity needs	None	None
Comments	None	None

Table 2-16. Malfunction Database Analysis, Numbers 25 and 26

Malfunction No.	25	26
Engine problem causes and STA-PSM symptom	PB measurement error high Hung deceleration, overthrust (not likely)	PB measurement error low Slow acceleration, could be hung acceleration, could roll back to underthrust condition
More details of the event	Examples: frozen measurement caused by pneumatic line blockage followed by deceleration, transducer failures which could cause overthrust/hung (latter not likely)	Examples: pneumatic line leak, transducer failure (latter not likely)
Flight phase	Any	Any
High or low power?	Mid-high	Low
Flight deck effect	Parameters higher than command	Parameters lower than command. With thrust lever at idle, could be at an elevated idle
Engine integrity needs	None, unless EGT exceedance	If above idle, can operate at part power. If subidle shutdown. Can attempt restart, but it may not be successful.
Typical of all engines?	Depends on engine/control architecture, disagree logic on FADECs can mitigate	Compensation logic has been used to prevent roll back
Engine control action to recover	Fault accommodation	Fault accommodation
FADEC fault accommodation	Prevent: model PB accurately and use in logic Mitigate: use modeled PB	Prevent: model PB accurately and use in logic Mitigate: use modeled PB
FADEC detection logic	Pressure sensor fault detection	Pressure sensor fault detection
Frequency of occurrence	Rare	Rare
Desired crew response	None (unless exceeding EGT limits)	If above idle; can operate at part power. If subidle: shutdown. Can attempt restart, but it may not be successful.
Timing for engine integrity needs	None (unless exceeding EGT limits)	None
Comments	None	None

Table 2-17. Malfunction Database Analysis, Numbers 27 and 28

Malfunction No.	27	28
Engine problem causes, and STA-PSM symptom	Fuel starvation Flameout	Fuel metering valve failed open Overthrust, could overspeed, depending on fuel input rate potential for Surge/nonrecoverable stall. Slow deceleration, hung deceleration.
More details of the event	Example: FMV failure, cracking of fuel system components, fuel leak, fuel pump failure, incorrect fuel transfer	Examples: FMV fails more open than commanded, or stuck in position when deceleration commanded. Hydromechanical unit shifts.
Flight phase	Any	Any
High or low power?	Any	Any
Flight deck effect	Fire warning (in the event of a leak), and subidle	Engine parameters do not respond to thrust lever. Rotor speed or EGT exceedances possible
Engine integrity needs	Shutdown, fire procedure (in the event of a leak)	No imminent need unless EGT or rotor speed exceedances. Need to shutdown to try to resume control.
Typical of all engines?	Yes	Yes
Engine control action to recover	None	Potential autofuel cut (depends on pilot control philosophy)
FADEC fault accommodation	Prevent: none Mitigate: none	Prevent: None Mitigate: Overthrust detection and annunciation, and if desired, accommodation by closure of shutoff valve
FADEC detection logic	None	Valve position detection
Frequency of occurrence	Rare	Rare
Desired crew response	Shutdown, fire procedure (in the event of a leak)	None, unless exceeding EGT limits or if overthrust excessive and causing operational concern. Then an engine shutdown is required.
Timing for engine integrity needs	Timely/prompt response desired	None (unless exceeding EGT limits)
Comments	None	None

FMU = Fuel metering valve

Table 2-18. Malfunction Database Analysis, Numbers 29 and 30

Malfunction No.	29	30
Engine problem causes and STA-PSM symptom	FMV failed closed Slow acceleration, hung acceleration, thrust shortfall, flameout	ECS check valve stuck open/ leaking Surge/nonrecoverable stall
More details of the event	Example: FMV failed more closed than command or fully closed	High stage compressor air allowed to re-circulate back to low stage
Flight phase	Any	Any
High or low power?	Any	Intermediate
Flight deck effect	Parameters dropping, goes subidle	Bang, noise depends on power level, EGT rising
Engine integrity needs	Engine shutdown no restart	Shutdown. Restart only with ECS flow disabled.
Typical of all engines?	Yes	Yes
Engine control action to recover	None	None
FADEC fault accommodation	Prevent: none Mitigate: annunciate failure	Prevent: none Mitigate: surge recovery
FADEC detection logic	Valve position detection	Bleed system detection (e.g., ECS flow sensing). Potentially airplane detection
Frequency of occurrence	Rare	Occasional
Desired crew response	None	Shutdown engine. Restart with airplane bleeds reconfigured. No high-pressure bleed off-takes and no ECS from that engine.
Timing for engine integrity needs	None	Timely/prompt response desired (due to stall)
Comments	None	None

FMU = Fuel metering valve
ECS = Environmental control system

Table 2-19. Malfunction Database Analysis, Numbers 31 and 32

Malfunction No.	31	32
Engine problem causes and STA-PSM symptom	Airplane bleed system switching malfunction, or engine control system malfunction Oscillation of parameters	T2 sensor error Thrust high or low
More details of the event	Possible FADEC malfunctions: control transition between inputs, oscillatory failure of sensed thrust set parameters, control loop stability, sluggish actuator response, failure recovery response (e.g., surge recovery)	T2 used in rating calculation
Flight phase	Any	Takeoff, climb (more noticeable at high power)
High or low power?	Any	Takeoff, climb (more noticeable at high power)
Flight deck effect	Shifts in EGT, fluctuation of parameters, could be subtle	Power setting parameter split with aligned thrust levers, or split thrust lever for aligned thrust setting parameter
Engine integrity needs	No imminent need, unless EGT or rotor speed exceedances. Change of power could restore normal operation. Continue to operate, perhaps at part power.	No imminent need, unless EGT or rotor speed exceedances. Potential for overboost in ALTN, failure to meet takeoff thrust.
Typical of all engines?	Yes	Yes
Engine control action to recover	None	Temperature fault accommodation
FADEC fault accommodation	Prevent: none Mitigate: annunciate fault	Prevent: none Mitigate: ALTN
FADEC detection logic	FADEC detection logic conceivable. Algorithm could potentially identify if ALTN or alternate engine power or bleed setting could eliminate or mitigate	There are common mode failures, such as icing, that could affect both engine and airplane sensors. Airplane and engine sensors need technology improvement.
Frequency of occurrence	Rare	Occasional
Desired crew response	Potentially change thrust mode, thrust lever, or bleed settings	ALTN, but common mode icing failure may affect airplane thrust target.

Table 2-19. Malfunction Database Analysis, Numbers 31 and 32 (Continued)

Malfunction No.	31	32
Timing for engine integrity needs	None	None
Comments	None	Possibly detectable by the FADEC with comparison with airplane sensor, except for common mode (icing) failures

ALTN = Alternate mode

Table 2-20. Malfunction Database Analysis, Number 33

Malfunction No.	33
Engine problem causes, and STA-PSM symptom	Deceleration schedule margin loss Hung deceleration (thrust not decelerating to command)
More details of the event	Examples: sensor failure (hydromechanical control), design deficiency (insufficient margin between operating line and deceleration schedule)
Flight phase	Descent, taxi
High or low power?	Low power
Flight deck effect	Parameters above idle with thrust lever closed. Parameter mismatch
Engine integrity needs	No imminent needs. Adding more bleed air could address
Typical of all engines?	Possible for all, but primarily hydromechanical
Engine control action to recover	Future: could potentially reduce deceleration schedule
FADEC fault accommodation	Prevent: none Mitigate: conceivable to detect no deceleration while on deceleration schedule and adjust schedule
FADEC detection logic	Conceivable to detect lack of deceleration relative to deceleration schedule
Frequency of occurrence	Rare (used to be more common on hydromechanical controlled engines)
Desired crew response	Adding more bleed air could address
Timing for engine integrity needs	None
Comments	None

2.1.3 Malfunction Database Results.

Analysis of the database determined that many different malfunctions result in the same symptoms and flight deck effects. These groupings have potential for crew annunciation. In particular, surge/nonrecoverable stall was the most frequently occurring symptom. These results are discussed in section 2.2.

The data was specifically analyzed for STA-PSM annunciation potential. Several other general concepts were reviewed since they were also recognized as being potentially relevant to PSMs other than annunciation of STAs. Engine damage, engine health monitoring, and surge margin tracking are summarized below.

2.1.3.1 Engine Damage.

The majority of the causes of surge/nonrecoverable stall events originate from damage to the engine or a malfunctioning control system.

To develop additional useful annunciations requires further research on engine damage. To make additional progress on annunciation for cases where engine damage exists requires an assessment of the extent of the damage and assessments whether the engine will relight and operate normally (see section 7.2).

2.1.3.2 Health Monitoring.

For many of the root cause PSMs reviewed, potential benefits of real-time prediction of engine operational capability or restart capability were noted. The feasibility of developing an in situ health monitoring algorithm that could provide the pilot with data during the flight when the malfunction occurred was reviewed. The ability to predict an imminent failure requires a sophisticated model. For example, a system that measures fan pressure ratio at a fan speed might be able to detect a performance loss. Unless nozzle area or fan blade shape changes, (i.e., damage) can be detected, it is difficult to conclude what the source of the performance loss is, and, therefore, how long the engine can be operated and whether the pilot needs to be informed. Another example is a core performance shift. Unless it can be determined whether the compressor or the turbine is responsible, it is difficult to predict how long the engine may continue to operate. A compressor typically cannot operate long with damage, but a turbine typically can.

Damage detection and annunciation warrants additional research (see sections 2.6.1 and 7.2). There are many difficult challenges with using real-time data to advise the pilot of engine damage, including the potential need for additional reliable sensors and sophisticated algorithm development. Health monitoring could be a component of an engine damage detection system. There are also some potential near-term benefits with real-time health monitoring. The capability could be incorporated incrementally. There are measurable performance shifts that often precede engine malfunctions, and work could be done to detect and provide crew awareness (if appropriate) or record maintenance information.

2.1.3.3 Tracking Compressor Surge Margin Loss.

Another area of potential malfunction detection strategy is the concept of monitoring the compressor operating line migration towards the surge line. Surge margin loss can be caused by both compressor operating line rise or surge line drop due to such things as tip clearances and deterioration. While operating line shifts can be tracked, surge line shifts are harder to detect. It is considered to be a future technology to monitor tip clearances and predict surge margin loss on an engine in-service. However, if loss of surge margin could be detected, the fuel schedules could be adapted to be less aggressive for short-term surge avoidance. This would compromise acceleration times and, therefore, would only be suitable as a get-home mode. In such a situation, an advanced control system implementation could alter the normal engine surge bleed schedule or variable geometry schedules to increase compressor stability margins, and a suitable message may be needed to inform the flight crew of degraded engine operation.

2.2 ENGINE SYMPTOM CATEGORY DATABASE DEVELOPMENT.

A review of the malfunction database determined that many of the 33 root cause malfunctions with common symptoms (i.e., final outcome, such as flameout) could be grouped together. These were then analyzed for potential annunciation categories. Considerations included common engine symptoms (including engine needs) and specifically grouped with pilot awareness and pilot procedure as a primary objective. Figure 2-14 illustrates the STA-PSM accommodation paradigm. Figure 2-15 illustrates the mapping of the 33 malfunctions attributes into the nine symptom categories.

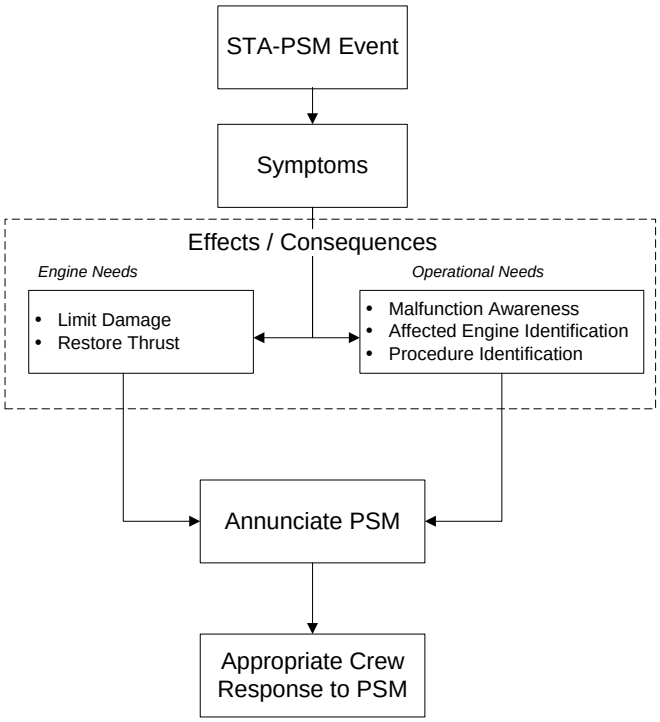


Figure 2-14. The STA-PSM Accommodation Paradigm

Failure attributes	Symptoms
Root cause	
Symptoms	
Contributing factors	
Flight phase dependence	Flameout
Engine power dependence	Surge/nonrecoverable stall
Flight deck effects	Continuous/multiple surge
Engine integrity needs	Thrust failed high/low (sensor)
Engine types	Thrust failed low (indicated)
FADEC accommodation	Thrust failed low (damage)
FADEC annunciation	Thrust failed high (indicated)
FADEC detection logic	Engine slow to respond
Frequency	Thrust Oscillations
Desired crew response	
Timing	

Figure 2-15. Mapping of Failure Attributes to Symptom Categories

The symptom categorization distinguished different engine needs that could affect the pilot procedures. For example, both flameout and surge/nonrecoverable stall are subidle conditions, but the need for timely action is different. An engine can operate for an unlimited time in a flameout condition and pilot action cannot reduce the potential for additional damage. For an engine in surge/nonrecoverable stall, timely removal of fuel is needed to clear the stall and potentially to prevent damage. Therefore, these two malfunctions have been defined to have different engine integrity needs. Some of the categories had both a clear pilot awareness and a clear desired pilot procedure (e.g., flameout, surge/nonrecoverable stall, and continuous/multiple surges and others did not and were then categorized in terms of similar engine symptoms and potential pilot awareness needs (thrust low, thrust high, etc.).

Each symptom category was characterized and documented the following assessments:

- Thrust change and timing characteristics
- Percentage of failures that fall within the general characterization
- Percentage of the particular sustained thrust anomaly relative to all sustained thrust anomaly
- FADEC accommodation
- How reliably the failure condition could be detected

- Engine needs (integrity and thrust recovery)
- Timing for the engine needs
- How reliably the engine needs can be detected
- Technology needs to provide the desired reliability for awareness annunciation and procedural guidance

The definitions of the categories are listed in table 2-21, and the characterizations of the nine STA symptom categories are listed in tables 2-22 to 2-30. The approximate occurrences of each symptom are shown in figures 2-16 (all STA-PSMs) and 2-17 (FADEC STA-PSMs).

Table 2-21. Symptom Attribute Definitions

Malfunction Symptom Criteria	Description
Characterization	The characterization was done to ensure a common understanding of the symptoms and timing of the failure in the particular category. The characterization was primarily needed to allow assessment of the impact on the flight deck and in the development of the annunciation criteria that would be required in the follow on task. Characterization included the expected characteristic of the thrust change and the expected timing. In cases where a characterization had to be too broad to cover all failures in a category, a more general characterization was developed that encompassed most of the population within each category. Then an assessment was made of what percentage of the failures fell within the general characterization.
Relative occurrence	An assessment of the relative occurrence of each event was made. An internal Boeing database of modern airplanes was used to provide a general (approximate) characterization. In many events, an engineering judgment had to be made based on the limited data, so it is assessed that a ±10% error margin is possible. However, this provides a sufficient sense of the magnitude of each failure condition for this research project. The database and analysis are included in section 2.4. The relative occurrences are for STA-PSMs.
Accommodation	For each category, an assessment was made as to whether the FADEC could accommodate the condition, whether the pilot could accommodate the condition, or whether it was not known how to accommodate the condition. An assessment was also made of the current FADEC capability and of potential future FADEC capability. The assessments were not made based on extensive study, but rather are general engineering estimates to help characterize the failure conditions and its annunciation and procedural potential both near and far term.

Table 2-21. Symptom Attribute Definitions (Continued)

Malfunction Symptom Criteria	Description
Annunciation Technology Reliability Risk Assessment (Hardware Technology Risk Assessment) (Algorithm Technology Risk Assessment)	This evaluation included a preliminary implementation risk assessment and timing assessment. In assessing the reliability, it was concluded that the achievable reliability is largely a function of the magnitude of thrust at the time of malfunction and of the engineering time needed to evaluate all possible transients, ambient conditions, and sensor shifts. The tighter the required detection threshold, the more effort is required to validate for reliability. The annunciation response timing also needs to account for the transmission and display timing delays. The technology risk assessment was split into hardware and algorithm development assessments. Prior to the beginning of the research, it was envisioned that the research would uncover new sensor needs. However, the research concluded there is a greater need for algorithm development. The technology risk assessment categories used were: Low: Algorithm and hardware currently exist and have a proven reliability record. Medium: Similar capability has been developed in the past. Changes to current algorithm and hardware appear feasible with moderate amount of effort. High: Specific annunciation logic and hardware have not been developed. Similar capability for accommodation may exist, but to apply to pilot annunciation implies additional risk. Significant work may be required to ensure reliability. A trade-off between reliability, development cost, and timing is likely to be needed. Engine data to design or substantiate is either not available or difficult to obtain. In this task, the technology risk assessment generally was to provide a relative assessment for the nine symptoms.
Annunciation timing assessment	An assessment was made of the timing achievable for annunciation of several specific characterizations of each failure.

Table 2-21. Symptom Attribute Definitions (Continued)

Malfunction Symptom Criteria	Description
Integrity needs	In general, the engine does not have any needs that are more important than flying the airplane. For each engine failure, it was assessed that the pilot needs to fly the airplane first and then can attend to the engine malfunction. The engine is able to operate for the period required to stabilize the airplane and achieve and maintain the desired flight path and airspeed. Additionally, the airplane has the capability to fly with a failed engine. In the context of this report, engine needs have two components with the following meanings: • engine integrity needs: integrity in this application means an assessment of engine damage avoidance needs and what pilot action is desired to avoid either causing or incurring additional engine damage. • thrust recovery needs: action required to resume normal engine thrust and what pilot action is desired to attempt to recover thrust. For some categories, a definite engine need was identified, and hence, a desired action identified (whether it be pilot action, or automatic system accommodation). For other categories, a definite engine need could not be identified, and hence, the annunciation would serve as pilot awareness.
Thrust recovery needs	The concept of thrust recovery needs is problematic. The majority of engine failures are caused by engine damage. The determination of what is required to try to recover thrust is just one aspect of this issue. The advisability of trying to recover thrust or whether operation at thrust could incur additional damage are difficult questions and are candidates for future engine damage research.
Integrity timing needs	An assessment was made of the desired response timing to address the engine integrity need, if one was identified. Usually, the timing was determined to be a function of the extent of engine damage being incurred. It is desirable to develop the capability to differentiate timing differences. This technology should be considered in any future engine damage research.
Engine needs detection reliability	This analysis included an assessment of the engine systems reliability to determine both what is required to address the engine integrity need and what is required to address the engine thrust recovery needs. Again, the issue of engine damage is a prime consideration, including the advisability of the thrust recovery needs action and development of specific guidance to the pilot. In general, current systems can determine what is required to address the engine integrity need. It would be desirable to reliably detect (or advise) on engine thrust recovery needs. This significant effort should be considered in any future engine damage research.

Table 2-22. Flameout Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	Quenching of the combustor flame causes the engine speeds to go subidle with rapid engine parameter decay, including EGT decay. The subidle condition will usually occur in 3 to 5 seconds following the flameout. In some cases, the combustor can extinguish slowly such that slower decay is possible. Flameout characteristics are described in figure 2-6.
Relative occurrence	Of all STA-PSMs, approximately 16% are engine flameout conditions. Of all FADEC STA-PSMs, approximately 17% are engine flameout conditions.
Accommodation	Flameout accommodation can include the pilot shutting off fuel and trying to restart the engine. Many FADEC engines accommodate flameout with automatic relight logic. For modern FADEC engines, approximately 20% of flameout conditions are restartable. The remaining cases are not restartable, since they were likely caused by engine damage.
Hardware technology risk assessment	The parameters required are N2 and EGT, which have been assessed to be low risk (sensor technology exists).
Algorithm technology risk assessment	An engine that has flamed out will decelerate to a subidle speed. Subidle detection is considered low risk. An algorithm that detects the combination of subidle and combustor quenching increases the risk to low-medium. An algorithm that detects combustor quenching (i.e., does not include a subidle criteria) increases the risk to medium.
Annunciation timing assessment	For a flameout condition, most will have immediate combustor quenching and likely decelerate subidle rapidly (within ~5 seconds). The detection of combustor quenching could be sooner (~2 to 5 seconds), but at higher annunciation risk. Some combustor failures may have a trickle failure, resulting in increased time for the engine to go subidle (timing risk assessment high, since thrust decay timing is not quantifiable). However, coverage of this condition could be covered by the annunciation for indicated thrust shortfall. If a flameout occurs at low power, detection could be within 2 to 5 seconds.
Integrity needs	There are no engine integrity needs for an engine flameout condition. The combustor has been quenched, the engine will be windmilling, and although fuel may be flowing, the engine is not likely incurring any additional damage. Hence, there is no need for the system or the pilot to provide any immediate action for the engine. In some cases, there may be additional damage being incurred but there is nothing the pilot can do to prevent this. The only exception for pilot action is for static operation on the ground where a dry motor is required to clear the unburnt fuel.

Table 2-22. Flameout Symptom Evaluation (Continued)

Malfunction Symptom Criteria	Description
Thrust recovery needs	Following a flameout, the engine thrust recovery needs are to relight the engine. This can be achieved by either automatic relight logic or a pilot initiated restart. However, the advisability of a relight or restart depends on the existence and extent of engine damage. There are several factors that contribute to whether an engine can relight or restart, and its restart needs are a function of several conditions. If the engine is in the windmill envelope, then the engine has one set of engine needs (i.e., ignition). If the engine is in the starter assist envelope, then the engine has another set of needs (e.g., starter air pressure, ignition). If the airplane is outside the restart envelope, then there may need to be an airplane altitude or speed adjustment. The thermal condition and the timing of the flameout accommodation may affect the engines capability to relight. This functionality could be provided by the airplane (pilot) or by the FADEC. Currently, FADECs can automatically provide accommodation within the windmill envelope (i.e., no pilot action required). Potentially, the FADECs could also control the starter air valve. Potentially, the FADEC could monitor the thermal condition and determine the appropriate time to restart the engine.
Integrity timing needs	The engine does not have a timing need for a flameout integrity need. The engine can operate in a flameout condition and likely not incur additional damage. There are some conditions where additional damage is being incurred, but there is nothing the pilot can do to mitigate this condition. There may be an airplane need if the engine failure has caused a failure in a fuel line to close the spar valve.
Engine needs detection reliability	FADEC system can reliably detect the engine restart needs. Current systems cannot reliably detect the advisability of a restart because it depends on the extent of engine damage (if damage was the cause of the flameout).

Table 2-23. Surge/Nonrecoverable Stall Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	Surge/nonrecoverable stall is an engine surge that has progressed to stall condition. The stall condition usually causes the engine to go subidle. There may be a small subset of surge/nonrecoverable stall that remain above idle. Subidle conditions usually occur rapidly (in ~5 to 10 seconds). Note that longer conditions and an above-idle surge/nonrecoverable stall could be covered by a thrust failed low annunciation. In this study, this condition does not cover a rotating stall. A rotating stall was not considered a STA because the typical small stall pocket does not produce a noticeable thrust loss. An engine in rotating stall can progress to surge/nonrecoverable stall when the thrust lever is advanced. Surge/nonrecoverable stall characteristics are described in figure 2-3.
Relative occurrence	Of all STA-PSMs, approximately 42% are engine surge/nonrecoverable stall conditions. Of all FADEC STA-PSMs, approximately 32% are engine surge/nonrecoverable stall conditions.
Accommodation	The assessment was that of all surge/nonrecoverable stall conditions, not many surge/nonrecoverable stall events on modern FADEC engines are restartable since they were likely caused by engine damage. Of those that are restartable, currently some of those are automatically accommodated, but in the future perhaps all could be.
Hardware technology risk assessment	The parameters that may be required include N2, PB, EGT, bleed valve positions, thrust set command, and thrust set parameter. These have been assessed to be low risk (sensor technology exists). As discussed above, a rotating stall was not considered an STA and detection not warranted. However, a technical risk assessment was completed for this failure condition, and the hardware risk assessment is high, since detection would require high response reliable probes in the correct locations. The likelihood of such an event is low, since the potential for rotating stalls are addressed during certification of the engine system. Also, it was assessed that indication when the condition has progressed to a full surge/nonrecoverable stall is sufficient. The addition of a system to detect a rotating stall was considered not warranted.
Algorithm technology risk assessment	An engine that has surged and progressed to a stall condition will likely go subidle. Subidle detection is considered low risk. An algorithm that detects the combination of subidle and a stall condition increases the risk to low-medium. An algorithm that detects a surge/nonrecoverable stall condition (i.e., does not include a subidle criteria) increases the risk to medium.

Table 2-23. Surge/Nonrecoverable Stall Symptom Evaluation (Continued)

Malfunction Symptom Criteria	Description
Annunciation timing assessment	For a surge/nonrecoverable stall condition, most will likely be subidle within ~5 seconds. The detection of a surge/nonrecoverable stall could be sooner (~2 to 5 seconds), but at a higher annunciation risk. A fraction of surge/nonrecoverable stall failures may result in an above-idle stall, which will likely be stable within ~5 seconds. But if not, coverage of this condition could be provided within ~5 seconds by an annunciation for indicated thrust shortfall. If a surge/nonrecoverable stall condition occurs at low power, detection would likely be within 2 to 5 seconds.
Integrity needs	There is an engine integrity need with a surge/nonrecoverable stall to clear the stall as soon as practical. This action is desired to prevent damage or incurring additional damage. To clear a surge/nonrecoverable stall requires the shutting off of fuel. If the engine is not damaged, the best action is to pulse fuel off and on, since this will provide the fastest engine recovery time. Note that this condition may include EGT exceedances (annunciated), which also identifies an engine integrity need (overtemperature can damage the engine).
Thrust recovery needs	The thrust recovery needs are to shutoff fuel to clear stall. The fuel shutoff can result in a flameout. Subsequently, a relight and restart can be attempted. This functionality could be provided by the airplane (pilot) or automatically by the FADEC. However, desirability to restart engine depends on the cause, the type of failure, and the extent of damage. An attempted restart may increase the amount of damage. As for the flameout condition, there are several other factors that contribute to whether an engine can relight and restart, and its restart needs are a function of several conditions (see table 2-22: thrust recovery needs).
Integrity timing needs	In a surge/nonrecoverable stall condition, there is a need to clear the stall quickly to maintain engine integrity (to prevent additional engine damage). This is accomplished by shutting off fuel. If the engine is not damaged, it is best to pulse fuel off and on. Note that this condition may include EGT exceedances with quick pilot action desired to maintain the engine integrity needs.
Engine needs detection Reliability	An FADEC system can reliably detect the engine needs to shutoff fuel to clear the stall. But, current systems cannot reliably detect the advisability of a restart because it depends on the extent of engine damage (if damage was the cause of the surge/nonrecoverable stall).

Table 2-24. Continuous/Multiple Surge Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	Two or more repetitions of a surge and recovery cycle (surge, recover, surge, recover, and so on, continuously surging multiple distinct surges). Clearing the continuous/multiple surging condition is most likely achieved by a reduction in FF. Continuous/multiple surge characteristics are described in figure 2-4.
Relative occurrence	Of all STA-PSMs, approximately 20% are continuous/multiple surge. Of all FADEC STA-PSMs, approximately 27% are continuous/multiple surge.
Accommodation	Most continuous/multiple conditions can be cleared with a reduction in fuel. Once the surging has been cleared, it then can be operated at full power. Currently, these are not automatically accommodated and, therefore, require pilot action (thrust lever reduction). Future consideration could be given to a FADEC commanded reduction in FF sufficient to clear the surging, although there are issues of above-idle thrust reduction without pilot input.
Hardware technology risk assessment	The parameters that may be required for detection include N2/N3, PB, EGT, bleed valve positions, thrust set command, and thrust set parameter. These have been assessed to be low risk (sensor technology exists). For these existing sensors, current sensing location and update rates are sufficient for high-power and low-altitude fault detection. Consideration could be given to the addition of fast response sensors for higher fidelity and faster response of engine burner pressure for low-power and high-altitude detection. However, the assessment is that, if implemented, algorithms (albeit difficult) could be developed and would likely be more cost-effective. The addition of fast response sensors has been assessed to be moderate technology risk (sensor technology exists, but not currently used in commercial production for burner pressure sensing).
Algorithm technology risk assessment	An algorithm to detect all types of continuous/multiple surge is considered high risk. Although there are algorithms to detect a surge, these have been developed for rapid accommodation of a surge. Since over-accommodation (i.e., accommodation when there has not been a surge) has no detrimental performance affect on the engine, these algorithms do not have the reliability for annunciation and would require additional development. Additionally, the characteristic of a subsequent surge could be different, and there is a lack of data suitable for algorithm development and validation.

Table 2-24. Continuous/Multiple Surge Symptom Evaluation (Continued)

Malfunction Symptom Criteria	Description
Annunciation timing assessment	For algorithm development, several timing criteria thresholds would need to be defined. First, the minimum time between surges to distinguish between what could be a single recoverable surge (with multiple subevents) and two distinct surges that could benefit from a fuel reduction. It was assessed that perhaps subsequent surges, which occur more than ~0.5 second after the first surge should be considered multiple surges. Second, the time between two surges that are far enough apart where a fuel reduction is not likely to address the problem (e.g., ~>20 seconds apart) and are likely indicative of another problem. This second time distinguishes continuous surging, requiring pilot response from separate single surges. For continuous/multiple surges, the interval between surges can vary. Event data indicates a general range of ~0.5 to 2 seconds, although other frequencies are possible. It was assessed that after the second distinct surge, a FF reduction could be beneficial.
Integrity needs	Engine integrity need for continuous/multiple surge event is to clear the surging as soon as practical. The desired response is to quickly retard thrust lever (FF reduction) until the continuous/multiple surging clears, since a sustained condition may cause engine damage or the engine may become unrecoverable. The thrust reduction required may be as low as to idle power.
Thrust recovery needs	The thrust recovery needs are to reduce FF to clear the surging and then reapply fuel to restore thrust. This functionality is currently provided by the pilot, but could be provided by the FADEC. However, the capability to restore normal thrust depends on the cause, the type of failure, and the amount of damage. The pilot can attempt to restore thrust, but may increase the amount of damage.
Integrity timing Needs	There is a potential need to clear the surging quickly to maintain engine integrity (to prevent potential additional engine damage). This is accomplished by retarding the thrust lever (reducing fuel) until the surging clears.
Engine needs detection reliability	A FADEC system could be developed to reliably detect the engine needs to reduce fuel to clear the surging. But, current systems cannot reliably detect the advisability of a restoring thrust because it depends on the extent of engine damage (if damage was the cause of the continuous/ multiple surging).

Table 2-25. Thrust Failed High/Low (Sensor) Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	The characterization of a thrust failed high/low (sensor) in actual thrust is higher or lower than commanded. Indicated thrust matches command (i.e., thrust set sensor parameter failure). The most common contributor to this symptom are EPR failures (P5 or P2). A less common contributor could be T2, since icing can cause a common mode failure (multiple sensors). Engines that use N1 for thrust control are less vulnerable to a sensor shift scenario. For other sensors (e.g., P0), there are multiple sensors from which to do fault detection and accommodation (and no common mode failures). Thrust failed high/low (sensor) characteristics are described in figures 2-10 and 2-11.
Relative occurrence	Of all propulsion STA-PSMs and FADEC STA-PSMs, less than 1% are engine thrust failed high/low (sensor) conditions.
Accommodation	The pilot should be able to select an alternate mode of operation. In this alternate mode, the FADEC logic can ensure that the thrust rating logic is conservative and the required thrust is achievable.
Hardware technology risk assessment	For EPR failures, the parameters that may be required include other engine parameters such as N1, N2, PB, and EGT. These have been assessed to be low risk (sensor technology exists). Although this is not considered an in-service safety issue, there is currently ongoing industry work to better understand the T2 probe icing characteristics at altitude. Currently, improved probe development is under assessment. For all other sensors, there could be multiple sources (e.g., P0), or the failure scenario unlikely (N1), such that no risk assessment is required.
Algorithm technology risk assessment	For EPR fault detection, it was assessed that to detect a thrust shift of ~10 to 30% is high risk. For a thrust shift > ~30%, the risk assessment is low-medium. FADECs currently have logic to detect and accommodate EPR shifts, but are designed conservatively (to preclude nuisance annunciation).
Annunciation timing assessment	The thrust change timing characteristic is not quantifiable, since there are so many different failure modes and characteristics that could result in this engine failure symptom.

Table 2-25. Thrust Failed High/Low (Sensor) Symptom Evaluation (Continued)

Malfunction Symptom Criteria	Description
Integrity needs	If there is an engine need, it will likely be indicated through an EGT exceedance. Most FADECs will not allow the engine to run over rotor speed red line limits. For other engines, an engine need based on a rotor speed exceedance will be indicated.
Thrust recovery needs	For FADEC engines, the pilot would revert to alternate mode operation to restore thrust. For non-FADEC engines, the pilot would need to adjust the thrust lever.
Integrity timing needs	Timely pilot response to an exceedance is desired.
Engine needs detection reliability	If there is an exceedance, the system can reliably detect the engine integrity need. Following a detection of sensor failure, a FADEC system can reliably detect the need for reversion to alternate mode to restore thrust.

Table 2-26. Thrust Failed Low (Indicated) Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	Thrust failed low (indicated) is when both actual and indicated thrust are less than commanded. This condition could be either an engine losing thrust after power set or not accelerating when command is increased, and could also include subidle conditions that are not flameout or surge/nonrecoverable stall. Most surge/nonrecoverable stall conditions would be detected by a subidle condition, but detection for thrust failed low (indicated) could additionally detect the infrequent above-idle stall conditions. Thrust failed low (indicated) characteristics are described in figure 2-7.
Relative occurrence	Of all STA-PSMs, approximately 8% are engine thrust failed low (indicated) conditions. Of all FADEC STA-PSMs, approximately 5% are engine thrust failed low (indicated) conditions.
Accommodation	There are so many different failure conditions that result in this symptom, that there is no reliable accommodation. The pilot can reduce then advance the thrust lever, or shutdown the engine and attempt restart (but restart cannot be guaranteed).
Hardware technology risk assessment	The parameters that may be required include thrust set command and the thrust set parameter. These have been assessed to be low risk (sensor technology exists).

Table 2-26. Thrust Failed Low (Indicated) Symptom Evaluation (Continued)

Malfunction Symptom Criteria	Description
Algorithm technology risk assessment	An algorithm to detect thrust failed low (indicated) is considered medium risk. The algorithm would likely involve expected engine response derived from thrust command. The level of risk is a function of the thrust loss detection threshold.
Annunciation timing assessment	The time to condition is not quantifiable because there are many different failure modes and characteristics that could result in this engine failure symptom.
Integrity needs	Since so many different failure conditions can result in this symptom, the engine integrity needs are indeterminate. It is likely there are no engine integrity needs unless there are parameter exceedances (for which the pilot should retard the thrust lever, and then shutdown the engine if the condition persists). If caused by damage, continued operation may increase the amount of engine damage.
Thrust recovery needs	The engine thrust recovery needs are unknown because there are many different failure conditions that can result in this symptom. Some options could be: • Retard thrust lever to see if it clears. • If it does not clear, can shutoff fuel (but may not be able to restart engine). • If caused by damage, continued operation may increase the amount of damage. • Can determine if a stall, but stall above idle is not a likely failure condition.
Integrity timing needs	The engine timing needs are unknown because there are many different failure conditions that can result in this symptom.
Engine needs detection reliability	The current FADEC systems cannot reliably detect the advisability of a pilot action because it depends on the failure type and condition of the engine.

Table 2-27. Thrust Failed Low (Damage) Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	During thrust failed low (damage), the indicated thrust matches target thrust, but the thrust is physically lower. The most likely cause is engine damage (e.g., fan blade damage or nozzle damage that results in open nozzle area). This category does not include subidle operation (for which the indicated thrust is less than the target). Thrust failed low (damage) characteristics are described in figure 2-8.
Relative occurrence	Of all STA-PSMs, approximately 4% are engine thrust failed low (damage) conditions. Of all FADEC STA-PSMs, approximately 5% are engine thrust failed low (damage) conditions.
Accommodation	There is no accommodation for a damaged engine that can restore thrust; maintenance is required. It may be appropriate to reduce thrust to idle to reduce the potential of incurring more damage, or perhaps even to shut the engine down.
Hardware technology risk assessment	It was assessed that the hardware risk may be high to detect thrust losses greater than 10% thrust. It was assessed that the hardware risk may be medium to detect thrust losses greater than 25% thrust.
Algorithm technology risk assessment	It was assessed that the algorithm risk may be high to detect thrust losses greater than 10% thrust. It was assessed that the algorithm risk may be medium to detect thrust losses greater than 25% thrust.
Annunciation timing assessment	The time to condition is not quantifiable, because there are many different failure modes and characteristics that could result in this engine failure symptom.
Integrity needs	It is likely that there are no engine integrity needs unless there are parameter exceedances. If vibrations and other parameters are within limits, then it is likely acceptable to allow the engine to continue to run. If there are parameter exceedances, or unusual engine noises, then it is appropriate to reduce thrust to idle to reduce the potential of incurring more damage, or perhaps even to shut the engine down.
Thrust recovery needs	There is nothing the pilot can do. What is required is to repair the engine (maintenance).
Integrity timing needs	If the failure has also resulted in an exceedance, then prompt pilot response is desired. Otherwise, there are too many different failure conditions to determine the specific engine timing needs.
Engine needs detection reliability	Except for a parameter exceedance, the current FADEC systems cannot reliably detect the advisability of a pilot action because it depends on the failure type and condition of the engine.

Table 2-28. Thrust Failed High (Indicated) Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	Thrust failed high (indicated) condition is where both actual and indicated thrusts are greater than commanded. This condition could be either an engine increasing thrust from power set or not decelerating when the command is decreased. The time to condition is not quantifiable because there are many failure conditions that could result in this symptom. Thrust failed high (indicated) characteristics are described in figure 2-9.
Relative occurrence	Of all STA-PSMs and all FADEC STA-PSMs, approximately 2% are engine thrust failed high (indicated) conditions.
Accommodation	There are many different failure conditions that result in this symptom where there is no reliable accommodation. The pilot may try a thrust lever advance and then thrust lever retard, but this is not considered advisable. To reduce thrust, the pilot would need to shutdown the engine, but a restart cannot be guaranteed. (Again, this assessment is a generalized engineering assessment, used only to characterize the failure and its annunciation and procedural potential both near and far term).
Hardware technology risk assessment	The parameters that may be required include thrust set command and the thrust set parameter. These have been assessed to be low risk (sensor technology exists).
Algorithm technology risk assessment	An algorithm to detect thrust failed high (indicated) is considered medium risk. The algorithm would likely involve expected engine response derived from thrust command. The level of risk is also a function of the desired level of detected thrust increase (i.e., the tighter the tolerances (e.g., thrust increase > ~10%), the higher the risk).
Annunciation timing assessment	The time to condition is not quantifiable because there are many different failure modes and characteristics that could result in this engine failure symptom.
Integrity needs	If there is an engine need, it will likely be indicated through a parameter exceedance.
Thrust recovery needs	The pilot can try to increase command to above actual to attempt to restore control, but likely this action would be of little value. The failure may be self-correcting, but likely the pilot needs to shutoff fuel to reduce thrust, but may not be able to restart.
Integrity timing needs	The engine timing needs are unknown since there are many different failure conditions that can result in this symptom.
Engine needs detection reliability	If there is a parameter exceedance, the system can detect the engine integrity need reliably. However, the current FADEC systems cannot reliably detect the advisability of a pilot action because it depends on the failure type, the condition of the engine, and the flight phase of the airplane.

Table 2-29. Engine Slow to Respond Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	An engine is slow to accelerate or decelerate to command. Engine slow to respond characteristics are described in figure 2-12.
Relative occurrence	Of all STA-PSMs, approximately 1% are engine slow to respond conditions.
Accommodation	There is likely nothing the pilot or a FADEC could do to restore engine performance.
Hardware risk assessment	The parameters that may be required include thrust set command and the thrust set parameter. These have been assessed to be low technical risk (sensor technology exists).
Algorithm risk assessment	An algorithm to detect an engine slow to accelerate or decelerate is considered medium-high risk. The algorithm would likely involve expected engine response derived from thrust command. Some of the complications involved in modeling the expected engine response are the rate of engine acceleration or deceleration changes as a function of altitude, temperature, bleed state, generator load, and level of engine deterioration. The level of technical risk is a function of the desired level of detected thrust difference and the timing. The tighter the tolerances (e.g., thrust anomaly > ~10%), or the tighter the timing threshold, the higher the risk.
Annunciation timing assessment	The time to condition is not quantifiable because there are many different failure modes and characteristics that could result in this engine failure symptom.
Integrity needs	There is likely no engine integrity need (it is unlikely there is a parameter exceedance).
Thrust recovery needs	There is likely nothing the pilot can do to restore thrust. The failure may be self-correcting. If not, the pilot could choose to keep the engine at idle, depending on the failure characteristics and flight regime.
Integrity timing needs	The engine timing needs are unknown since there are many different failure conditions that can result in this symptom.
Engine needs detection reliability	The current FADEC systems cannot reliably detect the advisability of a pilot action because it depends on the failure type, the condition of the engine, and the flight phase of the airplane.

Table 2-30. Thrust Oscillations Symptom Evaluation

Malfunction Symptom Criteria	Description
Characterization	Thrust oscillations are characterized by uncommanded thrust increases and decreases from power set command. Oscillations about a lower- or higher-than-commanded steady-state thrust setting are previously included in thrust failed high/low (indicated). Thrust oscillation characteristics are described in figure 2-13.
Relative occurrence	Of all STA-PSMs, approximately 7% are engine thrust oscillation conditions. Of all FADEC STA-PSMs, approximately 8% are engine thrust oscillation conditions.
Accommodation	It is possible that the source of the oscillations is due to a pressure fluctuation of the primary thrust set parameter (if controlling to engine pressure ratio). For this condition, the pilot could select alternate mode. If this does not correct the condition, then there is likely nothing the pilot or FADEC could do to restore performance. It could be that operation at a different power setting or flight condition may correct the problem.
Hardware technology risk assessment	The parameters that may be required include thrust set command and the thrust set parameter, and potentially parameters such as N2, N3, and PB. These have been assessed to be low risk (sensor technology exists).
Algorithm technology risk assessment	An algorithm to detect an engine thrust oscillation is considered medium risk. The technical risk assessment considers detection 1second after a second oscillation from a steady-state condition. Several criteria thresholds would need to be defined, such as thrust amplitude and frequency.
Annunciation timing assessment	The timing and characteristic of the thrust fluctuation is not quantifiable because there are so many different failure modes and characteristics that could result in this engine failure symptom.
Integrity needs	There is likely no engine integrity need (it is unlikely there is a parameter exceedance).
Thrust recovery needs	Alternate mode selection may restore thrust, if the cause is a fluctuation of the thrust set parameter. If not, there is likely nothing the pilot can do to restore thrust. The failure may be self-correcting. The pilot could choose to keep the engine at idle, depending on the failure characteristics and flight regime.
Integrity timing needs	The engine timing needs are unknown since there are many different failure conditions that can result in this symptom.
Engine needs detection reliability	The current FADEC systems could reliably provide the advisability of the first pilot action (selection of alternate mode), but not any subsequent action because it depends on the failure type, the condition of the engine, and the flight phase of the airplane.

PB = Burner pressure

2.3 IN-SERVICE DATA.

2.3.1 Propulsion Database.

The relative occurrence of STA-PSMs was assessed for this study.

Boeing maintains an internal database of in-service events, which is commonly used to assess propulsion system events. Although not all propulsion system events are reported to Boeing, and therefore, do not appear in the database, the number of airlines reporting is sufficient to make it statistically significant for a relative occurrence assessment.

The following are some of the criteria used to develop the propulsion systems events database:

- Loss of thrust
- Loss of thrust control
- Uncommanded thrust change (including engine surge)
- Engine flameout
- Engine shutdown other than normal shutdowns at the end of operation
- An engine exhaust system failure, malfunction, or defect that causes damage to the engine
- Engine separation

A study of the database entries between 9/1/99 to 5/31/04 was undertaken to determine how many occurrences of each symptom in the nine categories from section 2.2.1 were reported. The airplane models included in the study were B-727, B-737, B-747, B-757, B-767, and B-777. The basic technology level for flight deck annunciation in this study was modern airplanes, which have engines with modern control systems. Therefore, it was also determined how many of the events reported in the period were modern FADEC-controlled engines. The data is reported for FADEC and non-FADEC events. In conjunction with the number of reported events during the period, the total number of FADEC and non-FADEC engine hours are provided, so that an assessment of the relative rate of event could be considered. The results are shown in table 2-31. The relative occurrence of STA-PSMs is shown in figure 2-16, and for FADECs only in figure 2-17.

Table 2-31. Database Review of STAs 09/01/1999 to 05/31/2004

PSM Category	Total Events in Category	FADEC Events in Category	Non-FADEC Events in Category
1 Flameout	70	22	48
2 Surge/nonrecoverable stall	177	42	135
3 Thrust failed low (IND[2]<CMD[3])	35	12	23
4 Thrust failed low (IND=CMD)	17	6	11
5 Thrust failed high	9	3	6
6 Continuous/multiple surge	84	35	49
7 Engine slow to respond	4	0	4
8 Thrust low or high (ALTN)	1	0	1
9 Thrust Oscillations	29	11	18
Total	426	131	295
Engine flight hours during the same period[1]		18,066,930	22,828,806

[1] Note that these flight hours are totals for the evaluated time period, whereas the PSMs are from the airlines that have reported to the Boeing internal database. Flight hours are only provided to gauge the relative rates of occurrence of FADEC and non-FADEC PSMs.

[2] IND = Indicated thrust

[3] CMD = Commanded thrust

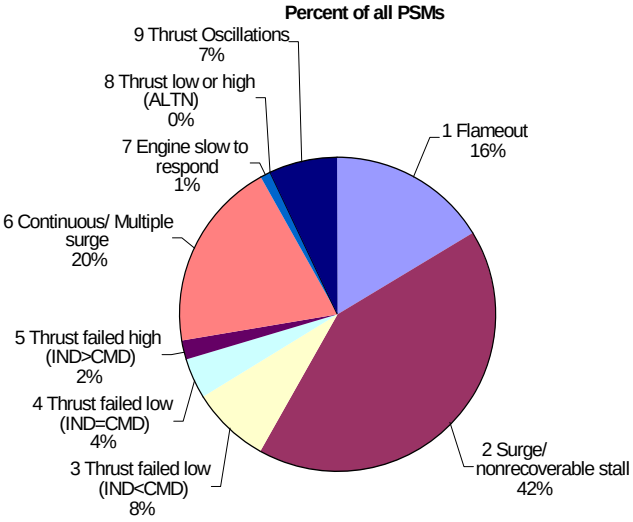


Figure 2-16. Relative Occurrence of all STA-PSMs

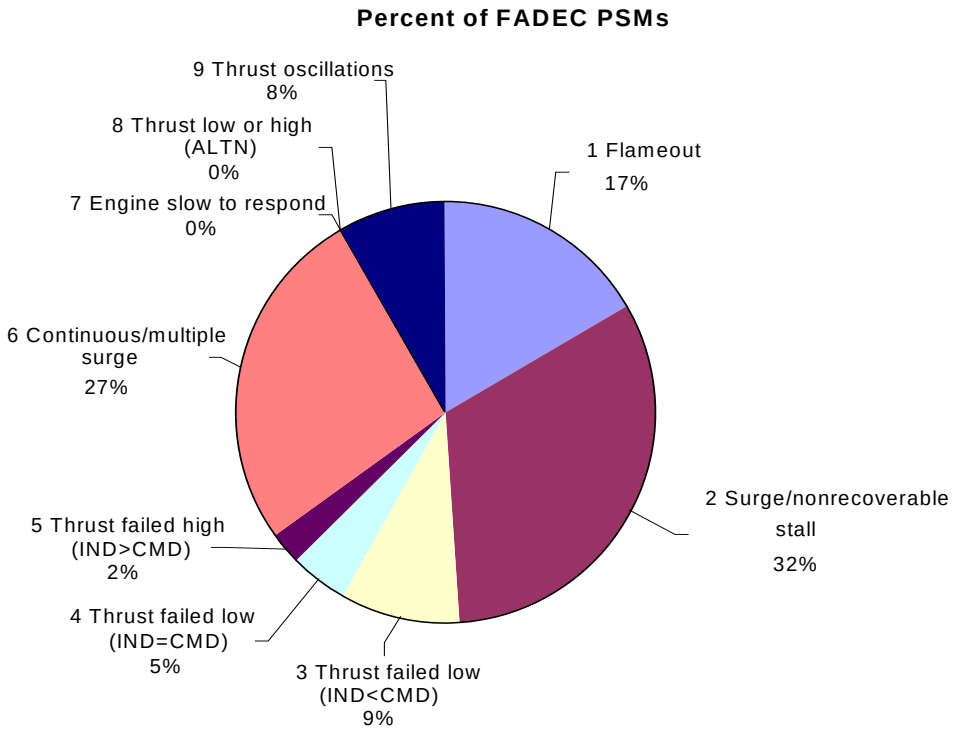


Figure 2-17. Relative Occurrence of FADEC STA-PSMs

2.3.2 Discussion of the Results.

Once the data was gathered, a determination was made for each event on whether it was a sustained anomaly lasting more than 5 seconds. This threshold is consistent with the flight deck analysis of the PSM+ICR database (see section 3). In addition, each event was categorized in terms of the symptom that was the most meaningful flight deck effect for a pilot. For example, in cases where a surge/nonrecoverable stall was preceded by parameter oscillation, the event was put into the surge/nonrecoverable stall category. In cases where a surge was followed by a flameout, the event was put into the flameout category.

During the data review, it was determined that a chronic problem can make up a large number of events in the period of study. In this application, chronic means a problem only found on a particular engine model, but is prevalent during a given time period. During any period of time, there is likely to be a chronic problem-causing surge on one engine type or another, which represents a large fraction of the events. Review of the actual events shows the impact on the surge data of a single chronic problem is about 10% of the total surge events. Another chronic problem that should be considered when drawing conclusions from the totals is an EPR sensor that resulted in engine-thrust oscillations. The occurrences of this single problem make up 12 of the 29 events (37%) in the category (and are included in the data).

It is important to consider the FADEC and non-FADEC engine data separately due to changes in design philosophy and the relative age of the fleet. The first-generation engines in the population are mostly high-cycle engines and exhibit loss of surge margin as they age. The non-FADEC

data is dominated by engines that have lost surge margin and are nearing the end of their useful life, but operators are keeping them on-wing for as long as possible. For more modern engines, it appears that a design philosophy for all engine manufacturers has changed so that engines come off-wing for reasons other than surge margin loss, such as loss of EGT margin.

In the process of identifying only surges that resulted in STA or stall, the number of recoverable surges was also collected and is reported separately. In some cases, following a surge, the thrust lever was pulled back immediately by the pilot. In those cases, a determination was made as to whether the engine would have been self-recoverable in view of the corrective action or root cause. For example, if during maintenance troubleshooting, a borescope showed significant compressor damage, it was judged that the stall would not have been recoverable.

The criteria for an event to be considered a continuous/multiple surge was two or more surges occurring greater than 0.5 a second apart, but within 20 seconds of each other. In some cases, the exact timing was not clear between surges reported simply as multiple bangs, in which case these were considered to be continuous/multiple surge. If the event description reported that the pilot pulled the thrust lever to idle after a single surge, and with thrust lever advance, the engine surged again, the event was considered continuous/multiple surges.

2.3.3 Thrust Recovery Assessment.

The PSM symptom categories assessments included pilot action to recover thrust. In many cases, thrust recovery includes restarting the engine; however, the advisability of a restart, or whether a restart is possible, was difficult to determine and remains an issue. To characterize this issue, surge/nonrecoverable stall and flameout data were reviewed to determine whether the engine might have restarted and operated normally had the pilot attempted a restart. Table 2-32 presents this estimate. Notable is the estimated increase in nonrestartability with FADEC (hence, newer) engine and controls.

Table 2-32. Damage-Related Restartabilty (Estimate)

STA	Damage Would Prevent Regaining Thrust	Damage Unknown But Engine Removed	Damage Would Not Prevent Regaining Thrust	Unknown	Total Events Evaluated
Flameout (FADEC)	12	2	3	5	22
Flameout (non-FADEC)	24	2	13	9	48
Surge/nonrecoverable stall (FADEC)	24	8	4	6	42
Surge/nonrecoverable stall (non-FADEC)	40	15	66	14	135

2.3.4 Surge/Nonrecoverable Stall That Resulted From Damage.

The FAA requested an assessment of how many surges were the result of engine damage. Two factors made it difficult to derive this information from the database. First, where compressor damage occurred, it was difficult to determine whether compressor damage caused the surge or the surge caused the compressor damage. These were all included in the surge caused by damage category. Second, there were sometimes incomplete troubleshooting data available in the report, so where it was unclear what the cause of the surge was, the event was counted in the unknown category. When an engine was removed following the surge, it could not always be determined that damage was the cause of the removal. In some instances, the airlines determined it was more convenient to do troubleshooting off-wing. However, it was unlikely that an engine would be removed if the surge was due to environmental causes such as crosswind, wake turbulence, or weather (i.e., there was no evidence of damage). The engine removals without reported damage were categorized separately.

The data shown in table 2-33 was separated into FADEC and non-FADEC engines, because as noted earlier, the non-FADEC data was dominated by engines with loss of surge margin. Damage in this context was interpreted to mean failed components. A deteriorated engine was not considered damaged, and there were many first-generation engines that have surge without damage.

Table 2-33. Surge/Nonrecoverable Stall-Related Damage Events (Estimate)

STA	Damage Caused Surge	Damage Unknown But Engine Removed	Damage Did Not Cause Surge	Unknown	Total Events Evaluated
Surge/Nonrecoverable Stall (non-FADEC)	76	13	35	11	135
Surge/Nonrecoverable Stall (FADEC)	28	7	3	4	42

2.4 FOLLOW-ON WORK.

There were several issues that were considered and evaluated as part of this contract, including engine damage, recoverable surge, and thrust lever splits.

2.4.1 Engine Damage.

Engine damage was considered during the development of Task 1 since it related to the annunciation of STA. Engine damage is the primary contributor to PSMs. If the damage results in a STA, then the pilot can be made aware of the malfunction and its operational impact through the suite of potential annunciations developed in this phase of the contract.

There is potential benefit for follow-on research work dedicated to detection and annunciation of engine damage. This not only encompasses the types of damage that could be annunciated, the

methods for detection, and the most appropriate method of annunciation to the flight crew, but also the recommended pilot procedures and operational guidance after engine damage has been sustained. Task 6 (section 7.2) has categorized engine damage in support of this work.

2.4.2 Recoverable Surge.

The annunciation of recoverable surges was not included in this phase of the contract since a recoverable surge is not an STA.

However, annunciation of recoverable surges was reviewed by engineering and pilot procedural managers, and the preliminary findings made during this phase of the contract are documented here since they may affect follow-on research.

One factor in considering a recoverable surge annunciation was a PSM+ICR event, where a damaged engine surged (or otherwise malfunctioned) appeared to recover and the pilot response was inappropriate.

There are several issues involved with the annunciation of recoverable surges. The following characterizations of recoverable surges were reviewed with the pilot procedural managers:

- A recoverable surge does not require any pilot action, hence the need for an annunciation is not readily apparent.
- Annunciations indicate existing conditions and typically clear when the condition clears.
- A recoverable surge is often the result of engine damage, which would normally require maintenance action prior to the next dispatch.
- The current FADEC detection of surge is biased towards false detects because the accommodation is benign to the engine.
- Reliable annunciation of meaningful surge is problematic, since meaningful includes anything needed to support required pilot tasks or decision making.

It has been suggested that an annunciation of a recoverable surge might be beneficial to the pilots to provide awareness and identify the source of the disturbance. It has also been suggested that it may be beneficial to provide surge information on a pull basis; i.e., if the pilot suspects an engine has surged, the information could be pulled from an information page on the flight deck to identify which engine surged. This approach would not require any new hardware and implementation could likely use existing surge detection logic. Detection for annunciation has more risk as the potential exists to create as many false indications as real indications.

However, based on the characterizations of the various types of surges and the existing flight deck philosophies, the procedural pilots' initial assessments are:

- Having a suite of surge annunciations that provide identifiable procedures for surges that require pilot action allow for training of no pilot action required for an unannunciated

surge. Such a suite could be the annunciations identified in this study, e.g., fuel cut for surge/nonrecoverable stall and fuel reduction for continuous/multiple surge. This approach is preferable to an annunciation that provides awareness only and could result in an unnecessary shutdown due to the annunciation.

- A pull page is not consistent with existing flight deck philosophy and would be problematic to implement operationally due to increased training requirements and commonality concerns.

- A possible approach may be to address the primary cause of engine surges: engine damage. Since surges are most likely caused by engine damage, and engine damage is likely to require some maintenance action prior to the subsequent dispatch, perhaps identification of a damaged engine as a status type message would be most beneficial. This would allow the pilot to pull the information in flight, within the existing annunciation philosophy, and ensure maintenance action to check the engine.

The annunciation of damage or potential damage associated recoverable surges could be considered together with any future follow-on work for engine damage.

2.4.3 Thrust Lever Split.

The focus for this contract phase was the detection and annunciation of engine malfunctions, which leads to a pilot awareness of the affected malfunctioning engine and the appropriate procedure. Thrust lever split was not considered an engine malfunction (per the Phase 2 definition), and focus on specific engine malfunctions was supported by the following summary from the Boeing Phase 1 Report:

- Annunciations which promote airspeed and attitude awareness, systems which promote effective airspeed and attitude control, annunciations which identify the PSM, the affected engine, and the appropriate crew response appear to have greater PSM+ICR prevention potential than thrust asymmetry detection and annunciation.

Stuck thrust lever is a special case of stuck thrust. Stuck thrust lever does not appear to be a difficulty with FADEC systems (no known events). Stuck thrust can cause a thrust asymmetry. Engine control malfunctions that cause the vast majority of stuck thrust conditions for modern FADECs are covered by the current research work.

Also, the focus of the Phase 2 research contract was for malfunctions associated with the modern fleet of airplanes with FADEC engines. Although thrust lever splits were a contributor to PSM+ICR, these were all caused by cable system thrust lever controls on older airplanes. The probability of a thrust lever split on a modern airplane is reduced by several orders of magnitude.

Additionally, stuck thrust lever is considered addressed by features included in modern airplanes: Modern airplanes provide affective airspeed and attitude control.

- Modern airplanes detect and annunciate the most likely causes of stuck thrust lever through autothrottle (A/T) disconnect (servo failures).

Since the focus of the Phase 2 research contract was on propulsion malfunction detection and annunciation challenges, it primarily included propulsion and flight deck expertise. The annunciation of split thrust lever would fall into the autoflight functionality on modern airplanes and
requires a different expertise to evaluate (autopilot, A/T, and pilots).

There is, perhaps, an area of research regarding the airplane level annunciation of failure accommodation that could be considered. For example, research work could be done on criteria for the appropriate combination of the following when it comes to failures:

- Automatic reconfiguration
- Fault compensation
- Annunciation and procedure
- Pilot detection and reaction

2.5 TASK 1 CONCLUSIONS.

Task 1 involved the development of criteria for flight crew annunciation of engine malfunctions, derived from what is operationally desired for the engine. Operational needs for the engine included both what was required to clear the malfunction and what is required to restore thrust.

The developed engine failure database, sorted by engine component failures and identifying engine symptoms and desired operational actions, resulted in nine symptom categories:

1. Flameout
2. Surge/nonrecoverable stall
3. Thrust failed low (indicated)
4. Thrust failed low (damage)
5. Thrust failed high (indicated)
6. Continuous/multiple surges
7. Engine slow to respond
8. Thrust high or low (sensor)
9. Thrust oscillations

These nine symptom categories will be used in conjunction with the results of Tasks 2 and 3 in the development of the Task 4 detection strategies.

Engine damage is a significant contributor to PSMs. The focus of this study was the annunciation of STAs, which includes failures caused by engine damage. However, the detection, annunciation, and recommended procedures for engine damage that do not result in STA is considered an area that warrants additional research and understanding.

3. TASK 2—PROPULSION SYSTEM MALFUNCTION DETECTION CRITERIA DERIVED FROM CREW OPERATIONAL REVIEW.

This section of the Phase 2 report documents crew operational criteria for PSM+ICR-related malfunction detection and annunciation. These criteria were provided to support the development of PSM detection criteria. Together, the crew operational and propulsion criteria will be used to develop malfunction detection strategies. These strategies will define application of current technology and identify new technology required to support desired PSM detection and annunciation.

The AIA/AECMA Project Report [1] specified four ICR categories: (1) Loss of control (LOC), (2) Shutdown or throttled good engine (SDTGE), (3) Other (O), and (4) Rejected takeoff above V1 (RTO>V1). Review and analysis of PSM+ICR events indicate that:

- Information (versus data) in general, and particularly information in context, has potential to mitigate LOC, SDTGE, and O (e.g., procedure related errors) ICR.

- LOC-related ICR is also mitigated by airspeed and attitude annunciations (indication enhancements and alerts) and flight control envelope protection. However, envelope protection that can mask a PSM must be considered.

- Malfunction annunciation itself has no potential to prevent or mitigate RTO>V1 ICR. However, annunciation control (e.g., alert takeoff inhibits) has some or limited potential to mitigate RTO>V1 ICR.

The Boeing Phase 1 Report [2] concluded that a consistent contributing factor in PSM+ICR events is lack of crew awareness that a PSM exists, or lack of a clear and explicit indication or annunciation of the affected engine(s). In general, the report recommended that the airplane flight crew be made aware

- that a PSM or symptom exists.

- of the specific engine affected.

- of the specific type or nature of the PSM or symptom, the manner and extent of its affect on the engine, and its affect on subsequent operations.

Specifically, the report recommended that the following PSMs should be assessed for feasibility of flight deck annunciation:

- Engine failure (subidle)
- Engine thrust shortfall
- Engine surge
- Engine overthrust

The report also recommended follow-on work to

- define PSM+ICR-related surge and powerloss detection requirements.
- validate and demonstrate desired surge and powerloss detection capability.
- determine surge and powerloss detection and annunciation implementation feasibility.

The objective of Task 2 was to develop PSM flight phase and timing operational criteria to support the development of detection and annunciation strategies for malfunctions associated with PSM+ICR events, especially those malfunctions related to STA.

The AIA/AECMA Project Report [1] documents that surge and powerloss events account for 77% of the PSMs observed in the PSM+ICR event database. The Boeing Phase 1 Report [2] cited that "surge and powerloss, [are] the major type PSMs associated with ICR," and noted that these malfunctions are among the top three in-service PSMs currently reported. Previous work suggests that Phase 2 work should focus primarily on powerloss and surge.

Task 2 operational criteria were developed from review and analysis of

- the 80 in-service PSM+ICR turbofan events described in the AIA/AECMA Project Report,

- Boeing Phase 1 analysis of PSM+ICR event data and PSM reports,

- twenty specific STA events selected from the 80 PSM+ICR events in the AIA/AECMA Project Report database,

- nonnormal thrust-related procedures, and

- Boeing flight deck design criteria and best practices.

Task 2 review and analysis focused on historical and selected PSM+ICR events that the Boeing Phase 1 Report identified as having malfunction annunciation related ICR prevention potential. Primary focus was on events with ICR prevention potential and STA events.

The Boeing Phase 1 Report 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 of the 12 hull loss fatal (HF) events. The HF 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 fail fixed thrust malfunctions.

As noted in the Boeing Phase 1 Report, PSM+ICR prevention potential is the estimated opportunity, through PSM annunciation, to prevent or mitigate undesired crew response by providing timely awareness, correct understanding, and linkage to the appropriate nonnormal procedure. 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.

The Boeing Phase 1 Report included a human factors review and evaluation of the cognitive mechanisms involved in undesired crew response to propulsion system malfunctions. The human factors review noted that in the absence of automated detection and annunciation, malfunction detection and interpretation tasks

- require substantial flight crew knowledge, effort, and time to identify and understand the malfunction and formulate an appropriate response. Note that such time is often not available in PSM+ICR events.

- increase the potential for crew error because it can be very difficult to interpret or understand even significant changes in airplane performance or engine parameters and determine how to respond.

The human factors review concluded that the flight deck interface and associated procedures should be as error proof as possible to aid the flight crew transition from malfunction detection to an appropriate response.

For malfunctions that require crew action or awareness

- where a malfunction can be reliably and feasibly detected and annunciated, an alert should be provided via a central alerting function such as the Boeing Engine Indication and Crew Alerting System (EICAS), and

- where it is found reliable and feasible to do so, means should be provided for improving flight crew understanding of the malfunction at airplane system and mission levels.

3.1 PSM+ICR EVENT REVIEW AND OPERATIONAL ANALYSIS.

The 80 historical PSM+ICR events documented in the AIA/AECMA Project Report, and the Boeing Phase 1 Report [2], were used to derive PSM, flight phase, and timing criteria. The criteria were derived to support the development of propulsion system detection criteria and malfunction detection strategies. The following pages document the PSM, flight phase, and timing analyses and criteria derived from operational analysis.

3.1.1 PSM Operational Analysis—Focus PSMs.

Figure 3-1 shows figure 4-2 from the Boeing Phase 1 Report. The figure illustrates the relationship between PSM and crew response for all 80 events in the AIA/AECMA Project Report database. Surge was the dominant PSM in SDTGE and RTO>V1 events, and a PSM in O events. Surge is not associated with LOC PSM+ICR events. Powerloss was distributed evenly across all crew response categories: LOC, O, SDTGE, and RTO>V1. Fail fixed thrust (mostly stuck thrust lever), is associated with LOC and shutdown good engine (SDGE) events. The majority of PSM+ICR events involve engine surge or powerloss. Surge and powerloss jointly occur in many PSM+ICR events. Such events were categorized using the PSM primarily associated with the ICR.

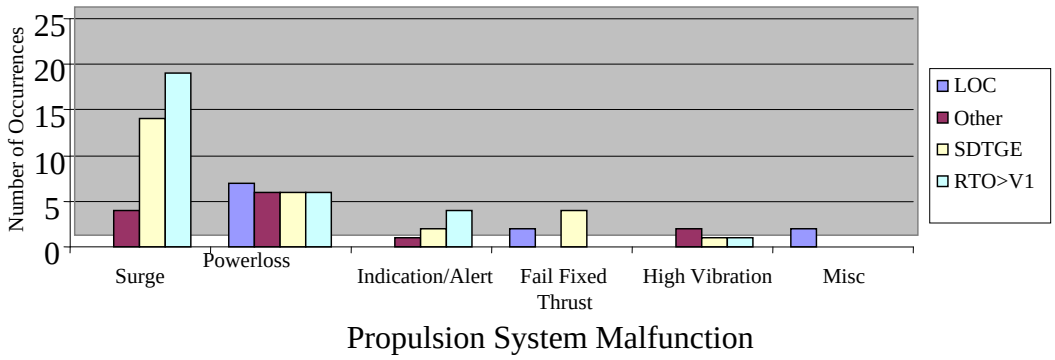


Figure 3-1. AIA Report Crew Response Category and Primary PSM

Here, table 3-1 shows table 4-3 from the Boeing Phase 1 Report. The table shows the relationships between CR, the primary PSM symptom, and event hazard for all 80 events documented in the AIA/AECMA Project Report database. As table 3-1 shows, powerloss, surge, and fail fixed thrust (primarily stuck thrust lever) account for

- all fatal PSM+ICR events (12 of 12 events having 430 fatalities), and
- most HF, substantial damage, and incidental PSM+ICR events (56 of 68 events).

Table 3-1. Crew Response, Malfunctions, Hazard, and PSM Recoverability

Crew Response and PSM/Symptom	Hazard[6]	Numerical Hazard [5]	Number of Fatalities	PSM Recoverability[6]
Loss of Control (11)	7 HF, 2 H, 1 S, 1 I	4.36	336 (7 events)	3 R, 5 NR, 3 Unknown
Powerloss (7) 5 Engine Fail w/Surge 1 Engine Subidle 1 Unknown Stuck Thrust lever (2) 1 at Climb power 1 at Idle power Thrust Reverser (2) 2 Fail to Deploy	5 HF, 1 H, 1 S 4 HF, 1 H 1 S 1 HF 2 HF 1 H, 1 I			
Other (13)	3 HF, 3 H, 0 S, 7 I	2.69	44 (3 events)	0 R, 11 NR, 2 Unknown
Powerloss (6) 5 Engine Fail w/Surge 1 Engine Fail/Subidle Surge (4) Excess Vibration (2) Low Oil Quantity (1)	2 HF, 1 H, 3 I 2 HF, 1 H, 2 I 1 I 1 HF, 1 H, 2 I 2 I 1 H			

Table 3-1. Crew Response, Malfunctions, Hazard, and PSM Recoverability (Continued)

Crew Response and PSM/Symptom	Hazard[6]	Numerical Hazard[5]	Number of Fatalities	PSM Recoverability[6]
Shutdown/Throttled Good Engine (27)	1 HF, 1 H, 0 S, 25 I	1.96[1]	47 (1 event)	10 R, 14 NR, 3 Unknown Shutdown [3] Throttled [4]
Surge (14)	1 HF, 1 H, 0 S, 12 I			
Powerloss (6)	6 I			
Stuck Thrust lever (3) 1 at Idle 1 at Medium to High 1 at High	3 I			
Fail Fixed/Subidle (1)	1 I			
Excess Vibration (1)	1 I			
Fire Warning (2)	2 I			
RTO>V1 (30)	1 HF, 5 H, 10 S, 14 I	2.33 [2]	3 (1 event)	5 R, 16 NR, 9 Unknown
Surge (19)	1 HF, 3 H, 6 S, 9 I1			
Powerloss (6) 2 Engine Fail w/Surge 3 Thrust Shortfall 1 Perceived	H, 2 S, 3 I			
Warning/Indication (4)	1 H, 2 S, 1 I			
Severe Vibration (1)	1 I			

[1]Numerical Hazard: SDGE on two-engine airplane = 2.14. SDGE on same side as malfunctioning engine on four-engine airplane = 2.0. Throttled Good Engine on two-engine airplane = 1.6.

[2]Numerical Hazard for RTO with wheels on ground (i.e., RTO before liftoff) is 2.15.

[3]Recoverability vs Nonrecoverability: SDGE = 7 R, 13 NR, 2 unknown.

[4]Recoverability vs Nonrecoverability: Throttled good engine = 3 R, 1 NR, 1 unknown.

[5]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 crew response category.

[6]HF = Hull loss fatal, H = Hull loss, S = Substantial damage, I = Incidental, R = Recoverable, and NR = Nonrecoverable.

Table 3-1 documents the primary PSM or symptom associated with each ICR. The Boeing Phase 1 Report event analysis was focused on malfunction detection and annunciation for the purpose of preventing or mitigating the event ICR. In the Boeing Phase 1 Report, the events where both surge and powerloss occurred were assessed to identify the PSM primarily associated with the ICR that occurred. The primary PSM or symptom was not always the initial malfunction or initial symptom that occurred. This was particularly the case when the engine failed subidle. Consequently, some Boeing Phase 1 Report events categorizations differ from the AIA/AECMA Report categorizations. Some events, which the AIA/AECMA Project Report categorized as surge or stall, or both surge and powerloss, were recategorized in the Boeing Phase 1 Report as powerloss involving surge/nonrecoverable stall. Other events where both

surge and powerloss occurred, but power remained at or above idle, were categorized as surge events involving thrust shortfall powerloss.

The Boeing Phase 1 Report and table 3-1 PSM+ICR event analysis indicate that:

- Powerloss, surge, and fail fixed thrust (primarily stuck thrust lever) occur as STAs in most fatal ICR events. A common factor among these PSMs is that indicated and actual thrust typically differs from commanded or target thrust. (The one exception was a recoverable-surge event that resulted in an SDGE event.)

- PSM+ICR powerloss events are typically indicated and the actual thrust (EPR or N1) is less than commanded thrust, or engine thrust subidle. Most in flight PSM+ICR powerloss events involve engine failure to subidle or below. Engine failure is considered a STA. Some powerloss events include surge. Fifty-eight percent of the fatal PSM+ICR events were powerloss (7 of 12), at least two of which also involved surge effects. Tables 3-2 and 3-3 list sustained powerloss events from the AIA/AECMA Project Report PSM+ICR database that were selected for further analysis. Based on the Propulsion Task 1 characterizations, engine surge/nonrecoverable stall was reclassified as a subidle powerloss event.

- PSM+ICR surge events involve either a single momentary surge, which self-clears, or involve surge/nonrecoverable stall or continuous/multiple surges that require crew action to clear or correct. Based on Propulsion Task 1 characterization of the three types of surges (recoverable surge, surge/nonrecoverable stall, and continuous/multiple surge), engine stall was recategorized as a subidle powerloss condition for this phase. Because event data is often limited or anecdotal, it is difficult and often not possible to reliably establish the occurrence of sustained continuous/multiple surge. In both single and repeated PSM+ICR surge events, the surge often precedes or accompanies a significant loss in engine thrust or engine failure. Table 3-2 and 3-3 list continuous/multiple surge events from the AIA/AECMA Project Report PSM+ICR database that were selected for further analysis.

- PSM+ICR stuck-thrust lever events all involved A/T engagement. The autopilot may, or may not, have been engaged. In the most hazardous events, a large thrust asymmetry occurred as the remaining thrust lever(s) were driven to an extreme high- or low-thrust position when the A/T attempted to maintain speed or drive the stuck thrust lever to a target thrust. On airplanes with moving thrust levers, a stuck thrust lever results in observable thrust lever splits, but does not result in observable commanded and indicated thrust differences. Seventeen percent of fatal PSM+ICR events involved stuck thrust levers (2 of 12): one thrust lever stuck at idle power in descent phase of flight, and one thrust lever stuck at climb power in Climb phase of flight. These stuck thrust lever events have the same airplane operational effects as STAs. Note that stuck thrust lever is a specific case of fail fixed thrust. Fail fixed thrust is typically a within limits failure condition, which results in a difference in commanded and indicated/actual thrust (e.g., a thrust shortfall or overthrust condition). Table 3-2 and 3-3 list sustained fail fixed thrust (stuck thrust lever) events from the AIA/AECMA Project Report PSM+ICR database that were selected for further analysis.

The potential for ICR is proportional to the overall annual report rates for powerloss, surge, and stuck thrust lever malfunctions. Annual reports indicate that powerloss and surge are among the most frequently occurring PSMs. The occurrence of stuck thrust lever events on modern airplanes has been significantly reduced with FADEC controlled engines (i.e., no engine thrust lever cables and modern A/T designs). Consequently, the annual report rate of stuck thrust lever events is relatively low compared to powerloss and surge report rates. Hence, the need to focus further detection/annunciation effort on stuck thrust lever malfunctions is questionable and of much lower priority than powerloss or surge. Further work in this area requires A/T and autopilot design expertise and a higher level focus on systems integration (as discussed in section 2.5.2). Modern FADEC systems are showing a different failure mode than the older non-FADEC systems. This is stuck thrust. In this failure mode, thrust does not change when commanded. This failure is detectable with a thrust failed high/low detection algorithm. Therefore, surge and powerloss are the primary focus of the current phase of work.

PSM+ICR event prevention potential is associated primarily with alert annunciation of powerloss, surge, and fail fixed thrust malfunctions. As previously noted, estimates of prevention potential are based on review of available, but often limited, data, and engineering judgment. Judgment of prevention potential indicates only that the opportunity for prevention appears to exist—i.e., that prevention potential is a possibility, not a certainty. The seven fatal STA events reviewed in this report account for 85% of all PSM+ICR fatalities. All but two of the STA events selected for further analysis were assessed in the Boeing Phase 1 as having prevention potential. Prevention potential in these two events was indeterminate.

Review and analysis of the 80 historical PSM+ICR event data indicates that powerloss, surge/Nonrecoverable stall, and fail fixed thrust detection and annunciation has potential benefit. These three malfunctions account for the majority of PSM-related ICR. All three malfunctions can be characterized as sustained thrust anomalies. Therefore, the following malfunction conditions are the primary candidates for detection and annunciation.

- Powerloss—Indicated and actual thrust (EPR or N1) is less than commanded thrust, subidle engine thrust, or engine flameout.

- Surge—Continuous/multiple engine surges, or sustained engine surge/nonrecoverable stall. Abnormal state, deviation, or fluctuation in engine parameter(s), pressure(s), or operating state(s) attributable to engine surge/nonrecoverable stall.

- Fail Fixed Thrust—Indicated and actual thrust (EPR or N1) is within limits but does not equal commanded/target thrust.

3.1.2 Sustained Thrust Anomaly PSM+ICR Events.

Based on Propulsion Engineering recommendation, and with the concurrence of all involved, it was decided to focus Phase 2 work on STAs. This recommendation was based on the observation that most of the hazardous PSM+ICR events involved STAs, and the assessment that focus on STAs had the greatest potential for feasible detection and annunciation.

Tables 3-2 and 3-3 list 20 STA events selected from the AIA/AECMA Project Report PSM+ICR event database—11 powerloss, 4 continuous/multiple surge, and 5 fail fixed thrust. Table ID numbers are from the reference 1 report database. The 20 events selected are representative of the major types of STAs associated with PSM+ICR events and were selected because enough data existed to analyze pilot response time. Many events simply do not have enough information to analyze the malfunction and the circumstances/factors affecting pilot response. Note that two of the events listed as continuous/multiple surge do not meet the reference 1 criteria of "an accident or incident where a single benign propulsion-system-malfunction occurred and the pilot did not appropriately respond." These two events (51 and 58) were dual engine (common mode) events, which were addressed through design and operational changes. These two events were included in the reference 2 database and tables 3-2 and 3-3 because they had sufficient data to support useful analysis.

The tables were developed by flight deck and propulsion engineering collaboration, and are based on event data review, engineering judgment, and the reclassification of surge based on the Task 1 propulsion malfunction characterizations. Flight data, accident report, and other formal data were used where available. The listed events represent a consensus that these events involve STAs. The tables document STA PSM events that were used to derive flight phase and timing criteria to support the development of propulsion system detection criteria and malfunction detection strategies.

Table 3-2. Sustained Thrust Anomaly PSM+ICR Events—By Event Classification

Event No.	ID Number	Year	Event Class[1]	Power (L/M/H)[5]	Altitude	PSM	ICR
10	73/1ST/2/HF	73	HF	L (ini) H	Approach (300′)	Powerloss	LOC
43	*85/2ND/2/HF	85	HF	H	Climb (450′)	Powerloss	LOC
51	88/2ND/2/HF	88	HF	H	Climb (300′)	Cont/multiple surge	Other [2]
61	*92/MNB/2/HF	92	HF	L	Descent (7200′)	Stuck thrust lever	LOC
74	*95/EWB/2/HF	95	HF	H	Climb (1500′)	Stuck thrust lever	LOC
77	95/2ND/2/HF	95	HF	L (ini) H	Approach (Unk/Low)	Powerloss	LOC
81	96/1ST/4/HF	96	HF	H	Takeoff roll < V1	Powerloss	Other
2	69/2ND/2/H	69	H	H	Takeoff climb (200')	Powerloss [6]	Throttled good engine
6	71/1ST/4/H	71	H	H	Takeoff (0'[1])	Powerloss	LOC
58	91/MNB/2/H	91	H	H	Takeoff climb (1125′)	Cont/multiple surge	Other [2]
39	*85/EWB/4/S	85	S	L-H	Cruise (FL410)	Powerloss	LOC
11	75/EWB/4/I-1	73	I	M	Cruise (FL370)	Powerloss [6]	SDGE
15	77/EWB/4/I	77	I	H	Climb (FL280)	Powerloss [6]	SDGE
41	85/EWB/4/I-2	85	I	H	Takeoff climb (100′)	Powerloss [6]	SDGE
59	92/MWB/2/I	92	I	L-M+	Cruise (FL390)	Powerloss	Other [3]
62	*93/MNB/2/I	93	I	H-M	Go around (2800')	Cont./multiple surge	Other [4]
66	*93/MNB/2/I	93	I	L	Approach (700′)	Stuck Thrust lever	SDGE
71	*94/MWB/4/I	94	I	H	Climb (1800′)	Cont./multiple surge	SDGE
73	*95/MWB/2/I-2	95	I	H	Climb (FL120)	Stuck thrust lever	SDGE
79	96/MNB/2/I	96	I	L	Approach (Unknown)	Stuck thrust lever	SDGE

[1]HF = hull loss fatal, H = hull loss, S = substantial damage, and I = incidental.
[2]Dual-engine surge. Procedure error—did not reduce thrust on affected engine(s) setting.
[3]Failure to detect powerloss.
[4]Difficulty identifying affected engine.
[5]L = low, M = medium, and H = high, and (ini) = initial power
[6]Powerloss was due to surge-nonrecoverable stall.
*Indicates additional event data exists—e.g., flight data recorder or safety investigation report

Table 3-3. Sustained Thrust Anomaly PSM+ICR Events—By PSM

Event No.	ID Number	Year	Event Class[1]	Power (L/M/H)	Altitude	PSM	ICR
10	73/1ST/2/HF	73	HF	L (ini) H	Approach (300′)	Powerloss	LOC
43	*85/2ND/2/HF	85	HF	H	Climb (450′)	Powerloss	LOC
77	95/2ND/2/HF	95	HF	L (ini) H	Approach (Unk/Low)	Powerloss	LOC
81	96/1ST/4/HF	96	HF	H	Takeoff roll < V1	Powerloss	Other
2	69/2ND/2/H	69	H	H	Takeoff climb (200′)	Powerloss [6]	Throttled good engine
6	71/1ST/4/H	71	H	H	Takeoff (0′)	Powerloss	LOC
39	*85/EWB/4/S	85	S	L-H	Cruise (FL410)	Powerloss	LOC
11	75/EWB/4/I-1	73	I	M	Cruise (FL370)	Powerloss [6]	SDGE
15	77/EWB/4/I	77	I	H	Climb (FL280)	Powerloss [6]	SDGE
41	85/EWB/4/I-2	85	I	H	Takeoff climb (100′)	Powerloss [6]	SDGE
59	92/MWB/2/I	92	I	M	Cruise (FL390)	Powerloss	Other [3]
51	88/2ND/2/HF	88	HF	H	Climb (300′)	Cont./multiple surge	Other [2]
58	91/MNB/2/H	91	H	H	Takeoff climb (1125′)	Cont./multiple surge	Other [2]
62	*93/MNB/2/I	93	I	H-M	Go around (2800′)	Cont./Multiple Surge	Other [4]
71	*94/MWB/4/I	94	I	H	Climb (1800′)	Cont./Multiple Surge	SDGE
61	*92/MNB/2/HF	92	HF	L	Descent (7200′)	Stuck thrust lever	LOC
74	*95/EWB/2/HF	95	HF	H	Climb (1500′)	Stuck thrust lever	LOC
66	*93/MNB/2/I	93	I	L	Approach (700′)	Stuck thrust lever	SDGE
73	*95/MWB/2/I-2	95	I	H	Climb (FL120)	Stuck thrust lever	SDGE
79	96/MNB/2/I	96	I	L	Approach (Unknown)	Stuck thrust lever	SDGE

[1]HF = Hull loss fatal, H = Hull loss, S = Substantial damage and, I = Incidental.
[2]Dual-engine surge. Procedure error—Did not reduce thrust on affected engine(s).
[3]Failure to detect powerloss.
[4]Difficulty identifying affected engine.
[5]L = low, M = medium, H = high, and (ini) = initial power setting.
[6]Powerloss was due to surge-nonrecoverable stall
*Indicates additional event data exists—e.g., flight data recorder or safety investigation report

The same PSM+ICR events are listed, but organized differently, in each table. Table 3-2 is organized by event classification (Hull Loss Fatal (HF), Hull Loss (H), Substantial Damage (S), and Incidental (I) events), then by date of occurrence. Table 3-3 is organized first by PSM, then by event classification. Event and ID numbers are provided to allow correlation with the original event data and descriptions in the AIA/AECMA Project Report and related reports.

All the HF powerloss events listed in table 3-3 (10, 43, 77, and 81), involved significant powerloss and thrust asymmetry. Event 10 was a subidle powerloss event. Event 43 was a likely subidle powerloss event. Propulsion review and analysis concluded that events 77 and 81 were likely subidle powerloss events. Note that based on propulsion engineering PSM characterizations during the collaborative review, some surge/nonrecoverable stall events were moved into the powerloss category. These events are identified parenthetically.

3.1.3 Flight Phase Operational Analysis.

3.1.3.1 Analysis of All 80 AIA/AECMA Project Report PSM+ICR Events.

Table 3-4 shows table 4-9 from the Boeing Phase 1 Report. The table documents the flight phase and altitude for all 80 PSM+ICR events, including 12 HF events, in the AIA/AECMA Project Report. Engine power level is implicit in phase of flight.

Table 3-4. Flight Phase, Altitude, Power, and Event Classification

Flight Phase	Takeoff (Ground Roll)	Climb	Cruise	Descent	Approach/Go Around
All Events (80)	36	27	10	2	5
HF Events (12)	0	8	1[1]	1[2]	2[2]
HF Event Altitudes	0	50′ to 2000′ [3]	FL 290	7200′	200′ to 300′

[1]The cruise HF event malfunction initiated at climb power, but the associated ICR (SDGE) occurred at low engine power.

[2]The descent and approach HF event malfunctions initiated at medium to low power, but the associated ICRs (LOC) occurred at high/go around power.

[3]Most HF event malfunctions appear to initiate below 500′.

Table 3-4 (notes revised for this phase) documents that most of the 80 PSM+ICR events initiated during the takeoff and climb phase of flight. Most of the fatal PSM+ICR event malfunctions in the AIA/AECMA Project Report database (67%) initiated at high power between 50 and 2000 feet in climb after takeoff or during go around. The remaining fatal PSM+ICR event malfunctions (33%) initiated at medium and low power in cruise, descent, or approach. Most HF event malfunctions appear to initiate in flight below 500′.

The cruise HF event malfunction initiated at climb power, the associated ICR (SDGE) occurred at low engine power, and the subsequent HF involved medium to high engine power. The descent and approach HF event malfunctions initiated at medium to low power, but the associated ICR (loss of control) occurred at high or go around power. Therefore, almost all HF PSM+ICR events at some point typically involve medium to high engine power.

Table 3-5 shows a slightly modified table 4-10 from the Boeing Phase 1 Report. The table documents the flight phase and altitude for all 80 PSM+ICR events, and all 12 HF events, in the AIA/AECMA Project Report. Engine power level is implicit in phase of flight.

Table 3-5. Flight Phase, Altitude, and PSM/Symptom and Hazard

Malfunction (No. of Events)	Takeoff (Ground Roll)	Climb	Cruise	Descent	Approach or Go Around
All Surge[3] (37)	17	15	5	-	-
HF Surge (3)		2 < 300′	1 @FL290 [1]		
All Powerloss (25)	10	7	5	1	2
HF Powerloss (7)		5 < 2000′			2 < 300′ [2]
All Stuck Throttles (5)		2		1	2
HF Stuck Throttles (2)		1 @1500′		1 @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.

[3]PSM+ICR events categorized as surge in the AIA/AECMA Project Report consist of a mix of single self-recovering surges, continuous/multiple repeated surges, and surge/nonrecoverable stall. These were characterized and differentiated in the current (Phase 2) work.

Table 3-5 shows that most PSM+ICR powerloss events occurred in takeoff, climb, or cruise where engine power is typically high to medium. Note that the takeoff powerloss events are mostly RTO>V1 events for which it has been judged that no malfunction annunciation-related prevention potential from malfunction annunciation exists. This issue should be periodically reviewed because knowledge and detection capability of PSM events and flight deck information displays advances. Most fatal PSM+ICR powerloss events occurred below 2000 feet in climb phase where engine power is typically high to medium. Two fatal PSM+ICR powerloss events initiated at low to medium power below 200 feet on approach, but the LOC crew response occurred during go around at high-commanded engine power. The 80 event data indicate that powerloss-related PSM+ICR is the most hazardous in the climb and approach and go around flight phases.

Table 3-5 shows that all PSM+ICR surge events occurred in takeoff, climb, or cruise flight phases where engine power is typically high to medium. Most occurred during takeoff and climb where engine power is typically high. Note that the takeoff surge events are mostly RTO>V1

events for which it is currently judged that no malfunction annunciation-related prevention potential exists. Two fatal surge events occurred below 300 feet in climb where engine power is typically high. One fatal surge event occurred at 29,000 feet during climb to cruise where engine power is typically medium to high. Note that the table shows no PSM+ICR surge events in the descent or approach/go around phases of flight. This suggests that surge-related PSM+ICR is not a significant concern during descent and approach/go around phases of flight. The 80 event data indicate that surge-related PSM+ICR is the most hazardous in the climb and cruise flight phases.

Table 3-5 shows that all PSM+ICR fail fixed thrust (stuck throttle) events occurred in climb, descent, or approach flight phases where engine power varies from high to low. Most fail fixed thrust events, which initiated during descent and approach, where engine power was low, became problems when higher power was commanded for level off or go around and a thrust lever stuck at low power. Two fatal fail fixed thrust events occurred, one in climb and one in descent, when changes in engine power and a stuck thrust lever produced thrust asymmetries, which led to LOC events. Note that the table shows no PSM+ICR fail fixed thrust events in the takeoff or cruise phases of flight. This suggests that fail fixed thrust-related PSM+ICR is not a significant concern during takeoff (ground roll) and cruise phases of flight. The 80 event data indicate that fail fixed thrust-related PSM+ICR events in the climb and descent flight phases are the most hazardous.

3.1.3.2 AIA/AECMA Project Report Events Flight Phase Criteria.

Tables 3-4 and 3-5 contain the PSM+ICR event data for all 80 historical PSM+ICR events. The overall event data indicate potential benefit associated with powerloss, surge, and stuck throttle (fail fixed thrust) detection and annunciation in flight per the following flight phase criteria:

- Powerloss: detection and annunciation in flight, particularly during takeoff climb, and during approach and go around when indicated/actual thrust is high or altitude is low. The all event data suggest that powerloss-related PSM+ICR events in the climb and approach/go around flight phases are the most hazardous.

- Surge: detection and annunciation in flight, particularly during takeoff climb, and during approach and go around when indicated/actual thrust is high or altitude is low. The all event data suggest that surge-related PSM+ICR events do not occur during descent and approach/go around phases of flight, and that surge-related PSM+ICR events in the climb and cruise flight phases are the most hazardous.

- Fail Fixed Thrust (including Stuck Thrust lever): detection and annunciation in flight, particularly during climb, descent, and approach/go around flight phases wherever or whenever engine power is modified or changed automatically or manually. The all event data suggest that fail fixed thrust-related PSM+ICR events does not occur during takeoff (ground roll) and cruise phases of flight, and that fail fixed thrust-related PSM+ICR events in the climb and descent flight phases are the most hazardous.

3.1.3.3 Sustained Thrust Anomaly Events Flight Phase Criteria.

Table 3-6 documents the flight phase and altitude analysis for the 20 STA events, including the 7 HF events, listed in tables 3-2 and 3-3.

Table 3-6. STA Events—Flight Phase, Altitude, Power, and Event Classification

Flight Phase	Takeoff (Ground Roll)	Climb	Cruise	Descent	Approach or Go Around
STA Events (20)	2	9	3	1	5
Event Altitudes	0	100′ to FL280	FL370 to FL410	7200′	300′ to 2800′
HF Events (7)	1	3	—	1	2
HF Event Altitudes	0	300′ to 1500′	—	7200′	300′

Tables 3-3 and 3-6 analysis of the STA PSM+ICR events selected indicates potential benefit associated with powerloss, continuous/multiple surge, and stuck throttle (fail fixed thrust) detection and annunciation in flight, and yields similar flight phase criteria:

- The STA powerloss events reviewed (including surge-related stall) occurred on ground during takeoff, and in flight during climb, cruise, and approach. Most events (9 of 11) occurred in flight between 100 and 41,000 feet altitude and at medium to high power.

- The STA continuous/multiple surge events reviewed occurred in flight during takeoff or go around climb between 300 and 2800 feet altitude. All events involved medium to high power.

- The fail fixed thrust (stuck throttle) events reviewed occurred in flight during climb, descent, and approach. Most events (4 of 5) occurred between 700 to 12,000 feet altitude. All events involved power changes where the malfunctioning thrust lever stuck either higher (3 of 5) or lower (2 of 5) than the normally operating thrust lever(s).

STA-based flight phase criteria is consistent with flight phase criteria developed from analysis of all 80 historical PSM+ICR events.

3.1.4 Timing Operational Analysis (of Selected STA Events).

Table 3-7 documents the power, flight phase/altitude, and timing analysis for the 20 STA events identified in tables 3-2 and 3-3.

This section contains an analysis of the time available for PSM detection and annunciation to have PSM+ICR event prevention potential or event mitigation potential. Time available is the opportunity or potential for detection and annunciation to affect the event outcome—i.e., to potentially prevent the ICR or mitigate the hazard associated with the ICR.

The operational analysis examined the time in each event from PSM to ICR to point of no recovery and estimated how much time was available to provide crew awareness that could prevent or mitigate the effects of the ICR.

In general, the AIA/AECMA Project PSM+ICR Report data and narratives do not explicitly quantify the time available for detection, annunciation, and crew response or awareness —e.g., do not provide the time between the onset of the PSM to the crew response nor the time after the crew response that is available for intervention. Where this information was not explicitly available, these times were estimated or inferred based on the phase of flight, altitude, the narrative information, and operational experience.

As noted, table 3-7 documents the estimated timing criteria for each of the 20 STA events selected for analysis. The following sections summarize the estimated time available for malfunction detection and annunciation to have PSM+ICR event prevention or mitigation potential.

3.1.4.1 Powerloss.

Four fatal powerloss PSM+ICR events are applicable to the current effort to develop crew operations and propulsion criteria that support the development of powerloss detection and annunciation strategies. Review indicates that on the order of 5 seconds at higher power, settings were available for powerloss detection and annunciation in these events.

Review of the remaining six other PSM+ICR powerloss events suggests that the time available for detection, annunciation, and crew intervention increases as event altitude increases and event hazard decreases. Where timing can be determined, review indicates 30 to 40 seconds and on the order of minutes may be available.

3.1.4.2 Continuous/Multiple Surge.

One fatal surge PSM+ICR event is applicable to the current effort to develop crew operations and propulsion criteria, which support the development of surge detection and annunciation strategies. Review indicates that 10 seconds or more were available for surge detection and annunciation in this event.

Table 3-7. Sustained Thrust Anomaly PSM+ICR Events—Power, Flight Phase, and Timing Criteria

Event No.	Event Class[1]	PSM	ICR[2]	Power (L/M/H)	Flight Phase/Altitude	Timing
10	HF	Powerloss	LOC	L (ini) H	Approach (300′)	5 to 10s after application of power[3]
43	HF	Powerloss	LOC	H	Climb (450′)	5 to 10 seconds[4]
77	HF	Powerloss	LOC	L (ini) H	Approach (Unk/Low)	5 seconds after power applied[3]
81	HF	Powerloss	Other	H	Takeoff Roll < V1	Available time unknown[4]
2	H	Powerloss[5]	TGE	H	Takeoff Climb (200′)	Unknown/Indeterminate
6	H	Powerloss	LOC	H	Takeoff (0′)	Unknown/Indeterminate
39	S	Powerloss	LOC	L-H	Cruise (FL410)	30 to 40 seconds
11	I	Powerloss[5]	SDGE	M	Cruise (FL370)	Unknown/Indeterminate
15	I	Powerloss[5]	SDGE	H	Climb (FL280)	Unknown/Indeterminate
41	I	Powerloss[5]	SDGE	H	Takeoff Climb (100′)	Unknown/Indeterminate
59	I	Powerloss	Other	M	Cruise (FL390)	Approximately 7 minutes or more
51	HF	Cont./multiple surge	Other	H	Climb (300′)	10 to 15 seconds
58	H	Cont./multiple surge	Other	H	Takeoff Climb (1125′)	11 to 39 seconds
62	I	Cont./multiple surge	Other	H-M	Climb (2800′)	Approximately 3 minutes or more
71	I	Cont./multiple surge	SDGE	H	Climb (1800′)	5 to 7 seconds
61	HF	Stuck throttle	LOC	Stuck L	Descent (7200′)	5 to 15 seconds
74	HF	Stuck throttle	LOC	Stuck H	Climb (1500′)	15 to 30 seconds
66	I	Stuck throttle	SDGE	Stuck H	Approach (700′)	10 seconds or more
73	I	Stuck throttle	SDGE	Stuck M-H	Climb (FL120)	10 to 15 seconds or more
79	I	Stuck throttle	SDGE	Stuck L	Approach (Unknown)	Unknown/Indeterminate

[1]HF=Hull loss fatal. H = Hull loss. S = Substantial damage. I = Incidental.
[2]LOC=Loss of control. TGE = Throttled good engine. SDGE = Shutdown good engine.
[3]More time available if detectable on approach before application of go around power.
[4]Prevention potential unknown.
[5]Powerloss was due to surge/nonrecoverable stall

Where timing can be determined, review of the remaining three other PSM+ICR continuous/multiple surge events listed in table 3-6 indicate that 5 seconds is available, and as much as a few minutes may be available. Review suggests that the time available for ICR prevention is least for SDGE and greatest for Other ICR. As previously noted, there are no surge-related PSM+ICR LOC events. Review does not suggest that the time available for detection, annunciation, and crew intervention increases as event altitude increases and event hazard decreases. However, because surge events are not associated with LOC events, it is expected that increased altitude provides more time for the crew to mitigate a SDGE or procedure error by restarting the engine or accomplishing the appropriate procedure.

3.1.4.3 Fail Fixed Thrust.

Two fatal fail fixed thrust (stuck throttle) PSM+ICR events are applicable to the current effort to develop crew operations and propulsion criteria which support the development of fail fixed thrust detection and annunciation strategies. Review indicates that at least 5 to 15 seconds, and as much as 15 to 30 seconds, appear available for detection and annunciation in these events.

Review of the remaining three other PSM+ICR fail fixed thrust events listed in table 3-6 indicates 10 to 15 seconds are available in these events. Review suggests that the time available for detection, annunciation, and crew intervention does not significantly increase as event altitude increases and event hazard decreases. However, as previously noted, fail fixed thrust is associated with LOC and SDGE events. It is expected that increased altitude provides more time for the crew to mitigate a SDGE by restarting the engine.

3.1.4.4 Propulsion System Malfunction Operational Detection and Annunciation-Timing Criteria Summary.

Where available time can be estimated, PSM+ICR event data analysis indicates that at least 5 seconds are available for detection and annunciation of powerloss, continuous/multiple surge, and fail fixed thrust malfunctions. Note that as a general rule, the earlier the detection and annunciation, the greater the prevention potential.

3.1.5 Summary of Operational Criteria.

Table 3-7 summarizes the PSM, power, flight phase, and timing criteria developed from operational review of the selected STA PSM+ICR events. In general, the criteria are consistent with the criteria developed from analysis of all 80 historical PSM+ICR events.

For all three PSMs (powerloss, surge, and fail fixed thrust), the higher the power and the lower the altitude, the more hazardous the event. Event altitude, and to some extent power level, affect the time available for crew recognition, response, and recovery.

The majority of PSM+ICR events in general, and STA events in particular, involve high power and low altitude. The majority of STA events involve altitudes below 7200′.

The 80-event data in general and the STA data in particular

- indicate that powerloss-related PSM+ICR events are most hazardous in the takeoff, climb, and approach/go around flight phases.

- show that surge-related PSM+ICR events do not occur during descent and approach/go around phases of flight, and indicate that surge-related PSM+ICR events are most hazardous in the takeoff climb flight phase.

- show that fail fixed thrust-related PSM+ICR events do not occur during takeoff (ground roll) and cruise phases of flight, and indicate that fail fixed thrust-related PSM+ICR in the climb and descent flight phases is the most hazardous.

In the STA events reviewed, at least 5 seconds appear available for powerloss and fail fixed thrust detection and annunciation to have potential benefit. At least 10 seconds appear available for continuous/multiple (repeated) surge detection and annunciation to have potential benefit. Generally, more time for potential prevention or event mitigation appears available as altitude increases and power decreases. In general, having a longer time period available to confirm and categorize the PSM event increases the reliability of the annunciation. Thus, longer diagnostic times are preferred. However, the times should not be so long that the pilot takes an action before an annunciation of the PSM event is displayed.

Note that malfunction annunciation is typically provided in all flight phases where the malfunction is possible and crew response or awareness is appropriate. Malfunction annunciation is only limited to a specific flight phase(s) when the desired crew awareness or response is limited to a specific flight phase(s). Special consideration is given to ensuring desired crew awareness and response, while guarding against undesired or inappropriate crew response during high workload, time-critical phases of flight. This is particularly true during the takeoff flight phase where the potential for unnecessary RTO in general, and RTO>V1 in particular, must be minimized to the maximum extent possible while still ensuring the requisite level of crew awareness and safety. These considerations may affect the ultimate implementation of malfunction detection and annunciation.

3.2 NONNORMAL THRUST-RELATED PROCEDURES REVIEW AND ANALYSIS.

The nonnormal procedures review and analysis had two objectives: (1) develop recommended best practices based on current and modern indications, annunciations, and procedures and (2) identify potential opportunities for improvement where the crew must currently monitor and interpret engine indications and other flight deck effects to detect or disposition engine malfunctions.

Crew workload and error potential are increased whenever the crew is expected to monitor, detect, and identify or interpret a PSM state or condition, and subsequently determine the appropriate procedure to accomplish or action to take. Objective 2 seeks to identify and eliminate or mitigate the malfunction-related potential for increased workload or crew error.

The nonnormal procedure analysis examined the annunciated and unannunciated nonnormal procedures associated with STAs. Note that the procedures analysis provides best practices, not necessarily safety-based criteria. Although the objective of best practices is to promote safe airplane operation, the best practices criteria and recommendations herein are not based on accident or incident event data. The procedures analysis sought to identify and recommend best practices based annunciation and procedural change opportunities that facilitate crew awareness and response to STA PSMs in general and those associated with ICR in particular.

Section 4 of this report documents a more comprehensive operational review of all engine-related normal, supplemental normal, and nonnormal procedures (NNP). It also documents some applicable policies and practices.

3.2.1 Nonnormal Thrust-Related Procedures.

Table 3-8 lists the NNPs that relate to thrust anomalies and are therefore the focus of the Task 2 operational procedures review. The table documents the NNP and checklist title, the alert level where applicable, the checklist condition statement used to provide crew awareness and understanding, and in a separate row following each, the associated procedure action(s)/information containing engine control checklist crew actions. Note that the checklists may contain other nonengine control information or crew actions that are not documented in table 3-8.

Table 3-8 contains eight nonnormal thrust-related checklists. Four of these checklists are annunciated (i.e., malfunction detection exists and an alert message is displayed to the pilot). The remaining four checklists are unannunciated (i.e., no malfunction detection exists, no alert message is displayed to the pilot, and the pilot is expected to detect the condition and perform the proper procedure).

The [ ] symbol preceding a checklist title indicates annunciated procedure (EICAS alert). Conditions associated with annunciated procedures are sensed/detected and alerted. Annunciated procedures typically contain crew action and crew awareness items (e.g., operational information and limitations). For electronic checklist, the [ ] is displayed preceding the EICAS message, and clears when the procedure has been completed. No *u* or [ ] indicates an annunciated procedure (pilot alert), which provides only a condition statement. The condition statement defines and explains the nonnormal condition.

The *u* symbol preceding a checklist title indicates an unannunciated checklist and procedure (i.e., no pilot alert). Conditions associated with unannunciated checklists are typically not sensed/detected and therefore are not alerted. Crew monitoring for, and detection of, the nonnormal condition is expected and accomplished using engine parameter indications, other flight deck effects (such as noise and vibration), and airplane level effects (such as yaw, roll, pitch, and speed changes).

Table 3-8. Nonnormal Engine Thrust-Related Procedures

	Checklist Title	Alert Level	Condition	Procedure Action(s)/Information
	[ ] ENG FAIL L, R	Caution	Engine speed is below idle.	A/T arm switch off. Thrust lever close. Fuel control switch cutoff. Restart may be attempted if no apparent damage. Monitor EGT during restart because autostart allows in flight exceedance.
	ENG IDLE DISAGREE	Advisory	One engine is at approach idle and the other engine is at minimum idle.	None specified. Alert provides condition awareness.
	ENG RPM LIMITED L, R	Advisory	Engine control is limiting affected engine thrust to prevent rotor speed from exceeding the rpm limit.	None specified. Alert provides condition awareness.
	ENG THRUST L, R	Caution	Engine is not producing commanded thrust.	None specified. Alert provides condition awareness.
	u DUAL ENG FAIL/STALL		Engine speed for both engines is below idle.	Fuel control switches (both) cutoff, then run. Airspeed above windmill start threshold
	u ENG LIM/SURGE/STALL L, R		Indications are abnormal or are approaching or exceeding limits, abnormal engine noises are heard, or there is no response to the thrust lever.	A/T arm switch off. Thrust lever retard. If indications abnormal or EGT continues to increase, then fuel control switch cutoff. If indications stabilized/EGT decreasing, then operate engine normally or at a reduced thrust level, which is surge and stall free.
	u ENG SVR DAMAGE/SEP L, R		Engine has severe damage, vibration, or has separated.	A/T arm switch off. Thrust lever close. Fuel control switch cutoff. Engine fire switch pull.
	u VOLCANIC ASH		Static discharge around the windshield, bright glow in the engine inlets, smoke or dust on the flight deck, or acrid odor indicates the airplane is in volcanic ash.	A/T disconnect switch push. Thrust levers close. If engines flamed out or stalled, or EGT rapidly approaching or exceeding limit, then Fuel control switches (both) cutoff, then run.

Notes: (1) [ ] indicates annunciated procedure (automated detection and annunciation—EICAS alert).
(2) *u* indicates unannunciated procedure (no detection and annunciation—no EICAS alert).
(3) indicates memorized crew action item.
L, R = left, right
rpm=revolutions per minute

Conditions are sensed, detected, and annunciated primarily as a function of the technological capability to provide detection and the availability and reliability with which such detection can be provided. Detection availability and reliability criteria and considerations are discussed in subsequent sections. Design, operational, and automation philosophies, flight deck commonality, mixed fleet flying considerations, and implementation feasibility (e.g., cost benefit) are also factors.

3.2.2 Procedures Review and Analysis.

Nonnormal procedures analysis indicates discrete and separate requirements for crew awareness of the following conditions. The criteria to differentiate each of these conditions is driven by a procedural need for the crew to take different action(s) and criteria for crew awareness of the specific condition.
The following conditions justify timely or immediate crew awareness. Most justify timely or prompt crew action.

- Dual engine failure to subidle engine speed.
- Engine indication exceeding a limit, continuous/multiple engine surge, or engine surge/ nonrecoverable stall.
- Severe engine damage or separation.
- The airplane has encountered volcanic ash.
- Single engine failure to subidle engine speed.
- Indicated/actual thrust is less than commanded engine thrust.

The following conditions justify routine crew awareness. Both conditions are detected and annunciated.

- One engine is at approach idle and the other engine is at minimum idle.
- Engine control is limiting affected engine thrust to prevent rotor speed from exceeding the RPM limit.

Detection and alert annunciation exists for subidle powerloss, thrust shortfall, and subidle surge/nonrecoverable stall conditions. Above-idle surge/nonrecoverable stall condition is alert annunciated only by a detected thrust shortfall—i.e., commanded thrust greater than indicated thrust. Detection and enhanced indication annunciation, but not alert annunciation, exists for N1, N2, N3, and EGT limit exceedances (red engine parameter indication display and digits).

Explicit detection and annunciation does not currently exist for the following conditions, which require crew awareness or action:

- Engine indication approaching limit

- Continuous/multiple engine surge
- Overthrust (indicated/actual thrust is greater than commanded engine thrust)
- Engine damage, severe engine damage, or engine separation
- Airplane has encountered volcanic ash
- Dual/multiple engine failure

Because the conditions listed are not explicitly detected and annunciated as specific pilot alerts, the crew must monitor and interpret engine indications and other flight deck effects to detect and identify them. Consistent with accepted best practices and principles, a desirable goal is that crew monitoring (of indications), detection (of abnormal values, patterns, or trends), and interpretation (of dynamic data to identify a malfunction and determine the appropriate procedure) tasks should be minimized and automated where sufficient reliability and feasibility can be demonstrated.

3.2.3 Human Factors Considerations.

The Phase 1 Report [2] made the following short-term human factors-related recommendations for 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 annunciate engine state changes."
>
> "In both cases, these annunciations or indication changes should also be supported by linking them to a central alerting function such as EICAS."

It was also noted that the analysis indicates:

> "Engine-related tasks can be separated into performance-monitoring tasks and health-monitoring tasks (which also include managing nonnormals).
>
> Performance Monitoring failures—e.g., lack of awareness that actual engine state does not equal commanded state, or a lack of awareness of commanded or actual engine state—are often major factors in propulsion system malfunction (PSM) events that result in crew error.
>
> Health Monitoring failures—e.g., failure to detect deviations from normal, correctly interpret those indications, and act in a timely way—are often factors in propulsion system malfunction (PSM) events that result in crew error."

3.2.4 Best Practices and Potential Improvements.

The following are recommended best practices based on a review of existing nonnormal procedures, associated engine indications, accepted man-machine interface design considerations, and on-going cross-model standardization and recall reduction efforts. In general, these are best practices that can be determined or inferred from a review of nonnormal procedures, associated indications, and existing malfunction detection and annunciation.

- Engine indications, controls, and information should be collocated, organized, and arranged in a fashion which facilitates normal and nonnormal propulsion system interface (e.g., review, assessment, understanding, and control), and minimizes the potential for crew error (e.g., misinterpretation, misunderstanding, or misselection). Specifically, organization and arrangement should facilitate correlation (of related annunciations, indications, and controls on the same engine), crosscheck (of like indications on different engines), and selection, deselection, and operation of system controls.

- Automatically sensible or detectable conditions requiring unique crew awareness or action should be treated as separate conditions. Consolidation of annunciation and procedures is acceptable where similar crew awareness or action is applicable.

- The number of separate unannunciated checklist procedures should be minimized, provided safety, crew awareness, and crew action requirements can be reliably achieved with a consolidated procedure(s). The number and uniqueness of memorized crew action items should be minimized—particularly in unannunciated checklists.

- Where provided, engine malfunction detection and annunciation should generally be engine specific—i.e., the specific engine affected should be identified. Exceptions should be made only on a case-by-case basis.

- For nonnormal conditions, the primary engine indication or parameter that is affected should be highlighted or otherwise graphically enhanced to facilitate pilot recognition of the affected engine and function, promote understanding of the nonnormal effect(s), and to guide pilot response. Where beneficial and feasible, supplemental information should be provided to ensure understanding and support appropriate pilot response.

- Provide collocated display of commanded and indicated thrust.

The following are potential detection and annunciation-related improvements that promote appropriate crew awareness and response. In general, pilot alerts should be provided where crew awareness or response is desired and detection and annunciation can be feasibly accomplished with the required reliability. Note that for the following potential improvements, the extent of the potential benefit, if any, has not been established and, in some cases, the detection capability is not currently available, mature, or feasible. The implementation of immature detection and annunciation can lead to more or greater problems than those they are intended to address. As such, the following list should not be interpreted as recommendations or requirements for implementation, but as areas of opportunity identified for further investigation.

- Automatic monitoring, detection, and alert annunciation of unannunciated checklist conditions is a desirable procedural improvement, specifically:

  - Engine parameter limit exceedances
  - Continuous/multiple surge
  - Severe engine damage or separation
  - Volcanic ash conditions
  - Dual/multiple engine failure

- Detection and annunciation of abnormal within limits disagreement between commanded and actual thrust or thrust asymmetry.

- Engine Damage detection, assessment, and annunciation is a desirable procedural improvement. Increased understanding of the relationship between engine damage, PSMs, and engine capability, recoverability, and restartability, is of potential operational and economic benefit.

- Differentiation of engine damage from time-critical severe engine damage or separation, and detection and annunciation of severe engine damage or separation is of potential operational and economic benefit.

Notes and qualifications for best practices and potential improvements are:

- Automatic monitoring, detection, and annunciation of engine indications abnormally approaching a limit could be beneficial. However, a demonstrable need could not be verified.

- Dual/multiple engine failures are very rare and are currently detected and annunciated as separate engine failures. The associated crew action is not easily reversible and potentially critical if erroneously accomplished, e.g., in response to a false alert. There is no integration of this detection and annunciation. Integrated monitoring, detection, annunciation of dual/multiple engine failures on 2-, 3-, and 4-engine airplanes can be adequately covered by individual PSM annunciations, if available.

- Volcanic ash events are very rare and are currently crew detected. The associated crew action is not easily reversible and potentially critical if erroneously accomplished, e.g., in response to a false alert. Currently, there is no automatic detection capability for flying in volcanic ash. This study did not address the issue of detecting operation in volcanic ash.

- Thrust asymmetry is considered an airplane level effect, not a PSM. Consequently, there is no engine-related nonnormal checklist procedure for thrust asymmetry. The current best practices recommendation for thrust asymmetry monitoring, detection, and annunciation is to address the condition at the airplane level through airspeed and attitude awareness (e.g., bank angle, airspeed low, and stall angle of attack annunciations) and control (e.g., bank and pitch envelope protection and thrust asymmetry compensation

systems). However, consideration could be given to detection and annunciation of in flight thrust splits, particularly when the A/T is engaged.

3.3 OPERATIONAL CONSIDERATIONS AND ANNUNCIATION CRITERIA.

3.3.1 General—Operationally Meaningful Thrust Anomaly.

Any unannunciated PSM symptom or effect that the crew can detect (see, feel, or hear) on the flight deck has positive potential to attract crew attention. However, unmediated indication or unexplained affects also have potential to undesirably increase crew workload, misdirect or distract the crew, be misinterpreted by the crew, and prompt inappropriate crew response. Alone, or in combination, such misdirection, distraction, misinterpretation, and higher workload increase the potential for crew error in general, and ICR in particular. Symptomatic or effect awareness alone does not necessarily support correct crew interpretation or understanding.

This section defines operationally meaningful thrust anomalies based on an assessment by flight deck engineers, pilots, and procedural managers based on operational experience, judgment, human factors considerations, and best practices. The criteria for operationally meaningful PSM are not necessarily or directly safety based, but based on best design and operational practices, pilot input, and engineering assessment.

In general, a condition is considered operationally meaningful if awareness of it is needed to support required pilot tasks or decision making. Any condition for which the absence of crew awareness or action could be hazardous or affect operational capability is operationally meaningful.

It is operationally meaningful whenever engine parameters are outside their normal operating range (e.g., engine subidle or limit exceedance). In general, any persistent or sustained difference in commanded versus indicated and actual thrust that exceeds normal engine operation or normal propulsion system response time is a candidate for crew awareness. Any persistent difference in commanded versus indicated and actual thrust that may affect a normal crew task (e.g., flight path control), requires either automatic or manual compensation or a nonnormal procedural response, is a candidate for crew awareness.

Surge detection and annunciation in particular should focus primarily on operationally meaningful continuous/multiple surge. Operationally, meaningful implies a demonstrable need for crew awareness or action. Continuous/multiple surge that the crew can detect audibly (e.g., booms), tactilely (e.g., vibration), or visually (e.g., through abnormal engine indication(s) or behavior) should be considered operationally meaningful. Surge that results in engine damage, or that has a high probability of resulting in engine damage, should also be considered operationally meaningful.

The following numerical criteria are preliminary informal assessments that have not been formally validated. They are based on experienced pilot estimates and are provided only as a ball park starting point for review and discussion. Depending on the phase of flight and nature of the malfunction, timing criteria could be increased (e.g., to 10 to 15 seconds) and still provide operational value. Conversely, the timing criteria may need to be shorter for time-critical thrust

loss (e.g., during takeoff or go around). In general, the higher the altitude and the lower the power, the more time available for malfunction detection and annunciation.

Steady state indicated and actual thrust is within normal operating range but does not equal commanded thrust—i.e., indicated and actual thrust abnormally deviates below or above commanded thrust. Indicated and actual thrust fails to dynamically respond or achieve commanded thrust within a normal response time, specifically:

- Uncommanded indicated thrust deviation from normal engine steady-state operation that continuously exceeds 10% to 15% of commanded thrust for approximately 3 to 5 seconds or more.

- Uncommanded rapid repeated indicated thrust fluctuations from normal engine steady-state operation that exceed 15% of commanded thrust and fail to stabilize within 5% of commanded thrust within 5 seconds of onset.

- Indicated engine thrust failure to dynamically respond and begin acceleration within approximately 3 to 5 seconds, or begin deceleration within 5 seconds, after initial pilot input.

- Indicated engine thrust that significantly lags normal acceleration or deceleration rates continuously for more than 5 seconds, or that results in a 15% to 25% or greater thrust difference between engines.

3.3.2 Annunciation Reliability Criteria.

Numeric annunciation reliability and availability criteria and related discussion for each malfunction considered are provided and documented in Task 4. A range of allowable reliability was specified with the most desirable reliability level specified first and an estimate of the minimum acceptable level of reliability specified second. The reliability criteria provided are based on existing alerting precedents and experienced engineering and operational judgments. These criteria should be considered reasonable and reliable starting points, but not absolute requirements. They are provided to support detection and annunciation strategy development and could change somewhat as the detection and annunciation strategies evolve and mature.

The following reliability criteria, and estimates from the ranges shown, were provided for each potential malfunction annunciation in table 3-9.

- P (True Detection/Alert) is the probability (P) or likelihood that the PSM will be detected/alerted when it actually exists: Low (~90%), Medium (~99%), High (~99.9%), Very High (~99.99%). In Task 4, this is also known as the annunciation availability. In general, the desired annunciation reliability varies as a function of power and altitude, the higher the power (greater the potential for damage and thrust asymmetry) and lower the altitude (closer the ground), the higher the desired reliability.

- P (Failure to Detect/Alert) is the probability (P) or likelihood that the PSM will not be detected/ alerted when it actually exists: High (~10%), Medium (~1%), Low (~0.1%), Very Low (~0.01%). This is also known as the annunciation unavailability. This probability reflects the criticality of lack of crew awareness or action, and the primary operational concern that the system will fail to detect a sustained abnormal engine condition, which significantly affects thrust, thrust control, or risks engine damage, if crew action is not taken.

- P (False Detection/Alert) is the probability (P) or likelihood that normal engine operation, or a minor engine anomaly, will be alerted as a sustained and meaningful engine malfunction. In Task 4, this is also known as the annunciation reliability. In general, the probability of false alert should be less than, or no more than on the order of, the probability of the malfunction itself. A critical need to ensure against failure to alert may drive or increase the likelihood of false alerting. Provided the potential consequences of false alerting are acceptable, false alerting may be necessary to ensure annunciation availability. This is particularly true when crew awareness or action is critical and such crew action can be tolerated if the alert is false. The amount of false alerting allowed depends on the absolute probability of the false alert and the criticality of crew awareness or action. False alerting can affect crew confidence in the airplane systems and monitoring. Excessive alerting, particularly false alerting, can desensitize the crew to alerting in general and to a specific alert in particular.

Table 3-9. Detection/Annunciation Reliability Criteria

Probability (True Detection/Alert)	P (Failure to Detect/Alert)	P (False Detection/Alert)
Very High ~99.99% (9999/10,000)High ~99.9% (999/1000 events)Medium ~99% (99/100 events)Low ~90% (90/100 events)	Very Low ~0.01% (1/10,000)Low ~0.1% (1/1000 events)Medium ~1% (1/100 events)High ~10% (10/100 events)	<~1E-9 to 1E-4 (<~1/1,000,000,000 to 10,000 engine hours)

The pilot action associated with false continuous/multiple surge annunciation (thrust lever reduction) is not operationally critical (i.e., does not significantly affect operational performance capability or safety margins). In general, the probability of a false alert should be low (e.g., on the order of at most 1E-5 per flight hour) and preferably on the order of 1E-6 or 1E-7 or less per flight hour. This ensures against overalerting an individual crew. In certain cases, such as single or dual engine failure, where pilot action is critical (engine shutdown/restart), the probability of false alerting must be very low, e.g., on the order of 1E-7 (single engine) to 1E-9 (dual engine) or less. Note that overall fleet operations and maintenance impact of false annunciation must be considered.

Criticality of annunciation coverage and reliability generally increase as thrust levels increase and altitude decreases. Criticality of failure to alert and PSM detection generally decrease as

thrust levels decrease and altitude increases. Criticality of false alerting is generally constant. Crew procedure may be used to mitigate (offset) weaknesses in detection strategies.

3.4 MALFUNCTION ANNUNCIATION CONCEPTS.

The following sections document high-level operational criteria for powerloss, surge, limit exceedance, and thrust anomaly conditions.

Flight crews should be alerted to operational and system failure conditions according to the severity of the condition and the criticality of flight crew awareness and time to take action.

The following alerting hierarchy is applicable:

- Time Critical Warnings—A nonnormal operational condition requiring immediate crew awareness (voice aural with primary flight display (PFD) annunciation) and immediate corrective or compensatory action to maintain safe flight. Memory recall action is generally justified.

- Warnings—A nonnormal operational or system condition requiring immediate crew awareness and corrective or compensatory action.

- Cautions—A nonnormal operational or system condition requiring immediate crew awareness. Corrective or compensatory action may be required.

- Advisories—A nonnormal operational or system condition requiring crew awareness. Corrective or compensatory action may be required.

The following nonalert message hierarchy is applicable:

- Communication Messages—Provide crew awareness of incoming datalink, cabin, or other normal communication (such as Selected Calling, Satellite Communications, interphone, e.g., high-low chime).

- Memo Messages—Crew reminders of routine operations, indicating current states of manually or certain automatically configured airplane systems. Noncancelable, except by altering the condition.

- Status Messages—Provide awareness of system faults that affect airplane dispatch before engine start, directly supporting airplane dispatch-related operations. Status messages are the responsibility of the pilots and ground crew.

- Maintenance Messages—Maintenance messages are the sole responsibility of the ground crew and maintenance and are detailed messages related to airplane faults.

3.4.1 High-Level PSM Annunciation Criteria.

Tables 3-10 to 3-13 document high-level annunciation criteria for surge, limit exceedance, and powerloss.

Table 3-10. Powerloss

Malfunction	Condition	Annunciation(s)	Annunciation Logic	Procedure Action(s)/Information
Powerloss				
Engine Failure	Engine speed is below idle.	Caution Alert: ENG FAIL L(R)	N1 engine speed below idle.	A/T arm switch off. Thrust lever close. Fuel control switch cutoff. Restart may be attempted if no apparent damage. Monitor EGT during restart because autostart allows in flight exceedance.
Surge-Stall		Amber affected engine thrust parameter indication.		

Table 3-11. Limit Exceedance

Malfunction	Condition	Annunciation(s)	Annunciation Logic	Procedure Action(s)/Information
Limit exceedance	Engine indication(s) are exceeding a limit.	Caution/warning alert: ENG LIMIT L(R)	Engine indication(s) approaching or exceeding a limit.	A/T arm switch off. Thrust lever retard. If indications abnormal or EGT continues to increase, then fuel control switch cutoff. If indications stabilized/EGT decreasing, then operate engine normally or at a reduced thrust level which prevents limit exceedance.
		Amber/red affected engine parameter indication.		

Notes/Issues:

1. Exceedance alert level and corresponding engine parameter indication color require evaluation.
2. Approaching/impending limit exceedance annunciation, alert level, and corresponding engine parameter indication color require evaluation.
3. Inhibit by ENG FAIL alerts requires evaluation.

Table 3-12. Surge

Malfunction	Condition	Annunciation(s)	Annunciation Logic	Procedure Action(s)/Information
Continuous/multiple surge	Two or more repetitions of a surge recovery cycle (e.g., surge and recover, surge and recover).	Caution alert: ENG SURGE L(R) Amber affected engine thrust parameter indication.	Commanded N1 above ~50% N1 and multiple engine surges detected.	A/T arm switch off. Thrust lever retard until alert clears. Operate engine normally or at a reduced thrust level that is surge free.

Notes/Issues:
1. Annunciation should clear when both commanded and actual N1 are less than 50% N1, or based on some combination of surge detection logic, surge free time, and affected engine thrust lever movement. Detail alert clearing logic is to be determined and requires engineering and operation validation.
2. Should be inhibited by: ENG FAIL alert, or ENG LIMIT alert.

Table 3-13. Thrust Anomaly

Malfunction	Condition	Annunciation(s)	Annunciation Logic	Procedure Action(s)/Information
Thrust Shortfall Overthrust	Commanded and indicated thrust disagree.	Caution Alert: ENG THRUST L(R) Amber affected engine commanded thrust sector indication.	Commanded thrust and indicated thrust differ by specified threshold/ persistence.	None specified. Alert provides condition awareness.

Notes/Issues: Inhibited by ENG FAIL alert.

3.4.2 ALERT MESSAGE DISPLAY AND CLEARING.

Crew alerts are displayed when nonnormal conditions exist that require crew awareness or action. In general, alerts are cleared when the nonnormal condition no longer exists or when crew awareness or action is no longer required. Most nonnormal conditions are persistent and continuous.

Powerloss, limit exceedance, and thrust anomaly are, in general, persistent conditions. Some nonnormal conditions are intermittent or mode dependent. To ensure appropriate crew awareness and action, alerts are often latched for intermittent or mode dependent conditions. The logic for clearing latched alerts is defined on a case-by-case basis.

By nature, engine surge in general, and continuous/multiple engine surge in particular, is more of a transient than a persistent malfunction condition. It is the transient nature of surge that in part complicates the detection strategy, necessitates alert latching, and requires special alert logic clearing.

The engine surge alert must ensure appropriate crew awareness (an engine malfunction exists and which engine is affected) and action (thrust reduction on affected engine). The alert level that ensures appropriate crew awareness and action is caution (accompanying glareshield master caution lights and caution aural). The alert logic that ensures appropriate crew awareness and action is to clear the alert when: (1) the surge condition no longer exists (e.g., the engine is surge free for some to be determined period of time sufficient to ensure the engine is not surging and sufficient to ensure crew awareness occurs before the alert is cleared) or (2) the surge condition cannot reliably be detected, but is unlikely to persist (e.g., the affected engine thrust lever lever and thrust are reduced to some predetermined level (such as 50% N1) or by some predetermined amount, such as 5 to 10 degrees lever movement). Affected engine thrust lever movement provides positive indication of appropriate crew awareness and response. Therefore, surge alert clearing based on some combination of surge-free time and affected engine thrust lever movement should be considered.

Based on the intermittent nature of continuous/multiple surge and the envisioned detection strategy (two or more surges within a 20 second period), the potential exists for unnecessary crew action (thrust lever reduction) because surging may stop after the alert has displayed. One possible strategy is to clear the alert based on some surge-free period of time after the alert has displayed. However, too short a time (e.g., 5 to 10 seconds) may remove the alert too quickly to ensure appropriate crew awareness and response. Too long a time (e.g., 15 to 30 seconds) risks unnecessary crew action (thrust lever reduction). It is not possible to anticipate all the operational circumstances or ways in which surge may occur. Surge alert clearing based solely on a minimum alert display time or some surge-free time may not adequately mitigate or prevent ICR to PSM. Any surge alert implementation should ensure appropriate crew awareness and action. Surge alert clearing logic should consider the potential for continued surge, the potential for unnecessary action (thrust lever reduction), the probability of a surge alert (on the order of 1E-5), and that the pilot action (thrust lever reduction) is easily reversible and can be mitigated by clearing the alert after some minimum surge-free time and thrust lever movement. Based on these considerations, the preliminary conclusion is that surge alert clearing should involve pilot action (thrust lever reduction), even at the risk of some unnecessary thrust lever reduction. Note that for surge alert clearing, the independent or combined use of thrust lever movement, surge detection, or time requires engineering and operational validation.

4. TASK 3—PROPULSION SYSTEM MALFUNCTION DETECTION CRITERIA DERIVED FROM NEW INDICATION CONCEPT.

4.1 TASK 3 INTRODUCTION AND OVERVIEW.

4.1.1 Introduction.

With increasing engine reliability, ICR or crew factor is a growing contributor and factor in PSM-related incidents and accidents. ICR typically occurs where the crew must

- monitor and detect (versus automated system monitoring and detection),
- interpret and understand data (versus information),
- determine the appropriate procedure, or
- take action in a novel situation (context).

In addition, engine automation awareness was identified as a consideration in developing crew information-based paradigms, which support PSM+ICR intervention strategies. Specifically, the lack of crew visibility into what engine automation is doing, when engine automation is active or doing what it does, and how such automation is progressing or succeeding in its goals and objectives, in particular, were identified as considerations for developing information-based paradigms that support PSM+ICR intervention strategies.

Task 3 reviewed the current most modern Boeing airplane normal, supplementary, and nonnormal engine procedures and associated engine indications and annunciations. Selected engine-related practices and policies were also reviewed.

The Task 3 objectives were to

- develop high-level operational criteria to provide a starting point for developing information-based (versus data- or parameter-based) engine indication paradigms and

- identify the issues that must be resolved, and the technology or detection needed, to enable information-based engine display paradigms.

Task 3 documents the

- procedure, practice, and policy (PPP) task review,
- opportunities to provide new information or improve existing information,
- automation opportunities, and
- detection required for information-based paradigm concepts.

Note that Task 3 criteria, results, and recommendations are based on PPP review, human factors considerations, and design and operational philosophies—not on PSM+ICR accident and incident event analysis. Task 3 criteria, results, and recommendations are therefore considered best practices-and principles-based, and are not directly or necessarily safety-based. However,

an indirect correlation between safety and some best practices exists, and some of the Task 3 recommendations address known PSM+ICR-related issues.

4.1.2 Relevant Boeing Phase 1 Report Excerpts.

The AIA/AECMA Project Report specified four ICR categories: (1) LOC, (2) SDTGE, (3) O, and (4) RTO>V1. Review and analysis of PSM+ICR events indicate that

- information (versus data) in general, and particularly information in context, has the potential to mitigate LOC, SDTGE, and O (procedure related errors) ICR.
- LOC-related ICR is also mitigated by airspeed and attitude annunciations (e.g., indication enhancements and alerts) and flight control envelope protection.
- information (versus data) and information control (e.g., alert takeoff inhibits) have some, but limited, potential to mitigate RTO>V1 ICR.

The Boeing Phase 1 Report [2] noted that:

> "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."
>
> "[Engine] 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."

Performance monitoring encompasses engine starting, thrust setting and monitoring, and normal engine shutdown.

> "[Engine] 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."

Health monitoring encompasses monitoring and detecting engine abnormalities which affect the current flight, keeping the engine running, helping the engine recover, and nonnormal engine shutdown/securing.

> "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 (thrust) 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."

Regarding performance monitoring, it was noted that:

> "The flight deck interface must support the flight crew in monitoring and controlling propulsion system performance, specifically, the fuel system and engines."

It was also noted 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."

Regarding health monitoring, it was noted that

> "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"
>
> "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 thrust levers, shutting down an engine, or executing a

nonnormal checklist (e.g., engine surge). Other flight control actions may be needed to manage the airplane."

Note that both performance monitoring and health monitoring failures, e.g., failure to detect deviations from normal, correctly interpret those indications, and act in a timely way, are often factors in PSM events that result in crew error.

4.1.3 Task 3 Report Overview.

The following sections document

- a summary of the normal, supplementary, nonnormal engine procedures and the practices and policies that were reviewed,
- the task review and analysis methodology,
- the results and summary of the review and analysis—information and automation opportunities identified,
- the high-level criteria and considerations for developing information-based engine display paradigms, and
- the Task 3 summary, conclusions, and recommendations.

4.2 ENGINE-RELATED PROCEDURES, PRACTICES, AND POLICIES.

Normal, supplementary, and nonnormal engine procedures, and selected and applicable practices and policies were reviewed to develop high-level operational and information criteria applicable to the development of information-based engine display paradigms. Specific information and automation opportunities were identified.

Boeing develops and provides normal, supplementary, and nonnormal procedures. Table 4-1 lists the normal and supplementary engine procedures and selected and representative engine-related practices and policies, which were reviewed and analyzed. Practices and policies in general, and policies in particular, are highly customer specific. Table 4-1 identifies representative policies, but customer-specific policy details were not identified or analyzed. Customer-specific practices and policies may influence the operational and information criteria applicable to the development or implementation of information-based engine display paradigms. Table 4-2 lists the nonnormal engine procedures that were reviewed and analyzed.

Table 4-1. Normal and Supplementary Procedures, Practices, and Policies Reviewed and Analyzed

Normal Procedures	Supplementary Procedures	Practices	Policies
Preflight	Engine cross-bleed start	Between engine comparison of same parameter(s)	Auto vs manual engine start
Engine start	Engine ground pneumatic start	Within engine monitoring for expected parameter value or NCD	RTO
Takeoff	Manual engine start	Within engine monitoring for parameter changes or change rate	Takeoff thrust setting
Approach	Manual override engine start	Assess operational versus engine needs	After takeoff thrust reduction
Go-Around	Cold weather operation		In-flight engine shutdown
Landing Roll	Severe turbulence		In-flight engine restart
Shutdown			Stabilized approach
			Go around

Note: Columns are read down rather then across.

Table 4-2. Nonnormal Procedures Reviewed and Analyzed

Nonnormal Procedures	
1. ABORTED ENGINE START L, R	12. ENG LIM/SURGE/STALL L, R[2]
2. DUAL ENG FAIL/STALL[2]	13. ENG OIL PRESS L, R
3. ENG AUTOSTART L, R[1]	14. ENG OIL TEMP L, R
4. ENG CONTROL L, R[1]	15. ENG RPM LIMITED L, R
5. ENG EEC MODE L, R	16. ENG START VALVE L, R
6. ENG FAIL L, R	17. ENG STARTER CUTOUT L, R
7. ENG FUEL FILTER L, R	18. ENG SVR DAMAGE/SEP L, R[2]
8. ENG FUEL VALVE L, R	19. ENG THRUST L, R
9. ENG IDLE DISAGREE	20. VOLCANIC ASH[2]
10. ENG IN–FLT START L, R	21. ENG AUTOSTART OFF
11. ENG LIMIT PROT L, R	22. RTO[3]

Notes:
[1]On-ground only alert.
[2]Unannunciated checklist.
[3]Nonnormal maneuver.
L = Left
SVR = Severe
EEC = Electronic engine control
RPM = Revolution per minute
R = Right

Normal procedures are used by the trained flight crew to ensure the airplane condition is acceptable and that the flight deck is correctly configured for each phase of flight. Normal procedures assume all systems are operating normally and automated features are fully utilized. Note that the normal procedures reviewed are a mix of normal checklist procedures and amplified normal procedures. Normal procedures are performed from recall and follow a panel flow. Normal checklist procedures contain only key and critical tasks. Amplified normal procedures document all expected crew tasks and pilot roles and responsibilities. The normal checklist procedures are typically contained in the airplane Quick Reference Handbook.

Supplementary procedures are tasks that are accomplished as required, rather than routinely performed on each flight.

Nonnormal procedures are used by the flight crew to cope with nonnormal situations involving airplane system faults, failures, and inappropriate configurations. Most nonnormal checklist procedures correspond to an EICAS alert. EICAS alerts are centralized on the center forward display and consists of color-coded alert messages, attention-getting glareshield caution and warning lamps in front of each pilot, and attention-getting caution and warning aurals. EICAS alerts annunciate the fault, failure, or configuration condition and cue the crew to select and accomplish the appropriate nonnormal checklist. Electronic checklist facilitates checklist selection and execution. EICAS alerts require automatic fault, failure, or configuration detection. Nonnormal checklists without a corresponding EICAS alert require crew fault, failure, and configuration monitoring, detection, and interpretation. These are called unannunciated (*u*) checklists or unannunciated checklist procedures. Table 4-2 contains both annunciated and unannunciated nonnormal procedures.

Practices and policies generally impose additional constraints and limitations beyond those in the procedures. Practices and policies are generally more, versus less, restrictive than the normal, supplementary, and nonnormal procedures. Practices and policies are highly customer airline specific.

Figures 4-1 and 4-2 illustrate the primary and secondary engine indications associated with the Task 3 review and analysis. These indications provide a mixture of data and information.

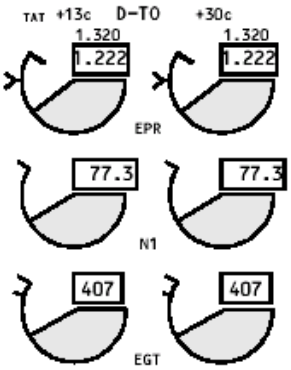


Figure 4-1. Typical Primary Engine Indications

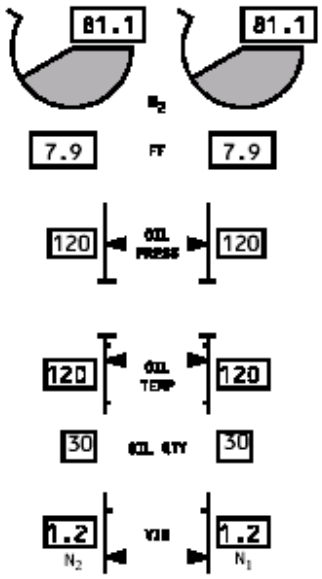


Figure 4-2. Typical Secondary Engine Indications

Primary and secondary engine indications support normal, supplementary, and nonnormal engine procedures and engine practices. The primary engine indications shown in figure 4-1 (EPR, N1, and EGT) mainly support engine performance monitoring and control. EGT and the secondary engine indications shown in figure 4-2 (N2, N3, FF, Oil Pressure/Temperature/Quantity, and Vibrations) primarily support engine health monitoring.

4.3 TASK 3 REVIEW AND ANALYSIS METHODOLOGY.

Monitoring, detection, and interpretation tasks are opportunities to implement automated detection and annunciation (to reduce or eliminate monitoring and detection) or provide information (versus data to minimize crew interpretation). Tables 4-3 and 4-4 do not contain data, but illustrate the analysis process used for this task. Table 4-3 shows how each top level engine procedure, practice, and policy task was divided into discrete subtasks for review and analysis. Table 4-4 shows how the subtasks in table 4-3 involving crew monitoring, detection, or interpretation were further reviewed as information and automation candidates.

Table 4-3 documented

- the source of each top level task (e.g., normal checklist, amplified normal, or supplementary procedure, annunciated or unannunciated nonnormal checklist procedure, practice or policy).

- the engine state for each subtask or group of subtasks was documented (e.g., shutdown, starting, running and associated thrust setting known or expected, malfunctioning, failed subidle).

- Subtask analysis for
  - the awareness, information, and understanding required to accomplish the subtask and
  - how that awareness, information, or understanding is currently provided or obtained by the crew.

Table 4-4 included the last three columns from table 4-3 and, in addition, documented

- what potential new, alternate, or additional information (versus data) can be provided.
- if existing or new capability or technology is required to provide the information.
- if the information is a candidate for automation.
- any unresolved or open issues.

Table 4-3. Procedure, Practice, and Policy Task Analysis Table

PPP Task Title	Source	Engine State	Flight Crew Subtask	Awareness, Information, and Understanding Required	How Awareness, Information, or Understanding Currently Obtained and Provided
Task 1			Subtask 1a		
			Subtask 1b		
			Subtask 1c		
			Subtask 1n		
Task 2			Subtask 2a		
			Subtask 2b		
Task 3			Subtask 3a		
Task n			Subtask na		

Example Format

Table 4-4. Task 3 Results—Information and Automation Opportunities

Flight Crew Subtask	Awareness, Information, and Understanding Required	How Awareness, Information, or Understanding Currently Obtained and Provided	Potential New, Alternate, or Additional Information (versus Data)	Existing or New Capability or Technology Required?	Automation Candidate?	Unresolved or Open Issues
A. NORMAL AND SUPPLEMENTARY NORMAL PROCEDURES						
B. NONNORMAL PROCEDURES						
C. POLICIES AND PRACTICES						

Example Format

The detail review and analysis produced PPP-related data and information criteria that were used for two purposes:

- To identify specific opportunities to provide new information or improve understanding of existing information and to identify automation opportunities. Information and automation opportunities were identified wherever the subtask involved crew monitoring, detection, or interpretation—these are typically opportunities to provide information and to automate monitoring and detection. Control automation opportunities were identified based on a review of subtasks involving manual control. Review and analysis for control automation opportunities focused identifying where the same or similar control action occurred in several subtasks and an analysis of the feasibility of control automation. The results are documented in appendix A and summarized in section 4.4.

- To develop general high-level operational criteria to provide a starting point for developing information-based (versus data or parameter-based) engine indication paradigms and identify the issues that must be resolved and the capability that must be developed to enable information-based engine display paradigms. The resulting criteria were developed from a review of all subtasks analyzed and are documented in section 4.5.

4.4 PROCEDURE, PRACTICE, AND POLICY ANALYSIS—SUMMARY AND RESULTS.

Table 4-5 summarizes the Task 3 PPP review and analysis. A total of 35 procedures, comprised of 102 subtasks, were reviewed for monitoring, detection, and interpretation activity. Information/automation opportunities were identified, which replace crew monitoring, detection,

and interpretation activity. The same, or highly similar, crew monitoring, detection, and interpretation activities were identified in different subtasks. Three top-level areas of information (display indication/annunciation) and control automation-related opportunities were identified:

- Engine start monitoring for normal start progression and need for start abort due to start fault abnormality, engine parameter exceedance, or start failure.

- Engine operational capability: engine capability of continued future operation, readiness for start/restart, or need for shutdown/isolation of affected engine.

- Airplane level performance: airplane acceleration/deceleration and flight path.

Table 4-5. Task Analysis Summary

PPP	No. Tasks	No. Subtasks	No. Monitoring, Detection, Interpretation Subtasks	No. Top Level Information/ Automation Areas of Opportunity
Normal Procedures	7	26	6	3
Supplementary Procedures	6	15	6	
Nonnormal Procedures	22	61	25	
Practices	4	-	4	
Policies*	8	-	-	—

*Policies are typically airline specific, i.e., vary from airline to airline. Eight candidate policies were identified for review and analysis. But the airline contact and coordination required to obtain, review and analyze airline policies exceeded the scope of the current effort.

4.4.1 Procedures and Practices.

The three general information areas identified differ as a function of the procedure type or practice. The following paragraphs summarize the analysis of procedures and practices. Appendix A documents the complete procedures and practices analysis.

- Normal Procedures

  - Engine capability: system readiness/capability for starting or operation.

  - Engine (auto): start monitoring for normal start progression and need for start abort due to start fault/abnormality, engine parameter exceedance, or start failure.

  - Airplane level performance monitoring (during takeoff and go around).

- Supplementary Normal Procedures

  - Engine (manual): start monitoring for normal start progression and need for start abort due to start fault/abnormality, engine parameter exceedance, or start failure.

  - Engine capability: system readiness/capability for starting or operation—takeoff operation.

- Nonnormal Procedures

  - Engine (auto and manual): start monitoring for normal start progression and need for start abort due to start fault/abnormality, engine parameter exceedance, or start failure.

  - Engine capability: system readiness/capability for starting, restart, or continued future operation. Engine need for shutdown/isolation. Unannunciated engine abnormalities potentially affecting engine operation that requires crew awareness and does, or may, require crew response.

- Practices

  - Engine capability: system readiness/capability for starting or operation. Unannunciated engine abnormalities potentially affecting engine operation that requires crew awareness and does, or may, require crew response, primarily between engine parameter differences and within engine parameter rate changes.

4.4.2 Results—Information Opportunities.

In general, information should be provided that promotes and supports normal, nonnormal, and automation-related crew awareness, understanding, and action. The following specific information opportunities were identified. Information opportunities imply automated monitoring and detection. Information opportunities are listed from most feasible to least feasible, based on preliminary estimates of implementation feasibility. Where annunciation is specified, the supporting monitoring and detection task(s) must be automated and associated crew role or procedure defined. Final implementation details and requirements require follow-on work.

- Engine start indication during auto and manual engine start on ground and in flight. The indication could inform the crew that the engine is starting, the start is progressing normally, and the extent of start progression (e.g., 10%, 50%, 90% complete).

- Engine start failure or start anomaly annunciation for manual on-ground engine start and for auto and manual in-flight engine start. Where it could benefit crew awareness or action, the failure or anomaly annunciation could identify the cause of start failure or anomaly and cue an appropriate crew consideration or response (e.g., to abort start, attempt restart, shutdown, and secure engine).

- Limit exceedance annunciation. An alert annunciation could be provided to ensure crew awareness and action.

- Thrust anomaly annunciation (commanded thrust is less than or greater than indicated/actual thrust). Thrust shortfall and overthrust identify no engine response to thrust lever. Such annunciation is of particularly value when A/T is engaged.

- Impending limit exceedance annunciation. An alert annunciation could be provided for any impending limit exceedance, which requires crew awareness or action.

- Continuous/multiple/repeated surge annunciation. An alert annunciation could be provided.

- Severe engine damage or separation annunciation. An alert annunciation could be provided to ensure crew awareness and action.

- Engine startability, operational, and capability information could be provided.

- Airplane, or engine thrust, performance information during takeoff. Monitoring for insufficient thrust or acceleration during takeoff.

    - Example of where engine thrust performance may best be monitored at the airplane level versus at the engine system level—e.g., graphical airport map that shows actual airplane position collocated with performance predictions.

    - Go-around airplane airspeed and climb performance supported by airspeed, acceleration, flight path vector (FPV), and other PFD indications and information.

    - Also applicable to airplane deceleration performance on Landing.

- Engine readiness for takeoff indication. Associated with cold weather operation oil temperature. Note: This is a special case of the more general case where indication/ annunciation could be provided if the engine is not ready for operation or flight.

- Integrated dual engine failure alert annunciation.*

- Rejected Takeoff (RTO) Go–No Go Indication/Annunciation.[1] For engine-related performance only. Established RTO criteria is: RTO <80 kts for any engine malfunction. RTO >80 kts, but <V1 only for engine thrust-related malfunctions that prevent safe flight and landing.

- ENG IDLE DISAGREE affected engine alert.*

[1] Possible opportunities, but lowest/least feasible implementation potential because of associated issues and estimated high cost/low benefit.

4.4.3 Detection Requirements.

The following detection capability is required to support the information and automation opportunities listed in the preceding section.

- Engine starting, start progressing, and start failure.
- Limit exceedance. Note: This capability currently exists.
- Overthrust (indicated thrust is greater than commanded thrust).
- Impending limit exceedance. Note: This may require/involve rate monitoring.
- Continuous/multiple/repeated surge.
- Severe engine damage or engine separation requiring immediate engine shutdown/ isolation.
- Engine damage: Engine startability/operational capability.
- Actual engine thrust or airplane acceleration/deceleration performance.
- Dual engine failure.
- Affected engine for idle disagree.

4.4.4 Flight Deck Control-Related Automation Opportunities.

Automation must be implemented without limiting the final authority of the crew. This implies that where automation is used, sufficient information and control must be provided to enable and ensure crew supervision, understanding, and control over the automation. In general, automation should be used to eliminate or minimize the potential for crew error by relieving the crew of airplane system monitoring, detection and interpretation tasks, and precluding the need for rapid crew action. Section 4.5.2 provides detail design philosophy and guidance.

For example, existing automatic engine surge accommodation, engine relight, and subidle automatic fuel control optimize the potential for engine recovery from flameout and surge. However, the pilots currently lack clear and explicit visibility and understanding as to what exactly the engine automation is doing, when the engine automation is functioning, and how well the engine automation is doing (e.g., functioning or progressing). The current crew procedure for any subidle engine malfunction requires the crew to select the fuel control switch to cutoff, determine no apparent engine damage exists, and then select the fuel control switch to run. This pilot response requirement combined with variability in operational circumstances and pilot monitoring, interpretation, decision-making, and response creates the potential to interrupt and unnecessarily delay engine recovery. Improved information and corresponding procedure changes that better reflect the automation and pilot roles have the potential to improve this situation.

Flight deck control-related automation opportunities were identified based on an overall review of available engine controls together with a review of subtasks involving manual engine control. Automation opportunities are typically associated with information opportunities. Review and analysis for control automation opportunities focused on identifying where the same or similar control action occurred in several different subtasks, together with a preliminary assessment and estimate of the feasibility of control automation.

The opportunity for control automation is limited to the relatively small number of flight deck engine controls provided on current modern airplanes. It is further limited by already existing automation such as engine start and A/T automation. In addition, the feasibility of automation is somewhat related to the nature, frequency, and importance of control use. For example, where control is provided as the primary means of the crew controlling the system or automation state on or off, automation is generally not feasible.

The typical modern overhead panel engine provides L/R Eng electronic engine control (EEC) Mode (NORM/ALTN), L/R Start/Continuous Ignition (OFF/START/CON), and Autostart (ON/OFF) switch controls. The aislestand thrust lever quadrant provides L/R thrust and reverse thrust lever controls, Takeoff and Go Around (TOGA) and A/T disconnect switches, and the L/R engine fuel control switches.

The overhead panel Eng EEC Mode (NORM/ALTN) and Autostart (ON/OFF) switches are normally set and forgotten—i.e., they always remain set in normal configuration (EEC Mode NORM and Autostart ON). The engine Start switches are used for each on-ground start. The engine fuel control switches are used for preflight engine start/run and for postflight engine shutdown. In flight, these controls are not normally operated, i.e., they are only operated in flight when a nonnormal condition exists.

The following specific opportunities for flight deck control-related automation were identified:

- Automatic selection of continuous ignition. Eliminate continuous ignition switch control.
- Automatic engine start only. Eliminate manual engine start and autostart ON/OFF control.
- Automatic start abort during manual engine start, and in-flight autostart for oil pressure failure to rise.
- Automatic EEC in-flight starter assist.
- Automate or eliminate manual fuel control switch action for single and dual/multiple engine failure.
- Automatic TOGA selection under limited circumstances—e.g., WINDSHEAR.

The following are not listed as engine control automation opportunities for reasons specified below.

- Engine thrust levers. These are already highly automated when A/T is engaged. Automatic A/T disconnect capability currently exists. A demonstrable need has been demonstrated for manual thrust lever control capability and manual A/T disconnect capability.

- Automatic EEC ALTN mode selection. There are no known crew response issues or operational benefit to automating EEC mode selection. Automation is not feasible because of the complexity and cost associated with system separation issues versus the potential benefit. Automation in this area is therefore unlikely.

- Automatic engine start initiation. The crew must have final authority and a means to initiate engine start. There are no known crew response issues or operational benefit to automating engine start initiation.

- Automatic start abort during manual engine start and in-flight autostart for EGT failure to rise. There is no engine need associated with EGT failure to rise. Control automation for this condition introduces unnecessary risk of preventing engine start.

4.5 HIGH-LEVEL OPERATIONAL AND INFORMATION CRITERIA FOR INFORMATION-BASED ENGINE DISPLAY PARADIGM.

Review of the engine PPP for current technology aircraft identified the crew tasks that must be supported and the associated operational information that must be provided by existing or future engine display paradigms.

While many criteria can be derived from existing task and indication precedent, these and other key operational and information criteria are derived primarily from design and operational philosophies based on human factors principles and considerations, operational experience, and lessons learned.

The following sections

- reiterate key human factors considerations cited in the Boeing Phase 1 Report.

- document applicable operational design and automation philosophies.

- summarize the high-level operational and information requirements and criteria for information-based display paradigms.

- discuss considerations for design changes and evolution.

4.5.1 Human Factors Considerations.

In general, the hierarchy of human factors design approaches to a hazard are:

- Remove the hazard, concern, or issue (e.g., prevent engine surge or limit exceedance).

- Create a barrier between the hazard and the people involved (e.g., interlock).
- Provide crew awareness and procedure (e.g., provide detection, alert, and crew procedure).

4.5.1.1 Data Versus Information.

The following human factors considerations were noted in the Boeing Phase 1 Report [2].

> "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 provides required crew awareness, or supports some specific flight crew procedure or some general flight crew task (e.g. aviate, navigate or communicate). 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."

4.5.1.2 Interpretation and Understanding.

The Boeing Phase 1 Report [2] posed and elaborated on three questions regarding interpreting and understanding engine indications.

> "What information types are needed to support the flight crew in assessing the fuel system and engines? In today's airplanes, 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?"

> "How should the interface describe the new state of the engine or fuel system? 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."
>
> "What remains working that can be used? 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."

It was also noted that:

> "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."

4.5.2 Applicable Flight Deck Design Philosophies, Principles, and Guidelines.

The following flight deck design philosophies are applicable to the development of engine indication paradigms.

- The pilot is the final authority for the operation of the airplane.
- Both crew members are ultimately responsible for the safe conduct of the flight.
- Flight crew tasks, in order of priority are safety, passenger comfort, and efficiency.
- Design for crew operations based on pilot's past training and operational experience.
- Design systems to be error-tolerant.
- The hierarchy of design alternatives is simplicity, redundancy, and automation.
- Apply automation as a tool to aid, not replace, the pilot.
- Address fundamental human strengths, limitations, and individual differences—for both normal and nonnormal operations.
- Use new technologies and functional capabilities only when

- they result in clear and distinct operational or efficiency advantages and
- there is no adverse effect to the human-machine or crew-centered interface.

The following flight deck design principles and guidelines are applicable to the development of engine indication paradigms.

- System indications and crew actions should be as simplified as possible. Minimize reliance on system indications or crew procedures when automation can be used. Indications and crew procedures should be used in lieu of automation where automation is not technically, economically, or philosophically feasible.

- Preclude the need for rapid crew actions.

- Relieve the crew of subsystem monitoring requirements.

- Be clearly understandable and manageable by the flight crew.

- Retain pilot situational awareness through appropriate automation mode feedback.

- Generally, add to but do not automatically replace information that is already displayed. An exception is the auto pop-up of the secondary engine format on the lower EICAS display when crew awareness is required, e.g., engine exceedance.

- Allow the pilot to select a level of automation for and to aid the pilot in the prioritization of tasks.

- Do not apply to systems having a direct effect on safety unless those systems can be made sufficiently reliable.

- Apply to repetitive subsystem responses to reduce unnecessary workload and allow more time to focus on higher-priority tasks.

- Design for easy manual override.

- Flight crew inputs to primary flight controls should always have priority over automatic systems.

- Autopilot operation should mimic the way an average pilot would manually fly the airplane.

- Be consistent and predictable in operation and compatible with pilots' expectations.

The following is a list of human factors guidelines and considerations for the automation's role. Where sufficient reliability is achievable and implementation is determined, feasible technology is best used to:

- Monitor for infrequent or subtle changes.

- Integrate sensor information (data), i.e., used to integrate separate indications to show larger effects or trends (if there are meaningful integrations).

- Prevent recognition biases that can lead to a confirmation bias mindset in which only confirmatory information is sought.

- Determine consequences and reason about machine behavior—e.g., to provide understanding about how well the system can perform and affects on the airplane mission.

- Track goals, support task management, and prevent loss of situation awareness by providing enhanced representations of current status.

- Identify and locate appropriate procedures. Technology (through interface design) offers more powerful means for guiding flight crews to the appropriate procedure and response.

- Guide detailed sets of actions—e.g., to provide the detailed guidance (since it cannot be remembered accurately) and aid the crew in adapting that guidance to the current conditions by making clear the intent of each step of the procedure and by showing the intended system, airplane, and mission consequences of the procedure.

- Convey intent of the agents; pilot flying, pilot monitoring, and the automation (autopilot, A/T, and automated system logic).

- Support smooth task completion—e.g., help the flight crew track what is being done or by alerting items that are not done.

In addition, technology should be structured to support effective and efficient execution of common tasks, e.g., by bringing all of the relevant information together [2].

4.5.3 High-Level Operational and Information Criteria for Information-Based Display Paradigms.

In general, an engine display paradigm must effectively and efficiently provide the crew with awareness of engine performance and health. The engine display paradigm should eliminate or minimize pilot monitoring, detection, and interpretation tasks. It should provide information and awareness that minimize manual crew interface. This supports primary crew focus on flying and navigating the airplane.

The crew's primary task is to fly the airplane. As previously noted:

- Performance-monitoring failures (e.g., lack of awareness that actual engine state does not equal commanded state, or a lack of awareness of commanded or actual engine state) are often major factors in PSM events that result in crew error.

- Health-monitoring failures (e.g., failure to detect deviations from normal, correctly interpret those indications, and act in a timely way) are often factors in PSM events that result in crew error.

An engine display paradigm should prevent, minimize, or mitigate engine performance and health-related crew errors, and minimize associated crew workload. As noted in the human factors hierarchy of design, this may be accomplished by eliminating the hazard (e.g., by developing an engine that does not surge), creating a barrier between the hazard and the people involved (e.g., via the use of predictive engine health monitoring), or by providing crew awareness and procedure that allow the crew to manage the hazard. The engine display paradigm plays an important role in providing such crew awareness and supporting crew procedure and action.

Display paradigms and pilot role or tasks are interrelated. The two must be designed and defined together. The operational philosophy defines the pilot role and guides display design. However, the display paradigm is either enabled or limited by available technology, existing capability, design reliability requirements and cost, which consequently define the required pilot role.

4.5.3.1 Engine Performance.

The main opportunity for new or evolved engine performance-related information paradigms is to provide engine performance in greater context. A secondary opportunity is to increase crew awareness and understanding of engine performance—particularly whenever engine system automation that may affect performance is involved.

Existing and evolving examples of engine performance in greater context involves providing engine thrust information in the context of airplane flight performance or navigation. Engine thrust can be used to control both airspeed and altitude—alone or in combination. Airplane pitch, and to a lesser extent airplane configuration, can also be used to control both airspeed and altitude—alone or in combination. Pitch and thrust control integration is achieved on the PFD through the collocation of airspeed, attitude, altitude, and vertical speed indications/information combined with airspeed predictions and FPV display on typical Boeing airplanes. The airspeed prediction cue is displayed on the airspeed indicator. The FPV is displayed on the attitude indicator. Airspeed prediction and FPV displayed in the context of the PFD airspeed, attitude, heading, vertical speed, and altitude indications allows the crew to see and understand the integrated effects of various combinations of power, pitch, and airplane configuration changes on airspeed and altitude. Even greater context is provided by superimposing such information on the outside visual scene or synthetic representations of the outside visual scene (e.g., runway, obstacles, terrain). Operational concepts vary by customer. Therefore, system designs must support diverse customer operational concepts and philosophies.

To support engine performance awareness, an information-based display paradigm should center primarily on providing the crew information that the engine is responding normally (as expected) to manual or A/T inputs. Information should elicit and support the primacy of crew understanding and appropriate crew action at the right time and in the desired manner. The following engine performance criteria are applicable to an information-based display paradigm:

- Collocated or integrated normal indications of engine on/off/starting state, current thrust level (e.g., minimum, intermediate, and maximum), and commanded/target and actual thrust indication/information.

- Automated detection and annunciation of nonnormal engine states where actual engine state or thrust does not equal commanded or allowable engine state or thrust, or performance exceeds a limit.

- Engine performance-related information in the larger context of the overall propulsion system, airplane airspeed and altitude control, airplane flight path control, airplane takeoff and landing performance. Examples of each are:

  - Graphical propulsion system synoptic

  - Airspeed prediction cue based on inertial airplane acceleration or deceleration integrated with airspeed indicator, and FPV indication showing airplane flight path is level, climbing, or descending straight forward, left drift, or right drift, integrated with attitude indicator that is collocated with altitude and vertical speed indications.

  - Superposition of airplane airspeed, altitude, and flight path control information on an actual or synthetic outside visual scene containing terrain and man-made features such as obstacles and runways—e.g., synthetic vision display or head-up display (HUD).

  - Collocated display of airplane position and takeoff/landing acceleration, deceleration, and performance predictions on a moving airport map.

  - Full-time performance information to ensure crew familiarity, proficiency in use, easy/ ready information availability and timely access.

4.5.3.2 Engine Health.

The main opportunity for new or evolved engine health-related information paradigms is to pursue automatic monitoring, detection, assessment, and annunciation. To support engine health awareness, an information-based display paradigm should center primarily on providing information to the crew that the engine is within normal operating limits, is performing in an optimal manner, and is performing as expected. In general, eliminate or minimize crew monitoring, detection and interpretation to the maximum extent possible. Airplane design and operational philosophies, capability and technology availability, and reliability-related cost-benefit must be considered. The following engine health criteria are applicable to an information-based display paradigm:

- Automated health monitoring to the maximum extent possible and feasible.

- Automated detection and annunciation of nonnormal engine states where long-term steady-state indications that are deviating from normal or changing significantly and affect, or are likely to affect, propulsion capability on the current flight.

- Nonnormal annunciations must ensure the crew is oriented to the affected engine(s), understand the nature of the abnormality, and are guided to appropriate action.

- Understanding of the engine system effects (e.g., on operational capability and startability) and airplane/mission level effects of an annunciated or unannunciated abnormality.

- Understanding of engine startability and operational capability.

- Sufficient information, awareness, and guidance to support crew assessment of unforeseen engine abnormalities and failures.

These criteria are consistent with the long-term human factors recommendations made for future fleet enhancements in the Boeing Phase 1 Report:

- Assess the value of more integrated engine displays for future flight decks.

- Assess an approach that moves beyond indications tied to individual parameters to support more automated health monitoring.

- Consider an interface that presents 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, and history, and
  - serve as task-oriented displays (and for which tasks).

Regarding enhancement opportunities for current engine indications, the Boeing Phase 1 Report [2] concluded that:

> "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."

4.6 TASK 3 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS.

Task 3 analysis identified general and specific opportunities to provide engine system level information and automation to support the crew in engine start, start abort, operational readiness decisions, and engine abnormality-related recovery or shutdown and secure decisions. In addition, some airplane level performance-related information opportunities were identified.

Information supporting crew supervision and intervention is typically a prerequisite for the control automation opportunities identified.

The primary motivations and justifications for flight deck improvements and changes are increased

- safety,
- operational efficiency, and
- customer value.

In general, change is driven by safety or economic benefits and requires a demonstrable benefit in one or more of these areas.

Historical precedent suggests that changes in flight deck engine indication and information paradigms will be evolutionary, not revolutionary. The existing engine indication paradigm is not flawed, and continues to evolve in a positive direction and manner. Evolution of the current engine indication paradigm will parallel the development of reliable and cost-effective technology and detection capability. It is envisioned that economics will drive technology and capability development of engine indications and display paradigms. Incremental increases in safety will be achieved through evolution as justifiable improvement opportunities arise. Technology-based development will involve increasing levels of system integration and automation. Increasing levels of display-based information and system control will occur, with display-based information leading display-based control. More information and less control will be required to support crew supervision, management, and final authority over system automation.

The proven reliability of existing engine control and information paradigms and the inertia associated with existing designs will preclude the introduction of revolutionary engine control and information paradigms. Potential changes within, and evolutions of, the existing paradigm are summarized below.

- Existing: Implement information and promote understanding within existing paradigm to provide:

  - New nonnormal annunciations—e.g., surge, engine limits, damage, start failure, airplane performance alerts, and procedures.

  - Engine parameter and procedure enhancements that support engine start, restart, and shutdown-related activities.

- Evolutionary: Modify existing information and control paradigm to provide:

  - New start mode, start progressing, start failure/anomaly indications and annunciations.

  - New airplane performance monitoring—e.g., HUD and airport map.

- New engine system health monitoring. The potential to eliminate or reduce the display of some existing secondary engine indications and parameters, and possibly some primary parameters, to drive towards information-based rather than data- or parameter-based displays.

- Higher-level representations of engine state and thrust may allow elimination or reduction of full-time display of many currently required parameters.

- Automation to eliminate some instances of manual crew input—e.g., fuel control switch for in-flight engine restart.

Further research, review, and analysis of customer specific practices and policies could identify operational and information criteria applicable to the development or implementation of information-based engine display paradigms. If implemented, representative customer airlines should be involved in development and implementation.

Follow-on research could support the development and implementation of enabling capability, the development of information-based engine display paradigms, and the development and implementation of information-based engine displays (see section 8.2.5).

5. TASK 4—SET OF POTENTIAL DETECTION STRATEGIES TO MEET CRITERIA OF TASKS 1, 2, AND 3.

The objective of Task 4 was to identify a set of separate possible malfunction detection strategies using the information gathered in Tasks 1, 2, and 3.

For each detection strategy, the parameter sensing, hardware processing, software processing, supporting inputs, and resulting output(s) were defined.

For each strategy, the strengths, weaknesses, limitations, and design considerations were assessed, as well as how well it satisfies operational and propulsion system criteria .

The information from Tasks 1, 2, and 3 were used to identify engine malfunction annunciation categories. The PSM+ICR database was then used to select the candidate malfunctions for annunciation strategy development:

- Flameout
- Surge/nonrecoverable stall
- Continuous/multiple surge
- STA (thrust failed low or high (indicated), slow to accelerate or decelerate)

Two or three annunciation strategies were developed for each of these malfunctions. In addition to analysis of the characteristics listed in the objectives, the development also included more specific flight crew operational criteria for reliability and availability. The annunciation strategy was developed jointly with the flight crew operational criteria in this phase, resulting in an integrated systems criteria that included an understanding of the specific malfunction and any mitigating conditions.

5.1 DEVELOPMENT OF THE ENGINE MALFUNCTION ANNUNCIATION CATEGORIES.

5.1.1 Task 1—Symptom Category Summary.

Task 1 developed PSM detection criteria derived from desired pilot accommodation following an engine malfunction. The analysis resulted in nine symptom categories (table 5-1).

Table 5-1. Engine STA-PSM Symptom Categories

STA-PSM Symptom	Engine Characteristic	Pilot Action
Flameout	Quenching of combustor	Restart (if no apparent damage)
Surge/nonrecoverable stall	Sustained surge (hung, stalled)	Clear stall (cycle fuel switch). Restart (if no apparent damage)
Continuous/multiple surge	Repetitive surging	Retard Thrust lever until surging clears. Operate engine normally or at a surge free thrust level.
Thrust high or low (sensor)	Primary thrust set parameter sensor failure	ALTN operation
Thrust failed low (indicated)	Thrust parameter is less than commanded thrust set parameter	Awareness (no specific procedure)
Thrust failed high (indicated)	Thrust parameter is higher than commanded thrust set parameter	Awareness (no specific procedure)
Engine slow to respond	Slow to accelerate/decelerate	Awareness (no specific procedure)
Thrust failed low (damage)	Indicated thrust parameter is equal to commanded thrust parameter, but physical thrust is low (e.g., fan blade/area damage)	Awareness (no specific procedure)
Thrust oscillations	Thrust oscillations	Awareness (no specific procedure)

5.1.2 Task 2—Operations Criteria Summary.

Task 2 developed STA-PSM detection criteria from crew operations analysis of pilot response derived from the PSM+ICR data and from an analysis of existing crew procedures.

The Task 2 PSM+ICR review and analysis focused on developing operational criteria for STA-PSM+ICR events with prevention potential. 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. Consistent with the Boeing Phase 1 Report [2], Task 2 review and analysis found that contributing factors in PSM+ICR events are

- lack of awareness an engine malfunction exists, or
- lack of awareness which engine(s) are affected, or
- difficulty determining which procedure to use.

The Task 2 procedure review and analysis suggests similar benefit for

- creating separate alerts for engine malfunction with specific procedures, which will provide awareness of the malfunction, the affected engine, and the appropriate procedure.

- create a single alert for engine malfunctions that do not have a specific procedure to provide awareness of the malfunction and the affected engine.

Recall that the procedure review recommendations are best practices (see section 3).

5.1.3 Task 3—Engine Indication Paradigm Criteria.

Task 3 identified high-level operational and information criteria to provide a starting point for developing an information-based engine indication paradigm beyond STA-PSM:

- Data and information criteria
- Opportunities to provide new information
- Opportunities to improve existing information
- Automation opportunities
- Detection technology and capability criteria for information-based paradigms and concepts

This analysis found the STA-PSM annunciations identified in Tasks 1 and 2 to be consistent with an information-based engine indication paradigm.

5.1.4 Task 4—Engine Malfunction Annunciation Categories.

5.1.4.1 Annunciation Category Selection Strategy.

The strategy for selection of categories appropriate for annunciation of engine malfunctions included an evaluation of the specific recommended pilot procedures for each engine malfunction symptom. Where the pilot procedure was common, a single annunciation is preferred (minimize crew training and memory items). Where the engine malfunction had a potentially different pilot procedure, a separate engine malfunction annunciation category was retained.

5.1.4.2 Malfunction Category Selection.

The Task 1 nine symptom categories were analyzed with the Tasks 2 and 3 results. These categories were separated by distinct engine malfunction symptoms, with distinct desired pilot awareness or action. As shown in table 5-1, for five of these symptom categories, there was no distinct pilot action identified for the specific malfunction. Following the criteria established in Task 2, with no specific associated pilot procedure, these five symptoms could be combined into a single engine malfunction category since they would identify the malfunction and identify which engine is affected.

The resultant merging of the symptom categories into the engine malfunction categories is shown in table 5-2.

Table 5-2. Mapping of Symptom Categories to Engine Malfunction Categories

Symptom Categories	Engine Malfunction Categories	Pilot Action
Flameout	Flameout	Restart affected engine
Surge/nonrecoverable stall	Surge/nonrecoverable stall	Clear surge and restart of affected engine
Continuous/multiple surge	Continuous/multiple surge	Retard throttle of affected engine
Thrust high or low (sensor)	Thrust high or low (sensor)	ALTN operation for affected engine
Thrust failed low (indicated)[1]	Other STA	Awareness of malfunction and affected engine
Thrust failed high (indicated)[1]		
Engine slow to respond		
Thrust failed low (damage)[1]		
Thrust Oscillations		

[1] Could be a separate indication if deemed useful.

5.1.4.3 Down Select for Strategy Development.

The PSM+ICR database was used to select the malfunctions for the Task 4 strategy development. Table 5-3 identifies the malfunctions, a summary of the strategies developed, and the recommended strategies based on the crew and engine operational criteria analyzed in this task.

One of the engine malfunction categories was not included in the malfunction strategies development: thrust failed low/high (sensor failure)—pilot awareness of affected engine and pilot procedure to select ALTN.

This malfunction is a thrust set parameter sensor error (primarily an EPR failure). There were no database ICR events associated with this PSM. This category is also a very small contributor to STA-PSMs. One accident is documented in this category; however, it was attributed to crew error affecting both engines. This event does not meet the reference 1 criteria of “an accident or incident where a single benign propulsion-system-malfunction occurred and the pilot did not appropriately respond”. EPR errors (and other failures) that result in transition to an alternate thrust setting mode are currently detected and annunciated on most modern airplanes. Pilot recognition of this failure has the potential to be more difficult than other STAs because there is no difference between the thrust set parameter and thrust set command (although, there will be differences in the other engine parameters). This category can result in a STA and thus annunciation of the condition has potential operational benefit. As such, it was considered in the analysis and included in the suite of annunciations recommended for consideration. However, it

was considered more appropriate that the details of detection and annunciation be worked by the individual engine manufacturer. (EPR failures are envisioned to be detected by modeling EPR with corrected N1 and Mach.)

Additionally, two of the subcategories of Other STA were not developed:

- Thrust failed low (damage)
- Thrust oscillations

Thrust failed low (damage) did not appear to be a PSM+ICR contributor. Additionally, there are likely to be other indications of this condition (vibrations, high rotor speeds). Pilot recognition of this failure has the potential to be more difficult than most other STAs because there is no difference between the thrust set parameter and thrust set command displayed to the crew. It is recommended that this condition be considered as part of the proposed follow-on research into engine damage.

Oscillations did not appear to be a PSM+ICR contributor. The common contributors to this condition are sensor failures (EPR failures), which could be considered in the development of EPR fault detection, and contaminated fuel metering units and sticky actuators.

Table 5-3. Task 4 Malfunction Strategy Development

Malfunction	Strategy 1	Strategy 2	Strategy 3
Flameout	**Subidle:** **HP rotor speed or PB less than subidle threshold (i.e., all subidle conditions)**	Subidle and EGT characteristic: HP rotor speed or burner pressure less than subidle threshold, and EGT characteristics of a flameout condition	
Surge/nonrecoverable stall	**Subidle:** **HP rotor speed or PB less than subidle threshold (i.e., all subidle conditions**	Subidle and EGT characteristic: HP rotor speed or BP less than subidle threshold, and EGT characteristics of a subidle surge/nonrecoverable stall condition	Surge/nonrecoverable stall characteristic: EGT, PB, HP rotor speed, thrust shortfall characteristics (can detect above-idle surge/nonrecoverable stall conditions
Continuous multiple surge	BP used to detect surge events. Monitor for two events within ~0.5 to 20 seconds time interval	**PB, HP rotor speed, and FF used to detect surge events. Monitor for two events within ~0.5 to 20 seconds time interval**	Multidimensional engine model, using several engine parameters (e.g., PB, N1, N2, EGT, FF, bleed valves, etc.) to monitor predicted and actual engine performance
Other STA: • Thrust low (indicated) • Thrust high (indicated) • Engine slow to respond	**Model of expected engine characteristics, derived from thrust set command**	Multidimensional engine model, using several engine parameters (e.g., TRA, N1/EPR, PB, N2, EGT, FF, bleed valves, etc.) to monitor predicted and actual engine performance	

Note: Bold indicates the recommended strategies, as a result of the analysis described in this task.

5.2 MALFUNCTION DETECTION STRATEGY DEVELOPMENT.

For each engine malfunction annunciation category, the following development process was established:

- Evaluate the engine operational criteria.
- Establish the crew operations system criteria (timing, flight phase, power, availability, and reliability).
- Establish potential detection strategies.
- Assess each potential detection strategy, including engine operational and crew operational criteria.

Table 5-4 defines the definitions of the malfunction characterization and engine and crew operational criteria. These were evaluated for each malfunction.

Table 5-5 defines the strategy characteristic definitions. These were evaluated for each of the detection strategies.

The following tables provide the engine malfunction detection strategy development:

- Table 5-6 provides the characterization and strategy criteria for flameout.
- Table 5-7 provides the flameout strategies.
- Table 5-8 provides the characterization and strategy criteria for surge/nonrecoverable stall.
- Table 5-9 provides the surge/nonrecoverable stall strategies.
- Table 5-10 provides the characterization and strategy criteria for continuous/multiple surge.
- Table 5-11 provides the continuous/multiple surge strategies.
- Table 5-12 provides the characterization and strategy criteria for other STA.
- Table 5-13 provides the Other STA strategies.

Table 5-4. Malfunction Characterization and Engine and Crew Operational Criteria Definitions

Malfunction Criteria	Definitions
Characterization	General description of the malfunction
Engine operations criteria	The engine operational criteria were established to assess each strategy. The engine system criteria were developed in Task 1, but are summarized below. Note that the engine does not have a need that supersedes the need to fly the airplane. Engine needs, in the context of this report, include two operational aspects of the engine, with the following definitions: • Integrity need defined as what is needed to reduce the potential for additional engine damage. • Thrust recovery need is defined as what is needed to recover thrust
Annunciation timing and flight phase	The annunciation timing and flight phases were established in Task 2 and will be summarized for each malfunction.
Annunciation availability criteria	The general crew operational criteria for availability and reliability were established in Task 2. The specific availability and reliability criteria for each annunciation category were developed jointly by propulsion engineers and flight crew operations engineers in Task 4 and are listed for each malfunction. The annunciation of an engine malfunction on an airplane is inherently an integrated system solution. Therefore, there must be a mutual understanding of the specific malfunction, detection capability, the expected pilot response, the desired pilot procedure, and any mitigating considerations before an integrated solution can be developed. In the context of this report, availability refers to the probability of malfunction detection.
Annunciation reliability criteria	In the context of this report, reliability refers to the probability of false malfunction detections.

Table 5-5. Strategy Characterization Definitions

Strategy Characterizations	Definitions
Parameter monitoring and sensing	Describes what parameters are assessed as being required for use in the algorithm.
Hardware processing	Describes what hardware processing is required for parameter monitoring and sensing.
Software processing	Describes what type of software processing is envisioned.
Supporting inputs	Describes what other parameters may be required (not primary sensing).
Resulting outputs	Describes the expected algorithm outputs.
Strengths	Assesses the strengths of the particular strategy. The assessment is from the propulsion perspective. It is noted if the flight crew operations perspective is different.
Weaknesses, limitations, and considerations	Assesses the weaknesses and limitations of the particular strategy. The assessment is from the propulsion perspective. It is noted if the flight crew operations perspective is different. Also includes any other pertinent considerations, including design or development considerations.
How well the propulsion system criteria are met	Describes how well the propulsion system criteria are met. This includes the performance of the strategy in general, and in particular, how the strategy satisfies the propulsion integrity needs and thrust recovery needs.
How well the operational system criteria are met	Describes how well the operational system criteria are met.

Table 5-6. Flameout Annunciation Criteria

Malfunction Criteria	Description
Characterization	The characterization of a flameout is a quenching of the combustor that causes the engine to go subidle. The subidle condition will usually occur in 3 to 5 seconds following the flameout (see figure 2-6).
Engine operations criteria	For a flameout condition, there is no engine integrity need; i.e., there is no engine timing criteria for a desired pilot response with respect to operation of the engine. At pilot discretion (if no apparent damage), the pilot can attempt to restore thrust by attempting a restart.
Annunciation timing/flight phase	The Task 2 analyses assessed that on the order of 5 seconds are available for flameout detection and annunciation in fatal events with prevention potential. Note that it would be operationally desirable to have the annunciation in less than 5 seconds. Event data indicates that more time is available for powerloss detection and annunciation as altitude increases and criticality consequently decreases. (At cruise in the one applicable substantial damage powerloss event, 30 to 40 seconds was available for detection and annunciation). The Task 2 analyses assessed that for PSM+ICR prevention potential, if annunciated, the flight phases for the annunciation should include: climb, cruise, descent, and approach. Note that engine flameout annunciation is operationally desirable in all flight phases.
Annunciation availability criteria	The crew operations criteria for detection of a flameout annunciation are: very high (~99.99%) to high (~99.9%) (i.e., 9999/10,000 to 999/1000 flameouts). Note that it would be operationally desirable to have the availability very, very high (~99.999%, 99,999/100,000 flameouts). Engine(s) failure is operationally significant in general (affects operational performance capability and safety margins). Lack of timely detection/awareness and response/action may adversely affect continued safe flight. Assuming the probability of a engine subidle due to flameout is 1E-5 to 1E-6 per engine hour, the probability of failure to detect and alert therefore would be on the order of 1E-8 to 1E-10 per flight hour.
Annunciation reliability criteria	The crew operations criteria for the probability of a false flameout annunciation is ~<1E-7 to 1E-5 (<1/10,000,000 to 100,000 engine hours). False engine failure alerting affects crew confidence in the airplane systems and monitoring. The joint probability of false dual or multiple engine failure detection/alert resulting in dual/multiple engine shutdown, should be <1E-9. False single engine failure detection/alert could result in an engine shutdown and thus affects in-flight shutdown rate. Pilot action (engine shutdown and restart) is operationally significant in general (affects operational performance capability and safety margins) and may occur at low altitude (near the ground) where recovery margins are reduced. The crew cannot readily (quickly and easily) reverse engine shutdown action. Possible mitigation is that the crew may determine the alert is false (and not take the action to shut down the engine).

Table 5-7. Flameout Strategies

Flameout	Strategy 1	Strategy 2
Strategy characterization	This strategy monitors for a subidle condition.	This strategy monitors for a subidle conditions and an EGT characteristic consistent with a flameout.
Parameter monitoring and sensing	The parameters that are the best candidates are those that are used for idle control (e.g., HP rotor speed or PB. HP rotor speed is a more reliable detection parameter.	The parameters that are the best candidates are those that are used for idle control (e.g., HP rotor speed or PB (HP rotor speed is a more reliable detection parameter) and EGT (exhaust gas temperature.
Hardware processing	There would be no new hardware processing since the parameters used for idle control are already processed by the FADEC.	There would be no new hardware processing since the parameters used for idle control and EGT are already processed by the FADEC.
Software processing	The software processing would involve a comparison of idle parameters with idle thresholds (this type of logic exists in many modern FADEC systems). The logic should consider the algorithm performance during starts (either inhibiting detection or accommodating the detection performance). The logic would need to consider fault tolerance.	The software processing would involve a comparison of idle parameters with idle thresholds (this type of logic exists in many modern FADEC systems). The algorithm would also involve an evaluation of the EGT characteristic and a determination that the characteristic is consistent with a flameout. The logic should consider the algorithm performance during starts (either inhibiting detection or accommodating the detection performance). The logic would need to consider fault tolerance.
Supporting inputs	No extra supporting inputs are required. The control logic for HP rotor or PB limits are typically in terms of corrected parameters (i.e., corrected to ambient temperatures or pressures), but this is already done within the idle control logic.	No extra supporting inputs are required. The control logic for HP rotor or PB limits are typically in terms of corrected parameters (i.e., corrected to ambient temperatures or pressures), but this is already done within the idle control logic.
Resulting outputs	The resulting output is a subidle indication for the affected engine.	The resulting output is a flameout indication for the affected engine.

Table 5-7. Flameout Strategies (Continued)

Flameout	Strategy 1	Strategy 2
Strengths	The strengths of this strategy are that • It provides highly reliable annunciation of this PSM • HP rotor/ PB subidle detection already exists in many modern systems	The strengths of this strategy are that • Can provide a highly reliable annunciation of a flameout with the combination of subidle and EGT characterization • Distinguishes flameout from surge/nonrecoverable stall
Weaknesses, limitations, and considerations	A weakness of this strategy (from an engine consideration) is that it does not distinguish between flameout, surge/nonrecoverable stall, or any other malfunction that has resulted in uncommanded subidle engine operation. These different engine malfunctions have different engine timing needs. The desired pilot response for a surge is more urgent than for a flameout. If a single annunciation for flameout and surge/nonrecoverable stall is used, then the procedure may need to be tailored to the most urgent need. This may result in advising the pilot to shutdown the engine for a surge/nonrecoverable stall, which may not be required for a flameout if the engine has relit on its own (shutting off fuel may delay the start). However, as long as the procedure is conservative, and meets the engines needs for all conditions, a single annunciation could be acceptable. Note that from a flight crew operations perspective, a single message for similar pilot procedures is considered an advantage.	A potential weakness with this strategy is that with different procedures for flameout and surge/nonrecoverable stall is that it may require making different pilot procedures (e.g., procedural steps, fuel control switch as memory item). Additionally, because of increased complexity, this annunciation may be less reliable and hence may set erroneously. It may be difficult to prove the reliability with the addition of an EGT characteristic criteria. It will take effort to determine the EGT characteristic and to ensure differentiation of flameout and surge/nonrecoverable stall meet the reliability criteria for annunciation (note that this type of data and logic already exists for detection (relight logic)). The amount of automation (e.g., auto-re-light) needs to be considered in the development, and then selection of the preferred strategy, and in the development of the pilot procedures.

Table 5-7. Flameout Strategies (Continued)

Flameout	Strategy 1	Strategy 2
Weaknesses, limitations, and considerations (continued)	The amount of automation (e.g., auto-re-light) needs to be considered in the development, and then selection of the preferred strategy, and in the development of the pilot procedures.	
How well the propulsion system criteria are met	The propulsion system criteria for a flameout are generally met with this strategy. There are no propulsion system integrity (timing) needs for a flameout, so a subidle annunciation (combining flameout and surge/nonrecoverable stall annunciation) provides the appropriate awareness, and the desired procedure (e.g., the desired pilot action may be to attempt to restart the engine). A prior step (for surge/nonrecoverable stall) may require the pilot to shutdown the engine first. (Note that a pilot shutdown may lengthen the restart, if auto-relight has relit the engine, see section 5.5).	The propulsion system criteria for a flameout are met with this strategy. The procedure would identify specifically what is expected of a pilot for a flameout condition.
How well the operational system criteria are met	The operational system criteria are met if the condition is annunciated as a caution level message. This strategy supports the availability and reliability criteria. This strategy also supports the operational procedural criteria because pilot training for dedicated flameout message would be the same as a subidle message, and operationally it is not desirable to have two annunciations with similar pilot procedures (reduction in pilot training and pilot memory items).	The operational system criteria are met if the condition is annunciated as a caution level message. This strategy supports the availability and reliability criteria. The operational system criteria are not met as efficiently with this strategy, since they would result in a need to train pilots for two procedures, which are quite similar (flameout and surge/nonrecoverable stall.

Table 5-8. Surge/Nonrecoverable Stall Annunciation Criteria

Malfunction Criteria	Description
Characterization	Surge/nonrecoverable stall is an engine surge that has progressed to a stall condition. The stall condition causes most engines to go subidle. Subidle condition usually occurs in 5-10 seconds. (figure 2-3). Note that longer thrust decay conditions and above-idle stall conditions could have timely indication by a thrust failed low annunciation.
Engine operations criteria	For a surge/nonrecoverable stall condition, there is an engine integrity need; i.e., it is desired to clear the surge/nonrecoverable stall since the potential exists for increased engine damage. The desired action is to shutoff fuel to clear the stall (select fuel switch from run to cutoff to shutoff FF to engine). At pilot discretion (if no apparent damage), the pilot can attempt to restore thrust by attempting a restart.
Annunciation timing and flight phase	The Task 2 analyses assessed that on the order of 5 seconds are available for surge/nonrecoverable stall detection and annunciation in fatal events with prevention potential. Note that it would be operationally desirable to have the annunciation in less than 5 seconds. Event data indicates that more time is available for powerloss detection and annunciation as altitude increases and criticality consequently decreases. (At cruise, in the one applicable substantial damage powerloss event, 30 to 40 seconds was available for detection and annunciation). The Task 2 analyses assessed that for PSM+ICR prevention potential, if annunciated, the flight phases for the annunciation should include: climb, cruise, descent, and approach. Note that engine surge/nonrecoverable stall annunciation is operationally desirable in all flight phases.
Annunciation availability criteria	The crew operations criteria for detection of a subidle stall annunciation are very high ~99.99% to high ~99.9% (9999/10,000 to 999/1000 flameouts). Note that it would be operationally desirable to have the availability very, very high ~99.999% (99,999/100,000 surge/nonrecoverable stalls). Note that these numbers are not applicable to above-idle surge/nonrecoverable stall, per comments and caveats below. Engine(s) failure is operationally significant in general (affects operational performance capability and safety margins). Lack of timely detection/ awareness and response/action may adversely affect continued safe flight. Note that an above-idle stall has been assessed as being possible, but unlikely. With an assessment of ~<1% (i.e., on the order of a 1E-7 event), the mitigating factors resulted in it being determined operationally acceptable to exclude above-idle surge/nonrecoverable stall annunciation. Mitigating factors for an above-idle surge/nonrecoverable stall are not likely to occur, likely to result in an EGT exceedance (flight crew annunciation), not likely to initiate at idle without going

Table 5-8. Surge/Nonrecoverable Stall Annunciation Criteria (Continued)

Malfunction Criteria	Description
Annunciation availability criteria (continued)	subidle, and would set a thrust shortfall annunciation in a timely manner (for conditions including for a go around). Assuming probability of engine subidle due to surge/nonrecoverable stall is 1E-5 to 1E-6 per engine hour, the probability of failure to detect would therefore be on the order of 1E-8 to 1E-10 per engine hour.
Annunciation reliability criteria	The crew operations criteria for the probability of a false surge/nonrecoverable stall annunciation are ~1E-7 to 1E-5 (<1/1,000,000 to 100,000 flight hours). False engine failure alerting affects crew confidence in the airplane systems and monitoring. The joint probability of false dual or multiple engine failure detection/alert resulting in dual/multiple engine shutdown should be <1E-9. False single engine failure detection/alert resulting in engine shutdown affects IFSD rate. Pilot action (engine shutdown and restart) is operationally significant in general (affects operational performance capability and safety margins) and may occur at low altitude (near the ground) where recovery margins are reduced. The crew cannot readily (quickly and easily) reverse engine shutdown action. Possible credit that the crew may determine the alert is false.

IFSD = In-flight shutdown

Table 5-9. Surge/Nonrecoverable Stall Strategies

Surge/Nonrecoverable Stall	Strategy 1	Strategy 2	Strategy 3
Strategy characterization	Monitors for a subidle condition.	Monitors for a subidle conditions and an EGT characteristic consistent with a surge/nonrecoverable stall.	Monitors EGT, PB, HP rotor speed, and thrust shortfall characteristics (thrust parameter no equal to command).
Parameter monitoring and sensing	The parameters that are the best candidates are those that are used for idle control (e.g., HP rotor speed or PB. HP rotor speed is a more reliable detection parameter.	The parameters that are the best candidates are those that are used for idle control (e.g., HP rotor speed or PB (HP rotor speed is a more reliable detection parameter), and EGT (exhaust gas temperature).	Surge/nonrecoverable stall characteristics (PB, N2/N3, EGT), and thrust shortfall characteristics (thrust parameter not equal to command).
Hardware processing	There would be no new hardware processing since the parameters used for idle control are already processed by the FADEC.	There would be no new hardware processing since the parameters used for idle control and EGT are already processed by the FADEC.	There would be no new hardware processing since the parameters used for stall detection and thrust shortfall detection are already processed by the FADEC (N1/EPR (thrust set parameter), PB, N2, EGT (currently measured in all FADEC systems).
Software processing	The software processing would involve a comparison of idle parameters with idle thresholds (this type of logic exists in many modern FADEC systems). The logic should consider the algorithm performance during starts (either inhibiting detection, or accommodating the detection performance). The logic would need to consider fault tolerance.	The software processing would involve a comparison of idle parameters with idle thresholds (this type of logic exists in many modern FADEC systems). The algorithm would also involve an evaluation of the EGT characteristic and a determination that the characteristic is consistent with a surge/nonrecoverable stall. The	The strategy is to monitor PB rate initially (rate indicative of a surge), then monitor EGT (high temp indicates stall condition), and sustained thrust shortfall condition (sensed control parameter less than command.

Table 5-9. Surge/Nonrecoverable Stall Strategies (Continued)

Surge/Nonrecoverable Stall	Strategy 1	Strategy 2	Strategy 3
Software processing (continued)		logic should consider the algorithm performance during starts (either inhibiting detection or accommodating the detection performance). The logic would need to consider fault tolerance.	
Supporting inputs	No extra supporting inputs are required. The control logic for HP rotor or PB limits are typically in terms of corrected parameters (i.e., corrected to ambient temperatures or pressures), but this is already done within the idle control logic.	No extra supporting inputs are required. The control logic for HP rotor or PB limits are typically in terms of corrected parameters (i.e., corrected to ambient temperatures or pressures), but this is already done within the idle control logic.	The control logic for may require corrected parameters (i.e., corrected to ambient temperatures or pressures) and thrust lever input, but these are already done within the FADEC control logic.
Resulting outputs	The resulting output is a subidle indication for the affected engine.	The resulting output is a sub-idle surge nonrecoverable stall indication for the affected engine.	The resulting output is a surge/nonrecoverable stall indication for the affected engine.
Strengths	The strengths of this strategy are that • it provides highly reliable annunciation of this PSM. • HP rotor/ PB subidle detection already exists in many modern systems.	The strengths of this strategy are that it— • can provide a highly reliable annunciation of surge nonrecoverable stall with the combination of subidle and EGT characterization. • distinguishes flameout from surge/nonrecoverable stall.	The strengths of this strategy is that it has the potential to detect stalls, which do not go subidle. Another benefit is the capability to detect a stall prior to EGT an exceedance.

Table 5-9. Surge/Nonrecoverable Stall Strategies (Continued)

Surge/Nonrecoverable Stall	Strategy 1	Strategy 2	Strategy 3
Weaknesses limitations and considerations	A weakness of this strategy (from an engine consideration) is that it does not distinguish between flameout, surge/nonrecoverable stall, or any other malfunction that has resulted in uncommanded subidle engine operation. These different engine malfunctions have different engine recovery and integrity (timing) needs. The desired pilot response for a surge is more urgent than for a flameout. If a single annunciation for flameout and surge/nonrecoverable stall is used, then the procedure must be tailored to the most critical/urgent need. This may result in advising the pilot to shutdown the engine for a surge or stall, which may not be required for a flameout if the engine has relit on its own (shutting off fuel may delay flameout recovery/start). However, as long as the procedure is conservative, and meets the engines needs for all conditions, a single annunciation could be acceptable.	A potential consideration with this strategy is that different procedures for flameout and surge/nonrecoverable stall would require making different pilot procedures (e.g., procedural steps, fuel control switch as memory item). A weakness is that increased complexity may make this annunciation less reliable and hence may set erroneously. It may be difficult to prove the reliability with the addition of an EGT characteristic criteria. It will take effort to determine the EGT characteristic and to ensure differentiation of flameout and surge/nonrecoverable stall meet the reliability criteria for annunciation (note that this type of data and logic already exists for detection (relight logic)). Similarly to strategy 1, this strategy does not cover the <1% of surge/nonrecoverable stalls that may not be subidle, and the same mitigating conditions apply. Also the same autoaccommodation considerations apply.	A potential weakness with this strategy is that more effort is required to provide reliability (without the use of the subidle condition). For detecting above-idle stalls, EGT must be differentiated from deterioration and other legitimate conditions where there is a high EGT. It would be more difficult to the meet reliability criteria, due to the complexity of the logic. Because the pilot action is to cut fuel, this annunciation is inherently high risk, since erroneous detection here means the pilot may cut fuel above idle when the engine is running. This strategy should be an enhancement of surge/nonrecoverable stall strategies 1 and 2, not a replacement. This covers a low probability occurrence of above-idle stall, and with the other mitigating factors (likely EGT exceedance) is considered to be not worth the effort (i.e., cost-benefit not likely).

Table 5-9. Surge/Nonrecoverable Stall Strategies (Continued)

Surge/Nonrecoverable Stall	Strategy 1	Strategy 2	Strategy 3
Weaknesses limitations, and considerations (continued)	Note that from a flight crew operations perspective, a single message for similar pilot procedures is operationally desirable and considered advantageous. This strategy does not cover the <1% of surge/nonrecoverable stalls that may not be subidle. There are, though, mitigating considerations: • An above-idle stall is not likely. • Another annunciation could provide pilot awareness for this condition (e.g., other STA annunciation). • An above-idle stall is likely to quickly exceed an EGT limit, providing appropriate pilot awareness and an identified pilot procedure. For all three strategies, the amount of automation (e.g., auto-re-light) needs to be considered in the development, and then selection of the preferred strategy, and in the development of the pilot procedures.		Similarly to Strategy 1 and 2, the autoaccommodation considerations apply. Additionally, since the strategy includes above-idle surge/nonrecoverable stalls, there may be a crew operations issue with allowing a system to automatically cycle fuel when an engine is above idle. The risks of nuisance shutdowns would need to be assessed.

Table 5-9. Surge/Nonrecoverable Stall Strategies (Continued)

Surge/Nonrecoverable Stall	Strategy 1	Strategy 2	Strategy 3
How well the propulsion system criteria are met	The propulsion system criteria for a surge/nonrecoverable stall can generally be met with this strategy if annunciated to ensure timely crew awareness. There is a propulsion system integrity (timing) need for a surge/nonrecoverable stall, to clear the surge/nonrecoverable stall in a timely manner. So a subidle annunciation (combining flameout and surge nonrecoverable stall annunciation) may not support propulsion integrity needs as well, since combined flameout/stall procedure will potentially not have the urgency to shutoff fuel (required to clear the stall). This may result in increased engine damage. However, pilot input is that although the subidle procedure does not require pilot shut fuel as quickly as possible, in practice the pilot would. This strategy can support propulsion thrust recovery needs as the pilot is made aware of need to restart the engine. Single annunciation for surge/nonrecoverable stall and flameout could be assessed as being acceptable from a propulsion integrity need standpoint as an EGT.	The propulsion system criteria for a surge/nonrecoverable stall are generally met with this strategy. The procedure would identify specifically what is expected of a pilot for a surge/nonrecoverable stall condition (desire for quick response, to cut fuel cut to clear stall, since stall may be incurring additional damage). Supports integrity needs for most surge/nonrecoverable stall events. This strategy does not cover an above-idle stall condition. However, this condition is not likely (~<1%), and could be assessed as being acceptable from a propulsion integrity needs standpoint since an annunciated EGT exceedance will likely protect the engine from damage.	The propulsion system criteria for a surge/nonrecoverable stall are met with this strategy. The procedure would identify specifically what is expected of a pilot for all surge/nonrecoverable stall conditions (desire for quick response, to cut fuel cut to clear stall, since stall may be incurring additional damage.

Table 5-9. Surge/Nonrecoverable Stall Strategies (Continued)

Surge/Nonrecoverable Stall	Strategy 1	Strategy 2	Strategy 3
How well the propulsion system criteria are met (continued)	Exceedance annunciation will likely protect the engine from damage. Since the same response by the pilot is appropriate, together with the pilot assessment of timely pilot response, one message might be satisfactory. Note that the FADEC system can automatically accommodate a surge/nonrecoverable stall and pilot procedure to shutoff fuel can delay the start (see section 5.5).		
How well the operational system criteria are met	The operational system criteria are met if the condition is annunciated as a caution level message. This strategy also supports the operational criteria because pilot training for dedicated surge/nonrecoverable stall message would be the same as a subidle message, and operationally it is not desirable to have two annunciations with similar pilot procedures (reduction in pilot training and pilot memory items.	The operational system criteria are met if the condition is annunciated as a caution level message. This strategy supports the availability and reliability criteria. The operational system criteria are not met as efficiently with this strategy since this would result in a need to train pilots for two procedures, which are quite similar (flameout and surge/nonrecoverable stall).	The operational system criteria are met if the condition is annunciated as a caution level message. This strategy could likely support the availability and reliability criteria, but with considerably more effort than surge/nonrecoverable stall strategies 1 or 2. The operational system criteria are not met as efficiently with this strategy since there would result in a need to train pilots for two quite similar procedures (flameout and surge/nonrecoverable stall).

Table 5-10. Continuous/Multiple Surge Annunciation Criteria

Malfunction Criteria	Description
Characterization	Two or more repetitions of a surge and recovery cycle (surge, recover, surge, recover . . . continuously surging multiple distinct surges). Clearing the continuous/multiple surging condition is most likely achieved by a reduction in FF. Continuous/multiple surge characteristics are described in figure 2-4.
Engine operation criteria	For a continuous/multiple surge condition, there is an engine integrity need; i.e., it is desirable to clear the surging since the potential exists for increased engine damage. The desired action is to reduce fuel to clear stall (retard the thrust lever until the surging clears, perhaps even to idle). At pilot discretion (if no apparent damage), the pilot can attempt to restore thrust by re-advancing the thrust lever. As described above, for continuous/multiple surges, several timing criteria thresholds need to be defined and verified (e.g., the minimum and maximum timing between surges). The delay in action to clear a surge increases potential for stall or flameout. The time criticality is unknown—i.e., action time delay versus damage potential or probability of consequential stall or flameout has not been quantified due to lack of empirical or experiential data.
Annunciation timing and flight phase	The Task 2 analyses assessed that on the order of 10 seconds or more generally appears available for continuous surge detection and annunciation in the surge events reviewed. Note that it would be operationally desirable to have the annunciation in less than 10 seconds. In less critical events (e.g., low power and high altitudes), longer times appear available. The Task 2 analyses assessed that for PSM+ICR prevention potential, if annunciated, the flight phases for the annunciation should include climb, cruise, cruise descent, and approach when thrust is at or above cruise or holding power setting. Note that detection and annunciation of continuous/multiple surge is operationally desirable, but not required, in all flight phases and at all power settings between minimum idle and maximum power. Detection at power levels below cruise (i.e., idle) is desirable because it supports early detection and annunciation of events, which initiate on approach prior to go around. However, the PSM+ICR event data indicates that continuous/multiple surge events occur at and above cruise power level. Surge detection and annunciation on the ground have no PSM+ICR prevention potential.

Table 5-10. Continuous/Multiple Surge Annunciation Criteria (Continued)

Malfunction Criteria	Description
Annunciation timing and flight phase (continued)	A strategy to limit detection and annunciation to cruise power and above is supported by • the diminishing likelihood and criticality of continuous/multiple surge at low power (idle), the consideration that such a condition is unlikely to cause engine damage, • the consideration that the engines generally do not operate between idle and a cruise/hold/approach power set (~50% N1), and • the probability that low power continuous/multiple surge will cause engine to go subidle (detectable via a subidle annunciation and procedure).
Annunciation availability criteria	The crew operations criteria for availability of a continuous/multiple surge annunciation are: medium ~99% to low ~90% (99/100 to 9/10 surges). Note that these numbers are not applicable to detection/annunciation of continuous/multiple surge below cruise and hold power settings, per the comments and caveats below. The continuous/multiple surge malfunction report rate is on the order of 1E-6. A ~90% annunciation reliability requirement implies that 9 of 10 continuous/multiple surges are detected. Failure to detect continuous/multiple surge rate should be ~1/10th the actual report rate, or on the order of 1E-7 per flight hour. A ~99% annunciation reliability implies that ~99 of 100 continuous/multiple surges are detected and the continuous/multiple surge detection failure rate should be 1/100th the actual report rate, or on the order of 1E-8 per flight hour. In general, the desired annunciation reliability varies as a function of power and altitude—the higher the power (greater the potential for damage and thrust asymmetry) and lower the altitude (closer the ground), the higher the desired reliability. Note that PSM+ICR event data indicates that continuous/multiple surge events occur at and above cruise power level. The diminishing likelihood and criticality of continuous/multiple surge at low power (idle), and probability that low-power continuous/multiple surge will cause engine to go subidle, supports strategy to limit the availability criteria to cruise power and above. This limitation on availability only affects descent, but

Table 5-10. Continuous/Multiple Surge Annunciation Criteria (Continued)

Malfunction Criteria	Description
Annunciation availability criteria (continued)	not approach. During descent, the condition is not operationally significant because of the small thrust asymmetry. A strategy limited to cruise powers and above is likely to be available for final approach. Most approaches are conducted at power levels consistent with low cruise power levels. Additionally, the availability of this annunciation is more important if a go around was commanded. If the command on the engine increased, it is likely the engine would not be able to accelerate and the lack of annunciation availability at low power is mitigated by an annunciation of a thrust shortfall.
Annunciation reliability criteria	The crew operations criteria for the probability of a false surge/nonrecoverable stall annunciation are ~1E-6 to 1E-5 (<1/1,000,000 to 100,000 engine hours). Provided crew action is limited to thrust lever reduction (versus engine shutdown), and the alert always clears before the engine reaches idle, the likelihood of low power continuous surge is low, and likelihood of low power continuous surge causing engine damage is low, pilot action to retard thrust lever/thrust is not operationally significant (i.e., does not significantly affect operational performance capability or safety margins). Provided crew action is limited to thrust lever reduction (versus engine shutdown), the crew can readily (quickly and easily) reverse their action. There is not a concern of detecting single surge as a multiple because overall probability of surge is on the order of 1E-5 and pilot action is not critical (irreversible). The concern is detecting normal engine operation as surge. Note that false surge alert rates that may be tolerable in ensuring against overalerting an individual pilot or crew may be unacceptable on a daily customer or industry fleet basis (maintenance impact).

Table 5-11. Continuous/Multiple Surge Strategies

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
Strategy characterization	Monitor for multiple surges using the rate of change of PB. Monitor for two events within a ~0.5- to 20-second interval.	Monitor for multiple surges using the PB, HP rotor speed, and FF rates. Monitor for two events within a ~0.5- to 20-second interval.	Monitor for multiple surges with an algorithm that relies on a multidimensional engine model by monitoring several engine parameters (PB, N1, N2, EGT, FF, bleed valves, etc). Monitor for two events within a ~0.5- to 20-second interval.
Parameter monitoring and sensing	The parameter to be sensed and monitored would be PB.	The parameter to be sensed and monitored would be PB, HP rotor speed, and FF.	The parameter to be sensed and monitored could include internal pressures (including PB), FF, rotor speeds, internal temperatures, bleed valve positions, stator vane positions, etc.
Hardware processing	There would be no new hardware processing since PB is processed by modern FADECs.	There would be no new hardware processing since PB is processed by modern FADECs.	There may need to be some new hardware processing since not all bleed valve positions are monitored accurately.
Software Processing	The software processing would involve a comparison of PB or PB rates with thresholds. This type of logic exists in modern FADEC systems, but just for accommodate and as a result tends to overdetect since the compensation is not operationally significant	The software processing would involve comparing PB and HP rotor speed rates relative to a threshold and relationship to FF. The logic would need to consider fault tolerance.	The minimal model size would be three parameters. The software will need to include a reliable multidimensional model that would predict engine performance based on command and thresholds, and to detect deviations from the models

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
Software processing (continued)	(opening bleed valves). The algorithm would need to be refined for annunciation. The logic would need to consider fault tolerance.		that are characteristic of continuous/multiple surging. The logic would need to consider fault tolerance.
Supporting inputs	PB level or rate threshold could be a function of power and ambient conditions.	The PB and rotor speed rate thresholds could be a function of power and ambient conditions.	The model and thresholds are likely to be a function of ambient conditions.
Resulting outputs	The resulting output is a continuous/multiple surge indication for the affected engine with reliability for high-power/low-altitude conditions.	The resulting output is a continuous/multiple surge indication for the affected engine with reliability likely for high-and mid-power conditions.	The resulting output is a continuous/multiple surge indication for the affected engine with reliability for high-, mid-, and low-power conditions.
Strengths	The strengths of this strategy are: Potential for high reliability/availability at high-engine power (>~70%N1)/low altitude (<~15K). PB has characteristics during a surge that can be used to detect a surge. This is currently the primary industry source of surge detection and accommodation.	Rotor speed and FF are the better validating parameters, better than another pressure or temperature. The strengths of this strategy are: Potential for high reliability/availability for mid-high power (~>50%N1)/low-mid altitude.	The strength of this strategy is the potential for high reliability/ availability at all power levels and altitudes.

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
Strengths (continued)	The current technology has sufficient FADEC sample rates and location of the FADED PB sensor (on fan cowl) to detect low-altitude/high-power engine surges.	PB, high-rotor speed, and FF have characteristics during a surge that can be used to detect a surge more reliably than PB alone. Use of multiple parameters will improve availability, including at mid and lower power. Normal transients at low speeds are slow (the control logic is likely not requesting fast decelerations near idle), so detection of surge with high-rotor speed is enhanced. Also enhances confirmation of a false input (fault detection). The current technology has sufficient FADEC sample rates of all parameters, and location of the FADEC PB sensor (on fan cowl) are likely adequate to detect medium-high power engine surges.	

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
Weaknesses, limitations, and considerations	There are several weaknesses of this strategy: It may be difficult to meet reliability criteria using just a single monitoring parameter. The current technology may not be sufficient for low-power surge detection. The ability to distinguish between a surge and normal operating transient conditions is challenged. An additional PB sensor at the compressor would provide high-fidelity PB rates (there are volumetric affects with sensors in the FADEC and PB lines to the FADEC); however, the engineering assessment is that although algorithm development could be difficult, it would likely be more cost-effective than adding additional pressure sensors.	There are several weaknesses of this strategy: It may not be able meet reliability criteria at low-power conditions, but is a significant improvement over use of just PB. Extensive engineering effort may be required to validate and ensure reliability. There are several limitations of this strategy: Validation data is required (same issues as in strategy 1). After the first surge, the engine control system has begun recovery procedures, which affect engine operation (same issue as for strategy 1).	A significant weakness of this strategy is the extensive engineering effort required to: Develop and validate an accurate and reliable model. Determine how the surging will be detected. Satisfy the criteria for reliability and availability for annunciation. In addition to the limitations of strategy 1 and 2 (validation data, characterizations of subsequent surges, engine response during recovery mode), there are limitations with the use of additional parameters. Although EGT can be a good indicator of surge, there are several limitations. Use of EGT should not be a primary or secondary validating parameter, perhaps tertiary.

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
Weaknesses limitations and considerations (continued)	The current FADEC sampling rate and fan case mounted burner pressure sensor works for single surges. But it may not be sufficient for multiple surges, which could be 8 to 15 surges per second. The technology exists for higher sampling rates, but also may not be necessary. There are several limitations of this strategy: Validation data is required. There is not a significant database of high-integrity (high-sample rate) engine data of multiple/continuous surges to validate algorithm development. The detection of second and subsequent surge(s) is more difficult than the first surge. If an engine surges/fully recovers/surges/ fully recovers; then the single-surge database can be used for algorithm development. But, potentially the multiple surges can occur when the engine has not fully recovered or the	There are several considerations for this strategy: First, transition from normal to surge is most significant, rate of pressure/high-rotor speed. Second, transient may be partial surge with other contributing characteristics (bleeds, FF, etc). The logic would need to ensure that PB and HP rotor decay rate thresholds for a surge are distinctly different than for a normal acceleration/deceleration. At high power, there is significant margin for normal accelerate/decelerate performance (although there may be significantly less margin for faster than normal decelerations required for some special operations). Also, at high power, other disturbances have less sensitive influences (e.g., stability bleeds, ECS), and likely do not need to accounted for. At low power, there is also margin relative to normal acceleration/	EGT thermocouples are not reliable (thin wires), have slow frequency response, and are not responsive at low airflow conditions (1 to 7 seconds). EGT performance is affected by control system response (FF bleed valves). EGT use depends on power setting (could be a 5-second time constant at low power). At all power settings, nonsurge-related thermodynamic effects (such as heat transfer and bleeds) can affect readings, but this affect is more significant at low power. Depending on probe characteristics, both low power and high altitude result in less airflow, resulting in a less responsive indication. There is a significant range of EGT for normal operation (bleeds, transient, heat transfer); and the range for a surge condition can be within desired detection thresholds. In addition to the considerations of strategy 1 and 2, the logic would need to consider fault tolerance, which is more challenged with the

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
Weaknesses, limitations, and considerations (continued)	pilot has begun to adjust the thrust lever, so the engine behavior is in recovery process from previous surge or transient, rather than normal operation, requiring additional algorithm development. After the first surge, the engine control system has begun recovery procedures, which affect engine operation (such as fuel schedule management, bleed valve opening, etc). This can affect the characteristic of the subsequent surge and can make the detection more problematic. A consideration is to set a trigger after the first surge is detected and then monitor for subsequent surge. There is a wealth of data for single surges, but not for subsequent surges. The trigger for the first surge can leverage off the existing high-frequency data. The threshold for subsequent surges can be more relaxed, and	deceleration, but there is more sensitivity to other influences (e.g., ECS, stability bleeds, signal noise ratio, external disturbances, etc). So, use of two sensors can improve reliability, but will require development of integrated detection (which could potentially double the cost due to development of two detection algorithms, logic and fault detection, sufficient throughput, etc). The potential to meet the reliability criteria exists, but requires significant effort to achieve. It is likely prudent to develop an algorithm that sets a trigger after the first surge is detected, and then monitors for subsequent surge (similar to strategy 1). Theoretically the surging could have a frequency similar to the sample rate, but this is unlikely.	use of a multidimensional model. Adding more parameters may decrease reliability (Failure Modes and Effects Analysis/fault tree), since there are more failure modes (false detects) and/or increased need for fault detection of the multiple sensors.

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
Weaknesses, limitations, considerations (continued)	leverage off the first surge. Another consideration is that theoretically the surging could have a frequency similar to the sample rate, but this is not a likely condition.		
How well the propulsion system criteria are met	The propulsion integrity needs are largely met with this strategy. This strategy is likely to detect most continuous/multiple surge conditions at high-power/low-altitude, but the reliability may not meet operational expectations. The high-power/low-altitude conditions are the most likely to cause engine damage, which is consistent with PSM+ICR database. Low-power (idle) continuous/multiple surge conditions are not likely to occur (there are not any in the PSM+ICR database), and if they occurred, are deemed less likely to cause engine damage and are likely to result in a subidle condition or an EGT exceedance (detectable conditions), so lack of reliable continuous /multiple surge detection at low-power conditions is mitigated.	The propulsion integrity needs are largely met with this strategy. This strategy is likely to detect most continuous/multiple surge conditions at high power/low altitude (which are the most likely to cause engine damage, consistent with PSM+ICR database), with improved reliability to detect midpower and high-altitude conditions. Low-power conditions are not likely to occur (there are not any in the PSM+ICR database), and if they occurred, are deemed less likely to cause engine damage and likely to result in a subidle condition or an EGT exceedance (detectable conditions), so lack of reliable continuous/multiple surge detection at low-power conditions is mitigated.	The propulsion integrity needs are met with this strategy. This strategy has the potential to detect continuous/multiple surges at all power settings throughout the entire flight envelope.

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
How well the operational system criteria are met	The lack of reliable detection at midpower may be an operational concern. It is operationally more challenging to have an annunciation that is only reliable at high power/low altitude in the development of the pilot procedures. If there is an annunciation for a subset of continuous/multiple surges, then a pilot will rely on the annunciation and its defined procedure for some of the failures (albeit the more significant ones), but the pilot would still be required to detect for the remaining (midpower) conditions, which would mean an unannunciated checklist and procedure would still need to exist. This is not considered operationally acceptable. The lack of detection at low power can be accepted operationally, given the characterization of low probability of the event and likelihood of alternate detection. Lack of detection that condition has cleared (with/thrust lever reduction)	The lack of detection at low power can be accepted operationally, given the characterization of low probability of the event and likelihood of alternate detection. Lack of detection that condition has cleared (with thrust lever reduction) can be accepted operationally, but needs to be covered procedurally: e.g., once set hold indication until thrust lever command and engine power get below threshold (or at idle). If the condition still persists at idle, the procedure will be to shutdown the engine. If the logic can only detect when the condition still persists above a certain threshold, the procedure may require re-advancement to above that power level. On an individual pilot operational basis, can err on the side of over annunciation for condition at high power, but over annunciation is likely not acceptable from a maintenance or fleet operational standpoint.	This strategy meets the desired operationally system criteria, but exceeds the minimum required operationally system criteria. The lack of detection at low power can be accepted operationally, given the characterization of low probability of the event and likelihood of alternate detection. On a pilot operational basis can err on the side of over annunciation for condition at high power, but over annunciation is likely not acceptable from a maintenance or fleet management standpoint.

Table 5-11. Continuous/Multiple Surge Strategies (Continued)

Continuous/ Multiple Surge	Strategy 1	Strategy 2	Strategy 3
How well the operational system criteria are met (continued)	can be accepted operationally, but needs to be covered procedurally: e.g., once set, hold indication until thrust lever command and engine power get below threshold (or at idle). If the condition still persists at idle, the procedure will be to shutdown the engine. If the logic can only detect that the condition still persists above a certain threshold, the procedure may require re-advancement to above that power level. From a crew operational standpoint, can err on the side of over annunciation for conditions at high power, but over annunciation is likely not acceptable from a maintenance or fleet operation standpoint.		

Table 5-12. Other STA Annunciation Criteria

Malfunction Criteria	Description
Characterization	The characterization of other STA for Task 4 is both actual and indicated thrust abnormally differing from commanded thrust. This condition could be either an engine increasing or decreasing thrust from power set, not accelerating/decelerating when thrust command is increased/decreased, could include subidle conditions that are not flameout or surge/nonrecoverable stall, and could include above-idle stall conditions (figures 2-7, 2-9, and 2-12). The timing and thrust characteristic of this condition is not quantifiable since there are so many failure conditions that could result in this symptom.
Engine operations criteria	For a sustained thrust anomaly condition, there is likely no engine integrity need, unless an there is an EGT exceedance (can be annunciated separately). It is not known what the thrust recovery need is, since there are so many different failure conditions that can result in this symptom.
Crew operations criteria	Operational need for crew action is not time-critical. Continued safe flight and landing is possible with thrust disagree and with one engine. Preservation of engine thrust is operationally desirable to maximize airplane performance and flight safety margin. Timely awareness of an engine malfunction is desired, even though no specific pilot action/procedure is identified. Immediate awareness implies caution level or higher alert. The intended purpose is to detect and annunciate persistent or abnormal disagree between commanded and indicated thrust. If annunciated, the logic should detect/alert indicated thrust deviation from static command (uncommanded thrust increase/decay), and should detect/alert failure of indicated thrust to change following a change in command. The logic could also detect continuous/multiple surge, which results in persistent thrust shortfall, and stalls which do not go subidle, if not annunciated by a dedicated annunciation. The pilot action is situation and thrust delta dependent, and based on policies and practices, and on crew judgment and discretion. The required threshold for abnormal thrust disagree is difficult to ascertain. Based on engineering judgment and in-service experience, a threshold of ~10% thrust could be used as a desired design criteria, since it is likely to exceed the criteria for a significant thrust difference and it can meet the annunciation availability/reliability criteria. Detection of slow to accelerate/decelerate is more problematic to distinguish between normal and abnormal accelerate/decelerate characteristics throughout the flight envelop. Detection and annunciation of slow to accelerate/decelerate could compliment

Table 5-12. Other STA Annunciation Criteria (Continued)

Malfunction Criteria	Description
Crew operations criteria (continued)	thrust shortfall and overthrust detection. For most operation, timely annunciation of slow to accelerate/decelerate detection is not operationally significant. The one condition where timely acceleration detection is operationally desired is during the command of a high-power go around.
Annunciation timing/flight phase	The Task 2 analyses assessed that on the order of 5 seconds appears available for thrust shortfall detection and annunciation in fatal events with prevention potential, which includes stuck high, stuck low, and slow to accelerate (go around). For a go around, 3 seconds or less are desired for thrust shortfall detection and thrust shortfall annunciation. This includes that this annunciation may be considered as mitigation for an above-idle stall, such that the condition is not annunciated until the go around is commanded. Event data indicates that more time is available for powerloss detection and annunciation as altitude increases and criticality consequently decreases. (At cruise, in the one applicable substantial damage powerloss event, 30 to 40 seconds was available for detection and annunciation). The Task 2 analyses assessed that for PSM+ICR prevention potential, if annunciated, the flight phases for the annunciation should include climb, cruise, cruise descent, and approach throughout normal thrust range. Engine malfunction detection is operationally desirable in all flight phases and at all power settings between minimum idle and maximum power.
Annunciation availability criteria	The crew operations criteria for detection of an other STA annunciation are medium ~99% to low ~90% (99/100 to 9/10 surges). Assuming probability of thrust shortfall event is 1E-5 to 1E-6 per engine hour, the joint probability of failure to detect/alert would therefore be on the order of 1E-6 to 1E-8 per flight hour. Assuming probability of overthrust event is 1E-7 per flight hour, the joint probability of failure to detect/alert would therefore be on the order of 1E-8 to 1E-9 per engine hour. The estimated operationally desired threshold of ~10% thrust could be used as a desired design criteria since it is likely to exceed the criteria for a significant thrust difference operationally and is likely to meet the annunciation availability criteria.

Table 5-12. Other STA Annunciation Criteria (Continued)

Malfunction Criteria	Description
Annunciation reliability criteria (continued)	Detection of slow to accelerate/decelerate is more problematic. Availability of timely slow to accelerate/decelerate detection is not operationally significant, except for timely powerloss detection during the command of a high-power go around, so lack of availability for accelerate/decelerate can be mitigated. The crew operations criteria for the probability of a false other STA annunciation are ~1E-6 to 1E-5 (<1/1,000,000 to 100,000 flight hours). Thrust shortfall annunciation provides pilot awareness and does not specify a pilot action. Therefore, within limits, false annunciation is not operationally significant (does not significantly affect operational performance capability or safety margins). The probability of a false thrust disagree annunciation should be low, e.g., on the order of at most 1E-5 or 1E-6 per flight hour, and preferably on the order of 1E-7 or less per flight hour. This ensures against overalerting an individual pilot, crew, or fleet. Note that false surge alert rates that may be tolerable in ensuring against overalerting an individual pilot or crew may be unacceptable on a daily customer or industry fleet basis (maintenance impact).

Table 5-13. Other STA Strategies

Other STA	Strategy 1	Strategy 2
Strategy characterization	This strategy models the expected engine characteristic (thrust set parameter) derived from thrust set command.	This strategy models the expected engine characteristic (thrust set parameter), derived from thrust set command and from a model of expected performance. This has the potential to provide timely annunciation of slow to accelerate/decelerate for all flight conditions.
Parameter monitoring/ sensing	The parameter to be sensed and monitored would be the thrust set parameter.	The parameters to be sensed and monitored could include: commanded thrust setting (e.g., derived from thrust lever position), measured thrust set parameter (e.g., EPR, N1), and diagnostics model parameters (FF, N1, EPR, N2, PB, EGT, VSV, bleed valves).
Hardware processing	There would be no new hardware processing since the thrust set parameter is processed by the FADEC.	There may be a need for some new hardware processing, since not all bleed valve positions may be monitored accurately.
Software processing	The software processing would involve a comparison of the thrust set parameter compared to a threshold derived from the command. The threshold would model the expected accelerate/decelerate characteristics when thrust set parameter does not equal the command (i.e., is the engine approaching command within the expected rates based on the expected range of normal engine response). The logic would need to consider fault tolerance.	The software will need to include a reliable multi-dimensional model, and thresholds to detect deviations from the model that are characteristic of slow to accelerate/decelerate and uncommanded deviations from command. The logic would need to consider fault tolerance.
Supporting inputs	Engine acceleration/deceleration characteristics are a function of power and ambient conditions.	The model and thresholds are likely to be a function of ambient conditions.

Table 5-13. Other STA Strategies (Continued)

Other STA	Strategy 1	Strategy 2
Resulting outputs	The resulting ouput is a STA indication for the affected engine (high or low), with reliability for a thrust increase or decrease from command.	The resulting output is a STA indication for the affected engine (high or low), with reliability for a thrust increase or decrease from command and for slow to accelerate/decelerate for all flight conditions and power settings.
Strengths	The strengths of this strategy are: • Uses existing FADEC parameters • Good for a sudden uncommanded thrust change from a steady state condition	The strength of this strategy is the potential to improve timing for slow to accelerate/decelerate detection.
Weaknesses, limitations, and considerations	There needs to be a significant margin for transients, so may not detect a slow to accelerate/decelerate PSMs quickly. This, however, is of most concern during a go around, where annunciation of 3 seconds is desired, but the engine accel characteristics are predictable and relatively quick for this condition.	A significant weakness of this strategy is the extensive engineering effort required to • develop and validate an accurate and reliable model. • Determine how the thrust anomaly will be detected.
How well the propulsion system criteria are met	This strategy does not identify propulsion integrity or thrust recovery needs, it only provides pilot awareness. However, the most likely integrity need would be an EGT exceedance, which could be annunciated separately.	Similarly to strategy 1, this strategy does not identify propulsion integrity or thrust recovery needs, it only provides pilot awareness. However, the most likely integrity need would be an EGT exceedance, which could be annunciated separately.

Table 5-13. Other STA Strategies (Continued)

Other STA	Strategy 1	Strategy 2
How well the operational system criteria are met	This strategy meets operational criteria. A condition of stuck thrust is annunciated in a timely manner. In addition, timely annunciation of slow to accelerate during go around is desirable. Slow to accelerate at other conditions, and slow to decelerate are not of concern for timely annunciation, and thus longer timing for annunciation acceptable.	This strategy meets the desired operationally system criteria, but exceeds the minimum required operationally system criteria. A condition of stuck thrust and slow to accelerate/decelerate are annunciated in a timely manner. However, only stuck thrust and slow to accel during go around are most desirable. Slow to accelerate at other conditions, and slow to decelerate, are not of concern for timely annunciation, and thus longer timing for annunciation acceptable.

5.3 CONCLUSIONS OF TASK 4 ANNUNCIATION CATEGORIES.

The strategies listed in table 5-3 were developed, and the results were used in Task 5 for technology risk assessment and detection strategy down selection.

In the course of the development of the annunciation strategies, the issue of autoaccommodation was reviewed and recognized as an important factor in detection and annunciation strategies and crew procedures and supporting indications development. During the development of the flameout and surge/nonrecoverable stall strategies, it became apparent that automation could impact both detection/annunciation/indications and pilot procedures. Although engine malfunction automation is malfunction accommodation rather than malfunction annunciation, the two are interrelated. Malfunction accommodation was recognized as being significant to any resolution, and hence, was reviewed in general as part of this research, and documented in section 5.5.

5.4 ENGINE MALFUNCTION AUTOACCOMMODATION.

System interface design (information and control), pilot role, and procedures for normal and nonnormal operations are defined in part by the airplane flight deck operational concept and philosophy. However, system design and interface are largely defined by regulatory (safety), technology (capability and reliability), and economic (cost-benefit) considerations. These considerations consequently define feasible detection and annunciation strategies and implementations, and the required pilot role and procedures. Optimization of these typically competing and often limiting considerations results in a balanced set of compromises intended to maximize benefit and minimize risk and cost. Specific tradeoffs between system interface design, system automation, pilot role, and malfunction procedures are the focus of this section.

In the Phase 1 and 2 studies, ICR-related PSMs were identified and PSM detection and annunciation criteria were developed from event data. Malfunction detection and annunciation strategies were defined. Strategy strengths, weaknesses, and technology risks were assessed. Best practices, principles, and potential detection and annunciation improvements were identified from nonnormal procedures review. High-level criteria (guidelines) for an information-based engine indication paradigm were developed from procedures, practices, and policies review and operational and interface design philosophy considerations. The follow-on question concerning ICR-related malfunction detection and annunciation is: What are the feasible roles of the system automation/accommodation and the pilots? The answer defines the relationship between system automation, pilot information and control interface, and pilot procedures.

Subidle powerloss (including surge/nonrecoverable stall) and continuous/multiple surge are the major ICR-related malfunctions discussed in this phase. The primary possible pilot actions to these two malfunctions are relatively limited. The pilots can

- retard the thrust lever(s). This reduces engine FF and power.
- select the engine fuel control switch to cutoff. This cuts the fuel, resets the EECs, and results in engine shutdown.

- select the engine fuel control switch to run. In-flight, this enables FF, engine relight, and initiates engine autostart. Additional restart related pilot action (e.g., airspeed, altitude, starter assist control) and monitoring may be required for successful restart.

- re-advance the thrust lever(s) and operate the engine normally or at reduced thrust.

- in the case of severe engine damage, the crew can elect to secure/isolate the engine with the engine fire handle.

Alternatively, modern FADECs can be designed with automation to attempt to recover thrust for a PSM. For example, for a flameout condition, the FADEC can incorporate auto-re-light/autostart logic. For a surge/nonrecoverable stall condition, the FADEC could incorporate logic to automatically dip fuel to clear the stall (which may or may not result in a flameout) and then use auto-re-light/autostart logic to recover thrust. For a continuous/multiple surge, FADEC logic could automatically reduce fuel until the surging clears and then automatically reapply fuel to regain normal operation.

The current phase focused on annunciation of the PSM. But annunciation achieves either pilot awareness (and possible ad hoc response) or leads the pilot to a procedure. The implementation of automation and supporting indication has the potential to change the role of the pilot from action to monitoring. As such, engine system automation and pilot procedures could be integrated to optimize engine thrust recovery. This suggests several areas appropriate for follow-on research work:

- Providing the appropriate information to the pilot in their role as supervisor and monitor. The more system automation, the more information may need to be provided to the pilot to support their managerial role. For example, in the event of auto-re-light, the pilot may need information such as (1) whether it is operating, (2) what is the status, and (3) how long until thrust recovery. The information methods, criteria, timing, and annunciation are all areas that require further investigation and evaluation.

- Auto-re-light can accommodate the engine failures, resulting in engine thrust recovery. A pilot procedure that calls for cycling, the fuel switch can have the effect of lengthening the start if the engine has already achieved auto-re-light. Additionally, there have been in service events where a pilot initiated start was interpreted by the pilot to be stalled and terminated, when the start was progressing normally but had typically slow acceleration to idle. Both of these issues suggest start mode indication has potential benefit.

- Flameout automatic accommodation is benign, activation of the igniters (auto-re-light). However, for either a surge/nonrecoverable stall (fuel dip which may flameout the engine), or continuous/multiple surge (above-idle fuel reduction), the automation has the potential to affect above idle thrust. Above-idle, automated control of engine fuel or power can introduce unacceptable failure modes and has the potential to take thrust control away from a pilot at a critical time. Therefore, the issue of whether the pilot or the engine control should have final authority for engine shutdown above idle requires evaluation.

- Currently, required crew response to single and multiple engine subidle conditions differ. For the multiple engine event, the crew procedure involves a time-critical memorized response to cycle the fuel control switch on both engines, which forces EEC resets and engine recoveries. Engine recovery from a single engine subidle condition is less critical than multiple engine recovery from subidle condition, and thus the procedure does not include memory items. It is possible that a dual-engine subidle event may be caused by a common or similar mode EEC fault. Consequently, reliable immediate action and an EEC reset is required for a multiple engine event even though it may not be necessary in all cases. Automation and autoaccommodation could potentially be used to standardize the pilot role for single and multiple failures. However, the cost-benefit, frequency of dual failures, risk and reliability would need to be considered.

5.5 TASK 4 CONCLUSIONS.

Ten engine malfunction detection strategies were developed and were used in Task 5 for the strategy down selection.

The development and assessment of the Task 4 malfunction strategies recognized that integration of FADEC autoaccommodation modified the expected and desired pilot response. The primary scope of this study was pilot awareness of the engine malfunction condition. However, it is recognized that design of automation and pilot procedures are interrelated. As such, research into flight deck annunciation of engine autoaccommodation (e.g., auto-re-light, start modes) and supporting engine capability should be considered for follow-on research.

6. TASK 5—TECHNOLOGY RISK ASSESSMENT AND DOWN SELECTION OF STRATEGIES.

Task 5 included a technology risk assessment of each strategy with the malfunction categories and down selection assessment of the Task 4 strategies.

An evaluation of the technology risks and potential benefits resulted in the selection of continuous/multiple surge annunciation for the Task 6 development plan.

6.1 TASK 5 ANALYSIS.

The objective of Task 5 was to conduct a technology risk assessment for each of the candidate detection strategies identified in Task 4. This assessment required close BCA/GE/PW coordination to identify potential technical hurdles. This risk assessment was used to guide a down selection of the strategies, with a recommendation made for the Task 6 development plan.

The technology assessment involved an assessment of the hardware and the algorithm. Although the contract was written assuming that an outcome would be sensor development needs, the research determined that the needs really lie in algorithm development. Thus, the technology assessment was developed to cover both hardware and algorithm development.

Task 1 included a preliminary technology risk assessment for a relative comparison of the nine symptoms. This task expanded the risk assessment to evaluate each malfunction detection strategy.

6.1.1 Technology Risk Assessment Criteria.

For the purpose of this study, the technology risk assessment was broken into three categories, with the following definitions:

a. Low

- Algorithm and hardware currently exists.
- Algorithm and hardware has a proven reliability record.

b. Medium

- Similar capability has been developed in the past.
- Changes to current algorithm and hardware appears feasible with moderate amount of effort.

c. High

- Specific annunciation detection logic has not been developed.
- Similar capability for accommodation may exist, but to apply to pilot annunciation incurs additional risk.

- May require significant work to ensure reliability.
- Trade between reliability, development cost, and timing likely.
- Data to design or substantiate either are not available or are difficult to obtain.

These same definitions were applied to both hardware and algorithm development.

6.1.2 Technology Assessment of Task 4 Strategies.

A technology assessment was made for each of the four engine malfunction annunciation categories developed in Task 4.

6.1.2.1 Flameout.

For flameout, two strategies were developed:

- Strategy 1: subidle (high-rotor speed)
- Strategy 2: subidle and flameout characteristic (high-rotor speed and EGT)

The hardware risk assessment is low for both strategies, since the hardware already exists in modern FADEC systems (high-rotor speed and EGT).

The algorithm risk assessment is a function of the strategy:

- Strategy 1: subidle: low
- Strategy 2: subidle and flameout: medium

6.1.2.2 Surge/Nonrecoverable Stall.

For surge/nonrecoverable stall, three strategies were developed:

- Strategy 1: subidle (high-rotor speed)
- Strategy 2: subidle and surge/nonrecoverable stall characteristic (high-rotor speed and EGT)
- Strategy 3: surge/nonrecoverable stall characteristic (PB, high-rotor speed, EGT, power set command, and actual power set parameter)

The hardware risk assessment is low for all three strategies, since the hardware already exists in modern FADEC systems (high-rotor speed, EGT, PB, power set command, and actual power set parameter).

The algorithm risk assessment is a function of the strategy:

- Strategy 1: subidle: low
- Strategy 2: subidle and surge/nonrecoverable stall: medium

- Strategy 3: surge/nonrecoverable stall: high

6.1.2.3 Continuous/Multiple Surge.

For continuous/multiple surge, three strategies were developed:

- Strategy 1: multiple-surge detection based on PB rate/threshold
- Strategy 2: multiple-surge detection based on PB, high-rotor speed, and FF rates/ thresholds
- Strategy 3: multiple-surge detection based on a multiparameter diagnostics model

The hardware risk assessment is low for strategies 1 and 2, since the hardware already exists in modern FADEC systems (PB, high-rotor speed, and FF). The hardware risk assessment is medium for strategy 3, which includes detection of continuous/multiple surges below 50% N1. For this strategy, additional PB sensors (e.g., high-response sensors) may be required.

The algorithm risk assessment is high for all the strategies. This assessment is based on the criteria defined for this task. Of all the annunciations identified, these strategies have the highest risk since all the high-risk development issues exist.

- This type of algorithm has not been developed.
- May require significant work to assure availability and reliability.
- Trade between development cost, reliability, and timing is likely.
- Lack of data to design and substantiate an algorithm.

However, it should be noted that the algorithm could leverage off of existing surge detection and accommodation logic, and that the flight deck design criteria of 10 seconds for annunciation and a N1 threshold of 50% N1 are considerations to mitigate the risk.

6.1.2.4 Other STA.

For other STA, two strategies were developed:

- Strategy 1: thrust set parameter relative to thrust set command
- Strategy 2: thrust set parameter relative to thrust set command, enhanced with a diagnostic model

The hardware risk assessment is low for both strategies, since the hardware already exists in modern FADEC systems (thrust set command and thrust set parameter).

The algorithm risk assessment is a function of the defined thrust anomaly threshold and the timing criteria:

- Medium, for thrust loss or increase > 10%

- Within 0.5 to 5 seconds from steady-state conditions within takeoff envelope

    - From takeoff condition: 0.5 to 2 seconds
    - From a cruise/climb condition: 2 to 5 seconds

- Up to 15 seconds for high altitude (outside of takeoff envelope)

- Slow to accelerate or decelerate:

    - Medium for thrust difference > ~10%, within 15 to 30 seconds
    - High for thrust difference > ~10%, within 5 seconds

Note that Task 5 did not develop strategies for thrust anomalies due to engine damage or oscillations. The preliminary assessment of including these anomalies in this annunciation category, if desired, changes the risk to high for a thrust loss or increase > 10%.

6.1.3 Engine Malfunction Annunciation Strategy Recommendations.

Task 4 evaluated several strategies for each of the selected STA categories. Based on the assessments of the engine operational needs, the crew operational needs, and the risks, the following strategies are recommended.

6.1.3.1 Flameout.

The recommendation is strategy 1: a subidle caution message. This strategy meets the engine operational needs and the crew operational needs.

6.1.3.2 Surge/Nonrecoverable Stall.

The recommendation is strategy 1: a subidle caution message. This strategy largely meets the engine operational needs, and does meet the crew operational needs. A subidle caution message does not distinguish between a flameout or surge/nonrecoverable stall, for which the engine needs differ, but the crew response for this combined message will result in a timely response, and a single message with similar crew actions is preferred from a training and crew operations perspective. Additionally, the crew operations input was that there was a lot of risk associated with trying to get the fast desired crew response for subidle surge/nonrecoverable stall. Obtaining desired engine need via annunciation and crew procedure is probably not possible without creating a bigger problem.

6.1.3.3 Continuous/Multiple Surge.

The recommendation is strategy 2: an algorithm that relies on two or three appropriate engine parameters (e.g., PB, high-rotor speed, and FF). This strategy will likely meet the engine operations needs and the crew operational needs when considering the mitigating conditions (enabling operational factors). It is not expected that the more complicated strategy 3 will be warranted.

6.1.3.4 Other STA.

The recommendation is strategy 1: an algorithm that relies on the expected characteristic of the thrust set parameter based on the command. None of the strategies fully meets the engine integrity needs, since the cause of the failure and symptoms are unknown. However, it is likely that the only integrity need may be due to an EGT exceedance, which can be separately annunciated. This strategy does provide the crew operational needs of timely awareness of the engine malfunction.

Note that since the recommended strategy for flameout and surge/nonrecoverable stall is a subidle indication, this annunciation would only apply to the above-idle STA malfunctions.

Note also that this strategy does not address STA due to engine damage or oscillation. These engine conditions do not appear to be contributors to PSM+ICR.

6.1.4 Crew Annunciation Category Conclusion.

Based on the assessments of the engine operational needs and the crew operational needs, the five engine malfunction annunciation categories were reduced to a recommended set of four crew annunciation categories. This is depicted in table 6-1.

Table 6-1. Down Selection of Crew Annunciation Categories

Engine Malfunction Annunciation Categories	Crew Annunciation Categories
Flameout	Subidle (includes flameout and surge/nonrecoverable stall)
Surge/nonrecoverable stall[1]	
Continuous/multiple surge	Multisurge
Thrust sensor failure	EEC mode
Other STA	Thrust anomaly

[1] For the purpose of this report, single surge events that recover are not considered a STA.

6.2 DOWN SELECTION OF STRATEGIES.

The technical risk assessment includes implementation and development risk. A summary of the technical risk assessment for the four crew annunciation categories is shown in table 6-2.

The annunciation with the most implementation and development technical risk is continuous/ multiple surge.

Table 6-2. Crew Annunciation Categories

Crew Annunciation Categories	Implementation and Development Technical Risk
Subidle (includes flameout and surge/nonrecoverable Stall)	Low (currently exists in many applications)
Continuous/multiple surge (Multiple surges)	High (does not currently exist)
EEC mode (actual thrust higher or lower than commanded due to failure of primary thrust set parameter (e.g., EPR failure))	Low-Medium (exists in many applications, however, an improvement to the current detection threshold increases the risk to medium)
Thrust anomaly (other STAs, not included in the other annunciation categories)	Medium-High (portions exist in some applications, risk depends on specific anomaly, and those anomalies that have PSM+ICR prevention potential have medium risk)

6.2.1 Summary of Operational Benefit.

The complete suite of annunciations has operational benefit since the annunciations collectively encompass detection and annunciation of all STAs.

However, each individual annunciation also has operational benefit, and consideration could be given to development of individual and appropriate subsets of annunciations. For example, the subidle annunciation, which accounts for approximately 50% of STA engine malfunctions, has the potential to address a significant number of the PSM+ICR events (including most hull loss and fatality accidents). The technical risk for detection and annunciation of the subidle condition is considered low.

A subidle annunciation has the lowest risk and highest potential benefit. The annunciation of highest implementation and technical development risk is for continuous/multiple surge due to lack of sufficient engine data to validate the reliability of a detection algorithm. The cost-benefit of this annunciation for existing or new airplane programs is not likely to be favorable until sufficient engine data becomes available.

This suite, a subset of the suite, or individual annunciations, provide varying degrees of operational benefit and prevention potential. A cost-benefit analysis is warranted when considering the implementation of new detection and annunciation capabilities.

It is estimated that the retrofit of existing airplanes with new detection and annunciation for STAs would not be supported by a cost-benefit analysis. However, a cost-benefit analysis was not within the scope of this study.

6.2.2 Down Select for Task 6.

In evaluating the potential operational benefit for the Task 6 down selections and for follow-on research work, consideration was given to the existing suite of annunciations available on many modern airplanes. Given existing PSM annunciations, the high risk (i.e., needs the most work) and the potential to enhance existing operational benefits, continuous/multiple surge detection and annunciation was selected for Task 6 (plan for development, demonstration and validation). Considerations also included the potential to eliminate an unannunciated pilot checklist, the reported PSM rate, and PSM+ICR prevention potential.

7. TASK 6—DEVELOPMENT, DEMONSTRATION, AND VALIDATION PLAN.

The Boeing team supported the preparation of a plan for development, including demonstration and validation of technologies required for propulsion malfunction detection and accommodation capabilities defined in Task 5. This included a detailed approach to develop, demonstrate, validate, and successfully mature the strategy.

In addition, Task 6 prepared the foundation for follow-on research on a development plan for detection and annunciation of engine damage.

7.1 DEVELOPMENT PLAN FOR ANNUNCIATION OF CONTINUOUS/MULTIPLE SURGE.

Task 6 included the preparation of a plan for development of the technologies required for the propulsion malfunction detection and accommodation capability selected in Task 5. Although the design criteria were established through Tasks 1 through 4, they are summarized to provide a complete definition in this task.

The results of Tasks 1 through 5 resulted in the decision to prepare a plan for the development of an ENG SURGE X annunciation, which would be provided in the cockpit if an engine was in the conditions of continuous/multiple surges. For this engine malfunction, an engine is exhibiting the characteristics of repetitive surges (surge/recover/surge/recover . . .) for which the desired pilot response is to retard the thrust lever for that engine (perhaps as far as to idle) to clear the surge condition.

As part of this study, a continuous/multiple surge event is defined as two or more surge events occurring within a 0.5-to 20-second interval. Multiple surge events occurring in less than 0.5 second, or occurring more than 20 seconds apart, are considered individual selfrecoverable surges. This definition may need to be revised since the detection algorithm is developed.

Surge annunciation is based on PSM+ICR and reported PSM event review and analysis. It is justified primarily by best practices and, therefore, falls into the product improvement category. Surge annunciation could be used in conjunction with the other annunciations defined in Task 4 to enhance the pilot awareness and procedure of an engine malfunction condition.

There were PSM+ICR events for which single and continuous/multiple surge was the engine malfunction. The current study is focused primarily on continuous/multiple surge. However, single surge data, knowledge, and experience may be used to aid development of continuous/multiple surge detection strategies. Surge is currently one of the top three PSMs reported.

This plan may need to be modified, based on findings during the development process or other system developments (e.g., if it is determined feasible to accommodate the failure automatically, the approach could change).

The development plan would include:

- Review of top level detection and annunciation criteria
- Development of continuous/multiple surge event database
- Continuous/multiple surge data analysis
- Development of lower level detection and annunciation software requirements
- Preliminary design reviews
- Tool development
- Detection and annunciation algorithm development
- Demonstration and validation of both detection and annunciation

7.1.1 Review of Top Level Detection and Annunciation Criteria.

7.1.1.1 Airplane Operational Level Criteria.

Flight deck engineers, procedures managers, and the pilots consider a continuous/multiple surge cockpit annunciation as potentially beneficial. Contributing factors in PSM+ICR events were

- lack of awareness an engine malfunction exists, or
- lack of awareness which engine(s) is affected, or
- difficulty in determining which procedure to use.

Currently, on most modern airplanes, the ENG LIM/SURGE/STALL is an unannunciated checklist. Consequently, the pilot may not be sure of the engine condition, which engine is affected, or which checklist to accomplish.

If shown to be feasible and reliable, the addition of an ENG SURGE X annunciation could make the pilot positively aware of the engine malfunction condition, positively identify which engine is affected, and link directly to the appropriate nonnormal checklist procedure.

7.1.1.2 Propulsion Criteria.

7.1.1.2.1 Engine Needs Criteria.

The engine does not have a need that is more important than the need to first fly the airplane.

Engine Needs, in the context of this report, includes operational aspects of the engine and has two components; what is operationally needed to address the engine malfunction, and what is the operational procedure recommended to restore thrust? Since both components affect crew operation, the following definitions were developed jointly with flight deck engineers, procedures managers, and the pilots. Therefore, any changes to the definitions should be developed jointly with these groups.

- Integrity need is defined as what is needed to reduce the potential for additional engine damage. For continuous/multiple surges, continued operation in this condition can induce additional damage. Note that the most likely cause of surge or

continuous/multiple surge is engine damage. To clear the continuous surging, a reduction in FF is generally beneficial.

- Thrust recovery need is defined as what is needed to recover thrust. To recover thrust, the surging condition must first be cleared. This may be achieved by a reduction in FF. The reduction is accomplished by retarding the thrust lever such that the demanded engine speed is below the actual speed. The combination of reduced FF and lower speed may be sufficient to clear the surging. Subsequently, the thrust lever can be readvanced to attempt to regain thrust.

Characterization of engine operation and the continuous/multiple surge condition is difficult since engine capability depends on the destabilizing factor(s) that caused surging and the extent of any damage. Some general characterizations include:

- A full recovery of thrust may not be achievable and attempts may result in continued or additional surging that may increase the extent of the damage.

- The likelihood of incurring or increasing engine damage is greater at higher-engine power/lower altitude. Conversely, the likelihood of incurring or increasing engine damage decreases at lower-engine power/higher altitude.

- The engine is less likely to be in, or continue in, a condition of continuous/multiple surge at low power, and if it were, it would tend to result in stall and go subidle and/or have an EGT exceedance.

7.1.1.2.2 Annunciation Risk Assessment.

The technical risk or difficulty for the development of continuous/multiple surge annunciation was assessed as high. Contributing factors are:

- Specific detection and annunciation logic has not been developed or validated.

- Similar capability for accommodation may exist, but providing pilot annunciation incurs additional risk of false or nuisance annunciations.

- May require significant work to ensure reliability.

- Trade-offs between reliability, development cost, and timing are likely to be required.

- Data to design and substantiate are either not available or are difficult to obtain.

There is a very small database of continuous/multiple surge events, and the only events identified for this study were digital flight data recorder (DFDR) type data (low frequency, ~ 0.5 to 1 Hz data). The lack of a comprehensive set of high-frequency data (20-50 Hz) makes algorithm development and validation very problematic.

7.1.1.3 Operational Criteria.

Operational criteria should not be developed in isolation, but should involve a design dialogue with the appropriate experts (pilots, procedure managers, flight deck engineers, propulsion system integrators, and FADEC software logic designer with engine performance and engine operational capability experience).

The developed criteria include considerations encompassing an understanding of the engine operational aspects and the airplane operational aspects, which must be mutually understood to develop an appropriate, integrated, and viable solution. The development of the operational criteria included algorithm development limitations and pertinent engine characteristics that could be used for mitigation.

The following lists the top level desired design criteria based on the mitigating factors listed. The development of final design details may involve a review and compromise to develop the lower level detection design criteria.

7.1.1.3.1 Detection and Annunciation Timing, Flight Phase, and Thrust Level Criteria.

7.1.1.3.1.1 Detection and Annunciation Timing Criteria.

Operational need for action is not time-critical, provided not all engines are affected. Continued safe flight and landing is possible with one engine. Preservation of engine function is operationally desirable to maximize airplane performance and flight safety margin.

Approximately 10 seconds or more generally appears available for continuous/multiple surge detection and annunciation in the surge events reviewed. In less critical events, longer times appear available. Event data indicate that 15 to 30 seconds appear available as event altitude increases and criticality decreases.

7.1.1.3.1.2 Flight Phase Criteria.

The detection operationally desired for PSM+ICR are climb, cruise, cruise descent, and approach when thrust is at or above cruise or holding power setting. Note that detection and annunciation of continuous/multiple surge is operationally desirable in all flight phases and at all power settings between minimum idle and maximum power, but can be operationally acceptable at or above cruise and hold power settings.

7.1.1.3.1.3 Thrust Level Criteria.

The PSM+ICR event data indicate that continuous/multiple surge events occur at and above cruise power level. Surge detection and annunciation have no PSM+ICR RTO>V1 prevention potential. An acceptable design strategy (thrust level criteria) is to limit detection and annunciation to revenue service cruise and hold power and above (~>50% N1).

Detection at power levels below cruise is desirable. Such detection supports early detection and annunciation of events that initiate on approach prior to go around. However, the minimum design criteria do not include annunciation of a continuous/multiple surge in the low-engine power range (idle to ~50% N1). Supporting rationale is:

- The challenge of detecting the condition below 50% N1.
- The likelihood that a low-power continuous/multiple surge will go subidle (can be mitigated by a subidle or thrust shortfall annunciation).
- Low power continuous/multiple surge is not likely to cause or increase engine damage.
- The thrust asymmetry is not significant for a low-power malfunction and can be mitigated by thrust shortfall annunciation if thrust does not increase when commanded (e.g., thrust asymmetry for go around).

7.1.1.3.2 Availability and Reliability Criteria.

The detection availability (detecting a true surge event) should be on the order of medium (~99%) to low (~90%).

The continuous/multiple surge malfunction report rate is on the order of 1E-6. A 90% annunciation availability requirement implies that nine of ten continuous/multiple surges are detected. Failure to detect a true continuous/multiple surge should be 1/10th the actual report rate, or on the order of 1E-7 per flight hour. A 99% annunciation reliability implies that 99 of 100 continuous/multiple surges are detected and the continuous/multiple surge detection failure rate should be 1/100th the actual report rate, or on the order of 1E-8 per engine hour.

The detection reliability (probability of false annunciation) should be on the order of ~1E-6 to 1E-5 (<1/1,000,000 to 100,000 engine hours).

The reliability criteria assumes that the crew procedure action is limited to thrust lever reduction (versus engine shutdown). An erroneous thrust lever reduction is easily and quickly reversible. A procedure involving engine shutdown would drive a higher reliability, since recovery from an erroneous or unnecessary engine shutdown is not quickly reversible.

The annunciation of a single surge as a continuous/multiple surge is not considered a false detection because (1) the overall probability of surge is low (on the order of 1E-5), (2) the malfunctions are similar, the pilot procedure action is not critical (i.e., is acceptable and easily reversible), and (3) the pilot is correctly made aware of which engine had the malfunction (i.e., affected engine). The detection reliability concern is falsely annunciating normal engine operation, control system faults, or control system disturbance inputs as surge. False surge alert rates on the order of 1E-5 to 1E-6 per engine hour may be tolerable in ensuring against overalerting an individual pilot or crew, but such frequency may be unacceptable on a customer or industry fleet basis. 1E-7 per engine hour false surge alert rates may be more acceptable in terms of fleet performance and maintenance impact.

The maintenance impact must be considered. Erroneous annunciation would prompt airline maintenance action and could lead to unnecessary and costly component replacement.

In general, the desired annunciation availability and reliability varies as a function of power and altitude—the higher the power (greater the potential for damage and/or thrust asymmetry) and lower the altitude (closer to the ground), the higher the desired availability and reliability.

7.1.1.3.3 Pilot Procedural Criteria.

The desired pilot response to continuous/multiple surge is to retard the affected engine thrust lever until the surging stops. Once surging stops, the pilot can advance the thrust lever and attempt to regain thrust.

The procedure must limit pilot action to retarding the thrust lever and avoid engine shutdown. The malfunction annunciation must be provided whenever the logic determines the condition exists.

Whatever threshold is selected as the design criteria, the detection logic shall be active above this threshold, and not active below this threshold. The annunciation should clear if the engine thrust lever and power are reduced to less than the N1 detection threshold. The annunciation should also clear based on some combination of surge detection logic, surge free time, and affected engine thrust lever movement. This study did not determine or validate what combination of surge detection logic, surge free time, and affected engine thrust lever movement should clear the alert. This would have to be accomplished as part of the piloted simulator cab testing.

Once the annunciation is displayed, and if the thrust lever is reduced, but not reduced below the design criteria threshold, it may take the FADEC a long time to determine if the condition has cleared (depending on the frequency of the surging and the persistence timer). For this case, the annunciation should remain set until a cleared condition has been confirmed. If the surge stops during this time, the continued annunciation will likely cause an unnecessary thrust lever reduction until the thrust lever and engine speed drop below the threshold. This is operationally acceptable. It may not be operationally acceptable or desirable for the annunciation to set and then clear based solely on some surge free time or pilot response.

Continuous or sustained engine operation below 50% N1 is not anticipated in normal operation, except for idle descent (i.e., pilots do not typically maintain thrust between idle and ~ 50% N1). For idle conditions, low-power continuous surge is unlikely to occur, is unlikely to persist, and would likely result in subidle operation (could be annunciated by a subidle alert). In addition, the likelihood of low-power, surge-related engine damage is low. Consequently, there is little if any demonstrable operational need to detect and annunciate continuous/multiple surge below 50% N1.

Initial assessment indicates that surge detection and annunciation reliability is proportional to engine power and speed, and detection development efforts and costs are inversely proportional to the engine power and speed detection threshold. The higher the engine power and speed, the more reliable the surge detection and annunciation. The lower the engine power and speed

detection threshold, the greater the detection development efforts and costs. A design detection threshold of ~70% N1 would result in more reliable, less costly, and more easily engineered detection and annunciation than a 50% N1 threshold.

However, a detection and annunciation threshold of ~70% N1 is not operationally desired. This would involve an annunciated procedure for continuous/multiple surges above the threshold and require an unannunciated procedure for continuous/multiple surges below the threshold (between 50% and 70% N1). This results in undesirable training and operational issues. The pilot would still need to monitor, detect, and interpret a subset of the continuous/multiple surge conditions sometimes, and not others, and it increases the potential for operational confusion and error.

There is no Boeing alerting system precedent for this sort of detection and annunciation implementation. In general, partial flight phase detection coverage and annunciation is operationally undesirable. The existing precedent for malfunction detection and annunciation is that it must be provided in all reasonable circumstances (i.e., flight phases) where crew awareness or response may be required. The crew expectation is that if an alert exists, it will be provided where and when appropriate. Exceptions go against this crew expectation, and incur operational impacts (e.g., additional training, crew monitoring, detection, interpretation), and must be handled on a case-by-case basis.

If it could be determined that continuous/multiple surge is very unlikely to occur in this range of 50% to 70% N1, and if it did occur would likely result in subidle operation, these mitigating factors could result in a relaxation of the detection threshold. Alternatively, the persistence timer could be varied judiciously for low-power/high-altitude events. For low-power/high-altitude events, the timing of the annunciation is less critical, and more time can be used to verify the condition before annunciation. This should result in higher availability and reliability.

7.1.2 Development of Continuous/Multiple Surge Event Database.

A surge event and normal operation database must be developed from which the engine characteristics can be analyzed, detection algorithms developed, and validation conducted.

7.1.2.1 Continuous/Multiple Surge Characteristic.

Engine behavior during, and as a result of, surge is dependent on the underlying component characteristics and on the engine response as a system. A compressor surge cycle is a rapid sequence including, momentary loss of pumping capacity, blow down of combustor pressure, potential flow reversal, and subsequent re-establishment of compressor pumping to approximately presurge capacity. One surge cycle takes about 100 milliseconds (ms), after which the engine could recover with the capability to return to normal operation or the surge cycle could be repeated. Compressor discharge pressure (also called burner pressure) is the FADEC parameter most directly linked to component behavior during surge. Engine speeds and FF are also typically responsive to surge and could be useful for identifying surge if sampled at the highest frequency available within most modern controls. At least 20 to 50 samples per second are required for these parameters to be useful.

During multiple surge events, the compressor may or may not return to a normal operating condition prior to the start of subsequent surge cycles.

Even a single recoverable surge changes speeds and other engine parameters, so additional time is required for the engine to return to the presurge or currently commanded condition. Power lever angle and other factors, such as altitude, FF, bleeds, or idle settings, also effect engine behavior. Between successive surges, engine behavior is governed by normal control schedules and limits within the capability of the control system. Behavior should be normal, but additional parameters are needed to understand cause and affect relationships. For such purposes, these parameters can generally be sampled at the lower rates typical of most existing data sample rates (0.5 to 1 Hz).

Event data captured using DFDR type sample rates (0.5 to 1 Hz) cannot be used to characterize or analyze continuous/multiple surge sufficiently to develop reliable detection and annunciation.

7.1.2.2 Existing Data.

A search of the existing data must be conducted. It would be appropriate to gather data from all available engines, to enhance the database, and to be able to develop general characteristics. It is likely that the specific characteristics may differ from engine type to engine type. It is also likely that the characteristics are a function of the nature and extent of the damage.

A search conducted for this contract determined that one of the biggest issues is the lack of high-frequency data from which to characterize subsequent surges. A high-frequency database for single surges is significant for each engine manufacturer, but does not exist for continuous/multiple surges. Subsequent surges are more difficult to characterize due to FADEC accommodation and the highly transient and somewhat unpredictable nature of the engine response until full recovery is achieved.

There are three possible sources of existing data: test stand, flight test, and in service. Although the test stand and flight test data tend to be of sufficiently high frequency, standard test procedure calls for the operators and pilots to reduce the fuel quickly following the initial engine malfunction (i.e., few continuous/multiple events with high-response data for subsequent surges). The in-service data is typically in the 0.5 to 1 Hz range. Since a typical individual engine surge cycle occurs in about 100 ms, this sample rate is not sufficient to develop a reliable and available algorithm (one that can be shown to meet the reliability and availability criteria).

7.1.2.3 Capture New Data.

The capture of high-fidelity data (high-sample rates and extended operation in continuous/multiple surges) would be very valuable in the development of a reliable and available algorithm.

There are several conceivable methods available:

- Use a test engine to induce continuous/multiple surges. This is not a realistic option since it would be prohibitively expensive and not likely to give sufficient results. Continuous/ multiple surge is usually a result of engine damage (i.e., potentially different engine characteristics depending on the nature of the damage), and the definition of the test inputs (frequency, amplitude) would be from an engineering assessment.

- Develop a cycle deck to model the various types and extent of engine damage and the trigger for continuous/multiple surges. This is not a realistic option either, since engine test data would still be required to develop and validate the model. This option would be prohibitively expensive and time intensive, validation difficult (high-fidelity data for a damaged engine), and may not give sufficient results.

- Gather data from revenue service events. A FADEC software version could be configured to detect any surge and then record data in nonvolital memory (NVM) (the specific amount of time both prior and postsurge event would need to be assessed). The recorded data should include engine parameters such as N1, N2, N3, EPR, PB, EGT, FF, bleed valve position, stator vane position, TRA, T25, T3, etc., at a high-sample rate (>20 Hz), and ambient parameters, such as P0, P2, T2 at a lower rate. This is the preferred and recommended method. A development program to configure a FADEC that can capture high-fidelity data of continuous/multiple surges should be considered.

7.1.2.4 Analysis.

There may be a need for analysis to enhance the database. This may include synthesizing high-fidelity characteristics (based on engineering analysis, evaluation, assessment, and conjecture) from the existing low-fidelity data or predicting high-fidelity characteristics for conditions for which there is no data, but where engineering analysis, assessment, and evaluation indicate that conditions could exist (such as low-power continuous/multiple surging, other possible failure characteristics, different extent of damage, control system malfunctions, etc.).

There will be a need to address surges that occur during acceleration and deceleration transients and thrust lever transients following the initial surge. Other conditions that can result in engine transients, such as bleed valve switching, fuel staging, and engine variable geometry control, need to be considered. External effects, such as ingestion of rain, hail, or ice, may also need to be considered.

The database may also need to be interpolated or extrapolated to cover the effects of airplane altitude and speed, and airplane bleed and power extraction.

This is considered high risk, since it involves engineering judgment/speculation, and is difficult to validate.

7.1.3 Continuous/Multiple Surge Data Analysis.

It was assessed during Task 4 that to meet the reliability and availability, criteria would likely drive an algorithm that used PB, HP rotor speed, FF, and TRA (or similar limited number of parameters currently available in the FADEC). It was assessed that PB and TRA may be sufficient, but this cannot be determined until the final evaluations are complete.

As such, for each engine parameter, the event database needs to be analyzed for:

- Characteristic behavior such as rate and range, for all normal, nonsurge operating conditions
- Distinguishing characteristics, including those between first and subsequent surges
- Impact of FADEC compensation
- Confirm minimum required sample rate is available
- Impact of commanded power level change
- Ambient-condition effects (e.g., altitude, mach, temperature)
- Power level effects
- Engine damage and control system malfunction effects

7.1.4 Development of Lower-Level Detection and Annunciation Software Requirements.

Once the top-level requirements are defined, the event database developed and analyzed, and the engine parameter database developed and analyzed, the lower-level (detailed) software requirements can be developed.

Because a high-frequency database does not exist for continuous/multiple surges, it will be difficult to quantitatively demonstrate that the detection and annunciation reliability and availability criteria are met. The potential benefit may not justify the cost of either an engine test program or a cycle model development program.

There is inherent flexibility in the flight deck design criteria, the annunciation implementation, and the crew procedure. These are developed together with each specific subsystem, and the design goals can be adjusted given design limitation and mitigating factors. For example, flight deck engineers can accept:

- A single (self-recovering) surge setting the annunciation. Flight deck engineers do not considered this an unacceptable false detect. False detect is defined as malfunction annunciation when no malfunction exists or has occurred—e.g., surge annunciation when no surge exists or has occurred.

- An engineering assessment of availability and reliability based on an enhanced (but limited) database, and estimates based on experienced engineering judgment.

- Biasing the detection towards annunciation after a single surge, rather than not detecting multiple surges initially. Subsequent data gathering can then be used to refine the algorithm.

- Biasing the detection away from annunciation at low-power settings below normal continuous or sustained power levels—i.e., below cruise and holding power settings.

- Using crew procedure after initial detection and annunciation to subsequently facilitate reliable malfunction verification by power manipulation or other crew input or action.

There is also a need to identify the requirements for reliability from the in-service maintenance and operational perspective, since these requirements may be more restrictive than the flight deck design requirements.

Consideration should also be given to autoaccommodation and the implications for both annunciation and crew operations and crew procedures.

7.1.4.1 Define Design Approach.

The data evaluation should define the required detection parameters, the required detection thresholds, the trigger and condition requirements, the confirmation requirements, and timing requirements (for setting and clearing the continuous/multiple surge annunciation).

- Consider the use of single surge as a trigger, with logic then set to detect a second event for annunciation. The initial trigger can leverage off the existing single surge database and, thus, have high reliability and availability. The detection of the subsequent surges can use a less discriminating threshold biasing toward ensuring detection of most multiple surges, thus allowing single surge to set the annunciation.

- Consider that existing logic for surge detection is designed for quick accommodation, since there is no detrimental effect to the engine for surge accommodation when a surge does not exist. The logic for surge annunciation can be a different set of logic, since the time available for annunciation is significantly longer.

- Re-evaluate the timing requirements (the initial assessment was that surges within ~0.5 second are not multiple, and that multiple surges more than ~20 seconds apart should be considered individual recoverable surge). However, the data analysis could result in different timing thresholds.

- Consider that a pilot may retard the thrust lever, but not enough to go below the threshold. Consideration may need to be given on how long to keep the annunciation active (how to verify no subsequent surges after stabilization at the lower-power setting).

- Consideration should also be given to integrating the current surge accommodations with the detection and annunciation strategy in ways that facilitate reliable detection and annunciation without compromising the accommodation(s).

7.1.4.2 Availability/Reliability Considerations.

Without a comprehensive database of high-response continuous/multiple surge events, it will be difficult to prove that availability and reliability requirements are met and a design is ready for revenue service. Even with a limited database, it will be difficult to prove availability and reliability, but a higher level of confidence can be achieved. It may be possible to use experienced engineering judgment in lieu of comprehensive data. This approach and methodology would involve flight deck and propulsion engineering collaboration, and include considerations of where liberalism or conservatism can and should be applied. This ranges from erring on the side of detection (overdetection) that provides pilot awareness for all events (which could include false detects and resultant unnecessary and expensive maintenance action), or erring on the side of detecting only the most obvious events (underdetection) thus minimizing unnecessary maintenance, but requiring the pilot to detect some events. Consideration should include the impact on pilot procedures (e.g., annunciated and unannunciated).

7.1.4.3 Define Specific Software Coding Requirements.

Develop the set of specific coding requirements that meet the criteria and considerations need to be developed.

7.1.5 Preliminary Design Review.

The following items need to be considered for the preliminary design review:

- Present to a group of subject matter experts the existing data, the lower-level design requirements, and the development plan. The expertise should include pilots, procedure managers, flight deck designers, propulsion system integrators, FADEC software logic designer, with engine performance, and engine operational capability experience.

- Agree on the scope and requirements.

- Get concurrence that the approach is feasible and the planned development activities are adequate.

7.1.6 Tool Development.

7.1.6.1 Time Histories.

The following items are needed for time histories:

- Create a set of time histories that provide a broad range of continuous/multiple surge characteristics to be used to validate the algorithm.

- The set should include a comprehensive representation of normal operations (steady state and transient) as well as a reproduction of the known failure signatures and conditions assessed to be appropriate to detect.

7.1.6.2 Engine Model Development.

Two engine models must be developed and used for simulation (i.e., real-time engine models). As discussed in section 7.1.2.3, a thermodynamically accurate model to develop surge characteristics is not a realistic option.

An engine model must be developed that can be used for the software development and validation process. The engine model must match the engine for normal steady-state and transient operations. The model must be able to include the proposed FADEC detection and annunciation algorithm. The model must include the capability to run the failure conditions. It would be acceptable to develop an open loop capability, which can import failure event time histories for development and validation of the detection algorithm.

Another model must be developed that can be used in a piloted simulator cab. The intent of the model is to validate annunciation logic and procedures, e.g., the logical triggers and timing of the setting and clearing of the annunciation. The model must respond to likely and possible pilot responses and inputs, and produce likely and possible continuous/multiple surge flight deck effects (top-level characteristics visible in the flight deck (e.g., primary- and secondary-parameter fluctuations and annunciations). The model would not need to duplicate the characteristics accurately, as long as the appropriate displays could be triggered. The model would include development of various surge scenarios with variable triggers, which control parameter fluctuations and fluctuation clearing. The fluctuations would need to appropriately set and clear the annunciation(s).

7.1.7 Detection and Annunciation Algorithm Development.

7.1.7.1 Continuous/Multiple Surge Detection Algorithm.

The algorithm should leverage off of existing and available surge detection logic, should leverage off of existing surge annunciation logic, and meet top- and lower-level requirements.

The algorithm should distinguish between surge detection/accommodation and surge detection/ annunciation, although the logic should be integrated.

The development of the detection algorithm will need to consider various operational aspects. For example, after the first surge, the FADEC may initiate accommodation that may need to be accounted for (e.g., surge detection can open the bleed valves, causing EGT rise. The logic would need to distinguish between an EGT rise caused by the accommodation rather than by a subsequent surge). The logic also needs to consider thrust lever position changes (i.e., engine response to a thrust lever reduction by the pilot may be falsely detected as a subsequent surge). This becomes more problematic at the lower-power levels and high altitudes. The logic needs to

consider operation near a point that causes a change in state of an engine component (bleeds, etc.) that can result in sudden engine parameter changes.

The logic will need to consider altitude, Mach number, temperature, and engine power level for the thresholds.

The logic will need to consider the setting and clearing of the trigger and gateway condition(s) (first event), if that is the design approach being developed.

The logic will also need to meet the operational requirements to set and clear the annunciation. This must be developed and validated jointly with the pilots, procedure managers, and flight deck engineers in simulator cab sessions. The logic includes a reduction of the thrust lever to idle power, but the engine is spooling down, and that a partial thrust lever reduction may or may not clear the surging. The algorithm would need to either retain or reset the annunciation based on the specified criteria.

The logic will need to consider fault accommodation of input parameter failures.

7.1.7.2 Engineering Evaluation of Algorithm Performance.

The model shall be used to validate that the logic does not detect and annunciate a failure condition during normal operations. A gauntlet test should be conducted, including the following test conditions throughout the flight envelope:

- Starting (on ground, in flight)
- Accelerations and decelerations (large and small) from various power levels
- Bodie (and inverse Bodie) type transients (large and small)
- Takeoff, RTO, climb, cruise, approach, and go-around type maneuvers and power manipulations (e.g., manual and automatic power changes to maintain glide slope)
- Conditions that cycle engine components (bleeds, VSVs) and can cause oscillations
- Flying in and out of various weather conditions including rain and hail.
- Consider engine accommodation modes for failed sensors, etc.

The model shall be used to validate the detection and annunciation logic performance for the failure conditions represented by the selected time histories.

It may be that not all failure conditions are detected (~1 to 10%) due to design restrictions (e.g., to meet the false detect criteria). The compromise in performance needs to be evaluated at the critical design review.

- Plan and execute piloted cab session(s) to assess detection and annunciation logic—e.g., time to hold trigger after first surge.

- May need to assess and include pilot response and reaction types and times, including procedure access and execution.

- Will also need to review, refine, and validate the logic to clear the annunciation.

7.1.7.3 Critical Design Review.

The following items need to be addressed in the CDR:

- Present to a broad spectrum of subject matter experts the results of the requirements development, issues, solutions, and results. The expertise should include pilots, procedure managers, flight deck designers, propulsion system integrators, and FADEC software logic designer with engine controls, engine performance, and engine operational capability experience.

- Prepare and present system risk and operational hazard assessments.

- Probe for assessment of potential false trips and potential for lack of availability. Probe for alternate solutions to issues and compromises.

- Get concurrence/consensus that the design objectives have been met and risks are acceptable or mitigation plans have been defined.

- Address any issues raised before developing the software.

7.1.8 Demonstration and Validation.

7.1.8.1 Develop the Software in a FADEC.

A program for a FADEC software development will be planned. The FADEC will need to include logic to detect and annunciate a continuous/multiple surge. The FADEC should also include the capability to record (e.g., in NVM) in-service event data sufficient to improve the algorithm.

Annunciation implies changes to flight deck software as well as FADEC software.

7.1.8.2 Assess That Detection and Annunciation Requirements are Satisfied.

7.1.8.2.1 Availability.

An assessment of system availability depends on the extent of high-response data availability.

- Acquiring data during a flight test program for a new engine is one option. However, the number of hours is limited from the standpoint of validation of availability. The

likelihood of a continuous/multiple surge event is low, and if an event were to occur, it may be corrected immediately (i.e., data for subsequent surging may not be captured). Flight test would be a valid basis for verifying no false trips (reliability) for a range of normal operating conditions.

- A second (better) option is to acquire data from an existing application in revenue service. A possible path forward is to develop the logic over several software builds, allow the FADEC logic to record event data and system performance (without being active), and then review the data, and adjust the logic before activation on a subsequent build.

As a minimum, the conditions developed for the performance evaluation need to be tested with the FADEC (i.e., run failure scenarios through FADEC and engine models). The performance evaluation needs to be assessed by crew operations engineers and procedural managers.

7.1.8.2.2 Reliability.

Several types of tests should be conducted to assess the system reliability (i.e., the potential for false trips):

- Run FADEC with engine model.
- Repeat gauntlet test and assess for potential false trips.
- Repeat gauntlet test on an engine (engine test stand).
- Acquire high-response data (time on wing).
- Acquire data during a flight test program for a new engine. The number of flight hours is likely sufficient to develop confidence for false detect reliability. Additionally, specific test conditions to challenge the reliability can be accomplished.
- Acquire data from an existing application in revenue service.

7.1.8.2.3 Performance.

To assess performance, normal operations and failures conditions should be evaluated in a piloted cab session to demonstrate crew operations criteria are met.

7.1.8.2.4 Update FADEC Software in Revenue Service as Issues Develop.

The demonstration and validation plan will need to include subsequent FADEC updates. Required changes are likely to be able to refine the logic based on the data captured in follow-on in-service events (false trips and lack of availability).

7.1.9 Conclusions.

The development of a flight deck annunciation of continuous/multiple surge could be used in conjunction with other annunciations of engine malfunctions to enhance the pilot awareness and procedure.

A plan for development, including demonstration and validation of a continuous/multiple surge detection and annunciation, has been developed.

Without an adequate database of high-response continuous/multiple surge events, it will be difficult to develop a highly available and reliable continuous/multiple surge annunciation. Of greatest concern is the N1 speed range of ~50% to 70% N1, for which reliable detection is most problematic but required for a viable annunciation strategy.

To progress work in this area, it is recommended that research funding be targeted to develop FADEC software to capture and record continuous/multiple surge events to acquire a database of high-frequency data for a range of operational conditions (altitude, power level, various engine damage conditions, etc.).

7.2 DEVELOPMENT PLAN FOR ANNUNCIATION OF ENGINE DAMAGE.

This task provides the basis for follow-on engine damage annunciation research work. By agreement with the FAA, this first step involves the classification of existing data to ensure that all types of engine damage are considered.

7.2.1 Engine Damage Classification.

An internal Boeing database was used to classify engine damage types by frequency of occurrence. This database typically contained enough information to pinpoint primary cause and description of related engine damage for the events. The database was polled for all removals and in-flight shutdowns (IFSD) for the period of January 01, 1999 to May 31, 2004. Airplane models included B-737 Classic, B-737 Next Generation, B-747, B-757, 767, and B-777 with engine models from all three major suppliers. A total of 33,269 removals and 2130 IFSDs were reviewed and categorized for originating engine damage.

Engine subsystem and component categories selected for this study are provided by the generic engine turbofan illustrated in figure 7-1 and the subsystem schematics provided in figure 7-2. The breakdown of these categories' contributions to removals and IFSDs is detailed in table 7-1. Major categories for both removals and IFSDs are discussed in sections 7.2.2 and 7.2.3.

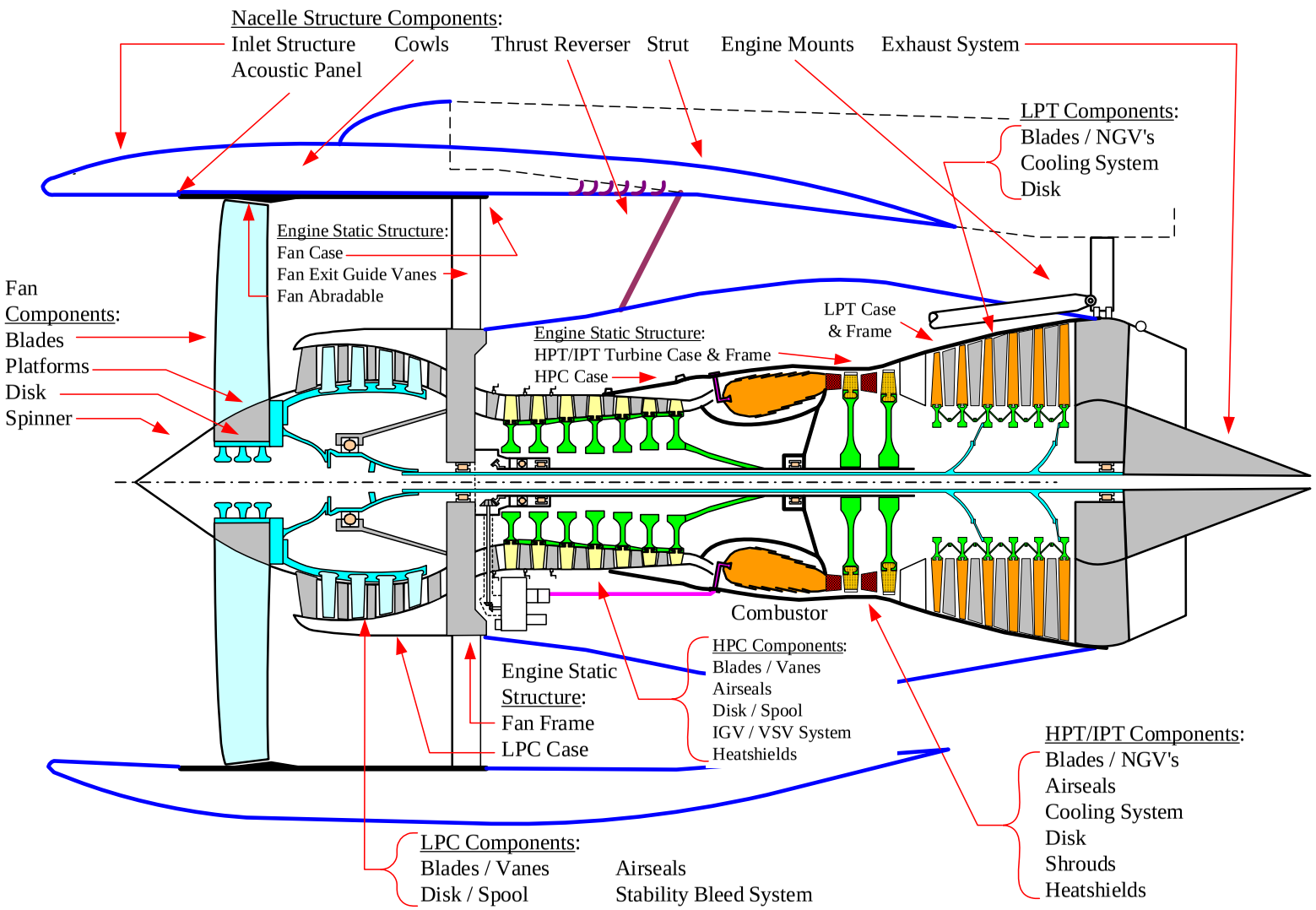
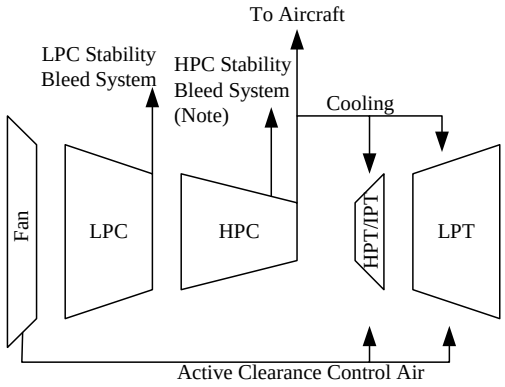


Figure 7-1. Turbofan Propulsion System—Damage Classification Categories

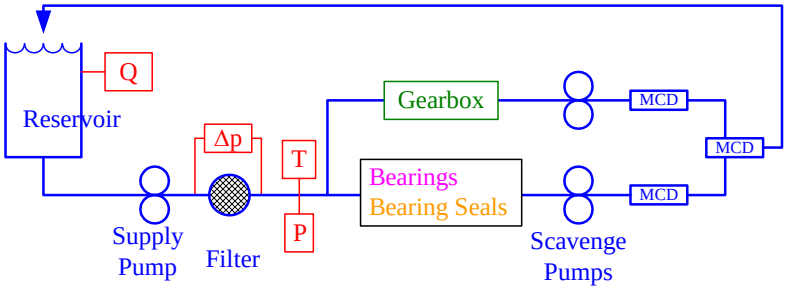
Air System Components



Note: No HPC Stability Bleed System Failures sufficient to cause an IFSD or engine removal were recorded during the studied period.

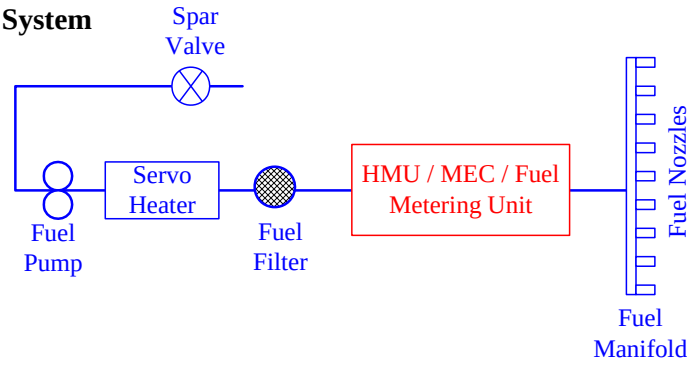
Component	Assigned Category
VBV System	LPC Stability Bleed System
2.5 Bleed System	
HPT ACC	HPT Cooling
LPT ACC	LPT Cooling
HPT/IPT Cooling	HPT Cooling
LPT Cooling	LPT Cooling
Manifolds	HPC Case
Offtakes	
Bleed Air Ducts:	
HP/IP Turbine Cooling	HPT Cooling
LP Turbine Cooling	LPT Cooling
Aircraft	Bleed Air System
PRSOV	Bleed Air System
Check Valve	
HPSOV	
Precooler	
FAMV	
Engine Control-related Bleed Air Valves and associated controllers	Pneumatic System
Pneumatic Sense Lines	

Lubricated Components



Lubricated Components Categories:
Bearings
Bearing Seals
Gearbox
Lube System
Controls &Sensors

Fuel System



Fuel System Categories:
Fuel Supply System
Controls & Sensors

Figure 7-2. Propulsion Subsystems Damage Classification Categories

Table 7-1. Unscheduled Removal and IFSD Breakdown by Specific Components

Major Category	Specific Component/ Subsystem	No. of Unscheduled Removals		No. of IFSDs	
Airplane Systems	Air Data System	1	0.0%	0	0.0%
	APU	5	0.0%	0	0.0%
	Autothrottle	0	0.0%	3	0.1%
	Bleed Air System	28	0.2%	44	2.1%
	DLODS	1	0.0%	3	0.1%
	Electrical Power System (including IDG/CSD and VSCF)	26	0.1%	20	0.9%
	FODS	5	0.0%	33	1.5%
	Hydraulic System	21	0.1%	7	0.3%
	Power Door Operating System	1	0.0%	0	0.0%
	Starter	9	0.1%	26	1.2%
	Thrust lever Cable	2	0.0%	18	0.8%
Combustor	Combustor	751	4.8%	3	0.1%
	Combustor Case	44	0.3%	0	0.0%
Controls and Sensors	AVM	9	0.1%	11	0.5%
	FADEC/MEC/PMC	17	0.1%	38	1.8%
	Fuel Metering Unit/HMU	29	0.2%	53	2.5%
	Ignition System	4	0.0%	1	0.0%
	Principle Magnet Alternate	14	0.1%	15	0.7%
	Pneumatic System	77	0.5%	38	1.8%
	Sensor	126	0.8%	152	7.1%
Engine Static Structure	Borescope Plug	28	0.2%	0	0.0%
	Diffuser Case	53	0.3%	0	0.0%
	Fan Abradable	123	0.8%	1	0.0%
	Fan Case	129	0.8%	6	0.3%
	Fan Exit Guide Vanes	27	0.2%	0	0.0%
	Fan Frame	38	0.2%	0	0.0%
	HPC Case	163	1.1%	6	0.3%
	HPT Case	2	0.0%	1	0.0%
	LPC Case	15	0.1%	1	0.0%
	LPT Case	27	0.2%	0	0.0%
	LPT Frame	6	0.0%	0	0.0%

Table 7-1. Unscheduled Removal and IFSD Breakdown by Specific Components (Continued)

Major Category	Specific Component/ Subsystem	No. of Unscheduled Removals		No. of IFSDs	
	Turbine	0	0.0%	1	0.0%
	Turbine Case	171	1.1%	0	0.0%
	Turbine Frame	55	0.4%	0	0.0%
Fan	Fan Blades	241	1.6%	85	4.0%
	Fan Disk	54	0.3%	0	0.0%
	Fan Imbalance	6	0.0%	2	0.1%
	Fan Platforms	8	0.1%	0	0.0%
	Fan Spinner	9	0.1%	13	0.6%
Fuel System	Fuel Filter	1	0.0%	1	0.0%
	Fuel Nozzles	45	0.3%	3	0.1%
	Fuel Plumbing	41	0.3%	28	1.3%
	Fuel Pump	35	0.2%	32	1.5%
	Fuel Servo Heater	0	0.0%	1	0.0%
	Fuel Spar Valve	4	0.0%	13	0.6%
	Fuel Starvation	0	0.0%	1	0.0%
	Fuel System Contamination	4	0.0%	14	0.7%
	Fuel Valve	3	0.0%	3	0.1%
HPC	HPC (nonspecific)	27	0.2%	1	0.0%
	HPC Airseal	251	1.6%	2	0.1%
	HPC Blades	2423	15.6%	158	7.4%
	HPC Disk	37	0.2%	3	0.1%
	HPC Heat shield	2	0.0%	0	0.0%
	Inlet Guide Vane System	23	0.1%	4	0.2%
	VSV Actuation System	522	3.4%	60	2.8%
HPT/IPT	HPT	5	0.0%	0	0.0%
	HPT Airseal	117	0.8%	7	0.3%

Table 7-1. Unscheduled Removal and IFSD Breakdown by Specific Components (Continued)

Major Category	Specific Component/ Subsystem	No. of Unscheduled Removals		No. of IFSDs	
	HPT Blades	2466	15.9%	75	3.5%
	HPT Cooling	58	0.4%	12	0.6%
	HPT Disk	50	0.3%	2	0.1%
	HPT Heatshield	6	0.0%	0	0.0%
	HPT Nozzle Guide Vane	1016	6.6%	7	0.3%
	HPT Shrouds	85	0.5%	2	0.1%
Indeterminate	Indeterminate	1661	10.7%	282	13.2%
LPC	LPC (nonspecific)	2	0.0%	0	0.0%
	LPC Airseal	5	0.0%	0	0.0%
	LPC Blades	91	0.6%	10	0.5%
	LPC Disk/Spool	23	0.1%	0	0.0%
	LPC Stability Bleed System	106	0.7%	3	0.1%
LPT	LPT Airseal	10	0.1%	0	0.0%
	LPT Blades	500	3.2%	35	1.6%
	LPT Cooling	10	0.1%	0	0.0%
	LPT Disk	4	0.0%	2	0.1%
Lubricated Components	Bearing	590	3.8%	110	5.3%
	Bearing Seal	606	3.9%	17	0.8%
	Gearbox	423	2.7%	115	5.4%
	Lube System (Plumbing, MCDs, etc.)	1147	7.4%	323	15.2%
Maintenance Error	Maintenance Error	388	2.5%	148	6.9%
Nacelle Structure/Cowls/ Thrust Reverser	Acoustic Panel	50	0.3%	4	0.2%
	Cowl	14	0.1%	0	0.0%
	Engine Mounts	14	0.1%	0	0.0%

Table 7-1. Unscheduled Removal and IFSD Breakdown by Specific Components (Continued)

Major Category	Specific Component/Subsystem	No. of Unscheduled Removals		No. of IFSDs	
	Exhaust System	11	0.1%	1	0.0%
	Inlet Structure	6	0.0%	0	0.0%
	Nacelle Structure	1	0.0%	1	0.0%
	Thrust Reverser	128	0.8%	5	0.2%
Other	Core Imbalance	19	0.1%	0	0.0%
	Deicing Fluid Ingestion	0	0.0%	1	0.0%
	No Damage	122	0.8%	32	1.5%
	Pilot Error	21	0.1%	31	1.5%
	Totals	15498		2130	

APU – Auxiliary Power Unit
DLODS – Duct Leak Overheat Detection System
IDG – Integrated Drive Generator
CSD - Constant Speed Drive
VSCF – Variable Speed Constant Frequency
FODS – Fire/overheat Detection System
AVM – Airborne Vibration Monitor
MEC – Main Engine Controller
PMC – Power management controller
HPC – High-pressure computer
HPT – High-pressure turbine
LPT – Low-pressure turbine

7.2.2 Removals.

Engine removals occur for both scheduled and unscheduled reasons. Scheduled reasons include limited life parts (LLP) cycle/time expiration, Service Bulletin (SB)/Airworthiness Directive (AD) compliance, performance-related removals (i.e., expiration of EGT margin), and other convenience-related events (lease expiration, ownership transfer, engine cycle/time staggering, etc.). The breakdown of these removals for the studied period occurred as shown in table 7-2.

Table 7-2. Engine Removals

Cause for Removal	No. of Removals	Percent
Scheduled:		
LLP Expiration/SB/AD Compliance	5270	15.8
Performance-Related	3052	9.2
Convenience	9449	28.4
Unscheduled	15,498	46.6
Total	33,269	100

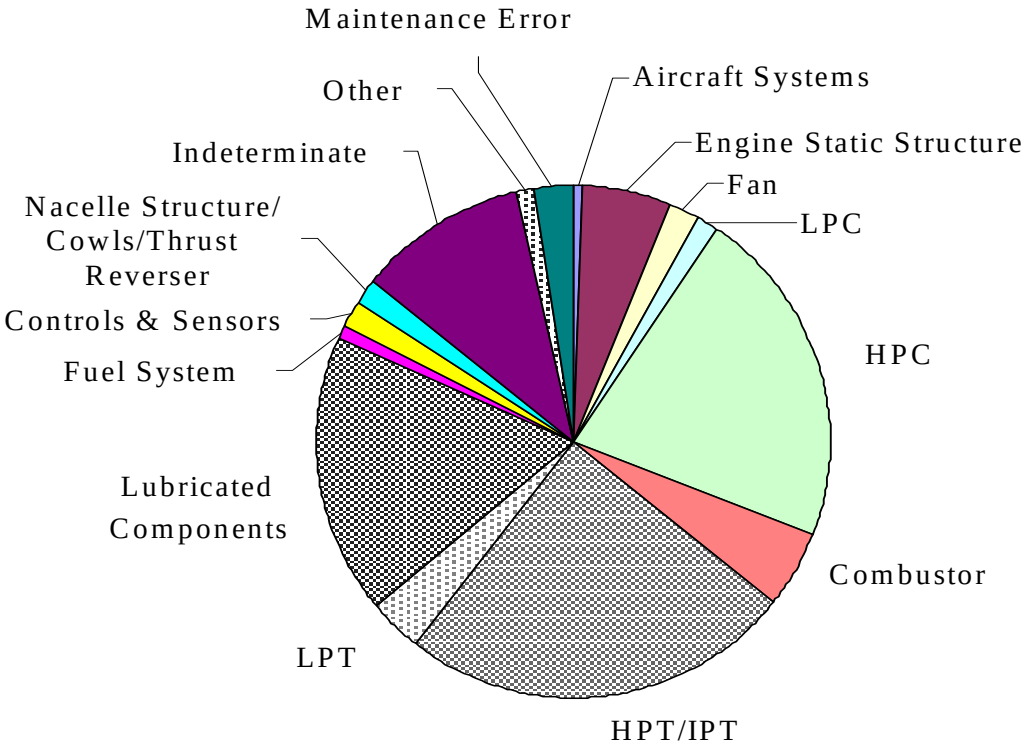
Of the unscheduled removals, figure 7-3 provides a breakdown of the events by the principally damaged major subsystem. Dominant amongst the causes were the following:

- High-Pressure Compressor (HPC). The principal contributor to this category was blade and vane damage from foreign and domestic objects.

- High/Intermediate-Pressure Turbine (HPT/IPT). Blade and nozzle guide vane (NGV) failures were most common.

- Lubricated Components. Damage in this category was rather evenly spread across components such as bearings, seals, gearboxes, and other lubrication system plumbing components such as valves, pumps, coolers, and tubing.

- Indeterminate. Those items relegated to this category did not contain sufficient text to indicate the damaged components. Interestingly, 23% of these events suffered some form of vibration or surge-related indication prior to removal.

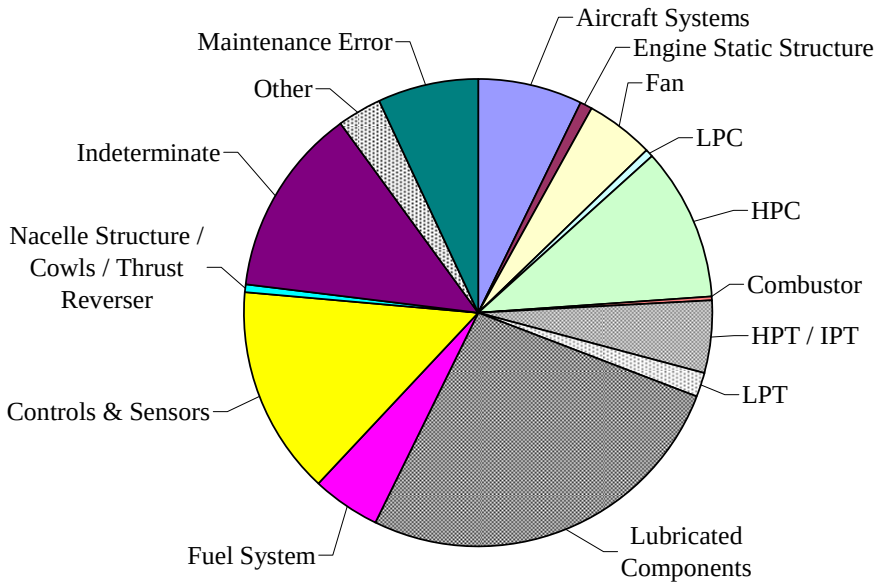


Major Categories	No. of Unscheduled Removals	Percent
Airplane Systems	99	0.6
Engine Static Structure	837	5.4
Fan	318	2.1
LPC	227	1.5
HPC	**3285**	**21.2**
Combustor	795	5.1
HPT/IPT	**3803**	**24.5**
LPT	524	3.4
Lubricated Components	**2766**	**17.8**
Fuel System	133	0.9
Controls & Sensors	276	1.8
Nacelle Structure/Cowls/Thrust Reverser	224	1.4
Indeterminate	**1661**	**10.7**
Other	162	1.0
Maintenance Error	388	2.5
Total	15,498	

Figure 7-3. Unscheduled Removal Causes (All Engines, January 01, 1999–May 31, 2004)

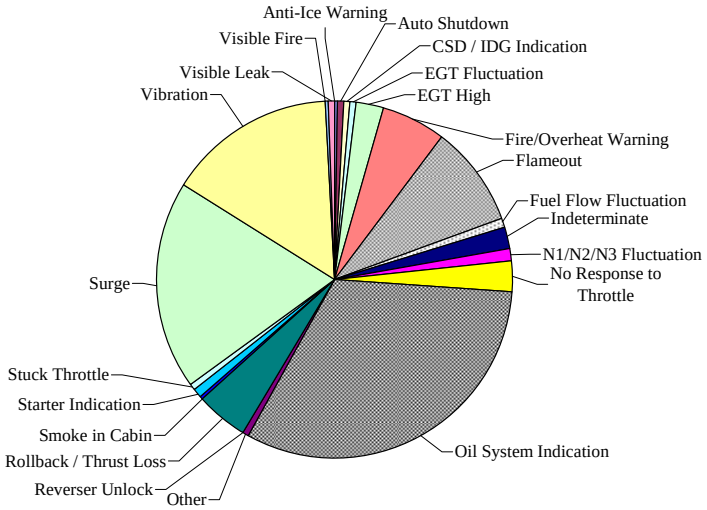
7.2.3 In-Flight Shutdowns.

In-flight shutdowns occurred for the reasons listed in figure 7-4. Figure 7-5 provides a similar breakdown of the primary cockpit indications immediately preceding the events. As indicated in these figures, IFSD causes are dominated by lubrication system events (low-oil pressure, high-oil temperature, oil filter bypass, high-oil consumption, etc.). Apart from the indeterminate events, HPC and controls/sensor failures led the remaining IFSD causes.



	No. of IFSDs	Percent of Total IFSDs	No. of IFSDs Resulting in Engine Removal	Removal Percent
Airplane Systems	154	7.2	12	8
Engine Static Structure	18	0.8	16	89
Fan	96	4.5	24	25
LPC	10	0.5	8	80
HPC	**229**	**10.8**	188	82
Combustor	4	0.2	4	100
HPT/IPT	106	5.0	92	87
LPT	34	1.6	27	79
Lubricated Components	**569**	**26.7**	309	54
Fuel System	97	4.6	17	18
Controls & Sensors	**307**	**14.4**	28	9
Nacelle Structure/Cowls/TR	14	0.7	9	64
Indeterminate	**281**	**13.2**	101	36
Other	64	3.0	3	5
Maintenance Error	147	6.9	38	26
Total	2130	100	876	26

Figure 7-4. In-Flight Shutdown Causes (All Engines, January 01, 1999–May 31, 2004)



IFSD Indications	No. of IFSDs	Percent
Anti-Ice Warning	3	0.2
Auto Shutdown	13	0.6
CSD/IDG Indication	11	0.5
EGT Fluctuation	11	0.5
EGT High	58	2.7
Fire/Overheat Warning	123	5.8
Flameout	**196**	**9.2**
FF Fluctuation	15	0.7
Indeterminate	41	1.9
N1/N2/N3 Fluctuation	27	1.3
No Response to Thrust lever	55	2.6
Oil System Indication	**685**	**32.2**
Other	9	0.4
Reverser Unlock	3	0.1
Roll-back/Thrust Loss	98	4.6
Smoke in Cabin	3	0.1
Starter Indication	18	0.8
Stuck Thrust lever	16	0.8
Surge	**403**	**18.9**
Vibration	**327**	**15.4**
Visible Fire	4	0.2
Visible Leak	11	0.5
Total	2130	100

CSD = Constant speed drive (generator) IDG = Integrated drive (generator)

Figure 7-5. In-Flight Shutdown Primary Indications (All Engines, January 01, 1999–May 31, 2004)

Primary cockpit indications were consistent with the postflight damage findings: oil system indications dominate followed by surge (generally associated with HPC damage) and high vibration and noise (encompassed rotating components). Some differences exist between the cause and primary indication specific percentage levels. In such cases, the cause was determined postflight to be related to something other than the primary indication. This difference was most evident in the comparison of the 685 IFSDs with oil system indications and the 569 IFSDs with cause attributable to lubricated component failures. As shown in table 7-3, not all lubricated component failures manifested themselves as oil system indications and, conversely, not all oil system indications were attributable to lubricated component failures. Of the 685 IFSDs with an oil system alert as the primary indication, 438 (64%) were ultimately traced to a failure of a lubricated component. Oil system sensor failures accounted for 13% with maintenance errors (e.g., oil-filler caps left off and plumbing lines not properly tightened) following close behind at 12% of the causes leading to oil system malfunction indications.

Also indicated in figure 7-4 is the number of IFSDs that resulted in engine removals for each of the major categories. As expected, categories containing significant engine gas path components, such as compressors, combustors, and turbines, realized the highest percentage of engine removals following an IFSD.

Table 7-3. In-Flight, Shutdown-Related Lubricated Components Failures Versus Oil System Indications

Primary Indication	Causes Due to Lubricated Components
Auto Shutdown	4
EGT Fluctuation	1
EGT High	5
Fire/Overheat Warning	4
Flameout	17
Indeterminate	3
N1/N2/N3 Fluctuation	2
No Response to Thrust lever	1
Oil System Indication	438
Roll-back/Thrust Loss	12
Smoke in Cabin	1
Surge	33
Vibration	48

Total Causes by Lubricated Components: 569

Originating Component	No. of Oil System Indications	Percent of Total Indications
Sensor	87	13
Maintenance Error	84	12
IDG/CSD	11	2
Indeterminate	20	3
Lubricated Components	438	64
Other	45	7
Total Oil System Indications:	685	101

IDG = Integrated drive generator
CSD = Constant speed drive generator

7.2.4 Engine Damage Development Conclusions.

A review of the database suggests that opportunity exists for improvement in engine damage detection and annunciation. As indicated in figure 7-5, nearly 37% of all IFSDs were initiated in response to indications that were either quite general or indeterminate (surge, vibration, other, and indeterminate categories). Further specificity in identifying engine damage associated with these events may have been successful in avoiding some of these IFSDs.

Regarding removals that are not precipitated by IFSDs, further work could also be done to better understand the initial precursor that leads to the ultimate unscheduled engine removal. Specifically, airplane logbook extracts are available for selected airlines. These extracts could be correlated to the removals to identify the initial symptoms and the subsequent operating period prior to removal.

7.3 TASK 6 CONCLUSIONS.

Task 6 included the development of two subtasks:

- Development plan for annunciation of continuous/multiple surge
- Engine damage classification for follow-on engine damage annunciation research

Both of these annunciation areas are technically high risk, since significant work remains to provide effective and reliable detection capability.

For continuous/multiple surge, the Task 6 work developed a comprehensive plan outline. The areas of most significance are the lack of high-frequency data to be able to demonstrate a reliable algorithm and the potential cost of developing such an algorithm, especially in the area of 50 to 70% N1 (i.e., a cost-benefit study may determine it to be not practical to implement until sufficient high-frequency data has been accumulated).

Engine damage was considered in this contract, but the topic is large enough to warrant a separate contract. It was recognized that engine damage is a significant contributor to engine malfunctions and would complement the research completed in this phase of the contract. Since it was recommended that a follow-on contract be considered, task 6 included work to lay the foundation for this follow-on contract. This subtask reviewed an extensive in-service database to catalogue the engine damage components that contributed to IFSDs and engine removals.

8. SUMMARY.

Phase 2 research evaluated the feasibility and appropriateness of detection and annunciation of specific PSMs common to turbofan engines and ICR.

The Boeing team (BCA propulsion and flight deck engineering, supported by PW and GE engineering groups) concluded that the current engine indication paradigm and malfunction detection and annunciation capability is not flawed, but that beneficial evolutionary improvement opportunities exist. Reliability and feasibility are major considerations. Caution is urged to ensure that changes or change-related regulatory actions do not introduce more or larger problems than they resolve.

8.1 ANNUNCIATION CATEGORIES FOR SUSTAINED THRUST ANOMALIES.

The Phase 2 research developed criteria for the detection and annunciation of STAs and identified engine indication-related information and annunciation opportunities. The development of the criteria involved an integrated propulsion and flight deck effort, which considered malfunction detection and annunciation criteria derived from:

- Propulsion system considerations
- Crew operation considerations
- PSM+ICR STA events and in-service PSM reports
- Best practices and principles, and new information-based indication concept considerations

Through normal and nonnormal procedures review, three top level areas of information and control automation opportunities were identified:

- Engine start monitoring—for normal start progression and need for start abort due to start fault or abnormality, engine parameter exceedance, or start failure.
- Engine operation—readiness and capability for start or restart or for future and continued operation.
- Aircraft level performance—aircraft acceleration, deceleration, and flight path.

Automatic monitoring, detection, and annunciation of engine malfunctions were identified as desirable procedural improvements. Engine malfunction detection and annunciation opportunities exist. However, great care must be taken to focus limited resources where favorable cost-benefit tradeoffs truly exist, and to ensure that detection and annunciation implementations do not create new or bigger problems.

The research work culminated in a suite of potential flight deck annunciations (shown in table 8-1) for STAs that satisfy the propulsion, crew operational, and information-based concepts criteria. The research concluded that new capability (algorithm development), not new technology (hardware development), is required to develop this suite of annunciations for modern and future airplane programs.

Table 8-1. Suite of STA-PSM Annunciations

Annunciation	STA-PSMs	Procedure
Subidle	Includes flameout, surge/nonrecoverable stall	Stall requires fuel cut to address malfunction. Flameout requires ignition. Subidle recovery may require starter or other assistance to recover to running (above idle).
Continuous/multiple surges	An engine with repetitive surges	A FF reduction, possibly to idle, needed to address engine malfunction. Thrust lever re-advancement needed to recover from thrust loss and verify normal engine operation.
Alternate EEC Mode	Failure of primary thrust parameter sensor	Reversion to alternate mode needed to address the engine malfunction and recover sustained thrust loss
Other STA	Indicated thrust high or low, or slow to respond	Awareness only annunciation—specific pilot action to address engine malfunction or recover thrust is context dependent and not procedurally specified.

The suite of potential annunciations provides operational benefit, as the annunciations address all STAs, to provide the appropriate awareness of the affected engine, information on the type of engine malfunction, and where feasible, the appropriate procedure for the engine malfunctions for each annunciation.

Implementation of an individual annunciation, or a subset of the annunciations, also provides operational benefit, since each provides the appropriate awareness of the affected engine, information on the type of engine malfunction, and where feasible, the appropriate procedure for the engine malfunction.

The PSM+ICR database was used to assess the types of engine malfunctions that warrant consideration and to provide guidance on flight phase, power levels, and timing criteria. The database review and analysis indicates that up to 5 seconds, perhaps more, appear available for annunciation, and that annunciations would be most beneficial at low altitude and/or high power in the climb, cruise, cruise descent, and approach flight phases.

8.1.1 Subidle.

This annunciation is for a failure condition that causes the engine to go subidle. This includes primarily engine flameouts and engine surges that progress to a stall condition. For the

surge/nonrecoverable stall condition, FF reduction or cut is required to clear the stall condition. A relight/restart may be required to recover thrust.

The detection and annunciation exists on many modern airplanes (a low-technical risk to implement) and covers ~49% of FADEC (~57% of all) reported STAs.

8.1.2 Continuous/Multiple Surge.

This annunciation is for an engine experiencing multiple surges (the engine surges and recovers, surges again and recovers again, and so on). For a single-engine surge that self recovers, no action is required. But if the engine continues to surge, a reduction in FF (thrust lever reduction), perhaps even to idle, is required to clear the condition. Thrust recovery requires clearing the continuous/multiple surging, and then re-advancement of the thrust lever.

The implementation of detection for this annunciation is considered a high technical risk because specific annunciation detection logic has not been developed. Similar capability for accommodation may exist, but to provide a flight deck annunciation incurs additional risk, since the annunciation must have sufficient reliability. Continuous/multiple surge detection may require:

- Significant work to ensure reliability
- Trade between reliability, development cost, and timing likely
- Data to design and substantiate is either not available or difficult to obtain

This annunciation could potentially cover ~27% of FADEC (~20% of all) reported STAs .

8.1.3 Alternate EEC Mode.

This annunciation is for a STA of actual thrust higher or lower than indicated due to a failure of the primary thrust set parameter sensor. This is primarily an EPR failure. To clear the malfunction and restore thrust requires a reversion to alternate mode.

The detection and annunciation exists on many modern airplanes and is low to medium technical risk to implement depending on the thrust shift threshold. The risk is increased when the threshold for detection of this malfunction is decreased. This annunciation covers ~ <1% of the STAs.

8.1.4 Other STA.

This annunciation could include all the other sustained thrust loss conditions not included in other annunciations. The several types of different conditions included all have the same characteristic with respect to flight deck annunciation: The pilot action to clear the malfunction and restore thrust are not procedurally specified, hence, the annunciation only provides awareness of an engine thrust malfunction and the affected engine.

This annunciation could include the following engine malfunction conditions:

- Indicated thrust failed low (but not subidle), ~8% of the STA.
- Indicated thrust failed high, ~2% of the STAs.
- Thrust failed low due to engine damage: actual thrust failed low, ~4% of the STAs.
- Engine slow to respond, slow to accelerate, or decelerate to command, ~1% of the STAs.
- Thrust oscillations, (some of these could be addressed by the selection of alternate mode), ~7% of the STAs.

Some portions of this annunciation exist on some modern airplanes. The overall technical risk of implementing all five conditions is preliminarily assessed in the medium-high range.

For indicated thrust failed low/high and engine slow to respond, the risk was assessed as medium because similar capability has been developed in the past and changes to current algorithm and hardware appear feasible with moderate amount of effort.

For thrust failed low due to engine damage, the risk was assessed as medium-high depending on the thrust threshold. The risk of implementing an annunciation of an STA caused by engine damage with a thrust loss <30% was assessed as high, the risk of implementing an annunciation of an STA caused by engine damage with a thrust loss >30% was assessed as medium. This could potentially be considered in follow-on engine damage research. Development of the other STA annunciation excluding this condition could be considered.

For thrust oscillations, the risk was assessed as medium-high. Engine system failures that resulted in thrust oscillations were not contributors to PSM+ICR, and thus development of the other STA annunciation excluding this engine malfunction could be considered.

8.2 FOLLOW-ON RESEARCH WORK.

In the course of this contract research work, several areas of possible future research work were identified. Future work is needed to continue progress in these areas. However, these should not be done without regard to their effectiveness and resource requirements. These questions should be asked in the context of all industry safety enhancement programs and initiatives.

8.2.1 Engine Damage Detection and Annunciation Research Work.

Follow-on work to identify engine damage modes that require flight crew awareness or action would be beneficial. This work is expected to support and advance the Phase 2 malfunction detection and annunciation conclusions.

This contract identified that significant work remains to develop detection of engine damage appropriate for annunciation. This contract laid the foundation for such a research program by

classifying engine damage components that resulted in in-service in-flight shutdowns and engine removals and by identifying several areas for consideration. Follow-on work should identify engine damage modes that may require flight crew awareness or action and identify engine damage modes that may require near-term maintenance action, i.e., that affect airplane dispatchability.

8.2.2 Acquisition of Continuous/Multiple Surge Data.

A program to obtain high-frequency/fidelity data would be beneficial. Annunciation of a continuous/ multiple surge engine malfunction was identified as being beneficial for the engine and the flight crew. However, this annunciation was assessed as being a high-technical risk due to the lack of sufficient high-fidelity data to meet the operational criteria of ensuring a reliable annunciation. To best address this concern, a program would be required to modify an FADEC to record high-frequency data during revenue service events and to acquire a suitable database for algorithm development and validation.

8.2.3 Engine Malfunction Autoaccommodation.

Additional investigation in the role of engine automation and accommodation, the interrelationship between automatic engine accommodation and pilot procedures, and the pilot information required to monitor and supervise engine automation would be beneficial.

The focus of the current study was detection and annunciation of an engine malfunction, primarily to provide pilot awareness of the engine malfunction/condition, provide awareness of the affected engine, and to provide guidance on pilot procedure. However, FADEC systems can provide automatic accommodation (e.g., FADECs attempt to relight/restart the engine if a flameout condition is detected). The introduction of engine malfunction detection raises the issue of how best to respond—with automatic system, manual pilot action, or both. This has the potential to result in the increased use of engine automation and corresponding modification of pilot responsibility and action. The use of automation results in the pilot role changing to that of supervisor/monitor, a role that typically requires providing the pilot with information that allows them to supervise monitor the automation. The role of engine automation/accommodation, the inter-relationship between automatic engine accommodation and pilot procedures, and the pilot information required warrant additional investigation, review, and consideration.

8.2.4 Airplane Level Malfunction Accommodation.

Future research is needed at an airplane level design and operational focus, which transcends engine system and malfunction annunciation. Detection/annunciation, if any, would only be a component in an overall integrated systems approach.

Although stuck thrust lever was a factor in PSM+ICR, it was not consistent with the focus of this research, because stuck thrust lever did not meet the definition of engine malfunction defined for this phase of the study.

Since the focus of the Phase 2 research contract was on engine malfunction detection and annunciation challenges, it primarily included propulsion and flight deck expertise. The split-thrust-lever-related issues fall into the autoflight functionality on modern airplanes, require different expertise to evaluate (autopilot, autothrottle, and pilots), and may or may not be best or effectively addressed by annunciation.

Thrust asymmetry is considered an airplane level effect compensated for automatically by a variety of airplane level systems on most modern airplanes (autopilot, envelope protection, thrust asymmetry compensation, etc). Future research requires an airplane level design and operational focus that transcends engine system and malfunction annunciation. For example, research work on the criteria for the appropriate combination of the following:

- Airplane level automatic accommodation/reconfiguration
- Fault compensation
- Annunciation and procedure
- Pilot detection and reaction

8.2.5 Information-Based Engine Display Paradigms and Displays.

Further research, review, and analysis of customer specific practices and policies is needed. This could identify operational/information criteria applicable to the development or implementation of information-based engine display paradigms. Representative customer airlines should be involved in development and implementation.

Further research is needed to support the development and implementation of enabling capability, the development of information-based engine display paradigms, and the development and implementation of information-based engine displays.

8.3 ADDITIONAL CONSIDERATIONS.

The focus of this research was on whether consideration should be given to the annunciation of STAs on new airplane programs. The research identified apparent operational benefits and opportunities for product improvement and future investigation.

A potential suite of engine malfunction annunciations and their design criteria were identified. The annunciations have operational benefit, since they address all STA-PSMs, were derived from integrated propulsion system and crew operational criteria, and have prevention potential for a majority of PSM+ICR events.

Implementation of an individual annunciation, or a subset of the annunciations, also provides operational benefit.

Engine malfunction detection and annunciation is not the only way to provide operational benefit. Other approaches such as malfunction recognition training; engine indications that facilitate malfunction detection and minimize interpretation; airplane level annunciations, such as abnormal airspeed/attitude/performance, that guard against loss of control or performance;

airplane level automation/compensation; prognostic maintenance (to reduce the number of PSMs); and improved crew procedures and practices, can provide operational benefit. As previously noted, PSM+ICR events consistently involve a lack of crew awareness that an engine malfunction exists, which engine is affected, or which procedure to accomplish. Where reliance is on crew awareness and response, an annunciation/alert is the most effective way to provide crew awareness and ensure an appropriate response. Engine malfunction annunciation/alerting should provide appropriate awareness of the affected engine, information on the type of engine malfunction, and where feasible, the appropriate procedure for the engine malfunction.

A cost-benefit study is always warranted when considering or assessing the implementation of new detection/annunciation capabilities.

The subidle annunciation, (which includes flameout and most surge/nonrecoverable stall conditions) has the lowest technical risk and the highest potential benefit. This single annunciation has the potential to address approximately 50% of STAs and provides prevention potential for a significant number of the PSM+ICR events (including most hull loss and fatality accidents).

The annunciation of highest technical risk is for continuous/multiple surge, due to lack of sufficient engine data to validate the reliability of a detection algorithm. The cost-benefit of this annunciation for future airplane programs is not likely to be favorable until sufficient engine data becomes available.

To modify or retrofit existing airplanes with new STA detection and annunciation capabilities is not presently considered feasible because the cost-benefit trade-off for these additions is not likely to be favorable. However, a cost-benefit trade-off was not within the scope of this study.

It is important to note that PSMs are a rare occurrence, and a PSM coupled with ICR is even more rare. Analysis indicates a potential benefit for annunciation of STA-PSM, but the benefit has not been quantified. Although an annunciation of a STA-PSM condition could be beneficial, the benefit is realized only if the annunciation is reliable. An unreliable annunciation could cause more problems than it resolves. In addition, systems and displays need to be developed and tested in simulators to validate their effectiveness and the potential to reduce PSM+ICR.

PSM annunciation is the only solution investigated in this study. Investigation and data analysis has provided sufficient understanding to state 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.

PSM annunciation may or may not be the most feasible approach, and therefore the preferred approach to reducing PSM-related ICR. It is important to consider alternative approaches and to quantify the comparative feasibility and effectiveness of PSM annunciations versus other approaches. Such feasibility should be established before any regulatory, implementation, or other action is taken.

It is perhaps most important that the approach to reducing PSM and PSM+ICR events be data-driven and coordinated with other high priority safety enhancements. The challenge is to emplace the most effective and efficient means of reducing fatal accident risk from all hazards.

9. 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 aurals are typical examples.
Annunciation	A broad category of normal (i.e., nonalert) and nonnormal (i.e., alert) indications and/or aurals 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.
Bodie	Snap deceleration followed by snap acceleration. Bodie testing usually includes a suite of conditions that turn around at various points during the deceleration (Inverse Bodie is the opposite)
Continuous/ Multiple Surge	Characterized by two or more repetitions of a surge and recovery cycle (surge, recover, surge, recover, and so on). A single recoverable surge could have multiple subevents that can still be considered as part of a single recoverable surge (i.e., there could be several distinct surges in the first ~0.5 second). The distinction between a single and a continuous/multiple surge is that a subsequent surge ~>0.5 second after the first is an indication that the engine is not able to recover and requires a reduction in FF to clear the surging. There can also be two surges separated by a long enough time that they would be characterized as distinct recoverable surges (~>20 seconds). These are not characterized as continuous/multiple surges, since it is unlikely that a reduction in FF alone will clear the surging and allow the engine to recover thrust. It is more likely environmental (ambient conditions), transient engine control dependency, propagation of damage, or flight phase condition causing intermittent surging.
Engine Exceedance	Engine speed, Exhaust Gas Temperature (EGT) 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 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.
Engine Slow to Respond	The characterization of an engine slow to respond is an engine is slow to accelerate or decelerate to command. This condition can be considered an STA, if the transient thrust characteristic differs significantly from the normal transient characteristic.
Flameout	Engine combustion is quenched (ceased), all engine parameters drop subidle and EGT decays.
Inappropriate Crew Response (ICR)	An event where the crew fails to follow the published procedures, operating policies, or training practices (PPP) in a timely manner. ICR includes events where the crew was provided insufficient information and inadequate procedures, as well as events where the crew exhibited unacceptable performance. The following situations would be considered ICR: (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. Note: The term ICR can inappropriately be construed to imply crew culpability or to indict the crew for their action(s). A more appropriate, neutral, and equally effective term is Undesired Crew Response (UCR). UCR acknowledges the crew role, but fosters an atmosphere more conducive to pilot and crew operations involvement. This better supports the goal of understanding and preventing or mitigating such events. Therefore, the use of neutral terminology is encouraged.
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, FF, 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 (IFSD)	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. B-717, B-737NG, B-747-400, B-757/767, B-777, MD-11, MD-90, A319, A320, A321, A330, and A340.
Nonrecoverable Propulsion System Malfunction (PSM)	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, engine flameout, or engine surge/nonrecoverable stall 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.
Recoverable Surge	During a recoverable surge, the airflow separates (resulting in a rapid compressor pressure drop) and then reattaches (resulting in the recovery to the original operating condition). A recoverable surge will complete the recovery cycle in a fraction of a second and regain the commanded thrust.

Rotating Stall	Rotating stall is a sector of stalled compressor blades. There can be fan rotating stall, low pressure/immediate pressure (LP/IP) compressor rotating stall, or high-pressure (HP) compressor rotating stall. A rotating stall does not cause a operationally significant thrust loss, unless it deteriorates to a surge/nonrecoverable stall. Fan Rotating Stall. A sector of stalled fan blades, causing airflow blockage, and loss of fan pumping capability. If engine controls to EPR, the response to hold EPR causes the N1 to climb, possibly accompanied by an EGT climb. An N1 controlled engine will see the engine pressures and core speed drop. The loss of fan work can cause the low-pressure compressor (LPC) operating line to rise, and it is possible for core surge to occur. There is likely to be a small thrust loss, but it is not likely to be sustained or operationally significant. The thrust loss is less discernable when controlling to EPR. LP/IP Compressor Rotating Stall. A sector of stalled compressor blades, typically not accompanied by noise. Engine airflow is disrupted but parameters stay within limits, with some EGT rise. A LP/IP compressor rotating stall tends towards a full stall, quickly at high power, and slowly at low power. Also, a rotating stall at low power will progress to a full stall with a commanded thrust increase. This condition can occur at mid-low power when the operating line meets the surge line on some compressors. There is not likely to be a discernable thrust loss. HP Compressor Rotating Stall. On rare occasions part span or localized HP compressor rotating stall can occur but in unlikely to be detectable without high-response pressure instrumentation. These instabilities are likely to result in full stall or disappear with thrust lever movement. Note that the terms rotating stall, rollback, rundown, and locked stall have been used in the industry to mean the resultant condition of a nonrecoverable surge. In this document, the term surge/nonrecoverable stall is used for this condition. In the database reviewed for this study, the use of the term rotating stall will denote only the occurrences that are not preceded by surge. Rotating stalls that were preceded by a surge were counted as surge/nonrecoverable stall events.
STA Crew Annunciation Categories	The suite of four STA crew annunciation categories, grouped with common pilot procedure/awareness: (1) subidle, (2) continuous/multiple surge, (3) thrust failed high/low (sensor), and (4) Thrust anomaly.

STA Engine Symptom Annunciation Categories	The suite of nine sustained thrust anomaly engine symptoms with potential for detection/annunciation: (1) flameout, (2) surge/nonrecoverable stall, (3) continuous/multiple surge, (4) thrust failed high/low (sensor), (5) thrust failed low (indicted), (6) thrust failed low (damage), (7) thrust failed high (indicated), (8) engine slow to respond, and (9) thrust oscillations.
STA Engine Malfunction Annunciation Categories	The suite of five STA engine malfunctions, grouped with unique engine procedure/pilot awareness: (1) flameout, (2) surge/nonrecoverable stall, (3) continuous/multiple surge, (4) thrust failed high/low (sensor), and (5) Thrust anomaly.
Surge	Surge refers to a condition where compressor airfoil flow separation has occurred. The term surge usually describes a transient phenomenon characterized by rapid flow separation and immediate reattachment. Surges audibly manifest themselves as pops or bangs depending on the degree of flow separation and compressor operating condition (pressure ratio and airflow). If the surge is violent enough, the attendant flow reversal can cause the combustion process to move forward out the inlet or aft out the tailpipe resulting in visible fireballs. There are three surge types defined for this document: (1) recoverable surge, (2) surge/nonrecoverable stall, and (3) continuous/multiple surge. Meaningful surge is defined as surge that requires crew action.
Surge/ Nonrecoverable Stall	Surge followed by stall is the typical progression for a nonrecoverable surge: a sudden flow reversal, often but not always accompanied by flames out the front of the engine and noise, followed by the engine entering locked stall. Rotor speeds decay as airflow is reduced due to a stalled packet of blades rotating in the compressor. This resultant quasi-steady-state condition, where one or more compressor stages have localized airflow separation on a sector of blades is known as stall or locked stall. The combustor remains lit, and due to the lack of airflow, EGT typically rises quickly (often exceeding limits) and the engine decelerates (usually below idle). Stalls are sometimes accompanied by audible engine rumble. Note that the terms rotating stall, rollback, rundown, and locked stall have been used in the industry to mean the resultant condition of a nonrecoverable surge. In this document, the term surge/nonrecoverable stall is used for this condition. Surge can be followed by flameout, if the surge is of a sufficient violence to extinguish the flame. In this case the outcome of the event would be identical to a flameout.
Thrust Failed High (Indicated)	The characterization of a thrust failed high (indicated) condition is both actual and indicated thrust are greater than commanded. This condition could be either an engine increasing thrust from power setting or not decelerating when the command is decreased (thrust lever retarded).

Thrust Failed High (Sensor)	The characterization of a thrust failed high (sensor) malfunction is the indicated thrust matches commanded thrust, but actual thrust is higher. This is primarily caused by a failure of the sensor used to measure thrust (e.g., EPR). In this case, the measurement is erroneously low, so fuel is increased to bring the measured parameter to command, increasing actual thrust. In this condition, symmetric thrust levers would produce asymmetric thrust. Selection of alternate mode is required to correct this condition. Alternate mode uses a simpler thrust setting schedule, allowing the pilot to achieve the desired thrust with symmetric thrust levers.
Thrust Failed Low (Damage)	The characterization of a thrust failed low (damage) malfunction is the indicated thrust matches target thrust, but thrust is physically lower. The most likely cause is engine damage (e.g., fan blade damage or nozzle damage that results in open nozzle area). The thrust loss would be more pronounced when controlling to N1. When controlling to EPR, the thrust loss would be less.
Thrust Failed Low (Indicated)	The characterization of a thrust failed low (indicated) malfunction is when both actual and indicated thrust are less than commanded. This condition could be either an engine losing thrust after power set (engine can not maintain target thrust lever setting, rotor speeds and FF drop) or not accelerating when command is increased (thrust lever is advanced). One type of thrust failed low anomaly is rollback. A rollback is characterized as the condition where the engine can not schedule enough fuel to maintain the commanded power setting (for example, due to airflow blockage or inclement weather) and the engine speed decays. This condition is included in the thrust failed low (indicated) category. Often a rollback progresses to the point where combustion can no longer be supported and a flameout occurs (covered in the flameout category). Another type of anomaly is where the control is operating on a limiting function where FF is purposely being restricted to protect a limit and commanded thrust is therefore not achievable.

Thrust Failed Low (sensor)	The characterization of a thrust failed low (sensor) malfunction is the indicated thrust matches commanded thrust, but actual thrust is physically lower. This failure is primarily caused by a failure of the sensor used to measure thrust (e.g., EPR, and T2). In this case, the measurement is erroneously high, so fuel is decreased to bring the measured parameter to command, decreasing actual thrust. In this condition, symmetric thrust levers would produce asymmetric thrust. Selection of alternate mode is required to correct this condition. Alternate mode uses a simpler thrust setting schedule, allowing the pilot to achieve the desired thrust with symmetric thrust levers.
Thrust Oscillations	The characterization of a thrust oscillation is uncommanded thrust increases and decreases from power set command. In this report, thrust oscillations refer to oscillations having a mean thrust equal to thrust command. Failures that result in a change in the mean thrust (whether high or low), but also include oscillations, are categorized as thrust failed high or thrust failed low.
V1	Takeoff decision speed
Vr	Takeoff rotation speed

10. REFERENCES.

1. AIA/AECMA Project Report on Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR), Volume 2, 1 November 1998.

2. Clark, S.T., Iverson, R.E., Mumaw, R.J., Sikora, J.A., Vian, J.L., and Winters, V.J., "Indications of Propulsion System Malfunctions," FAA report DOT/FAA/AR-03/72, November 2004.

Table A-1. Procedure, Practice, and Policy Analysis

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
NORMAL PROCEDURES						
Ground engine autostart. Position fuel control switch to RUN.	Engine is starting. Engine start is proceeding normally.	Crew action and observation/confirmation of fuel control switch position/state. Crew action and observation/confirmation of various engine indications (e.g., Engine speed, EGT, FF indication, etc). Note: No FF monitoring task.	Engine starting/ progressing normally indication.	Existing capability/ technology.	TBD—Fuel Control switch action.	(1) Start indication implementation. (2) Eng shutdown method if start fuel control switch action automated.
Ground engine autostart. Observe oil P increase after initial EGT rise. [Monitor to detect oil system fault—i.e., protect against engine damage].	Engine is starting. (Engine oil pressure is normal for start operation. Engine start is proceeding normally.)	Crew monitoring and observation/confirmation of digital and graphical EGT and oil pressure indications for rise/increase. Potential detection or interpretation task errors.	Engine starting/ progressing normally indication.	Existing capability/ technology.	Yes—Add to autostart.	(1) Automation vs monitor and alert annunciation with manual crew action.
Ground engine autostart. Abort start if no oil P increase after initial EGT rise. RE u ABORTED ENGINE START checklist. [Abort start for other abnormal start indications or alerts—e.g., excess vibration or ENG FIRE warning].	Engine start abort is required. TBD if reason (abnormal engine oil pressure) is required info/awareness?	Crew monitoring and detection of indication threshold or exceedance annunciation(s) or EICAS oil P and T or other engine-related alerts displayed. Crew monitoring, detection, and interpretation of other (e.g., within range) abnormal engine indication(s) or behavior. Potential excess vibration detection and interpretation task issues/errors.	Engine start fail or start anomaly annunciation and/or indication. Engine starting/ progressing indication.	Existing capability/ technology.	Yes—Add autostart abort for low oil pressure or whatever abnormal start indications can be defined and detected.	(1) Automation vs monitor and alert annunciation with manual crew action. (2) Vibration thresholds and associated potential for nuisance start aborts. (3) Manual override capability.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
NORMAL PROCEDURES (continued)						
Takeoff. Adjust takeoff thrust prior to 80 knots, if required. [Detect abnormal thrust]	Correct/required takeoff thrust set (i.e., thrust is sufficient for takeoff) or thrust adjustment required. Aircraft takeoff performance is adequate/ acceptable.	Crew monitoring, detection, and interpretation of aircraft takeoff performance. Crew monitoring, detection, and interpretation of digital and graphical dial EPR or N1 indications and thrust targets. Potential takeoff performance detection and interpretation task issues/errors. No EICAS ENG THRUST or ENG FAIL alerts displayed.	Aircraft or engine performance—takeoff/ takeoff thrust.	New capability. New technology TBD.	Yes—Engine system or takeoff performance monitoring for alerts or other annunciations.	Engine system versus aircraft performance alerts or other annunciations, versus performance display indications (e.g., graphical airport map takeoff performance indications).
Takeoff. Monitor engine instruments throughout takeoff. Call out any abnormal indications. [Verify normal engine operation. Detect abnormal eng operation.]	Engine operation is normal and within limits—e.g., no abnormal indications requiring/justifying crew awareness or action. Aircraft takeoff performance is adequate/ acceptable.	Crew monitoring, detection, and interpretation of digital and graphical dial EPR or N1 indications and thrust targets. Normal/expected primary engine indication of: EPR, N1, EGT. Normal/ expected secondary engine indication of: N2, N3, FF, oil P/T/Qty, and Vib. Potential takeoff performance detection and interpretation task issues/errors. No secondary engine page auto pop-up displayed. No EICAS ENG THRUST or ENG FAIL alerts displayed. No Eng Oil P and T alerts displayed. No EGT or other exceedance annunciation displayed.	Aircraft or engine performance—takeoff/ takeoff thrust.	Existing technology. New capability.	Yes—Engine system or takeoff performance monitoring for alerts or other annunciations.	Engine system versus aircraft performance alerts or other annunciations versus performance display indications (e.g., graphical airport map takeoff performance indications). Implementation issues.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
NORMAL PROCEDURES (continued)						
Go around. Verify thrust adequate for go around and adjust if necessary.	Correct/required thrust set (i.e., thrust is sufficient for go around). Engine thrust is normal. Aircraft go around performance is adequate/acceptable.	Crew monitoring of engine and aircraft performance. Observation of digital and graphical dial EPR or N1 thrust indications, and observation/confirmation of aircraft attitude, speed, vertical speed, altitude, and flight path indications. PFD Flight Mode annunciations (e.g., TOGA). Potential go around performance detection and interpretation task issues/errors.	Aircraft performance—go around.	Existing capability/ technology.	Yes—Performance monitoring for alerts or other annunciations.	Implementation issues.
SUPPLEMENTARY NORMAL PROCEDURES						
Manual ground engine start. Observe oil P increase. [Monitor to detect oil system fault—i.e., protect against engine damage].	Engine start is proceeding normally. TBD if engine oil pressure is normal for start operation is required information/awareness.	Crew monitoring and observation/confirmation of digital and graphical scale oil pressure indication for rise/ increase. Potential detection or interpretation task errors.	Engine starting/ progressing normally indication.	Existing capability/ technology	Yes—autostart only, or automate monitoring and eliminate procedure step.	
Manual ground engine start. Observe initial EGT rise and EGT within limits. [Monitor to ensure engine ignition and detect hot start].	Engine start is proceeding normally—i.e., engine ignition has occurred, EGT is normal for start operation, and start is proceeding normally.	Crew monitoring and observation/confirmation of digital and graphical scale EGT indication for rise/increase. Potential detection or interpretation task errors.	Engine starting/ progressing normally indication.	Existing capability/ technology	Yes—autostart only, or automate monitoring and eliminate procedure step.	

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
SUPPLEMENTARY NORMAL PROCEDURES (continued)						
Manual ground engine start. Monitor engine displays for start parameters until engine is stabilized at idle (oil P, EGT rise within xx seconds, N1 rotation indication by xx% N2, N2 or N3 @ idle within xx minutes of selecting RUN).	Engine is starting normally, or engine is running normally. Engine start is progressing normally, or has stabilized and start is complete.	Crew monitoring—i.e., observation/confirmation of indication threshold or exceedance annunciation. Observation and detection/ confirmation of digital and graphical scale oil P, and digital and graphical dial EGT, N1, N2, and N3 indications. EICAS oil P and T alerts. Potential start detection and interpretation task issues/errors.	Engine starting/ progressing normally indication.	Existing capability/ technology	Yes—autostart only, or automate monitoring and eliminate procedure step.	
Manual Ground Engine Start. Abort start for no FF, EGT exceedance or approaching exceedance, low or high oil P, high oil T, low oil Qty, high Vib, or engine speed (N1, N2, or N3) exceedance. Abort start for abnormal engine indications.	Engine start fault/ abnormality, failure, or exceedance. Engine start failure and abort is required for abnormal engine oil pressure, threshold annunciation or exceedance indication, or other abnormal engine indications or behavior.	Crew monitoring and detection of indication threshold or exceedance annunciation(s) or EICAS oil P and T alerts. Potential detection task issues/errors. Crew monitoring, detection, and interpretation of other abnormal engine indication(s) or behavior—e.g., observation and detection/ confirmation of digital and graphical scale oil P, and digital and graphical dial EGT, N2, N3, and Vib indications, or displayed EICAS oil press or temp alerts. Potential detection and interpretation task issues/errors.	Engine start fail or start anomaly annunciation and/or indication. Engine starting/ progressing indication.	Existing capability/ technology.	Yes—autostart only, or automate monitoring for alert annunciation.	(1) Manual override capability. (2) Cost-benefit.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
SUPPLEMENTARY NORMAL PROCEDURES (continued)						
Cold weather operation. Oil pressure may be slow to rise and higher than normal.	Engine starting normally ot engine start fault/failure/exceedance and manual engine start abort is required (for abnormal oil pressure?).	Crew monitoring—i.e., observation and detection/confirmation of abnormal digital and graphical scale oil pressure indication. EICAS low oil press alert displayed? Potential monitoring and interpretation task errors/issues.	Engine starting/ progressing normally indication.	Existing capability/ technology	Yes—autostart only, or automate monitoring and eliminate procedure step.	Implementation logic and associated potential for nuisance start aborts.
Cold weather operation. Oil Temperature must be at least xx degrees C prior to takeoff.	Engine(s) ready for takeoff or not ready for takeoff. [Oil temperature meets or does not meet takeoff requirements].	Crew monitoring—i.e., observation and detection/ confirmation of digital and graphical scale oil temperature indication. Potential detection and interpretation task errors/issues.	Engine readiness for takeoff—ready indication, or not ready alert annunciation.	Existing capability/ technology.	Yes—monitoring for alert annunciation.	

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
NONNORMAL PROCEDURES						
DUAL ENG FAIL/STALL. Restart engines. No. of Fuel control switches (affected engines) CUTOFF, then RUN. [Monitor engine start.]	Engine is starting. Engine start has initiated and is progressing normally.	Crew observation and confirmation of fuel control switch cycling. Crew monitoring—i.e., observation and interpretation of graphical and/or digital engine speed (N1, N2, N3), EGT, FF, oil P and T, and other engine indications. Potential start monitoring and interpretation task issues/errors.	Engine starting/ progressing normally indication.	Indication: Existing capability/ technology. Control automation: New capability. Existing technology.	Yes—automated fuel control switch action.	(1) Start indication implementation. (2) EEC reliability/failure modes. (3) Manual override capability. (4) Cost-Benefit.
ENG FAIL L, R. Determine/decide if engine start should be attempted. [Assess operational versus engine needs. determine operational impact of continued engine shutdown versus operation].	Engine start and operation is possible. Engine damaged or undamaged. Engine startable or unstartable.	Crew observation and interpretation of digital and graphical engine indications (e.g., EPR, N1, EGT, FF, N2, Vib, N3, oil P/T/Qty). Potential start-related interpretation/integration task issues/errors.	Engine operability—system readiness/ capability for starting and operation.	New capability/ technology.	Yes—automated assessment of engine readiness for starting or operation.	(1) Damage assessment. (2) Cost-benefit.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG FAIL. Fuel Control Switch RUN.	Engine is starting. If autostart off: engine is ready for fuel.	Crew monitoring—i.e., observation and detection/verification of max motoring N2 for autostart off. Crew verification of fuel control switch position. Potential start interpretation issues/errors.	Engine starting/ progressing normally indication.	Existing capability/ technology.	Yes—automated fuel control switch action.	(1) Start indication implementation. (2) EEC reliability/failure modes. (3) Manual override capability. (4) Cost-benefit.
ENG FAIL. Monitor engine start. Monitor EGT during start.	Engine is starting. Engine start is progressing normally.	Crew monitoring—i.e., observation and detection/confirmation of normal engine start behavior—e.g., N2 steadily rising, EGT rising and within limits, other engine indications normal and within range. Digital and graphical engine indications (e.g., EPR, N1, EGT, FF, N2, N3, oil P and T). Potential start-related monitoring and interpretation task related issues/errors.	Engine starting/ progressing normally indication.	Existing capability/ technology.	Yes—automated monitoring. TBD automated accommodation.	(1) Start indication implementation.
ENG IN–FLIGHT START. Fuel Control Switch RUN.	Engine is starting. If autostart off: engine is ready for fuel.	Crew monitoring—i.e., observation and detection/verification of max motoring N2 for autostart off. Crew verification of fuel control switch position. Potential start interpretation issues/errors.	Engine starting/ progressing normally indication.	Existing capability/ technology.	Yes—automated monitoring. TBD automated accommodation.	(1) Start indication implementation.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG IN–FLIGHT START. Monitor engine start. Monitor EGT during start	Engine is starting. Engine start is progressing normally.	Crew monitoring—i.e., observation and detection/confirmation of normal engine start behavior, e.g., N2 steadily rising, EGT rising and within limits, other engine indications normal and within range. Digital and graphical engine indications (e.g., EPR, N1, EGT, FF, N2, N3, oil P and T). Potential start monitoring and interpretation task-related issues/errors.	Engine starting/ progressing normally indication.	Existing capability/ technology.	Yes—automated monitoring. TBD automated accommodation.	(1) Start indication implementation.
VOLCANIC ASH. Fuel Control Switches CUTOFF then RUN	Engines are starting. Engine starts are progressing normally.	Crew monitoring—i.e., observation and detection/verification of engine indications. Potential start interpretation issues/errors.	Engine Starting/ Progressing Normally Indication.	Existing capability/ technology.	Yes —automated monitoring. TBD automated accommodation. automated fuel control switch action	(1) Start indication implementation. (2) EEC reliability/failure modes. (3) Manual override capability. (4) Cost-benefit.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ABORTED ENGINE START. Monitor and Detect start parameters exceeded or EGT rising rapidly and approaching limit during manual or in-flight start. Select appropriate unannunciated checklist.	Engine shutdown required. Engine start fault, failure, or exceedance. UAborted Engine Start procedure should be accomplished.	Crew monitoring—i.e., observation and detection of start parameter exceedance, or indication threshold annunciation or exceedance. EGT digital and graphical dial indication change rate or red exceedance annunciation displayed. EICAS oil pressure and temperature alerts displayed. Potential for detection and/or interpretation issues/errors.	Engine start fail or start anomaly annunciation and/or indication. Engine starting/ progressing indication.	Existing capability/ technology.	Yes—automated monitoring and annunciation. TBD—auto abort. Current autostart design does not abort in-flight for other than seized rotor.	(1) Automation vs monitor and alert annunciation with manual crew action. (2) Potential for in-flight nuisance or undesired start aborts if abort is automated.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG FAIL. Abort start if no oil P increase after initial EGT rise. RE u ABORTED ENGINE START checklist. [Abort start for other abnormal start indications or alerts—e.g., excess vibration or ENG FIRE warning].	Engine start fault/failure/ exceedance. Engine shutdown required. Engine start abort procedure is required.	. Crew monitoring and detection of EGT exceedance annunciation(s), engine oil P failure to rise, or EICAS oil P and T or other engine-related alerts. Crew monitoring, detection, and interpretation of other (e.g., within range) abnormal engine indication(s) or behavior. Potential start-related detection and interpretation task issues/errors.	Engine start fail or start anomaly annunciation and/or indication. Engine Starting/ Progressing Indication.	Existing capability/ technology.	Yes—automated monitoring and annunciation. TBD—autoabort. Current autostart design does not abort in flight for other than seized rotor.	(1) Automation vs monitor and alert annunciation with manual crew action. (2) Potential for in-flight nuisance or undesired start aborts if abort is automated.
ENG IN–FLIGHT START. Abort engine start if no EGT rise within xx seconds. Fuel control switch to CUTOFF. [Verify/ confirm engine shutdown.]	Engine shutdown required. Engine start failure or exceedance. Engine start abort procedure is required. Elapsed time. Engine start failed or did not progress normally.	Crew monitoring—i.e., observation of EGT digital and graphical engine indication. Detection/confirmation of failed or abnormal engine start. Potential monitoring/ interpretation task issues/errors. Crew observation and verification/ confirmation of digital and graphical engine indications (e.g., decreasing EGT for shutdown.	Engine start fail or start anomaly annunciation and/or indication. Engine starting/ progressing indication.	Existing capability/ technology.	Yes—automated monitoring and annunciation. TBD—autoabort. Current autostart design does not abort in flight for other than seized rotor.	(1) Automation vs monitor and alert annunciation with manual crew action. (2) Potential for in-flight nuisance or undesired start aborts if abort is automated.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG AUTOSTART (On-ground only alert). [Determine/decide if additional auto or manual start should be attempted].	Engine start is possible/allowable. Operational requirements. Engine start attempt options and limitations—i.e., engine start is possible or limited. If limited, how so?	Crew monitoring—i.e., observation and interpretation of graphical and/or digital engine speed (N1, N2, N3), EGT, FF, oil P and T, and other engine indications. Procedures, Policies, Practices. Training. Experience. Potential start related interpretation task issues/errors.	Engine startability/ operability indication. Engine needs.	New technology and capability.	N/A	Engine damage related. Potential for erroneous determinations.
ENG IN-FLIGHT START. [Determine/decide if engine start should be attempted.] [Assess Operational versus Engine Needs—e.g. determine operational impact of continued engine shutdown versus operation]. [1]Select appropriate unannunciated checklist.	Engine start and operation is possible. Operational and engine needs assessment. Engine damaged or undamaged. Engine startable or unstartable.	Crew observation and interpretation of digital and graphical engine indications (e.g., EPR, N1, EGT, FF, N2, N3, FF, Vib, oil P/T/Qty). Potential start-related interpretation/integration issues/errors.	Engine startability/operability indication. Engine needs.	New technology and capability.	N/A	Engine damage related. Potential for erroneous determinations.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG OIL TEMP. If oil temp exceeds red line limit, or above amber limit for xx minutes, Fuel Control Switch—CUTOFF	Engine start fault/failure/exceedance. Engine shutdown required. Oil temperature greater than limit(s) and elapsed time.	Crew monitoring—i.e.,observation and verification of oil T indication. Oil temperature on indicated engine. Engine oil temperature limits. Elapsed time. Potential monitoring and detection task issues/errors. Secondary end	Engine start fail or start anomaly annunciation and/or indication. Engine startability/operability indication. Engine needs.	Existing technology and new capability.	N/A	Engine damage or capability related. Potential for erroneous determinations.
ENG FAIL. Determine/decide if engine start should be attempted. [Assess Operational versus Engine Needs. Determine operational impact of continued engine shutdown versus operation].	Engine start and operation is possible. Engine damaged or undamaged. Engine startable or unstartable.	Crew observation and interpretation of digital and graphical engine indications (e.g., EPR, N1, EGT, FF, N2, Vib, N3, oil P/T/Qty). Potential start-related interpretation/integration task issues/errors.	Engine startability/operability indication. Engine needs.	New technology and capability.	N/A	Engine damage related. Potential for erroneous determinations.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG OIL PRESS. Assess operational versus engine needs? [Determine operational impact of continued engine operation versus shutdown].	Operational and engine needs. Engine startability and operability.	Crew assessment and integration of operational and engine needs based on phase of flight and engine indications and performance. Potential interpretation/integration task issues/errors?	Engine startability/operability indication. Engine needs.	New technology and capability.	N/A	Dual engine noncorrectable issue only. Engine damage or capability related. Potential for erroneous determinations.
ENG OIL TEMP. Assess operational versus engine needs? [Determine operational impact of continued engine operation versus shutdown].	Operational and engine needs. Engine startability and operability.	Crew Assessment and integration of operational and engine needs based on phase of flight and engine indications and performance. Potential interpretation/integration task issues/errors?	Engine startability/operability indication. Engine needs	New technology and capability.	N/A	Dual engine noncorrectable issue only. Engine damage or capability related. Potential for erroneous determinations.
ENG SVR DAMAGE/SEP. No. Thrust lever—CLOSE. [Confirm affected engine]. [Confirm engine affected/severly damaged]? Select appropriate unannunciated checklist and accomplish memory items.	Immediate engine shutdown and isolation required. Severe engine damage, and affected engine.	Crew monitoring—observation, detection, and interpretation of engine indications (e.g., NCD or indications blank. Abnormal EGT, N1, N2, N3, Vib, oil P/T/.Qty.]. EGT rising rapidly. High vibration. No engine rotation. Potential affected engine and damage-related detection/interpretation task issues/errors.	Engine operability indication. Engine needs. Severe engine damage and affected engine annunciation.	New capability—damage detection and assessment. TBD if existing/new technology.	N/A	(1) Severe engine damage detection/assessment strategy/capability. Engine damage or capability related. (2) Potential for erroneous determinations.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG SVR DAMAGE/SEP. Assess operational versus engine needs. [Determine operational impact of continued engine operation versus shutdown].	Operational and engine needs. Engine startability and operability.	Crew assessment and integration of operational and engine needs based on phase of flight and engine indications and performance. Potential interpretation/integration task issues/errors.	Engine startability/operability indication. Engine needs.	New technology and capability.	N/A	Severe engine damage detection schema/capability. Engine damage or capability related. Potential for erroneous determinations.
ENG LIM/ SURGES/STALL. Monitor/Detect/Interpret Engine Condition (Engine indications are abnormal or are approaching or exceeding limits, abnormal engine noises are heard, or there is no response to thrust lever movement). Select appropriate unannunciated checklist and accomplish memory items.	Operational and engine needs. Engine startability and operability.	Crew monitoring— Observation, detection, and interpretation of abnormal engine indications— graphical and/or digital engine EPR, N1, N2, N3, EGT, Oil P/T/Qty, Vib, FF indications. EICAS alert for subidle surge/stall. EICAS alert for oil P and T. EICAS EGT annunciation for EGT limit exceedance. Potential limit or surge-related and affected engine-related detection task and interpretation task issues/errors.	Impending limit exceedance alert. Limit exceedance alert. Surge alert.	Impending and limit exceedance: Existing capability/technology. Surge: New capability. Existing technology.	Yes—automated monitoring and annunciation.	Alert levels. Detection schema/strategy. Alert/annunciation implementation.
ENG LIM/SURGES/STALL. Detect engine indications exceeding limits.	Engine shutdown required. Engine limit exceedance.	Crew monitoring— observation, detection, and interpretation of engine indications (e.g., EGT, oil P/T/Qty, Vib, EPR:, N1?, N2?, N3?) exceeding limits. Potential monitoring and detection task issues/errors.	Limit exceedance alert.	Existing capability/technology.	Yes—automated monitoring and annunciation.	Alert levels. Alert/annunciation implementation.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG LIM/SURGE/STALL. Detect engine indications approaching limits.	Engine shutdown may be required. Impending engine limit exceedance.	Crew monitoring—observation, detection, and interpretation of engine indications (e.g., EGT, oil P/T/Qty, Vib, EPR?, N1?, N2?, N3?) approaching limits. Potential approaching exceedance-related detection task and/or interpretation task issues/errors.	Impending limit exceedance alert.	New capability. TBD existing/new technology.	Yes—automated monitoring and annunciation. New capability. TBD existing/new technology.	Alert levels. Detection schema/strategy. Alert/annunciation implementation.
ENG LIM/SURGE/STALL. Assess operational versus engine needs. [Determine operational impact of continued engine operation versus shutdown].	Operational and Engine Needs. Engine startability and operability.	Crew assessment and integration of operational and engine needs based on phase of flight and engine indications and performance. Potential interpretation/integration task issues/errors.	Engine operability/startability indication. Engine needs.	New technology and capability	N/A	Engine damage related. Potential for erroneous determinations.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
ENG IDLE DISAGREE. [Determine/confirm affected engine]	Engine fault and affected engine.	EICAS ENG IDLE DISAGREE alert (non-engine specific). Crew observation and confirmation of engine thrust EPR and/or N1. Potential engine identification/interpretation task issues/errors.	Affected engine annunciation.	Existing capability/technology	Yes—automated monitoring and annunciation.	Cost-Benefit.
DUAK ENG FAIL/STALL. Monitor and detect multiple engine failure. Select appropriate unannunciated checklist and accomplish memory items.	Dual or multiple engines are failed subidle.	Individual EICAS engine failure alerts. Unannunciated procedure. Crew verification/confirmation of engine failure via engine indications (n1, N2, N3, EGT, FF, etc) and airspeed/attitude/altitude changes. Potential single versus dual engine failure interpretation task issues/errors.	Integrated dual engine failure alert/annunciation.	Existing capability/technology..	Yes—automated monitoring for dual engine failure.	Implementation risk issues. Cost-Benefit.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
Monito/detect engine condition.	RTO is required	EICAS engine-related alerts, indication annunciations and display pop-up. Crew monitoring—i.e., of engine indications and aircraft performance (e.g., aircraft airspeed and position). Potential indication and performance monitoring and interpretation task issues/errors. RE Normal takeoff task.	Go, No-Go indication.	New capability, technology TBD.	Yes—automated monitoring and annunciation.	Complexity. Implementation risk. Cost-Benefit.
PRACTICES						
(1) Between Engine Comparison of Same Parameter(s). Monitor and detect difference in same indicated parameter on different engines. Determine if nonnormal/actionable.	Meaningful between engine differences. Action required	Between engine monitoring, detection, and interpretation of primary and/or secondary engine indications (EPR, N1, EGT, N2, N3, FF, oil P/T/qty, and vib). Potential monitoring, detection, or interpretation task issues/errors.	Health monitoring indication/annunciation/alert.	New capability, technology TBD,	Yes—automated monitoring and annunciation.	Engine damage or capability related. Potential for erroneous or nuisance determinations.

Table A-1. Procedure, Practice, and Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
(2) Within engine monitoring for expected parameter value or NCD. Monitor and detect unexpected engine indication value. Determine if nonnormal/actionable.	Meaningful engine indication Action required.	Within engine monitoring, detection, and interpretation of primary and/or secondary engine indications (EPR, N1, EGT, N2, N3, FF, oil P/T/qty, and vib). Potential monitoring, detection, or interpretation task issues/errors.	Health monitoring indication/annunciation/ alert.	New capability, technology TBD.	Yes—automated monitoring and annunciation.	Engine damage or capability related. Potential for erroneous or nuisance determinations.
(3) Within engine monitoring for parameter changes or change rate. Monitor and detect unexpected engine indication change or rate of change. Determine if nonnormal/actionable	Meaningful indication change or rate of change. Action required	Within engine monitoring, detection, and interpretation of primary and/or secondary engine indications (EPR, N1, EGT, N2, N3, FF, oil P/T/ Qty, and Vib) for change or rates of change. Potential monitoring, detection, or interpretation task issues/ errors.	Health monitoring indication/annunciation/ alert.	New capability, technology TBD.	Yes—automated monitoring and annunciation	Engine damage or capability related. Potential for erroneous or nuisance determinations.

Table A-1. Procedure, Practice, And Policy Analysis (Continued)

Flight Crew Subtask [Implied tasks in brackets]	Awareness, Information, and Understanding Required (To support subtask)	How Awareness, Information, Understanding Currently Obtained or Provided	Potential New, Alternate, or Additional Information (vs Data)	Existing Capability/ Technology or New Capability/ Technology	Automation Candidate	Comments and Unresolved/ Open Issues
(4) Assess operational versus engine needs before shutdown or restart. Determine operational impact of continued engine operation versus shutdown..	Operational and engine needs. Engine startability and operability	Crew assessment and integration of operational and engine needs based on phase of flight and engine indications and performance. Potential interpretation task issues/errors.	Engine startability or operability indication. Engine needs.	New capability, technology TBD.	Yes—automated monitoring and annunciation.	Engine damage or capability related. Potential for erroneous or nuisance determinations.

P = Pressure
T = Temperature
FF = Fuel flow
TBD = To be determined
EGT = Exhaust gas temperature
EPR = Engine pressure ratio
EICAS = Engine indication and crew alerting system
PFD = Primary flight display
TOGA = Takeoff go around
VIB = Vibration

L = left
R = right
SVR = severe
NCD = no computed data
N1 = fan speed
N2 = core HPT (2-spool engine)
N3 = core HPT (3-spool engine)
Qty = quantity
SEP = Separation