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Engine Damage-Related Propulsion System Malfunctions

December 2008

Final Report

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16. Abstract

This document describes the research conducted as part of FAA contract DTFACT-03-C-00O33. The purpose was to research the operational effects and causes of engine damage and develop damage detection strategies using combinations of existing sensors (sensor fusion). The research included a comprehensive study of engine damage causes and effects from in-service data, an assessment of how and why engine damage should be annunciated to the flight crew, development of high-level sensor fusion-based damage detection strategies, and an assessment of the benefits and implementation considerations.

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TABLE OF CONTENTS

			Page
EXECUTIVE SUMMARY			xvii
1.	BACKGROUND		1-1
	1.1	Previous Work	1-1
		1.1.1 The PSM+ICR Research Phase 1	1-1
		1.1.2 The PSM+ICR Research Phase 2	1-2
	1.2	The PSM+ICR Research Phase 3 Summary	1-3
	1.3	Phase 3 Statement of Work	1-5
		1.3.1 Task 1: Determine Detectable Engine Damage Modes	1-6
		1.3.2 Task 2: Assess Damage Modes for Pilot Awareness and Action	1-6
		1.3.3 Task 3: Establish Operational Criteria for Detection and Annunciation	1-6
		1.3.4 Task 4: Develop Sensor Fusion Detection Strategies	1-6
2.	TASK 1: DETECTABLE ENGINE DAMAGE MODES		2-1
	2.1	Task 1 Objectives	2-1
	2.2	Task 1 Results Summary	2-1
	2.3	Engine Damage Mode Paradigm	2-2
	2.4	Generic Engine Description	2-2
		2.4.1 Fan Module	2-4
		2.4.2 Low-Pressure Compressor	2-5
		2.4.3 High-Pressure Compressor	2-7
		2.4.4 Combustor/Diffuser	2-8
		2.4.5 High-Pressure/Intermediate-Pressure Turbine	2-9
		2.4.6 Low-Pressure Turbine and Exhaust System	2-11
		2.4.7 Engine Subsystems	2-12
		2.4.8 Other Aircraft Systems	2-18
		2.4.9 Nacelle Structure	2-18
	2.5	Source Data Description	2-19
	2.6	Principal Engine Damage Modes	2-27
		2.6.1 Fan Damage Modes	2-43
		2.6.2 Low-Pressure Compressor Damage Modes	2-43

2.6.3 High-Pressure Compressor Damage Modes 2-44

2.6.4 Combustor and Diffuser 2-44

2.6.5 High-Pressure Turbine Damage Modes 2-45

2.6.6 Low-Pressure Turbine Damage Modes 2-46

2.6.7 Nacelle Components Damage Modes 2-46

2.6.8 Propulsion Subsystems: Bleed Air and Fire Protection System Damage Modes 2-46

2.6.9 Propulsion Subsystems: Lubrication System Damage Modes 2-47

2.6.10 Propulsion Subsystems: Lubricated Components Damage Modes 2-47

2.6.11 Propulsion Subsystems: Fuel Supply and Control System Components Damage Modes 2-51

2.6.12 Propulsion Subsystems: Other Aircraft System Components Damage Modes 2-51

2.6.13 Indeterminate Damage Modes 2-53

2.6.14 Potential New Coverage Provided by Sensor Fusion 2-53

2.7 In-Service Data Application 2-55
2.8 Engine Damage During ICR Events 2-56
2.9 Task 1 Conclusions 2-60

3. TASK 2: ENGINE DAMAGE MODES ASSESSMENT FOR PILOT AWARENESS AND ACTION 3-1

3.1 Task 2 Objectives 3-1
3.2 Task 2 Results Summary 3-2
3.3 Engine Damage Annunciation Concepts 3-2
3.4 Response to Engine Damage: Operational Versus Economic Effects 3-26
3.5 Continued Engine Operation With Known Damage 3-31
3.6 Engine Restartability Assessment 3-31
3.7 Damaged Engine Power Capability Determination 3-37
3.8 Task 2 Conclusions 3-38

4. TASK 3: OPERATIONAL CRITERIA FOR DAMAGE DETECTION AND ANNUNCIATION 4-1

4.1 Task 3 Objectives 4-1
4.2 Task 3 Results 4-1
4.3 Flight Deck Overview of Displays, Controls, and Alerting 4-3
4.4 General Crew Annunciation and Alerting Considerations 4-7

4.5 Crew Alerting-Related Awareness and Response Considerations 4-8
4.6 Nonnormal Checklist Considerations 4-9
4.7 Inappropriate Crew Response Considerations 4-10
4.8 Operational Analysis 4-10
4.9 Operational Annunciation Criteria 4-11
4.10 Failure to Alert Versus False Alert Considerations 4-12
4.11 Annunciation/Alerting Criteria 4-13
4.12 Supporting Engine Indications 4-15
4.13 New Engine Damage Alerts 4-15

4.13.1 Engine Gas Path L/R (Awareness/Restrict Thrust) 4-15
4.13.2 Engine Lubrication System L/R (Shutdown) 4-17

4.14 Detection and Annunciation Determinism 4-18
4.15 Task 3 Conclusions 4-19

5. TASK 4: DAMAGE DETECTION STRATEGIES 5-1

5.1 Task 4 Objectives 5-1
5.2 Task 4 Results Summary 5-2
5.3 In-Service Report Review 5-4
5.4 Available and Potential Detection Strategies 5-28
5.5 Sensor Usage for Damage Detection Considerations 5-31

5.5.1 Gas Path Pressures and Temperatures 5-31
5.5.2 Rotor Speeds 5-32
5.5.3 Oil System Sensors 5-32
5.5.4 Airborne Vibration Monitor 5-34

5.6 Sensor Fusion Damage Detection Strategies 5-40

5.6.1 Sensor Fusion Strategy Common Features 5-40

5.6.2 Strategy 1: Two-Parameter Shift Detection 5-43

5.6.3 Strategy 2: Shift Detection Supplemented With Other Engine Parameters 5-46

5.6.4 Strategy 3: Shift Detection Enhanced With Performance Model 5-49

5.6.5 Strategy 4: Shift Detection Enhanced With Trend-Based Model 5-51

5.7 Sensor Fusion Annunciation and Response Considerations 5-53

5.7.1 Annunciation and Alert Latching 5-53
5.7.2 Potential Consolidation and Cascading of Engine Damage Alerts 5-54

5.8 Task 4 Conclusions 5-55

6. DAMAGE DETECTION IMPLEMENTATION CONSIDERATIONS 6-1

6.1 Indicated Vibration Annunciation 6-1
6.2 Damage Detection System Benefit Comparison 6-2
6.3 Damage Detection System Development Risk Assessment 6-4

7. CONCLUSIONS 7-1

7.1 Task 1 Conclusions 7-1
7.2 Task 2 Conclusions 7-2
7.3 Task 3 Conclusions 7-3
7.4 Task 4 Conclusions 7-3
7.5 Cost/Benefit Conclusions 7-5

8. FUTURE WORK 8-1

8.1 Detailed In-Service Engine Damage Data Collection 8-1
8.2 Damage Detection Technology Development 8-1
8.3 Advanced Engine Display Paradigms 8-2

9. DEFINITIONS 9-1

10. REFERENCES 10-1

LIST OF FIGURES

Figure		Page
1-1	Engine Damage Paradigm	1-4
1-2	Phase 3 Task Relationship	1-5
2-1	Task 1 Description and Approach	2-1
2-2	Generic High Bypass Turbofan Engine	2-3
2-3	Fan Module	2-5
2-4	Low-Pressure Compressor Module	2-6
2-5	High-Pressure Compressor Module	2-8
2-6	Combustor/Diffuser Module	2-9
2-7	High-Pressure Turbine Module	2-10
2-8	Low-Pressure Turbine and Exhaust System Module	2-12
2-9	Engine Lubrication System	2-13
2-10	Lubricated Components	2-14
2-11	Engine Fuel System	2-15
2-12	Bleed Air System	2-17
2-13	Modern Turbofan Engine Controls and Sensors	2-18
2-14	Nacelle Components	2-19
2-15	Unscheduled Engine Removal Cause Distribution	2-25
2-16	In-Flight Shutdown Cause Distribution	2-26
2-17	Estimated Baseline Annunciation Coverage for IFSDs	2-54
2-18	Estimated Baseline Annunciation Coverage for UERs	2-54
2-19	Removal Event Distillation	2-55
2-20	Event Distillation of IFSD	2-55
2-21	Engine Damage During PSM+ICR Events	2-56

2-22	The PSM+ICR Event Assessment	2-58
3-1	Task 2 Approach	3-1
3-2	Awareness/Restrict Thrust Alert and Response Sequence	3-17
3-3	Relationship Between UERs, UERs With Flight Deck Effects, and IFSDs	3-18
3-4	Engine Component Rates for Isolate Bleed Air Response Category	3-19
3-5	Engine Component Rates for Restrict Thrust Response Category	3-20
3-6	Engine Component Rates for Shutdown Response Category	3-22
3-7	Engine Component Rates for Immediate Shutdown Category	3-23
3-8	Engine Component Rates for Failures Leading to Uncommanded Shutdown	3-24
3-9	Engine Component Rates for Failures Already Covered by Existing Annunciations or Alerts	3-25
3-10	Damage Annunciation Categories	3-39
4-1	Task 3 Approach	4-2
4-2	Typical Modern Commercial Transport Flight Deck	4-4
4-3	Typical Commercial Transport Flight Deck Displays and Controls	4-5
4-4	Engine Gas Path Damage Annunciation, No Indicated Thrust Restriction	4-16
4-5	Engine Gas Path Damage Annunciation, Indicated Thrust Restriction	4-17
4-6	Engine Lubrication System Alert	4-18
5-1	Task 4 Approach	5-1
5-2	Unplanned Engine Removal Distribution vs Potential Damage Detection Means	5-5
5-3	Desired Engine Damage Time History Data	5-6
5-4	Unscheduled Engine Removals With In-Flight Detectable Effects (Gas Path and Lubricated Components Only)	5-8
5-5	Fan Spinner Damage In-Flight Effects	5-13
5-6	Fan Abradable Damage In-Flight Effects	5-14
5-7	Fan Blades Damage In-Flight Effects	5-15

5-8	Fan Exit Guide Vanes Damage In-Flight Effects	5-16
5-9	Disk Damage In-Flight Effects	5-17
5-10	Low-Pressure Compressor Blades and Vanes Damage In-Flight Effects	5-18
5-11	High-Pressure Compressor Blades and Vanes Damage In-Flight Effects	5-19
5-12	High-Pressure Compressor Air Seal Damage In-Flight Effects	5-20
5-13	Combustor Damage In-Flight Effects	5-21
5-14	High-Pressure Turbine Nozzle Guide Vane Damage In-Flight Effects	5-22
5-15	High-Pressure Turbbine Air Seal and Shroud Damage In-Flight Effects	5-23
5-16	High-Pressure Turbine Blades Damage In-Flight Effects	5-24
5-17	Low-Pressure Turbine Blade and Nozzle Guide Vane Damage In-Flight Effects	5-25
5-18	Bearing Damage In-Flight Effects	5-26
5-19	Gearbox Damage In-Flight Effects	5-27
5-20	Sensor Fusion Annunciation Capability	5-30
5-21	Gas Path Pressure and Temperature Sensors	5-32
5-22	Typical Oil System Sensor Configuration	5-33
5-23	Airborne Vibration Monitor Installation and Signal Processing	5-35
5-24	Accelerometer Locations and Bearing Support Arrangements	5-35
5-25	Fan Blade Icing Time History	5-38
5-26	Vibration Characteristics: Fan Blade Icing vs Damage	5-39
5-27	Trend Shift Monitoring Top-Level Concept	5-41
5-28	Sensor Fusion Surge Accommodation	5-42
5-29	Reference 4 Service Mishap Time History Data	5-44
5-30	Component Damage Correlated to Sensor Effects	5-48
5-31	Vibration Trend Model	5-50
5-32	The EGT Trend Model	5-51

5-33 Indicated Vibration Trending 5-52

5-34 Exhaust Gas Temperature Trending 5-53

5-35 Alert and Response Sequencing 5-55

LIST OF TABLES

Table		Page
2-1	In-Service Engine Damage Data	2-20
2-2	Prescribed Sensor Examples	2-30
2-3	Engine Damage Mode Assessment (Fan Module)	2-31
2-4	Engine Damage Mode Assessment (LPC Module)	2-32
2-5	Engine Damage Mode Assessment (HPC Module)	2-33
2-6	Engine Damage Mode Assessment (Combustor/Diffuser Module)	2-34
2-7	Engine Damage Mode Assessment (HPT Module)	2-35
2-8	Engine Damage Mode Assessment (HPT and LPT Modules)	2-36
2-9	Engine Damage Mode Assessment (LPT Module)	2-37
2-10	Engine Damage Mode Assessment (Exhaust System and Cowls)	2-38
2-11	Engine Damage Mode Assessment (Inlet and Thrust Reverser)	2-39
2-12	Engine Damage Mode Assessment (Nacelle Structure)	2-40
2-13	Bleed Air and Fire Protection System Damage Mode Assessment	2-41
2-14	Engine Damage Mode Assessment (Lubrication System)	2-42
2-15	Engine Damage Mode Assessment (Lubricated Components)	2-48
2-16	Engine Damage Mode Assessment (Fuel Supply and Controls)	2-50
2-17	Engine Damage Mode Assessment (Other Aircraft Systems)	2-52
2-18	Percentage of Sums of ISFDs and UERs	2-53
2-19	The PSM+ICR Event Analysis: Damage Alerting ICR Prevention Potential	2-60
3-1	Initial Response to Detected Damage: Fan Components	3-5
3-2	Initial Response to Detected Damage: LPC Components	3-6
3-3	Initial Response to Detected Damage: HPC Components	3-7
3-4	Initial Response to Detected Damage: Combustor and Ignition System Components	3-8

3-5	Initial Response to Detected Damage: HPT Components	3-9
3-6	Initial Response to Detected Damage: LPT Components	3-10
3-7	Initial Response to Detected Damage: Nacelle Components	3-11
3-8	Initial Response to Detected Damage: Engine Subsystem Components	3-12
3-9	Initial Response to Detected Damage: Lubrication System and Lubricated Components	3-13
3-10	Engine Module Damage Response Summary	3-14
3-11	Rate Summary by Response Category	3-26
3-12	Propulsion System End Effects: Compression System Components	3-28
3-13	Propulsion System End Effects: Hot Section Components	3-29
3-14	Propulsion System End Effects: Engine Subsystems Components	3-30
3-15	Minimum Requirements for Engine Restart (Compression System Components)	3-33
3-16	Minimum Requirements for Engine Restart (Hot Section Components)	3-34
3-17	Minimum Requirements for Engine Restart (Exhaust System and Nacelle Structure)	3-35
3-18	Minimum Requirements for Engine Restart (Engine Subsystems Components)	3-36
4-1	Message Types, Levels, Implementations, and Definitions	4-6
4-2	Proposed Annunciation Strategy and Criteria	4-14
5-1	Gas Path and Lubricated Component Engine Damage Detected Through Postflight Inspection and In-Flight Effects	5-7
5-2	Damage Detection System Concepts and Capabilities	5-29
5-3	Vibration Signal Content	5-37
5-4	Damage Detection Surge Accommodation Scheme	5-41
5-5	Strategy 2 Comparison to Strategy 1	5-47
5-6	Example Damaged Engine Automated Power Determination Requirements	5-57
6-1	Engine Damage Detection Benefits Comparison	6-3
6-2	Engine Damage Detection Implementation Risk Assessment	6-5

LIST OF ACRONYMS

ACC	Active Clearance Control
AD	Airworthiness Directive
AHM	Airborne health monitoring
AIA	Aerospace Industries Association
APU	Auxiliary power unit
AVM	Airborne Vibration Monitor
CFR	Code of Federal Regulations
DLODS	Duct Leak Overheat Detection System
ECS	Environmental control system
EEC	Electronic Engine Control (Used interchangeably with FADEC)
EGT	Exhaust gas temperature
EHM	Engine health monitoring
EICAS	Engine Indication and Crew Alerting System
EPR	Engine pressure ratio (Engine Exhaust Pressure divided by Inlet Pressure)
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control (Used interchangeably with EEC)
FDE	Flight deck effect
FDR	Flight data recorder
FOD	Foreign object damage
FODS	Fire/Overheat Detection System
HP	High pressure
HPC	High-pressure compressor
HPT	High-pressure turbine
ICR	Inappropriate crew response
IFSD	In-flight shutdown
IGV	Inlet guide vane
IPC	Intermediate-pressure compressor
IPT	Intermediate-pressure turbine
LLP	Life-limited part
LOC	Loss of Control
LP	Low pressure
LPC	Low-pressure compressor
LPT	Low-pressure turbine
LRU	Line replaceable unit
MFD	Multifunction display
ND	Navigation display
NGV	Nozzle guide vane
PFD	Primary flight display
PMA	Permanent magnet alternator
PSM	Propulsion System Malfunction
RTO	Rejected takeoff
SDGE	Shutdown good engine

STA	Sustained thrust anomaly
UER	Unplanned engine removal
VSV	Variable stator vane

EXECUTIVE SUMMARY

Modern commercial transport turbofan engines are highly reliable. Propulsion system malfunctions significant enough to result in unscheduled engine removal occur less than once per 15,000 engine hours, and for in-flight shutdowns, less than once per 100,000 engine hours. When an engine malfunction does occur, however, flight crew awareness of the specifically affected engine and nature of the malfunction has the potential to reduce the likelihood of inappropriate crew response.

This report documents the Phase 3 of an ongoing Federal Aviation Administration-sponsored, multiyear study of Propulsion System Malfunctions + Inappropriate Crew Response (PSM+ICR).

Phase 1 determined that detection and alerting had the potential to prevent or mitigate PSM+ICR, documented the reduced potential for PSM+ICR in modern aircraft, and identified additional new detection and alerting to further reduce the potential for PSM+ICR.

Phase 2 focused on the development of detection and annunciation strategies for sustained thrust anomalies.

Phase 3 focused on the detection and annunciation of failure conditions for which the engine continues to operate, and for which the damage is significant enough to justify flight crew awareness or response. This study did not seek to evaluate the efficacy of long-term engine health monitoring, but rather, focused on engine damage significant enough to operationally affect the current flight or subsequent dispatchability.

Phase 3 concluded that sensor fusion-based engine damage detection provides a benefit toward preventing shutdown good engine (SDGE) ICR events. Phase 3 further concluded that a sensor fusion damage detection system would likely have annunciated damage during the Kegworth, Leicestershire, January 8, 1989, event. Thus, such engine damage annunciation may have prevented the SDGE ICR that led to hull loss and fatalities in this incident. To ensure such detection and alerting do not cause unintended in-flight shutdowns, diversions, air turnbacks, or unnecessary maintenance, the damage detection threshold should be set high enough so that crew action would likely be required within the current flight.

Phase 3 was divided into four distinct tasks. During Task 1, service data for engine removals and in-flight shutdowns over a 6-year period were analyzed and classified for frequency of occurrence and principally damaged engine component. A detailed failure mode assessment was performed on a typical, modern, electronically controlled turbofan propulsion system. This included an assessment of the operational and economic consequences, existing flight deck effects, indications, alerts, and engine sensor effects resulting from specific damage types. These damage modes were further characterized for detection potential through the use of existing standalone sensors, combination of existing sensors (hereafter defined as sensor fusion) or new sensors. Task 2 used the Task 1 service data and failure analysis to determine that damage alerting should be combined into common response groups. As such, the following engine

components were determined to be the best candidates for evaluation of damage detection using sensor fusion:

- Gas path components: fan, compressor, and turbine blades; vanes and seals; and the combustor.

- Lubricated components: bearings, seals, and gearboxes.

Task 3 used the service engine damage rate data to establish operational criteria for engine damage detection and annunciation reliability both in terms of failure to detect actual damage events as well as the avoidance of false alarms. The relative infrequency of engine damage events coupled with stringent flight deck engine damage alerting requirements indicated that multiple sensor inputs, or sensor fusion, may be necessary to meet the false alerting criteria. Engine damage modes were evaluated in terms of five crew response categories:

- No action (Awareness Only)
- Restrict Thrust
- Shutdown (Caution level)
- Immediate Shutdown (Warning level)
- Isolate Bleed Air

Ultimately, Phase 3 concluded that, of these five response categories, only two damage types were not typically covered by dedicated alerts on existing large transport aircraft. Specifically, these two damage types could result in the following potential new alerts:

- Awareness/Restrict Thrust for gas path component damage
- Shutdown for lubricated component damage

Task 4 considered a spectrum of engine damage detection and alerting concepts for capability, complexity, and feasibility of implementation. These concepts ranged from existing single-sensor, limit-exceedance schemes to fusion of existing sensors to engine model-based systems fully integrated with engine health monitoring.

Based on a high-level assessment of the potential concepts, two general approaches for detection of engine damage through fusion of existing sensors were selected for more detailed evaluation:

1. Shifts of two or more parameters during steady-state commanded thrust. Schemes that used only vibration signals and exhaust gas temperature were compared against concepts that employed the full suite of available engine parameters. Since this detection method does not detect damage if a thrust change occurred between the sensor shifts, it was determined to be not operationally acceptable.

2. Multiparameter shift sensing supplemented by table lookup engine performance models. These schemes enabled damage detection of parameter shifts separated in time and at different throttle settings.

With the addition of engine performance models, detection and alerting for engine damage levels below limit exceedance may be both possible and operationally feasible, but implementation and operational issues require further consideration. Specifically, the study concluded that:

- Improved engine damage detection primarily has the potential to reduce SDGE ICR by explicit awareness of the specifically-damaged engine. In the case of lubricated component damage, a sensor fusion system would likely provide a deterministic response (shutdown).

- Inappropriate threshold selection for an engine damage alert has the potential for undesirable consequences, which may include increased in-flight shutdowns, diversions, air turnbacks, and unnecessary airline maintenance. Establishing the appropriate threshold is likely to require collecting in-service time history data correlated with shop findings for engine damage events. Although such data were not available for this study, information from existing flight data recorder or quick access recorder systems may provide adequate insight for assessing potential threshold levels. Once collected, these data would also support the development of advanced information-based engine system displays. Such advanced displays have the potential to reduce ICR by reducing pilot monitoring, detection, and interpretation of the existing prescriptive individual parameter displays.

- The engine damage alert benefit is considered modest for two reasons. First, the evaluated schemes were unable to couple an alert with a unique pilot response procedure for gas path component damage scenarios. Second, the majority of the Aerospace Industries Association and European Association of Aerospace Industries Project PSM+ICR events were assessed to be either (1) not addressable by an alert (e.g., rejected takeoff above V1); (2) already covered by existing alerts (e.g., fire warning); or (3) covered by the Phase 2 sustained thrust anomaly alerts (some of which include existing certified designs).

- Full-scale development and implementation of sensor fusion damage detection will require careful correlation of damaged engine data against the supporting engine performance models to establish practicable damage annunciation thresholds.

- The primary focus of the study was feasibility, and as such, the study did not involve a cost/benefit analysis. Implementation and operational considerations were identified for the sensor fusion schemes as well as alternatives such as indicated vibration alerting.

- Further study to advance the following areas is recommended:

  - Collection of in-service data for sensor fusion algorithm development and feasibility confirmation.

  - Advanced engine performance models for expanded damage detection. A better understanding of engine damage detection capability could enhance an information-based display system. Further, engine damage detection could also

enable both (1) adaptive controls that provide continued damaged engine operation (although at potentially lower thrust) for the remainder of the flight; and (2) prediction of damaged engine power and restart capability.

- Explore potential benefits of new sensors for engine damage detection and adaptive engine control.

- The basic strategies outlined for operational damage detection are similar in nature to more sophisticated concepts already in use or in advanced stages of development for engine health monitoring (EHM). EHM exists primarily to provide timely notification of required maintenance. Timely maintenance reduces the occurrence of PSM, thus EHM reduces the opportunity for ICR.

1. BACKGROUND.

This report documents the third phase of an ongoing Federal Aviation Administration (FAA)-sponsored, multiyear study of Propulsion System Malfunction + Inappropriate Crew Response (PSM+ICR). This phase focused on detectable engine damage using existing engine sensors and built upon the research work of the previous phases described below.

1.1 PREVIOUS WORK.

Recent aerospace industry research into PSM+ICR initiated with the Aerospace Industries Association (AIA) and European Association of Aerospace Industries 1998 Project Report [1]. Undertaken in response to a prior FAA request, this study was motivated in part by a 1994 turboprop airplane accident. The accident was attributed to inappropriate interpretation of a recovery function warning light as indicative of an engine malfunction.

Reference 1 documented 80 events where turbofan PSMs occurred including 34 accidents. The report principally focused on PSM recognition and potential improvements to crew training. The report concluded that improper PSM recognition coupled with the relative infrequency of PSM events had resulted in a fairly constant annual level of PSM+ICR events. Among the reference 1 recommendations were the following statements:

> "The requirements for propulsion system instrumentation should be reviewed, and requirements and advisory material related to powerplant and propellers should be established:
>
> - A review of propulsion system parameters should be completed to determine if improved engine and propeller displays or methods can be found to present information in a manner which would help the flight crew diagnose malfunctions.
>
> - Failure and malfunction annunciation and warnings to provide improved means for crews to identify propulsion system malfunctions. The areas for consideration include, the types of annunciation and warnings (visual, aural, tactile, etc.), introduction of annunciations for engine surge, asymmetric thrust, engine failure, tire failure; and standardization of warning and annunciation inhibits."

These recommendations formed the basis for follow-on, FAA-sponsored research into the detailed causes and potential remedies for PSM+ICR.

1.1.1 The PSM+ICR Research—Phase 1.

Completed in 2004, Phase 1 [2] probed the causes of service-related PSM+ICR events. The PSM+ICR events were determined to stem primarily from unannuciated malfunctions for which

no alerting system cues were available to direct specific pilot awareness or action. PSM+ICR events were divided into four categories:

- Rejected Takeoff Above V1 (go/no-go takeoff decision speed)
- Nonnormal Procedure Errors
- Shutdown Good Engine (SDGE)
- Loss of Control (LOC)

Reference 2 concluded "a consistent contributing factor in PSM+ICR events is the lack of crew awareness of the existence, location, or type of the PSM, i.e., there is no clear, explicit indication or annunciation of the engine malfunction or the affected engine(s). In many cases, even when the crew is aware a malfunction exists, they are unaware that it is propulsion system related. High workload, limited time for analysis and assessment, autothrottle or autopilot engagement, and poor crew communication or resource management are often among the contributing factors."

The Phase 1 research specifically evaluated the ICR prevention potential for improved PSM annunciation. LOC was determined to be best prevented by improved airspeed and attitude awareness. Rejected takeoff above V1 scenarios were determined to benefit most from improved training. However, for the remaining PSM+ICR categories, the Phase 1 research concluded "annunciations which identify the presence of a PSM, identify the affected engine(s), and identify the specific type of PSM, have potential for ICR prevention and risk mitigation."

The study recommended "follow-on work to define PSM+ICR-related surge and powerloss detection requirements, validate and demonstrate desired surge and powerloss detection capability, and determine surge and powerloss detection and annunciation implementation feasibility."

1.1.2 The PSM+ICR Research—Phase 2.

Building on the Phase 1's recommendations, the Phase 2 PSM+ICR research [3] focused on detection and annunciation of sustained thrust anomalies (STA). Such anomalies were defined to include:

- Flameout—quenching of the combustor flame with an attendant drop in engine rotor speeds.

- Nonrecoverable Surge or Stall—compression system airflow interruption that progresses to a steady-state stall condition usually resulting in an uncommanded deceleration to subidle rotor speeds.

- Continuous Multiple Surge—repeated sequential instances of compression system surge and recovery.

- Thrust Failed High or Low (sensor)—actual engine thrust significantly differs from indicated thrust due to a thrust control sensor malfunction.

- Thrust Failed High or Low (indicated)—actual engine thrust differs significantly from commanded thrust.

- Thrust Failed Low (damage)—indicated and commanded thrust agree, but actual thrust is significantly lower due to fan system damage (high bypass turbofan propulsion system).

- Engine Slow to Accelerate or Decelerate—the transient thrust response of the engine following throttle movement differs significantly from the normal expected response.

- Thrust Oscillations—actual thrust cycles uncommanded low and high around the commanded setpoint.

Each STA was characterized for principal symptoms, relative occurrence, engine control accommodation, potential operational benefit of annunciation, and annunciation timing and reliability requirements. Further, the study evaluated the risks associated with developing STA detection hardware, algorithms, and annunciation technology. The detection system integrity requirements were assessed from both engine and aircraft "needs" perspectives.

The Phase 2 effort conducted preliminary research on influence of engine damage in PSM+ICR. Specifically, in-service, in-flight shutdown (IFSD) and unplanned engine removal (UER) data were assessed to determine principally damaged components and primary failure indications. These source data formed the basis for the Phase 3 follow-on effort.

1.2 THE PSM+ICR RESEARCH—PHASE 3 SUMMARY.

The PSM+ICR Phase 3 research reviewed the role of engine damage in PSM+ICR events and focused on how engine damage detection and annunciation could be improved over existing systems. For study purposes, a damaged engine was defined as having suffered some form of mechanical disruption, which causes the engine to either not operate or operate in a not-as-designed manner. Since the term "engine damage" potentially covers a very wide scope, ranging from subtle performance deterioration to complete failure, this study adopted the paradigm shown in figure 1-1. As indicated in this figure, this study focused on detection of damage occurring above maintenance manual limits. Thus, engine health monitoring (EHM) was not undertaken during the Phase 3 research. Rather, the Phase 3 study considered engine damage modes primarily where propulsion system hardware was degraded to the extent that engine operation could be affected during the current or next flight (flight crew awareness or action was desired to maintain propulsion system operation or continued flight safety). The study also considered detection and isolation of engine damage modes to the major module level. Such capability could supplement existing line replaceable unit (LRU)-based maintenance messages and, therefore, benefit dispatch-related maintenance.

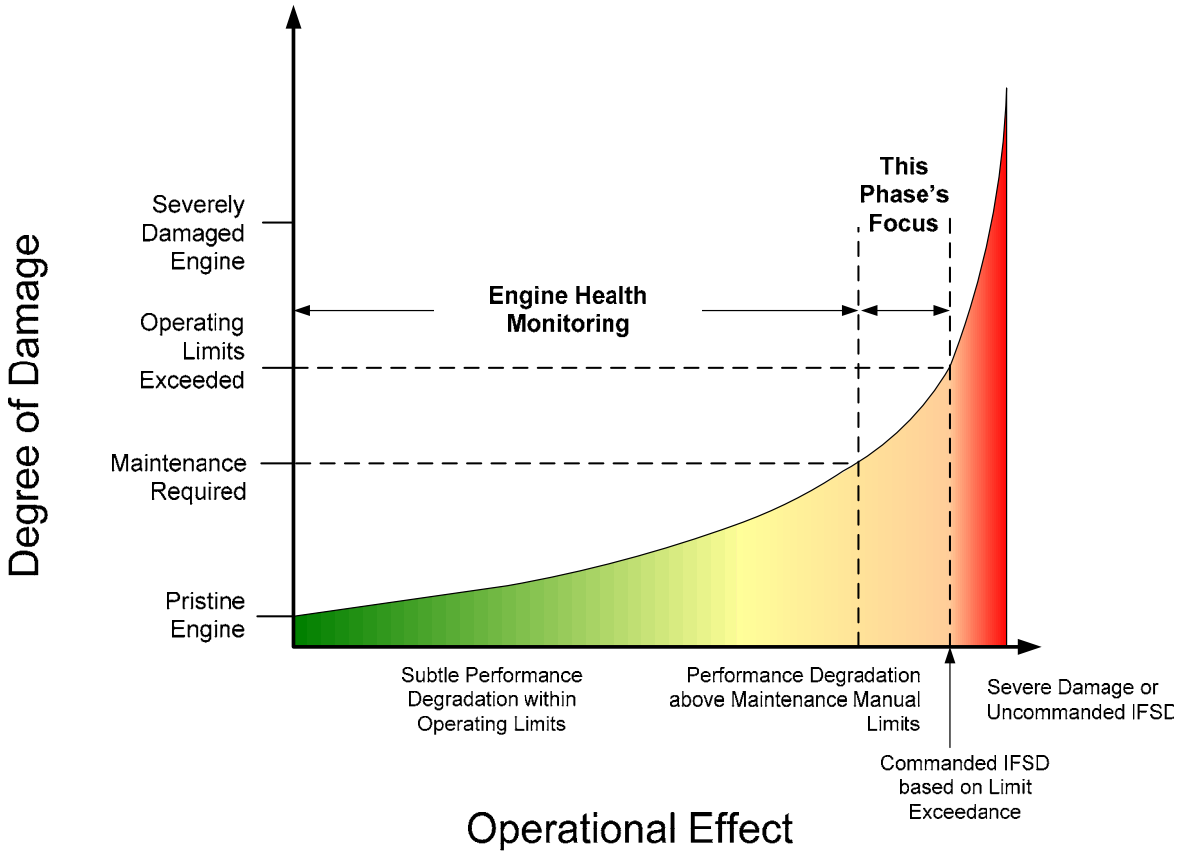


Figure 1-1. Engine Damage Paradigm

The study first completed a comprehensive review of significant engine damage modes and assessed operational effects and detectability. The study then completed an assessment of desired damage annunciation features from a flight crew perspective.

The flight crew-desired features were further applied toward the development of engine damage annunciation criteria. The Phase 3 research evaluated engine damage detection methods that integrate multiple sensor inputs from common and disparate propulsion subsystems (hereafter referred to as sensor fusion). The Phase 3 research concluded with an assessment of the sensor fusion strategies' performance against the desired operational features.

As detailed in section 2, the study assumed a propulsion system and sensor suite configuration equivalent to current-generation high bypass ratio Full Authority Digital Electronic Control (FADEC)-equipped gas turbine engines. The study focused on engine damage detection within the following propulsion subsystems: fan, engine power section (booster, compressor, combustor, and turbine), and fuel supply and lubrication systems. The sensed engine damage modes were integrated to provide an engine damage annunciation. The study also determined the recommended response to the engine damage annunciation.

The study was conducted with inputs from two commercial transport engine companies (Pratt & Whitney and General Electric) and one EHM system supplier (Meggitt Aerospace).

The Phase 3 study assumed current-generation engine sensors and aircraft instrumentation, and sought to answer the following questions:

- Can engine damage be detected, differentiated to the affected engine, and quantified for the specific amount of performance degradation?
- Can it be determined if a damaged engine is restartable?

Even though engine sensors are integral to the propulsion system, the Phase 3 study did not specifically focus on sensor failures. Existing sensors were evaluated for both reliability and appropriateness for expanded engine damage detection.

1.3 PHASE 3 STATEMENT OF WORK.

The Phase 3 Statement of Work was released in June 2005. Portions of this Statement of Work are summarized in the following paragraphs. The Phase 3 effort was divided into four distinct research tasks plus a final documentation task. The overall relationship between the Phase 3 tasks is depicted in figure 1-2, with the individual task descriptions documented in the following sections.

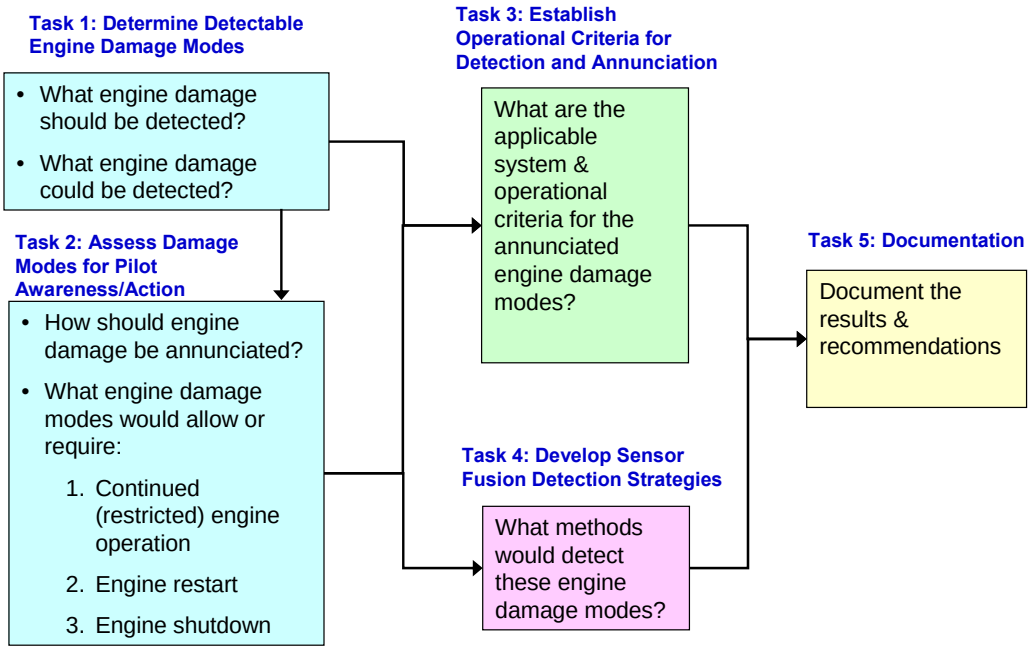


Figure 1-2. Phase 3 Task Relationship

1.3.1 Task 1: Determine Detectable Engine Damage Modes.

Task 1 determined the various types of engine damage and what types of engine damage could be detected with current sensors, fusion of current sensors, or new sensors. Those damage modes assessed to be detectable with sensor fusion were specifically carried forward for further development in Task 4.

1.3.2 Task 2: Assess Damage Modes for Pilot Awareness and Action.

Task 2 determined desired operational features for annunciation of engine damage and assessed damage modes for pilot awareness. The analysis included assessments of

- the potential to determine what power might be delivered from a damaged engine.
- which damage events might be restartable and which would not.
- damage detection fidelity requirements for dispatch-related maintenance.

1.3.3 Task 3: Establish Operational Criteria for Detection and Annunciation.

Task 3 developed annunciation strategies and criteria to address the requirements of Tasks 1 and 2. The Task 3 effort considered the integration of new damage alerting or annunciations with existing flight deck displays and crew checklists.

1.3.4 Task 4: Develop Sensor Fusion Detection Strategies.

Task 4 documented the general range of available detection concepts to address both the damage modes identified in Task 1 and the operational considerations of Task 2. Detection strategies using sensor fusion were developed in Task 4 along with the advantages and disadvantages of each strategy.

2. TASK 1: DETECTABLE ENGINE DAMAGE MODES.

2.1 TASK 1 OBJECTIVES.

The overall approach to Task 1 execution is illustrated in figure 2-1. In general, Task 1 sought to quantify the significant engine failure modes from an operational perspective. The type of engine damage and the related flight deck indications, alerts, and annunciations were considered. The engine failure modes were then evaluated for improved detection capability using fusion of existing sensors.

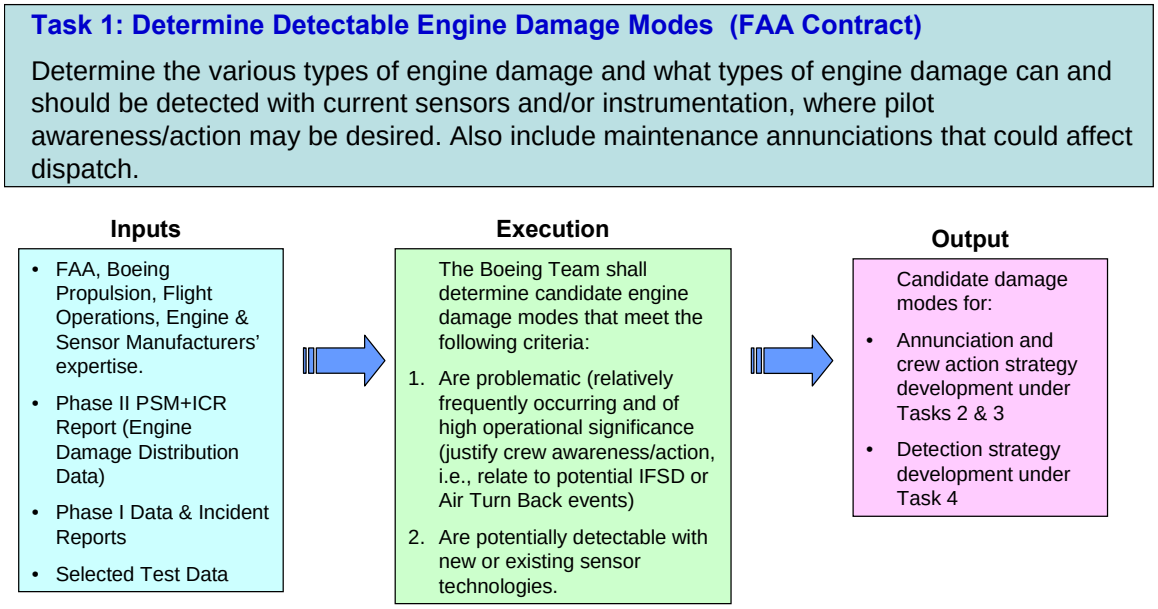


Figure 2-1. Task 1 Description and Approach

2.2 TASK 1 RESULTS SUMMARY.

Engine damage modes were categorized through both an in-service report and a detailed failure mode analysis of the turbofan propulsion system. Six years of in-service reports were extracted from an internal Boeing database that documents engine removals and IFSDs. The unplanned engine removals and IFSDs were reviewed and categorized for principally damaged engine subcomponent and related flight deck effects (FDE) such as indications, alerts, and annunciations that preceded the event. The categorized data were then used to establish the failure frequency of specific propulsion system subcomponents.

The in-service report review was accompanied by a failure mode assessment of the principal propulsion system components. This assessment considered the failure modes expected to drive a postflight engine removal or cause significant operational effects such as a thrust reduction or (commanded or uncommanded) IFSD. For each failure mode, the principal existing means of detection (either sensor or postflight inspection-based) was evaluated. The flight deck indications, alerts, and annunciations that attend these failure modes were documented for relative likelihood of occurrence. The results of the failure analysis were correlated against the failure frequency data from the in-service reports. The combined results were then applied to

establish the best damage mode candidates for improved damage detection. Engine gas path and lubricated components emerged from this evaluation as the best candidates for improved damage detection using fusion of existing sensors.

Task 1 undertook a review of the 80 PSM+ICR events, documented in references 1 and 2, to determine which events included engine damage and thus might have benefited from damage detection and annunciation. This review concluded that at least 55 of the 80 events, or ~69%, involved some form of engine damage. The review also concluded that damage detection and annunciation may have been the primary means of ICR prevention in approximately 5%-11% of these events.

2.3 ENGINE DAMAGE MODE PARADIGM.

The engine damage spectrum ranges from minor leaks, subtle performance deterioration, wear and chafing of noncritical components, or noncritical LRU failure to failures that induce uncommanded engine shutdown, complete separation or other potentially hazardous effects. The noncritical end of this spectrum (i.e., damage modes addressable via routine engine maintenance or engine health monitoring) was not evaluated. Rather, the damage types of specific interest to this phase's research were those modes severe enough to warrant flight crew awareness or action during the current or immediately subsequent flight. As previously indicated in figure 1-1, such modes typically involved engine performance degradation near or above operating or maintenance manual limits.

2.4 GENERIC ENGINE DESCRIPTION.

A two-spool, high bypass turbofan engine design was selected for the basis of damage evaluation in the Phase 3 research[*]. This engine configuration has been the large transport commercial service standard for over three decades and has accumulated a very large amount of service experience. While not specifically evaluated in this study, the elements of a turboprop engine design, such as the core components and subsystems, are relatively similar to the turbofan propulsion system.

A generic engine model was developed for this research to encompass common aspects of engine designs from the major engine manufacturers. An overall pictorial of this model is provided in figure 2-2, and the individual major modules and supporting subsystems are detailed in the following sections. The generic paradigm considered the following major elements of a typical modern commercial turbofan propulsion system.

- The "bare" engine (consisting primarily of the gas path and casing components)—In this context, gas path refers to the engine components dedicated to the compression, diffusion, combustion, and expansion of the inducted air stream.

- Engine subsystems—Those components necessary to control and provide lubrication, fuel, and extract secondary power and bleed air from the gas path.

[*] Relevant differences between two- and three-spool turbofan engine designs are described in section 2.4.2.

- Engine installation—The mounting and aerodynamic fairing structure that houses the engine and provides (1) a load path for thrust transmission to the aircraft and (2) routing for pneumatic, fuel, hydraulic, and other services between the aircraft and engine. The engine installation also enfolds the thrust reverser.

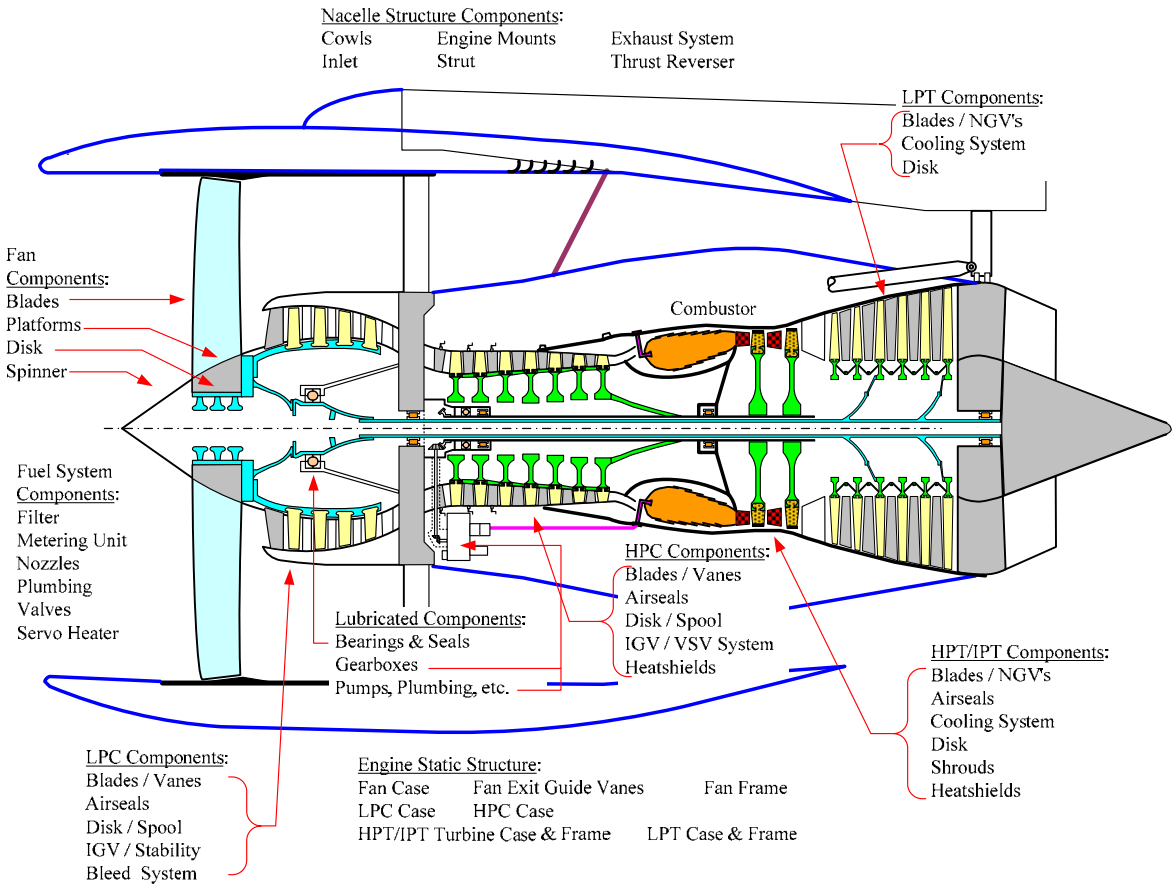


Figure 2-2. Generic High Bypass Turbofan Engine

Consideration of the relevant engine damage modes required segregating the propulsion system into constituent modules, subsystems, and installation structure. Sections 2.4.1 through 2.4.9 detail the major elements of each module. The generalization employed in the generic engine design melds together certain features that may be unique to specific engine manufacturers, but the information is intended to reflect common attributes of all current commercial turbofan designs. The propulsion system is described in a "front-to-back" order and consists of the following elements:

- Fan Module
- Low-Pressure Compressor (LPC) Module
- High-Pressure Compressor (HPC) Module
- Combustor/Diffuser Module

- High-Pressure Turbine (HPT) Module
- Low-Pressure Turbine (LPT) Module
- Engine Subsystems:

    - Lubrication System
    - Lubricated Components
    - Bleed Air System
    - Fuel Supply System
    - Controls and Sensors

- Engine Installation:

    - Inlet
    - Thrust Reverser
    - Nacelle Structure including Strut, Cowls, and Fairings
    - Exhaust System

2.4.1 Fan Module.

The fan inducts ambient air and imparts work to the flow for two purposes. The majority of the flow bypasses the core section and is accelerated through the fan nozzle to provide thrust. In a high bypass design, this fan air stream is the principal contributor to thrust. The remaining portion of the fan air stream near the hub is provided to the core compression system. The fan rotor is driven by the LPT. The fan module is shown in figure 2-3 and includes the following major elements:

- Fan Blades—The blades rotate to impart work to the ambient air flow. In commercial turbofan designs, the fan blades are the first set of airfoils encountered by the incoming flow. Consequently, fan blades are often the first component damaged when foreign objects, such as birds, are ingested. Further, commercial fan designs are universally single stage (i.e., employ only one row of fan blades). Early high bypass engine designs incorporated midspan shrouds to attenuate vibration. Later, "wide-chord" fan designs were able to eliminate the shroud feature.

- Fan Spinner—This component provides an aerodynamic fairing for the fan disk and blade attachment regions.

- Platform/Annulus Filler—Attached at the base of the fan blades, these components also provide aerodynamic fairing for the fan blade-disk attachment interface.

- Fan Case—The fan case houses the fan and forms the outer boundary for the fan air flow. As a major engine structural member, the fan case is sometimes used as the forward engine mount attachment point. The fan case also provides a protective barrier for the aircraft in the event a fan blade is released due to failure. Depending on the engine design, the fan case may employ a reinforced containment wrap section to bolster the fan blade-out capability.

- Fan Abradable Coating/Rubstrip—Minimization of fan tip clearance to the case (and therefore maximization of fan aerodynamic efficiency) necessitates a sacrificial coating on the interior of the fan case at the fan blade track location.

- Fan Outlet Guide Vanes—This component serves two functions: (1) it removes the swirl from the fan flow and (2) provides the structural support for the fan case. Some engine designs accomplish these two functions in separate fan struts and guide vanes, while other designs integrate the two features, as shown in figure 2-3.

- Fan Hub Frame—The fan hub frame completes the fan case attachment from the outlet guide vanes back to the engine case.

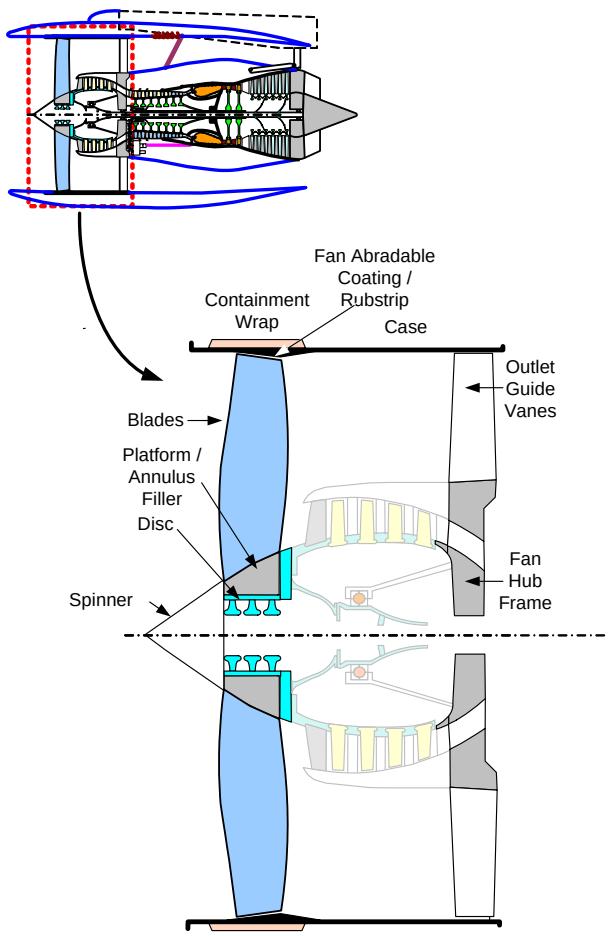


Figure 2-3. Fan Module

2.4.2 Low-Pressure Compressor.

The LPC, or booster module, is the next element downstream of the fan in the core air stream. In the two-spool engine design shown in figure 2-2, the LPC is driven by the LPT and, thus, rotates at fan shaft speed. In a three-spool engine design (not shown in this report), an intermediate-pressure compressor (IPC) is added between the fan and HPC. A separate intermediate-pressure turbine (IPT) that rotates independently of the other two HPC shafts drives the IPC.

The LPC further compresses the core air stream beyond the level provided by the upstream fan. Major elements of the LPC are shown in figure 2-4 and described below.

- LPC Splitter—This component divides the fan flow between the portion directed to the fan nozzle and the portion entering the core air stream.
- LPC Case—This component provides the inner flow path for the fan air leaving the fan blades and entering the outlet guide vanes as well as structural support for the LPC vanes.
- LPC Blades and Vanes—These airfoils compress and direct the air into the HPC.
- LPC Drum/Disk—This component retains the LPC blades and is connected to the driving LPT through the forward fan shaft/fan disk.
- LPC Air Seals—The pressurized airflow is sealed at each stage of the LPC by inner and outer air seals. Typically, the outer air seals are formed by close contact between the rotating LPC blades and an abradable coating on the stationary segments between the LPC vanes. The inner diameter of the vanes is typically sealed by toothed labyrinths.

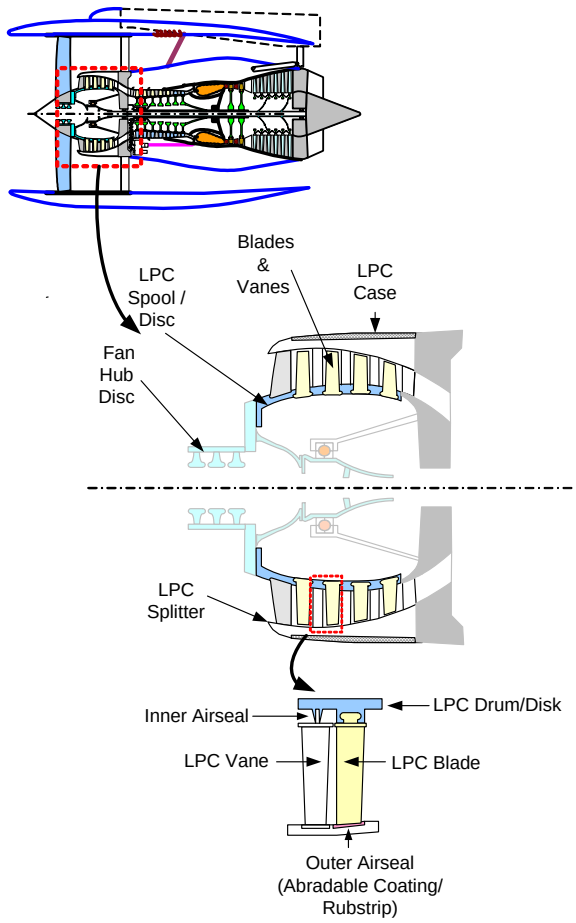


Figure 2-4. Low-Pressure Compressor Module

2.4.3 High-Pressure Compressor.

The HPC is the final element in the compression system module. In a two-spool turbofan design, the HPC does the bulk of the core air compression task. As such, it usually comprises the greatest number of compression path distinct stages, and hence, airfoil quantity. As shown in figure 2-5, HPC components typically include the following.

- Inlet Guide Vanes (IGV)—The IGVs provide the initial flow conditioning for the HPC. These airfoils are usually designed to have variable incidence angle and, as such, are rotatable through a mechanical drive system. Along with the variable stator vanes, the variable nature of the IGVs allows the HPC to function with aerodynamic stability (i.e., surge and stall free) over the entire engine operating range.

- Variable Stator Vanes (VSV)—Analogous to the IGVs, the VSVs are also incidence angle-controllable airfoils that comprise the initial two to three stages of the HPC.

- IGV/VSV Actuation System—The incidence angle of the IGVs and VSVs is controlled by rotating the blades with lever arms that protrude from the HPC case at each variable stage. To ensure all blades rotate a uniform amount, the lever arms are tied together with a unison ring. The unison rings are, in turn, driven by a linear actuator connected to the unison rings through a lever mechanism.

- HPC Case—The HPC case houses the blades and vanes.

- HPC Disks—Each stage of HPC blades are attached at the root to a disk. The disks in turn are ultimately driven through the high-pressure (HP) shaft by the HPT.

- HPC Air Seals—Seals are necessary in the HPC to prevent leakage across the blade tips and between stages. Depending on the specific engine design and engine manufacturer, an abradable coating may be used to provide the blade tip sealing. The interstage sealing at the inner diameter of the vanes is usually accomplished with labyrinth seals.

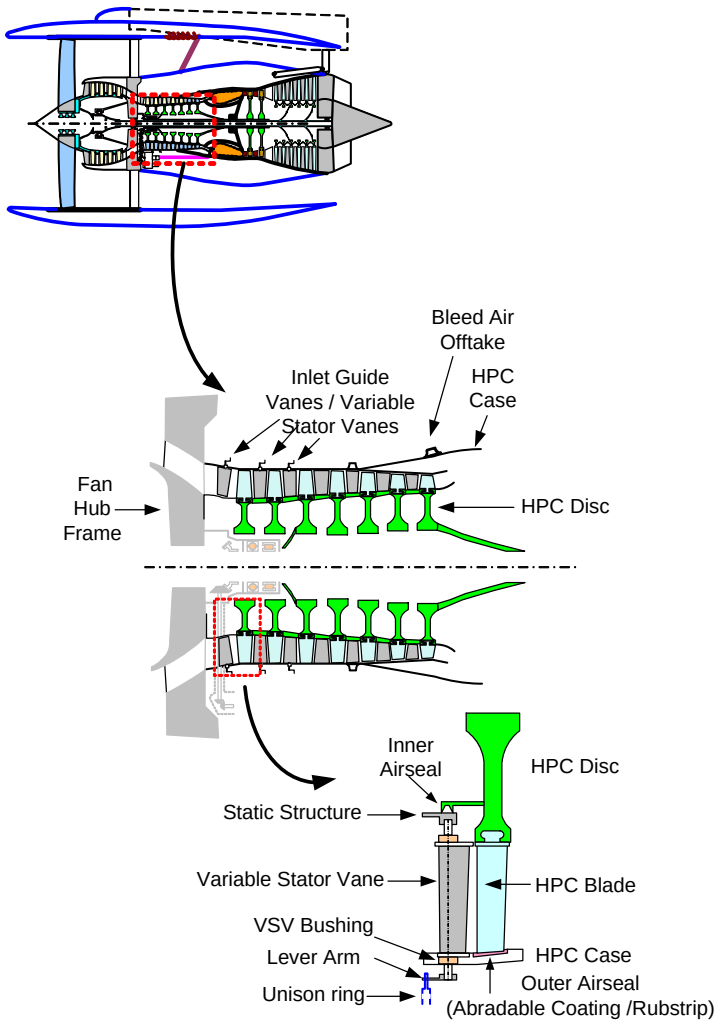


Figure 2-5. High-Pressure Compressor Module

2.4.4 Combustor/Diffuser.

The combustor adds energy to the compressed air by oxidizing fuel delivered through the fuel supply system. Principal combustor/diffuser components are described below and shown in figure 2-6.

- Diffuser—After exiting the HPC, the air velocity is reduced in the diffuser prior to entry into the combustion chamber.

- Fuel Nozzles—The fuel is injected at high pressure and atomized for combustion through a series of fuel nozzles.

- Ignitor—During engine start, combustion is initiated by a high-voltage electrical arc at one or more ignitors.

- Combustor Liner—The burning gases are confined to the interior of the combustor liner that shields the combustor case from the high temperatures.

- Combustor Case—The combustor case is a pressure vessel that houses the combustor liner. Typically, the combustor case is segregated from the liner by a layer of HPC discharge air.

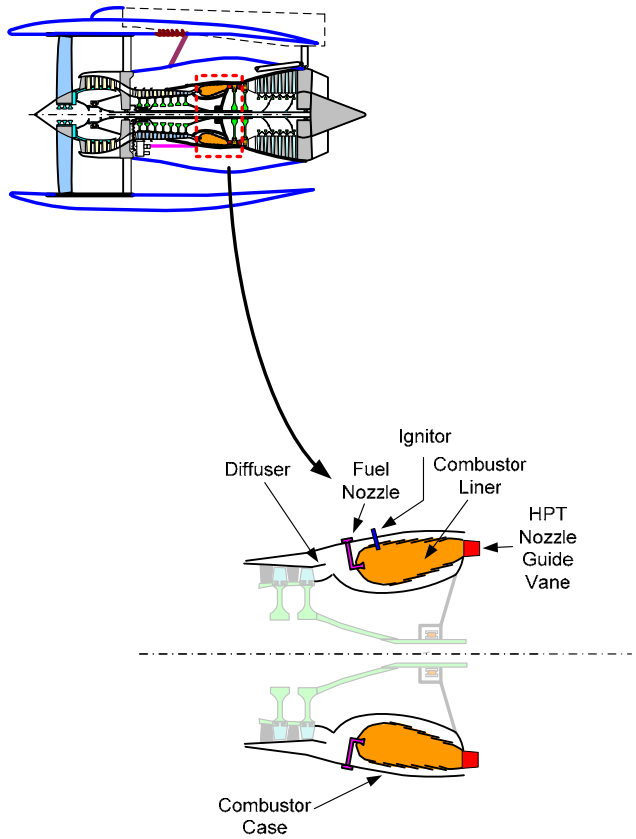


Figure 2-6. Combustor/Diffuser Module

2.4.5 High-Pressure/Intermediate-Pressure Turbine.

Following the heat addition in the combustor, the high-pressure and high-temperature gas is fed to the HPT. The principal function of the HPT is to drive the HPC. Depending on the engine design, the HPT may consist of one or two stages. In three-spool engines, the second stage of the HPT is replaced with an IPT, which is coupled to the IPC and rotates independently of both the low pressure (LP) and HP shafts. The HPT elements are shown in figure 2-7 and are described below.

- Nozzle Guide Vanes (NGV)—The NGVs accelerate the flow prior to entering the blades. Since the gas temperature usually exceeds the NGV metal temperature capability, the NGVs are porous to allow the injection of cooling air. Further temperature protection is provided in the form of antioxidation and thermal barrier coatings.

- HPT Blades—The HPT blades extract work from the hot gas and provide torque through the HPT disks to the HP shaft, which, in turn, drives the HPC. Similar to the HPT NGVs, the HPT blades incorporate cooling and insulating features to protect the metal blades from the high-temperature gases.

- HPT Outer Air Seal (Shroud)—Hot gas leakage across the HPT blade tips is sealed by the static shrouds. Similar to the HPT blades and NGVs, the shrouds are typically cooled and insulated from high-temperature gas.

- HPT Rotating Air Seals—Sealing the gas from leakage between HPT stages or leakage to other parts of the engine are one or more rotating air seals. These air seals are typically labyrinth designs.

- HPT Disks—The HPT blades are attached at the root of the HPT disk. The disk also provides an attachment to the HP shaft. The HPT disks are usually directly cooled with compressor air.

- HPT Case—The HPT blades and vanes are housed within the HPT case. Virtually all modern turbofans include an Active Clearance Control mechanism that controls the HPT blade tip clearance by cooling the case.

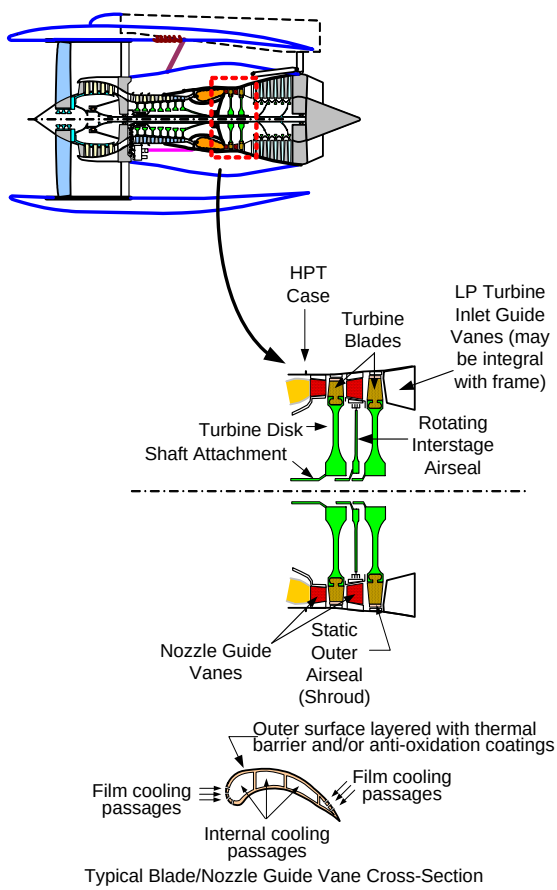


Figure 2-7. High-Pressure Turbine Module

2.4.6 Low-Pressure Turbine and Exhaust System.

The next element downstream from the HPT is the LPT. The LPT extracts energy from the gas to drive the fan and usually consists of three or more stages of blades and NGVs. Gas exiting the LPT is then routed through the exhaust system, which recoups thrust from the remaining core gas energy. The LPT and exhaust system module is illustrated in figure 2-8. The elements of the LPT and exhaust system are described below.

- LPT NGVs—Analogous to the HPT NGVs, the LPT NGVs accelerate and direct the flow into each downstream row of blades. Depending on the engine design and associated operating temperature, initial stages of the LPT NGVs may be cooled.

- LPT Blades—The LPT blades extract work from the gas to drive the fan. Due to the reduced gas temperature from the upstream HPT work extraction, LPT blade cooling is usually not required in most modern high bypass turbofan designs.

- Interstage Air Seal—Leakage between LPT stages is controlled through seals that are typically labyrinth configurations.

- LPT Disks—The LPT disks attach the LPT blades at the blade root and transmit the blade torque to the fan through the LP shaft.

- Turbine Rear Frame—The LPT exhaust gas is directed through an exit structure that contains struts to deswirl the flow prior to entering the primary nozzle. The Turbine Rear Frame can act as the attachment point for the aft engine mount.

- Turbine Case—The LPT case houses the blades and vanes. Analogous to the HPT case, the LPT case usually incorporates an Active Clearance Control System, which actively manages the cooling flow to the outer case as a means of controlling LPT blade tip clearance.

- Primary Nozzle/Exhaust Plug—The last element in the core gas path is the primary nozzle. The primary nozzle accelerates the exhaust gas to provide a portion of the overall engine thrust (the majority of engine thrust is provided by the fan stream in a high bypass turbofan). The exhaust plug forms the interior attachment point for the nozzle flow.

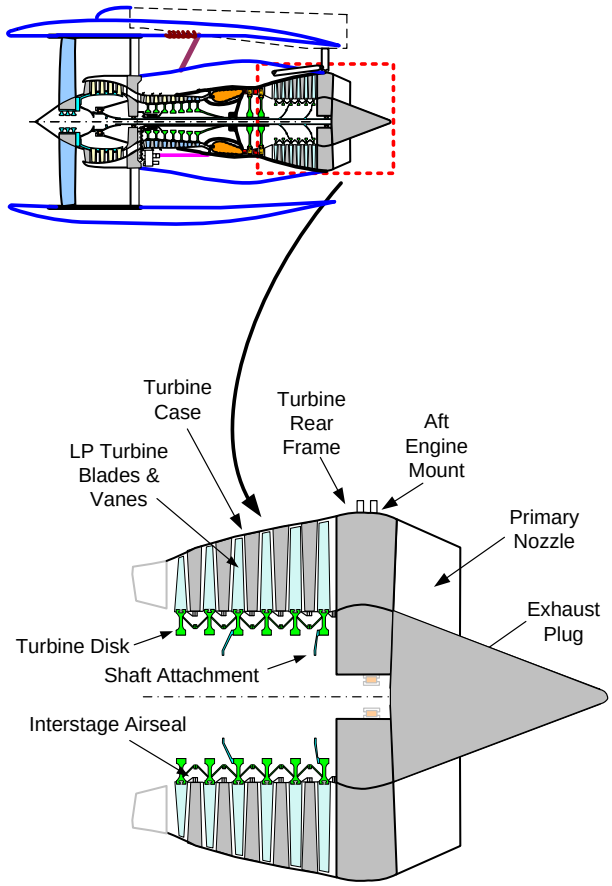


Figure 2-8. Low-Pressure Turbine and Exhaust System Module

2.4.7 Engine Subsystems.

Various engine subsystems, including the lubrication system, lubricated components, fuel supply system, bleed air system, and engine controls and sensors supporting the operation of the principal gas path components, are described in sections 2.4.7.1 through 2.4.7.5.

2.4.7.1 Lubrication System.

The lubrication system stores, conditions, and distributes oil to the lubricated components (described in section 2.4.7.2). Typical elements and the arrangement of a turbofan lubrication system are shown in figure 2-9 and are described below. [Note: The illustrated lubrication system assumes a configuration where the engine-driven electrical generator lubrication system is segregated from the engine lubrication system.]

- Oil Reservoir—The bulk of the lubrication system oil is stored in the oil reservoir (tank). The oil reservoir is equipped with a level sensor to remotely indicate available oil quantity. The oil reservoir also serves as the final deaeration point before the oil is supplied back to the engine. Provisions to replenish oil are generally fitted directly to the oil reservoir.

- Supply Pump—Oil is drawn from the reservoir through the supply pump where the pressure is elevated to provide sufficient head to supply the downstream lubricated components.

- Supply/Scavenge Filter—Particulate contamination is removed from the oil by one or more filters. Depending on the engine design, a filter may be incorporated after the supply pump (supply filter) or prior to the oil return to the reservoir (scavenge filter). All oil filters incorporate provisions for bypass in the event of clogging. At least one of the filters is required to also provide remote indication of impending bypass.

- Oil Cooler(s)—Heat is added to the oil in the lubricated components. This heat is removed by one or more oil coolers, which transfers the heat to either air or fuel.

- Scavenge Pumps—After the cooled and filtered oil has been supplied to either the main bearing sumps or gearboxes (described in section 2.4.7.2), scavenge pumps route the return air-oil mixture back to the oil reservoir. Since most current engine designs employ air-buffered oil seals, the scavenge oil is, typically, highly aerated. Prior to final entry back into the oil reservoir, the scavenge oil will pass through a deaerator to remove entrained air ingested by the oil through the buffered seals.

- Magnetic Chip Detectors—Most engine lubrication system designs include one or more magnetic chip detectors in the scavenge plumbing. Such detectors collect ferrous particles entrained in the oil and are used for maintenance troubleshooting.

- Other Oil System Sensors—Lubrication systems are also required to include remote indications of oil pressure and temperature and, thus, include dedicated sensors for this purpose. Lastly, many modern turbofan engine designs incorporate an oil debris sensor or electronic chip detection system.

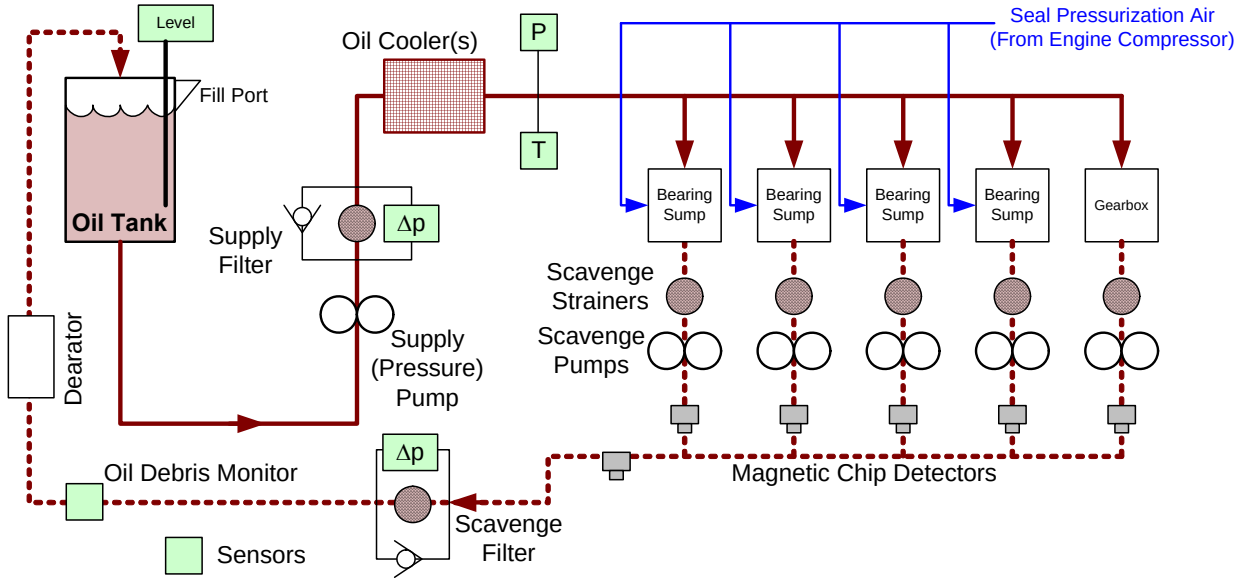


Figure 2-9. Engine Lubrication System

2.4.7.2 Lubricated Components.

Lubricated components include the components that use the conditioned oil provided by the lubrication system. While engine main shaft bearing and gearbox arrangements vary with each individual engine design, a typical configuration is shown in figure 2-10, and the principal components are described below.

- Main Shaft Bearings—Bearings are installed for each main shaft of the turbofan engine. Two general classes of bearings are used, depending on the type of reacted load:

  - Ball bearings are designed to support various combinations of radial and thrust loads.

  - Roller bearings are used to react radial loads only.

- Gearboxes—A set of gearboxes is installed to extract shaft power from the core (high-speed shaft). The shaft power is used to drive engine accessories such as the fuel metering unit, engine fuel pump, lubrication pump, and the permanent magnet alternator (PMA), as well as aircraft system devices, including the hydraulic pump and generators. The gearbox also mounts the engine starter and, thus, transmits starter torque to the high-speed shaft during ground and in-flight starting. In general, three separate gearboxes are installed:

  - An internal gearbox connected directly to the end of the high-speed main shaft.

  - A transfer gearbox that radially transmits the internal gearbox torque to the externally mounted accessory gearbox.

  - An accessory gearbox mounted to either the fan or compressor case. The accessory gearbox directly mounts and provides shaft power to the engine and aircraft accessories described above.

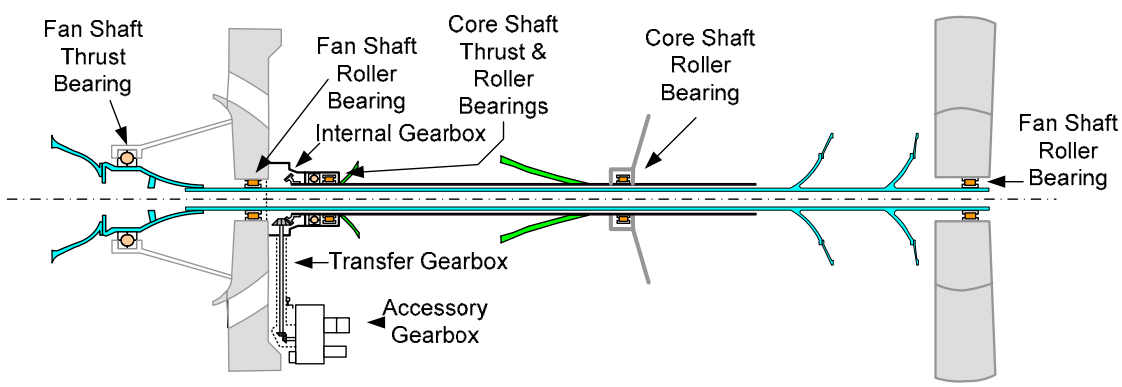


Figure 2-10. Lubricated Components

2.4.7.3 Fuel Supply System.

The engine receives relatively low-pressure (LP) fuel from the aircraft and further pressurizes and filters the fuel prior to usage within the combustor and engine control system. Typical elements of the engine fuel system are shown in figure 2-11 and are described below.

- Main Fuel Pump—Usually mechanically driven through the accessory gearbox, most modern main fuel pumps incorporate two stages, as shown in figure 2-11. The LP pump routes the fuel through a fuel filter prior to passing through a high-pressure (HP) stage that elevates the pressure sufficiently to allow (1) atomization in the combustor and (2) muscle pressure for fuel-actuated servo valves.

- Fuel Oil Cooler—A cooler is usually included upstream of the filter to provide cooling to the lubrication oil. In some applications, the fuel oil cooler may also act as a fuel heater and thus prevent system clogging due to icing.

- Fuel Filter—The fuel is filtered to avoid clogging of combustor fuel nozzles or other sensitive components in the control and actuation system. Similar to the oil filters described in the previous section, the fuel filter is equipped with bypass capability and a sensor to indicate impending filter bypass.

- Hydro-Mechanical Unit/Fuel Metering Unit—This component meters the HP fuel to both the fuel-actuated servo valves and the combustor fuel nozzles.

- Fuel-Actuated Servo Valves—Most engine designs employ HP fuel to drive various engine control devices such as VSV actuators.

- Fuel Flow Meter—A flow meter that measures fuel consumption is included downstream of the Hydro-Mechanical Unit/Fuel Metering Unit and prior to the fuel entry into the fuel nozzle manifold.

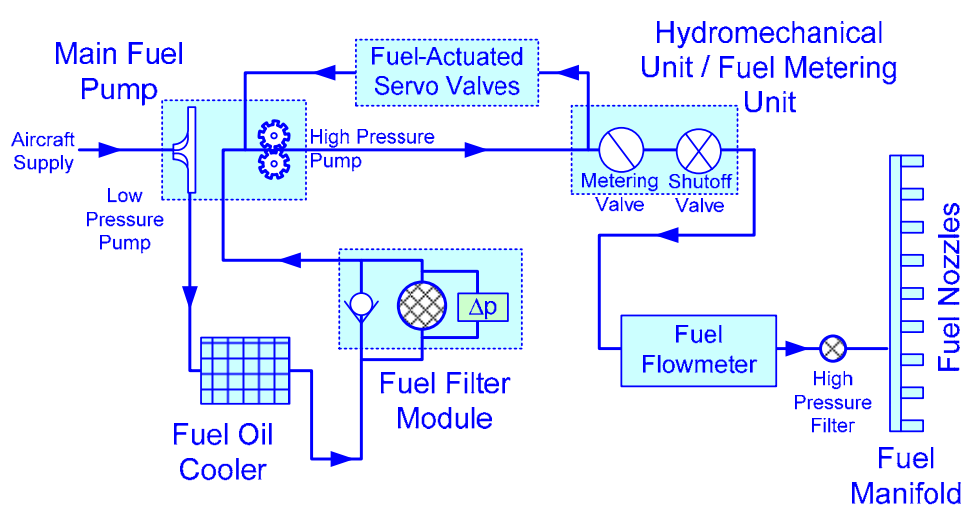


Figure 2-11. Engine Fuel System

2.4.7.4 Bleed Air System.

Compressed air is bled from the engine at the fan and one or more stages of the LP and HP compressors for both domestic (engine) and aircraft usage. A typical engine bleed air system is shown in figure 2-12 and includes the components described below.

- Engine System:
  - Engine External Component Cooling—Fan air is often used to directly cool sensitive externally mounted components located in the relatively hot core compartment.
  - LPC Stability Bleed—LPC exit air is dumped to the fan stream during certain engine operating modes to ensure LPC stability.
  - HPC Stability Bleed—In addition to the HPC IGVs and VSVs, some engine designs employ stability bleed systems that dump excess air from one or more compressor stages to the fan stream.
  - Turbine Cooling—As noted in sections 2.4.5 and 2.4.6, compressor air is provided to the blades, disks, and NGVs to ensure metal temperatures are maintained within limits.
  - Turbine Active Clearance Control—Fan air is supplied to the HPT and LPT case to control the thermal expansion and, therefore, relative clearance to the rotating blades.
- Aircraft Systems:
  - Inlet Cowl Anti-Ice—High stage compressor air is routed forward to the inlet and distributed around the lip to limit ice accretion at this location.
  - Environmental Control System—Most aircraft bleed air from one or more stages of the HPC to provide cabin pressurization. The air must be cooled prior to routing to the air conditioning pack, so a precooler is used to dump compressor air heat to the fan stream. The amount of fan air supplied to the precooler is typically regulated through a fan air modulating valve. Pressure regulation and isolation capability for the compressor bleed air is provided by the pressure regulating shutoff valve and HP shutoff valve. One or more check valves prevent air from backflowing from a higher to a lower compressor stage.
  - Engine Start System—During engine start, air is provided from another operating engine, the onboard auxiliary power unit (APU), or a ground air cart to the engine air turbine starter.

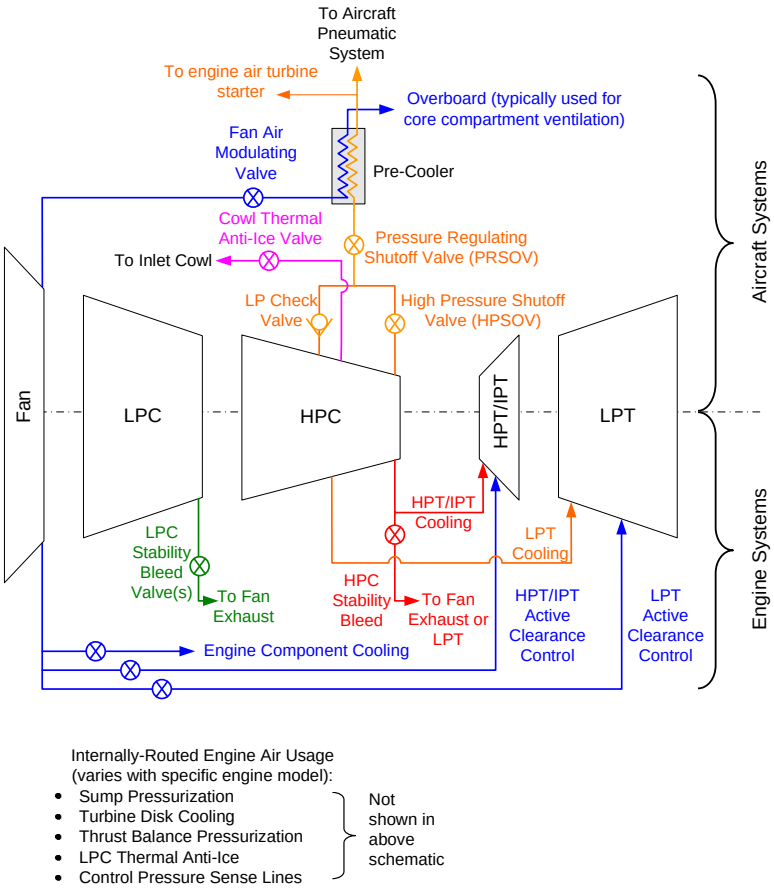


Figure 2-12. Bleed Air System

2.4.7.5 Controls and Sensors.

The engine configuration evaluated in this study assumed control via an electronic engine control (EEC). Such an engine controller is sometimes referred as a Full Authority Digital Engine Controller (FADEC) to distinguish it from earlier design supervisory control systems. The sensor suite evaluated in this study is shown in figure 2-13. The sensor category also included pneumatic system components such as pressure sense lines and pneumatic actuators.

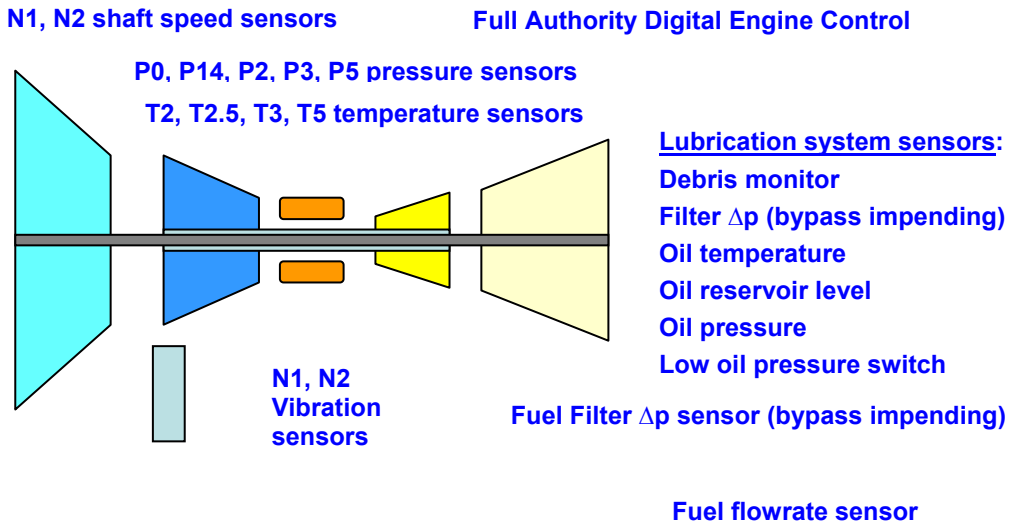


Figure 2-13. Modern Turbofan Engine Controls and Sensors

2.4.8 Other Aircraft Systems.

Although not a principal focus of this study, for completeness, the following additional aircraft system components typically are driven by an accessory gearbox in the engine nacelle:

- Engine-driven hydraulic pump and associated plumbing
- Aircraft generator and associated wiring

2.4.9 Nacelle Structure.

The turbofan engine is mounted in the nacelle. A typical underwing nacelle configuration is shown in figure 2-14. Other configurations, such as fuselage-mounted nacelles, contain principal features similar to those described below.

- Inlet—The inlet is designed to provide properly conditioned flow to the fan in all ground and flight-operating conditions. As described in section 2.4.7.4, the inlet lip is provided with anti-ice protection.

- Acoustic Panels—Forward of the fan case front flange, acoustically treated panels form the outer flow path boundary downstream of the inlet lip and attenuate noise emanating from the fan.

- Thrust Reverser—A translating sleeve thrust reverser is shown in figure 2-14. While other thrust reverser designs are used in modern transport aircraft, all engine nacelles incorporate some form of firewall protection for the engine. In the design shown in figure 2-14, the inner wall of the thrust reverser fulfills this firewall function.

- Strut—The nacelle is attached to the aircraft structure (in this case the wing) via a strut. The strut forms the load path to transmit the engine-generated thrust to the aircraft and also serves to route wires, fuel, and other services from the aircraft to the engine.

- Engine Mounts—The engine mounts typically consist of fore and aft attachments between the strut and engine case. Depending on the size of the engine, the engine load path may be reinforced with axial struts and diagonal braces.

- Fan Cowl—The fan cowl forms the exterior flow boundary for the nacelle and, depending on the installation design, may attach portions of the thrust reverser system.

- Heatshield—Heatshields are often employed to protect thermally sensitive aircraft structure from the relatively high-temperature engine exhaust gas.

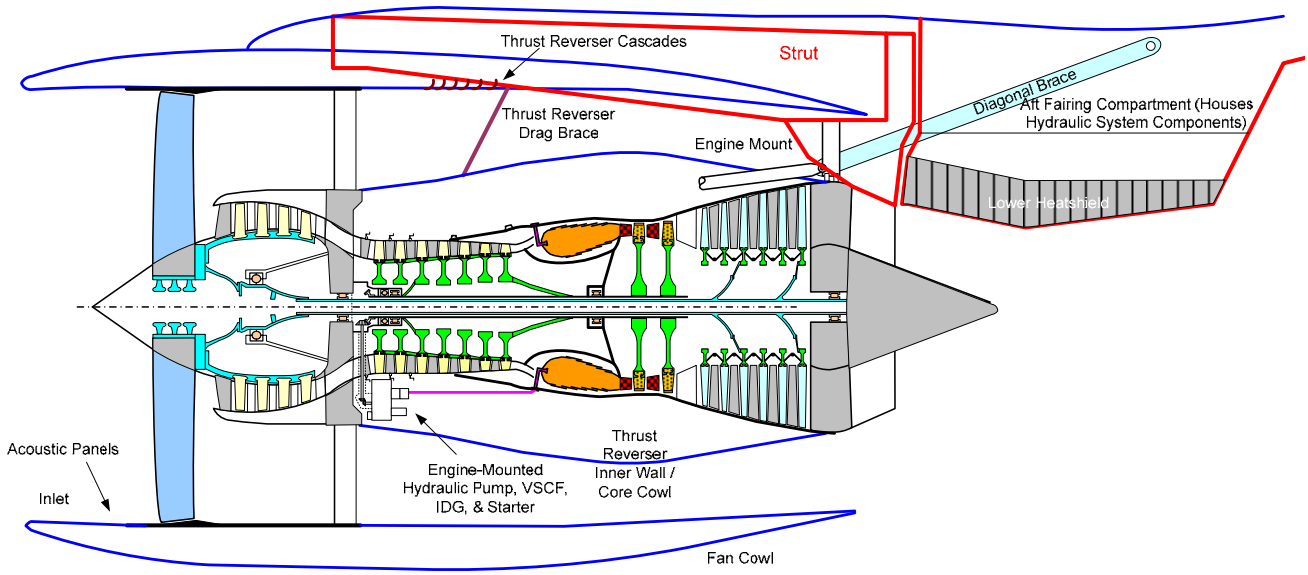


Figure 2-14. Nacelle Components

2.5 SOURCE DATA DESCRIPTION.

An internal Boeing engine removal and in-flight shutdown database formed the principal tool for evaluation of engine damage causes, effects, and relative frequency of occurrence. This database was also used in reference 2. For the Phase 3 PSM+ICR research effort, the in-service period was extended another year to cover the range of events occurring between 1 January 1999 and 31 December 2005. Removal and IFSD data were collected from airplane models including B-737 Classic, B-737 Next Generation, B-747, B-757, B-767, and B-777 with engine models from all three major turbofan suppliers. A total of 42,496 engine removals and 2,657 IFSDs were reviewed and categorized according to the following criteria:

- Scheduled or Unscheduled Removal—Engine removals that occurred due to life-limited part (LLP) replacement, Service Bulletin/Airworthiness Directive (AD) Compliance, Scheduled Overhaul, or Convenience (e.g., engine cycle stagger, lease expiration,

ownership transfer, etc.) were separated from those events considered unscheduled due to engine damage. Also considered separately from UERs were engines removed for performance restoration (i.e., consumption of exhaust gas temperature (EGT) margin). With these distinctions, the number of remaining events classified as UERs was 18,719, or 44% of all removals.

- Principally Damaged Component—Both removals and IFSDs were evaluated to determine the principally damaged component. In many cases, the principally damaged component was not necessarily the root cause of failure.

- Principal Flight Deck Indication—For both UERs and IFSDs, the principal FDE available to the flight crew was recorded. As discussed later in section 5.3, many UERs resulted from postflight inspection alone (i.e., preceding the removal, no FDEs were noted).

The results of this in-service event review are tabulated in table 2-1. Note: Damaged component types that contributed to more than 5% of the overall total removals or IFSDs are highlighted in this table.

Table 2-1. In-Service Engine Damage Data

Major System	Detailed System	No. of Events		Precent of Totals	
		Removals	IFSD	Removals	IFSD
Aircraft Systems	Air Data System	1	0	0.0	0.0
	APU	8	0	0.0	0.0
	Autothrottle	0	3	0.0	0.1
	Bleed Air System	64	60	0.3	2.3
	DLODS	1	4	0.0	0.2
	Electrical Power System (including IDG/CSD and VSCF)	26	25	0.1	0.9
	FODS	7	39	0.0	1.5
	Hydraulic System	22	8	0.1	0.3
	PDOS	1	0	0.0	0.0
	Starter	13	32	0.1	1.2
	Throttle Cable	2	17	0.0	0.6
Combustor	Combustor	920	4	4.9	0.2
	Combustor Case	58	1	0.3	0.0

Table 2-1. In-Service Engine Damage Data (Continued)

Major System	Detailed System	No. of Events		Percent of Totals	
		Removals	IFSD	Removal	IFSD
Controls and Sensors	AVM	9	12	0.0	0.5
	FADEC/MEC/PMC	20	41	0.1	1.5
	Fuel Metering Unit	37	75	0.2	2.8
	Ignition System	10	1	0.1	0.0
	PMA	27	26	0.1	1.0
	Pneumatic System	87	63	0.5	2.4
	Sensor	150	184	0.8	6.9
	VSV Linkage System	398	25	2.1	0.9
	VSV Actuation System	30	36	0.2	1.4
Engine Static Structure	Bearing Support	16	2	0.1	0.1
	Borescope Plug	37	0	0.2	0.0
	Diffuser Case	55	0	0.3	0.0
	Externals	5	0	0.0	0.0
	Fan Abradable	147	1	0.8	0.0
	Fan Case	162	0	0.9	0.0
	Fan Exit Guide Vanes	37	0	0.2	0.0
	Fan Frame	41	1	0.2	0.0
	HPC Case	200	7	1.1	0.3
	HPT Case	2	0	0.0	0.0
	LPC Case	18	2	0.1	0.1
	LPT Case	28	0	0.1	0.0
	LPT Frame	5	0	0.0	0.0
	Turbine	1	1	0.0	0.0
	Turbine Case	212	2	1.1	0.1
	Turbine Frame	67	0	0.4	0.0
Fan	Fan Blades	275	104	1.5	3.9
	Fan Disk	47	0	0.3	0.0
	Fan Platforms	23	4	0.1	0.2
	Fan Shaft	1	0	0.0	0.0
	Fan Spinner	11	12	0.1	0.5

Table 2-1. In-Service Engine Damage Data (Continued)

Major System	Detailed System	No. of Events		Percent of Totals	
		Removals	IFSD	Removals	IFSD
Fuel System	Fuel Filter	0	2	0.0	0.1
	Fuel Nozzles	63	5	0.3	0.2
	Fuel Pump	40	38	0.2	1.4
	Fuel Servo Heater	5	4	0.0	0.2
	Fuel Spar Valve	4	14	0.0	0.5
	Fuel Plumbing	56	38	0.3	1.4
	Fuel Starvation	0	2	0.0	0.1
	Fuel Supply System	0	8	0.0	0.3
	Fuel System Contamination	4	15	0.0	0.6
	Fuel Valve	4	2	0.0	0.1
HPC	HPC	47	2	0.3	0.1
	HPC Air Seal	234	3	1.3	0.1
	HPC Blades and Vanes	2998	215	16.0	8.1
	HPC Disk	44	2	0.2	0.1
	HPC Heat shield	3	0	0.0	0.0
	Inlet Guide Vanes	22	4	0.1	0.2
HPT/IPT	HPT	9	1	0.0	0.0
	HPT Airseal	140	7	0.7	0.3
	HPT Blades	2973	111	15.9	4.2
	HPT Cooling	61	9	0.3	0.3
	HPT Disk	27	2	0.1	0.1
	HPT Heatshield	6	0	0.0	0.0
	HPT NGV	1272	10	6.8	0.4
	HPT Shrouds	115	2	0.6	0.1

Table 2-1. In-Service Engine Damage Data (Continued)

Major System	Detailed System	No. of Events		Percent of Totals	
		Removals	IFSD	Removals	IFSD
Indeterminate	Indeterminate—Insufficient Information	827	106	4.4	4.0
	Indeterminate—High Vibration	426	54	2.3	2.0
	Indeterminate—Lubricated Components/Lube System	485	54	2.6	2.0
	Indeterminate—Performance/Operability-Related	578	159	3.1	6.0
	Indeterminate—Widespread Damage	18	0	0.1	0.0
LPC	LPC	3	0	0.0	0.0
	LPC Air Seal	6	0	0.0	0.0
	LPC Blades and Vanes	122	9	0.7	0.3
	LPC Disk/Spool	6	0	0.0	0.0
	Stability Bleed System	163	3	0.9	0.1
LPT	LPT Air Seal	13	0	0.1	0.0
	LPT Blades and NGVs	655	38	3.5	1.4
	LPT Cooling	10	0	0.1	0.0
	LPT Disk	6	3	0.0	0.1
	LPT Shaft	0	0	0.0	0.0
Lubricated Components/ Lube System	Bearing	642	137	3.4	5.2
	Bearing Seal	500	20	2.7	0.8
	Gearbox	611	148	3.3	5.6
	Lube System	1325	376	7.1	14.2

Table 2-1. In-Service Engine Damage Data (Continued)

Major System	Detailed System	No. of Events		Percent of Totals	
		Removals	IFSD	Removals	IFSD
Nacelle Structure/ Cowls/ Thrust Reverser	Acoustic Panel	54	5	0.3	0.2
	Cowl	20	3	0.1	0.1
	Engine Mounts	13	1	0.1	0.0
	Exhaust System	11	1	0.1	0.0
	Inlet Structure	5	0	0.0	0.0
	Nacelle Structure	1	1	0.0	0.0
	Thrust Reverser	151	5	0.8	0.2
Other	Core Imbalance	20	0	0.1	0.0
	Fan Imbalance	7	1	0.0	0.0
	Deicing Fluid Ingestion	0	1	0.0	0.0
	No Damage	147	37	0.8	1.4
	Pilot Error	22	32	0.1	1.2
	Maintenance Error	464	175	2.5	6.6

Total Unscheduled Removals	18,719
Total IFSD	2657

Unscheduled	18,719	44.3%	Distribution of all Removal Causes (Unscheduled and Scheduled)
Low EGT Margin	3,735	8.8%	
LLP Expiration	6,587	15.4%	
Scheduled Overhaul/Convenience	12,616	29.6%	
Service Bulletin/AD Compliance	839	2.0%	
Total All Removals	42,496	100%	

DLODS = Duct Leak Overheat Detection System
IDG = Integrated drive generator (Later generation version of CSD)
CSD = Constant speed drive (Electrical generator)
VSCF = Variable-speed constant frequency (Generator)
FODS = Fire/Overheat Detection System
AVM = Airborne vibration monitor
MEC = Main Engine Controller
PMC = Power Management Computer
PDOS = Power-Door Operating System

Figure 2-15 indicates that UERs were most frequently motivated by damage to gas path components. As a general category, gas path components were followed next by engine subsystem components. These results were expected—apart from on-wing fan blade or line replaceable unit (LRU) replacements, repair of gas path or lubricated components, such as main bearings, generally require a shop visit.

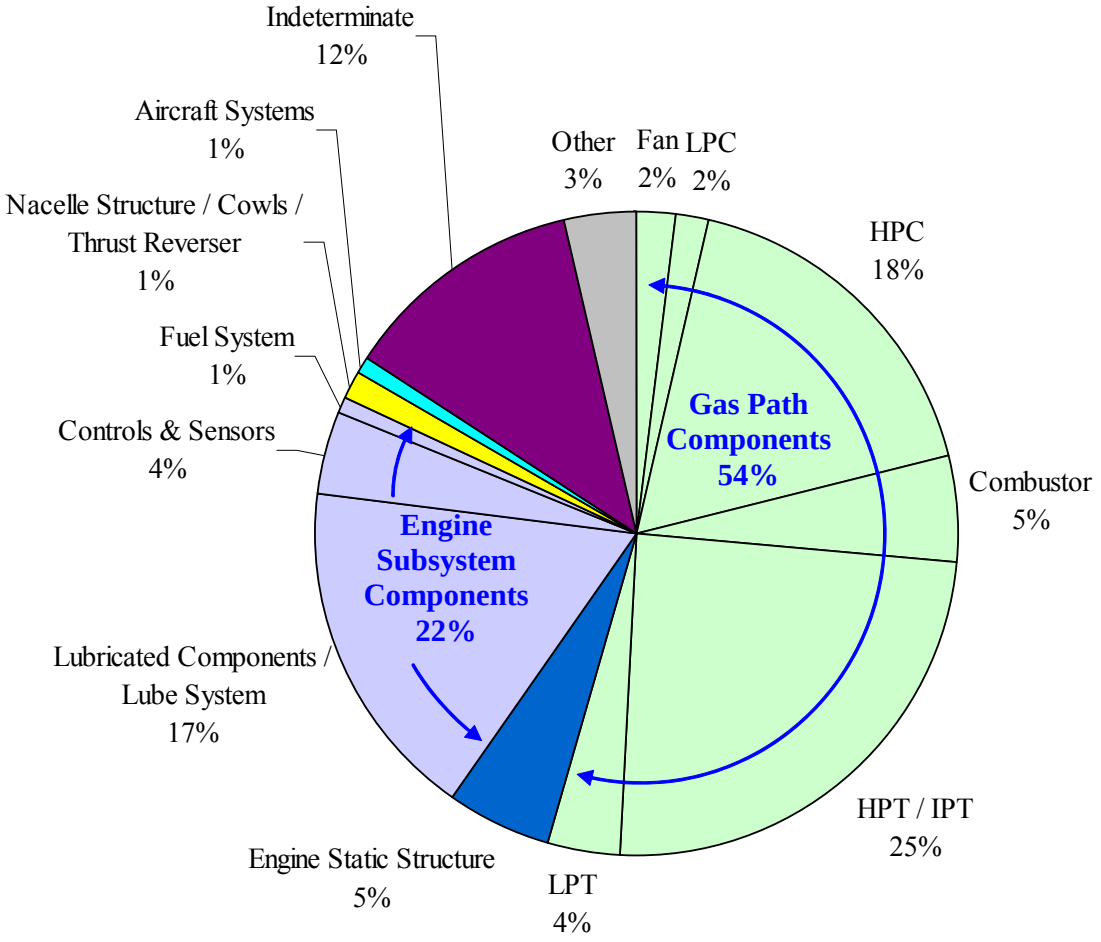


Figure 2-15. Unscheduled Engine Removal Cause Distribution

IFSD reports present a slightly different picture. As shown in figure 2-16, engine subsystem component failures account for almost half of all IFSDs. Gas path component failures are still a significant contributor, but account for less than half the contribution of engine subsystem components. This dissimilarity in the relative contributions to UERs and IFSDs for subsystem and gas path components is attributable to LRUs. Specifically, a larger percentage of IFSDs were caused by LRUs and, therefore, were addressable without an engine removal.

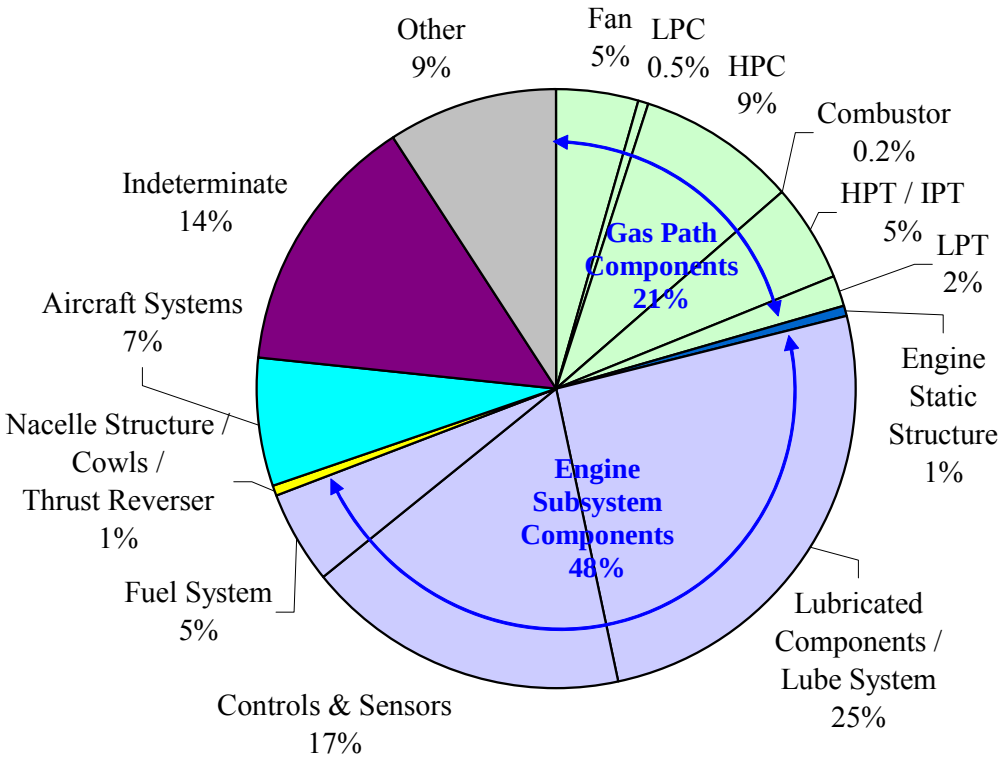


Figure 2-16. In-Flight Shutdown Cause Distribution

Engine sensor failures were not a focus of this phase's research into engine damage mode frequency and effects. In general, sensor failures are not a significant contributor to ICR. However, the relatively significant contribution of sensor failures to IFSDs prompted further evaluation of the specific types of sensor failures. The sensor category includes both engine control and monitoring sensors as well as aircraft system sensors such as the Fire/Overheat Detection System (FODS) and Duct Leak/Overheat Detection System (DLODS). This research considered the sensor as an entire system and included the sensor itself, associated wiring and fluid piping, and the flight deck display. Overall, this combination of engine and aircraft sensors contributes to about 9% of all IFSDs.

This study focused primarily on engine damage exclusive of sensor failures. As part of the Task 1 service review however, sensor failure contributions to UERs and IFSDs were quantified. The sensor failures were dominated by older design engines. In general, sensor reliability improvements have progressively been made with the advent of newer engine designs and thus have led to a reduction in sensor-caused IFSDs.

Notably, most sensors failure-caused IFSDs were due to sensors that do not interface with the FADEC (i.e., oil system sensors, FODS, and DLODS). For FADEC-monitored sensors, fault checking and accommodation mitigates the effects of sensor failures and, thus, has led to a general reduction in sensor failure-induced IFSDs over earlier non-FADEC engine designs. Similarly, this fault detection and accommodation should be applied to oil system sensors prior to any expanded use for engine damage detection (refer to section 5.5.3 for further discussion).

2.6 PRINCIPAL ENGINE DAMAGE MODES.

A principal Task 1 objective was to determine engine damage modes relevant to current flight operation or subsequent flight dispatch. To this end, a "bottom-up" failure analysis was completed for each major propulsion system module. This analysis considered the following engine damage mode attributes.

- Specific module component or subsystem
- Type of Damage—Damage modes limited to those severe enough to cause unscheduled removal or an operational effect (e.g., abnormal engine indication, surge, tactile vibration, thrust loss, or IFSD).
- Existing Means of Damage Detection—Flight deck effects or postflight/shop visit visual inspection. Note: Where "Vibration Monitor" is listed as the principal existing means of detection, this primarily implies the one-per-revolution or broadband detection schemes discussed in section 5.5.4. In some cases, other advanced algorithms are necessary to detect bearing failures, etc., although such advanced algorithms are not yet in widespread use.
- Potential for sensor-based detection
- The likelihood of damage propagation to other engine components

Based on the in-service report review and expert experience, each damage mode was assessed to determine the relative likelihood of triggering a flight deck indication. The following categories of flight deck effects were considered:

- Sensor-based indications:
  - Engine pressure ratio (EPR) and/or shaft speed off-schedule (high, low, or fluctuating)
  - Exhaust gas temperature (EGT) high, low, or fluctuating
  - Oil system parameter fluctuation (pressure, temperature, filter differential pressure, or quantity)
  - Indicated vibration high or fluctuating
- Other existing flight deck indications or symptoms:
  - Surge/Stall (single recoverable, unrecoverable, or continuous/multiple)—Definitions of these events were consistent with the Phase 2 research:
    - Recoverable Surge—Airflow separates in the compression path and subsequently reattaches, allowing the engine to regain commanded thrust.

    - Unrecoverable Stall—Compression path disruption that results in a quasi-steady-state condition of localized airflow separation on a sector of blades. Accompanied by rapid EGT rise and rotor speed decay.
    - Continuous/Multiple Surge—Two or more repetitions of recoverable surge
  - Flameout—Quenching of the combustion process resulting in a subidle power loss
  - Power loss (subidle) or uncommanded shutdown
  - Power loss (above idle, partial thrust loss or engine rollback)
  - No response to throttle (overthrust)
  - Sensible/audible airframe vibration
  - Smoke (flight deck or cabin)
- Flight deck alerts and annunciations:
  - Engine subidle alert
  - Engine commanded thrust disagreement alert (indicated thrust differs from commanded thrust)
  - Engine limit exceedance alert (high or low)—Examples include high EGT or rotor speed alert
  - Vibration exceedance annunciation—High indicated engine tracked-order or broadband vibration
  - Engine oil (temperature, pressure, differential pressure or quantity) alert or annunciation
  - Fire/overheat alert/annunciation
  - Engine anti-ice alert/annunciation
  - Generator alert/annunciation
  - Thrust reverser unlock alert/annunciation
  - Start system alert
  - Fuel imbalance alert/annunciation
  - Other dedicated annunciation or alert

The results of this analysis are provided in tables with color-coding applied to distinguish:

- Whether the specific damage mode was adequately covered by existing sensors or, conversely, should be evaluated for detection capability using sensor fusion or, lastly, was not a focus of this research (i.e., would likely require new sensor technology or sophisticated modeling to provide improved detection).

  A given damage mode's candidacy for improved detection was determined by consideration of several factors.

  - Detectable via Postflight Visual or Shop Teardown Only—These damage modes typically included cracks to engine casings or airfoils that exceeded maintenance manual limits and would likely be undetectable by vibration or gas path pressure/temperature parameter shifts. These damage modes are highlighted in gray.

  - Detectable With Existing Prescribed Instruments—Specific dedicated detection, alerts, and annunciations are required by Title 14 Code of Federal Regulations (CFR) Part 25 Airworthiness Standards pertaining to Transport Category Airplanes. While not an exhaustive list, table 2-2 does provide examples of these prescriptive instruments and their associated damage detection capability. These damage modes are highlighted in light blue.

  - Potentially Detectable With a Combination of Existing Sensors—Damage modes typically related to rotating gas path or lubricated components with improved detection potential through fused inputs from the existing prescribed sensors plus other sensors required for engine control or that currently exist for EHM. Included in this category are damage modes potentially detectable via more advanced vibration signal processing than is currently available in fielded AVM. These damage modes are highlighted in green and formed the principal focus of Task 4.

  - Potentially Detectable With New Sensors—Damage modes that were assessed to require more sophisticated means of detection beyond fusion of existing sensors to isolate the specifically damaged component. Generally, these damage modes were related to internal fluid leaks that were not otherwise detectable by a significant shift in existing gas path parameters such as EGT, rotor speed, or vibration. These damage modes are highlighted in orange.

- The Relative Frequency of FDE Occurrence—The following frequency definitions were employed in this assessment:

  - Highly Likely—Damage mode directly related to the indication (indication was generally dedicated to this damage mode).

  - Likely—Indication was not directly related or dedicated to this damage mode, but damage mode usually triggered this indication.

- Possible—Damage mode sometimes produced this indication, but not necessarily consistently.

- Unlikely—Damage mode was unlikely to produce the specified indication or effect.

The correlation of the in-service event reports with the damage effects analysis is provided in the columns "Relative Frequency of Occurrence" in tables 2-3 through 2-14.

The principal damage modes and existing indications for each major module are discussed in the following sections. These sections contain a specific evaluation of damage mode detection candidacy using fusion of existing sensors (Task 4 focus). In many cases however, sensor fusion was considered unnecessary (i.e., damage was adequately detectable through existing sensors) or required the development of new sensors.

Table 2-2. Prescribed Sensor Examples

14 CFR Part	Instrument	Example Engine Damage Mode Applicability
25.1305 (a) (3)	Oil quantity	Lubrication system leaks
25.1305 (a) (4)	Oil pressure	Lubrication system leaks, pump failures, etc.
25.1305 (a) (5)	Oil pressure warning	Lubrication system leaks, pump failures, etc.
25.1305 (a) (6)	Oil temperature	Lubrication system leaks, pump failures, lubricated component failures, oil cooler failures
25.1305 (c) (7)	Oil filter bypass impending	Lubricated component failures or contaminated oil
25.1305 (a) (7)	Fire warning	Ignited flammable fluid leak in fire zone
25.1203 (a)	Fire/overheat detection	Ignited flammable fluid leak in fire zone, hot-air duct or pressure vessel leak
25.1199 (c)	Fire extinguishing agent quantity	Fire-extinguishing system leak
25.1305 (c) (1)	EGT	Gas path component failure, engine fuel control system failures
25.1305 (c) (3)	Rotor speed tachometer	Gas path component failure
25.1305 (c) (4)	Starter malfunction	Starter failure
25.1305 (c) (5)	Anti-ice function	Engine inlet anti-ice system failure
25.1305 (c) (6)	Fuel filter bypass impending	Fuel system component failure or contaminated fuel
25.1305 (d) (2)	Thrust reverser function	Thrust reverser failure
25.1305 (d) (3)	Rotor system unbalance	Rotating component failure
25.1141 (f)	Powerplant control valve status	Fuel spar valve failure

Table 2-3. Engine Damage Mode Assessment (Fan Module)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible Fire/Visible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Fan																																			
	Blade	Missing Section	3.88%	0.60%	Vibration Monitor	X				*	X	X	X			X		*				X		X	*										*
	Blade	Bent Blade			Vibration Monitor	X				*	X	X	X			X		✓				X		X	*										
	Blade	Crack (beyond service limits)		0.88%	Post-Flight Visual																														
	Spinner	Liberation, Distortion, or Missing Section	0.45%	0.06%	Vibration Monitor, Post-Flight Visual					*	X	X	X					✓				X		X	✓										*
	Platforms / Annulus Fller	Missing Section	0.15%	0.12%	Vibration Monitor, Post-Flight Visual					*	X	X	X					✓				X		X	✓										*
	Hub/Disk	Missing Section	0.00%	0.02%	Vibration Monitor					X					*			✓				*			X										*
	Hub/Disk	Crack (beyond service limits)		0.23%	Post-Flight Visual (upon teardown)																														
	Case	Crack (beyond service limits)		0.86%	Post-Flight Visual																														
	Abradable	Missing Section	0.08%	0.77%	Vibration Monitor					✓	X	X	X					✓				X		X	X										*
	Fan Hub Frame	Crack		0.25%	Post-Flight Visual (upon teardown)																														
	Fan Hub Frame	Missing Section	0.04%	0.01%	Vibration Monitor													✓																	*
	Outlet Guide Vanes / Fan Case Struts	Missing Section	0.00%	0.01%	Vibration Monitor, Post-Flight Visual											X		✓																	
	Outlet Guide Vanes / Fan Case Struts	Crack (beyond service limits)		0.19%	Post-Flight Visual																														

Table 2-4. Engine Damage Mode Assessment (LPC Module)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Low or Intermediate Pressure Compressor																																				
Blade / Vane	Missing Section		0.34%	0.17%	Vibration Monitor					✓	X	✓	X					✓				X		X	X										*
Blade / Vane	Bent Blade				Vibration Monitor					✓	X	✓	X					✓				X		X	X										*
Blade / Vane	Crack (beyond service limits)			0.48%	Post-Flight Visual																														
Hub / Rotor	Crack (beyond service limits)			0.02%	Post-Flight Visual (upon teardown)																														
Hub / Rotor /Drum	Missing Section		0.00%	0.01%	Vibration Monitor					X					*			✓				*			X										*
Air Seal	Excessive Leakage		0.00%	0.02%							X	✓	X									X		X											
Air Seal	Missing Section									✓	X	✓	X									X		X	X										*
Air Seal	Crack (beyond service limits)			0.05%	Post-Flight Visual (upon teardown)																														
Case	Crack (beyond service limits)		0.08%	0.10%	Post-Flight Visual																														
Case	Leak				Post-Flight Visual																														
Stability Control System (Variable Bypass / Stability Bleed)	Air Leak			0.66%	Post-Flight Visual																														
Stability Control System (Variable Bypass / Stability Bleed)	Jammed or failed actuator (failed closed)		0.11%	0.21%	Position Error						*	✓	✓								✓	*		X											
Stability Control System (Variable Bypass / Stability Bleed)	Failed Open				Position Error		✓				X										✓	X		X											

Table 2-5. Engine Damage Mode Assessment (HPC Module)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible Fire/Visible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annunciation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
High Pressure Compressor																																			
	Blade / Vane	Missing Section	8.32%	4.14%	Vibration Monitor	X	✓	X		✓	✓	*	*	✓								✓		✓	✓										*
	Blade / Vane	Bent Blade	↓	↓	Post-Flight Visual (borescope)	X	✓	X		✓	X	✓	✓	X								X		X	✓										
	Blade / Vane	Crack (beyond service limits)		12.12%	Post-Flight Visual																														
	Hub / Rotor	Missing Section	0.08%	0.03%	Vibration Monitor					X					*							*			X										*
	Hub / Rotor	Crack (beyond service limits)		0.21%	Post-Flight Visual (upon teardown)																														
	Case	Crack (beyond service limits)		0.72%	Post-Flight Visual																														
	Case	Leak	0.26%	0.34%	Fire / Overheat detection system (depending on stage of leak); Post-Flight Visual															X						✓									
	Air Seal	Excessive Internal Leakage	0.11%	0.13%					X		X	✓	X									X		X		X									
	Air Seal	Missing Section	↓	↓					X	✓	X	✓	X									X		X	X	X									*
	Air Seal	Crack (beyond service limits)		1.11%	Post-Flight Visual																														
	Actuation (IGV's / VSV's)	Excessive freeplay	1.36%	0.16%	Post-Flight Visual	X				X		✓												X	X										
	Actuation (IGV's / VSV's)	Lever arm / linkage system failure	↓	↓						X		✓												X	X										
	Actuation (IGV's / VSV's)	Jammed or failed actuator (failed closed)	0.94%	2.11%	Position Error	X					X	X										X		X											
	Actuation (IGV's / VSV's)	Jammed or failed actuator (failed open)	↓	↓	Position Error						*	✓	✓								X	*		✓											

Table 2-6. Engine Damage Mode Assessment (Combustor/Diffuser Module)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Combustor / Diffuser																																			
Liner	Crack (beyond service limits)			4.54%	Post-Flight Visual (borescope)																														
Liner	Missing Section		0.15%	0.33%	Post-Flight Visual (borescope); AVM							✓		*								*		X											
Case	Crack (beyond service limits)			0.56%	Post-Flight Visual																														
Case	Leak		0.04%	0.04%	Fire / Overheat Detection System															X							*								
Fuel Manifold / Nozzles	Internal Leak		0.19%	0.34%	EGT sensor	X	X	X						X	X	X						X	X	X											*
Fuel Manifold / Nozzles	Clogged Nozzle		↓	↓	EGT sensor	X	X	X						X	X	X						X	X												*
Fuel Manifold / Nozzles	External Leak		1.43%	0.30%	Fire / Overheat Detection System	X	X	X						X	X	X				X		X	X				*								
Engine Ignition System																																			
Exciter	Failure to		0.04%	0.05%	Checked on ground start.																*														
Wiring	Break		↓	↓																	*														
Ignitors	Failure to function																				*														

Table 2-7. Engine Damage Mode Assessment (HPT Module)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
High or Intermediate Pressure Turbine																																			
Blade / Vane	Crack (beyond service limits)			20.33%	Post-Flight Visual (borescope)																														
Blade / Vane	Excessive Erosion/Oxidation (beyond service limits)				Post-Flight Visual (borescope)																														
Blade / Vane	Missing Section	4.52%	2.17%		Vibration Monitor	X	✓			*					X							X		X	✓										*
Shroud	Crack and/or erosion (beyond service limits)		0.45%		Post-Flight Visual (borescope)																														
Shroud	Missing section	0.08%	0.16%		Post-Flight Visual (borescope) or EGT shift		✓					X											X												*
Air Seal	Excessive Leakage	0.26%	0.46%		Post-Flight Visual (borescope) or EGT shift		✓																X												
Air Seal	Missing Section				Vibration Monitor		✓			✓													X	X											
Air Seal	Crack (beyond service limits)		0.29%		Post-Flight Visual (upon teardown)																														
Hub / Rotor	Fretting at blade root interface		0.12%		Post-Flight Visual (upon teardown)																														
Hub / Rotor	Crack (beyond service limits)				Post-Flight Visual (upon teardown)																														
Hub / Rotor	Missing Section	0.08%	0.02%		Vibration Monitor										*							*													*
HPT Shaft	Complete failure	0.00%	0.00%		Speed Sensor	*									*			✓				*													*

Table 2-8. Engine Damage Mode Assessment (HPT and LPT Modules)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
High or Intermediate Pressure Turbine (cont.)																																			
	Cooling Air Supply	Blocked Passage \ Reduced Cooling Flow		0.21%	Post-Flight Visual (borescope)																														
	Cooling Air Supply	External Leak	0.34%	0.12%	Fire / Overheat Detection System																					*									
	Case/Frame	Crack (beyond service limits)		1.11%	Post-Flight Visual																														
	Case	Leak	0.08%	0.03%	Fire / Overheat Detection System																					*									
Low Pressure Turbine																																			
	Blade / Vane	Crack (beyond service limits)		2.75%	Post-Flight Visual (borescope)																														
	Blade / Vane	Excessive Erosion/Oxidation (beyond service limits)			Post-Flight Visual (borescope)																														
	Blade / Vane	Missing Section	1.43%	0.71%	Vibration Monitor	X	✓			*		X		X	X							X		X	✓										*
	Hub / Rotor	Fretting		0.01%	Post-Flight Visual (upon teardown)																														
	Hub / Rotor	Crack (beyond service limits)			Shop Visit Visual (upon teardown)																														
	Hub / Rotor	Missing Section	0.11%	0.03%	Vibration Monitor					*					*							*			✓										*

Table 2-9. Engine Damage Mode Assessment (LPT Module)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3	Existing Engine Indications: High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible Fire Visible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Low Pressure Turbine (cont.)																																				
LPT Shaft	Complete failure		0.00%	0.01%	Speed sensors	*										*			✓				*													*
Air Seal	Excessive Leakage		0.00%	0.02%			✓																		X											
Air Seal	Crack (beyond service limits)			0.05%	Post-Flight Visual (borescope)																															
Shroud	Crack (beyond service limits)				Post-Flight Visual (borescope)																															
Shroud	Excessive Erosion/Oxidation (beyond service limits)				Shop visit Visual (borescope)																															
Cooling Air Supply	Blocked Passage \ Reduced Cooling Flow			0.05%	Post-Flight Visual (borescope)																															
Cooling Air Supply	External Leak		0.00%	0.00%	Fire / Overheat Detection System (depending on sensor location)																							✓								
Frame	Crack (beyond service limits)			0.07%	Post-Flight Visual																															
Case	Crack (beyond service limits)			0.14%	Post-Flight Visual																															
Case	Leak		0.00%	0.01%	Fire / Overheat Detection System																							✓								

Table 2-10. Engine Damage Mode Assessment (Exhaust System and Cowls)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Exhaust System																																		
	Primary Nozzle	Crack (beyond service limits)		0.06%	Post-Flight Visual																													
	Primary Nozzle	Missing Section	0.04%		Vibration Monitor, Post-Flight Visual													X																
	Primary Nozzle	Looseness			Vibration Monitor, Post-Flight Visual													X																
	Exhaust Shields	Thermal damage			Post-flight visual																													
	Exhaust Shields	Crack (beyond service limits)			Post-flight visual																													
	Exhaust Shields	Missing Section			Vibration Monitor, Post-Flight Visual													X																
Cowls																																		
	Powered Door Operating System	Failure to function		0.00%	During compartment access attempt																													
	Powered Door Operating System	Leak			Post-Flight Visual (drain)																													
	Cowls	Missing Section	0.11%	0.11%	Vibration Monitor, Post-Flight Visual													X																
	Cowls	Damaged or unsecured latch			Vibration Monitor, Post-Flight Visual													X																

Table 2-11. Engine Damage Mode Assessment (Inlet and Thrust Reverser)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible Fire/Visible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Inlet																																				
	Acoustic Liner	Missing Section	0.19%	0.29%	Vibration Monitor; Post Flight visual					X	X							✓				X			X										*
	Acoustic Liner	Impact damage			Post Flight visual																															
	Inlet Structure	Impact damage	0.00%	0.03%	Post Flight visual																															
	Anti-Ice System	Leak			Duct Leak Overheat Detection System																						*									
	Anti-Ice System	Failure to			Valve BIT																							*								
	Anti-Ice System	Stuck open valve (system failed on)			Valve BIT																							*								
Thrust Reverser																																				
	Cascades	Missing Section		0.80%	Post-Flight Visual													✓																		
	Actuation & Indication System	Failure to function	0.19%		RVDT / LVDT																										*					
	Actuation & Indication System	Leak			Post-flight visual; thrust reverser BIT															✓							X				*					
	Translating Sleeve	Jam																													*					
	Blocker Doors	Missing Section			Post-flight visual													✓																		
	Inner or outer wall	Failure / Missing section			Post-flight visual													✓																		
	Translating Sleeve	Missing Section			Post-flight visual													✓																		

Table 2-12. Engine Damage Mode Assessment (Nacelle Structure)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Nacelle Structure																																			
	Frames	Crack (beyond service limits)		0.04%	Post-flight visual																														
	Frames	Sealant damage			Post-flight visual																														
	Frames	Thermal damage			Post-flight visual																														
	Panels	Crack (beyond service limits)			Post-flight visual																														
	Panels	Thermal damage			Post-flight visual																														
	Panels	Looseness / missing fasteners	0.01%		PostFlight visual													X																	
	Panels	Missing Section			PostFlight visual													X																	
	Drains	Clogs / Leaks			Post-flight visual															X															
	Engine Mounts / Thrust Links	Crack		0.09%	post-flight visual																														
	Engine Mounts / Thrust Links	Complete failure			Vibration Monitor; PostFlight visual					*					*			*							*										

Table 2-13. Bleed Air and Fire Protection System Damage Mode Assessment

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Bleed Air																																			
	Offtakes	Cracks / Leaks	2.22%	0.34%	Fire / Overheat Detection System																						✓								
	Ducts	Cracks / Leaks			Fire / Overheat Detection System																						✓								
	Couplings	Loose / Missing			Fire / Overheat Detection System																						✓								
	Valves	Failure to function (open or closed)			Valve BIT						✓											✓		X											
Fire / Overheat Detection System																																			
	Sensors	Sensors Failure	1.47%	0.04%	BIT																						*								
	Duct Leak Detection System	False Alarm	0.15%	0.01%	BIT																						*								
Fire Extinguishing System																																			
	Plumbing	Leak			Post-Flight visual																														
	Bottle	Leak			BIT																						*								

Table 2-14. Engine Damage Mode Assessment (Lubrication System)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/NT/N2/N3	Existing Engine Indications: High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Engine Lube System																																				
Reservoir	Leaks / low level		14.34%	7.05%	Level sensor					*																			*							
Pumps	Low output				Reservoir level sensor, Pressure sensor					*																			*							
Pumps	Failure				Reservoir level sensor, Pressure sensor					*																			*							
Filters	Clogged / Bypass				Delta-P switch or sensor					*																			*							
Tubing / Hoses	Leaks				Reservoir level sensor, Pressure sensor					*																			*	X						
Tubing / Hoses	Collapsed liners				Reservoir level sensor, Pressure sensor					*																			*							
Tubing / Hoses	Damaged sleeves				Post-Flight visual																															
Coolers	Fouling				Oil temperature sensor					*																			*							
Coolers	Internal leaks				Reservoir level sensor					*																			*							
Coolers	External leaks				Reservoir level sensor, Pressure sensor					*																			*	X						
Couplings	Loose / Missing				Reservoir level sensor, Pressure sensor					*																			*	X						

2.6.1 Fan Damage Modes (Table 2-3).

The fan is most commonly damaged by ingestion of foreign objects such as birds, runway debris, and other objects. As a result of being the largest target presented to such foreign objects, the most frequently damaged subcomponents in the fan module are the fan blades. Unlike most other downstream gas path components, fan blades are often replaceable or repairable without an engine removal. Damage that alters the fan system balance, such as partial or full blade loss, has a high likelihood of registering both increased indicated vibration and sensible (tactile) vibration. (Refer to section 5.5.4 for a detailed discussion on vibration sensing). As such, fan blade damage that results in blade material loss is generally well-detected with existing AVM systems. Damage resulting in airfoil damage without material loss (e.g., bird strike) may result in nonsynchronous vibration due to aerodynamic instability and, as such, may be sensed as tactile or broadband indicated vibration rather than one-per-revolution indicated vibration. (Refer to section 5.5.4 for further discussion.) A potential annunciation alternative for vibration-based damage detection is discussed in section 6.1.

With the exception of fan disks, the other two principal rotating components (spinner and platforms) usually register vibration shifts when damaged. Fan disks are a Life-Limited Part (LLP) and are carefully controlled both in the manufacturing process and during service usage. As a result of these controls, fan disk failures are exceedingly rare. During the 6-year study period, no IFSDs were attributable to this component. Further, there were no instances in the same study period where fan disk damage was preceded by a Flight Deck Effect (FDE). In the very unlikely event of a fan disk failure, the resulting damage to the propulsion system is usually substantial enough to cause an immediate uncommanded shutdown. Table 2-1 ascribes 47 UER events to fan disk damage. In each case, such damage was discovered during postflight inspection and usually involved excessive fretting at the disk's fan blade retention slots.

The static components of the fan module, including the fan case, fan abradable, outlet guide vanes/struts, and fan frame, only accounted for two IFSDs during the 6-year study period. One event was attributable to a fan frame bearing support failure, which led to a subsequent main bearing failure. The other IFSD event involved excessive wear to the fan abradable material that registered excessive indicated vibration. In general, most of the fan static structure damage was discovered during postflight visual inspection and, as such, registered few in-flight effects.

2.6.2 Low-Pressure Compressor Damage Modes (Table 2-4).

The LPC is the first component downstream of the fan and is, therefore, vulnerable to foreign object damage (FOD). LPC blades and vanes are the principal FOD target and the most likely damaged components in this module. Damage to the LPC blades may provoke high indicated vibration, but due to the lower blade mass, the associated vibration amplitude is usually much lower than that associated with fan damage. Behind the LPC blades and vanes, the next most frequently damaged component in this module is the stability bleed system. Of the three IFSDs attributable to this component, all the failures involved anomalies within the actuation system (i.e., broken or jammed linkages). Effects attending stability bleed system failures are often surge or high EGT.

2.6.3 High-Pressure Compressor Damage Modes (Table 2-5).

The HPC is one of the leading contributors to both unscheduled removals and IFSDs (roughly 16% and 8%, respectively). HPC blade and vane failures account for most of these events because, like the upstream fan and LPC, such components are vulnerable to FOD. In the case of the HPC, however, several factors combine to make the HPC more damage-prone than the fan or the LPC: (1) Any upstream damage often cascades downstream. (2) By virtue of a relatively large total airfoil count and high rotation speed, the HPC module also presents more FOD targets than the fewer-bladed and slower rotating fan and LPC module. (3) As the compression path constricts through the HPC, the blades become smaller and thinner and, thus, more vulnerable to FOD.

Damage to HPC blades and vanes is often accompanied by surge or stall and, if the engine continues to run, can also result in a fuel flow shift, high EGT, or rotor speed shift as the damaged compressor rematches to an off-design operating condition. In some cases, the HPC damage is severe enough to result in a large enough disruption of flow to the combustor that flameout ensues. Damage to the rotating HPC blades will generate increased indicated vibrations as high-speed rotor imbalance is tracked and displayed independently from the low-speed rotor (fan, LPC, and LPT).

Other rotating HPC components that showed damage during the service data review included HPC disks and air seals. As with fan disks, these components are generally LLPs and failures are very rare. A very small number of HPC disk failures during the 6-year study period caused IFSDs. In these cases, while the disk damage was confined to relatively small mass parts such as lugs or attachment appendages (rather than the main body of the disk), the damage was severe enough to cause an immediate uncommanded shutdown.

HPC static structure damage to items, such as the casing or static air seals, generally resulted in hot-air leakage to the core compartment and subsequent triggering of the Fire/Overheat Detection System (FODS).

Most HPCs incorporate variable inlet given vanes and stator vanes (IGVs and VSVs) in the early stages of the module. Exceptions to this rule are three-spool engine designs with either no variable geometry or variable geometry confined to the IPC. This study segregated the VSV system into three subsystems: (1) the actuated airfoils, which were included with the remaining nonvariable vanes; (2) the VSV/IGV linkage system, which connects the actuator to the individual airfoils; and (3) the VSV actuator itself. Detection of VSV/IGV airfoil damage is similar to the stationary vanes, as described above. The VSV/IGV actuator usually incorporates position feedback and, thus, is capable of detecting jams or failures to stroke. However, failures within the linkage system are usually downstream of the actuator position detection and thus, without the introduction of new sensors, are not likely detectable with combinations of existing sensors.

2.6.4 Combustor and Diffuser (Table 2-6).

Combustor and diffuser module failures are generally associated with the high operating temperatures of the subcomponents. Since the subcomponents of this module are nonrotating,

the most common symptoms are EGT shift, fuel flow shift, or flameout rather than high vibration. Elevated vibration was typically noted only when the damaged combustor or diffuser case was weakened enough to respond to the normal imbalance of the otherwise undamaged high and low rotors. If the combustor damage mode involved case leakage, the most frequent indication was a fire or overheat warning from the FODS sensors specifically placed for this purpose. Combustor liner and/or fuel nozzle damage may lead to a distorted exit temperature profile and, thus, induce premature wear out of the downstream HPT components.

Since combustor damage was most frequently detected by routine maintenance visual inspection (rather than a reported FDE), damage to this module drove a much higher percentage of UERs than IFSDs (~5% versus 0.2%).

2.6.5 High-Pressure Turbine Damage Modes (Tables 2-7 and 2-8).

HPT blade failures are the most common form of damage to this module and account for ~16% of all UERs and ~8% of all IFSDs. While not included as unplanned removals, performance-related removals driven by low EGT margin often relate to degraded HPT blades. While HPT blade damage is sometimes induced by FOD, high gas temperature exposure and the resulting gradual oxidation, creep, and thermal-mechanical fatigue are the more frequent causes of HPT blade damage. Blade damage usually causes an upward EGT shift and is often attended by high vibration as portions of the turbine blades erode away asymmetrically and induce high-speed rotor imbalance. Significant HPT blade material erosion may result in an overall engine power loss if the turbine becomes too weak to drive the HPC at the commanded thrust.

Close behind the HPT blades are NGV failures, which account for ~7% of UERs but only 0.4% of IFSDs. The same conditions that promote HPT blade damage affect the HPT NGVs (oxidation, creep, thermal-mechanical fatigue, and to a lesser extent, FOD). This disparity between UER and IFSD event percentages is driven primarily by the fact that NGV damage is most frequently detected by postflight visual inspection. When in-flight effects are present with NGV damage, most frequently, an upward shift in EGT is notable.

Other HPT rotating components noted to cause UERs and IFSDs included HPT disks and air seals. As with HPC disks and air seals, both components are generally massive enough to warrant designation as LLPs. Failures of these components are very rare, but when they do occur, immediate uncommanded shutdown usually results. In the case of an air seal, which suffers excessive internal leakage (i.e., hot gas does not leak outside the engine case), detection of this failure mode with existing sensors is considered difficult and will likely require new sensor technology or complex interpretation of current sensors.

Significant HPT static structural components include the HPT case, HPT frame (some engine designs), and the HPT shrouds. HPT case damage usually results in hot gas leaks sufficient to set off the FODS. Turbine frame damage generally relates to visually discovered cracks. HPT shroud damage has analogous effects to NGV damage, in that such damage is normally detected during postflight visual inspection, but in rare cases, may cause sufficiently high EGT excursions to provoke IFSD.

2.6.6 Low-Pressure Turbine Damage Modes (Tables 2-8 and 2-9).

Due to a less arduous thermal environment, the LPT accounts for a much smaller percentage of UERs and IFSDs than the HPT (~4% of UERs and 1.4% of IFSDs). As with the HPT, LPT blades and vanes constitute the predominately damaged component of this module. Although LPT blade and vane damage often caused high vibration or EGT shift, partial or significant power loss was relatively more common with the LPT than with the HPT. Since the main task of the LPT is to drive the fan, a weakened LPT can directly affect the principal thrust producer.

As with all other high-energy engine components, LPT disks are classified as LLPs. LPT disk failures are very rare and typically result in immediate uncommanded IFSDs.

Table 2-9 shows several LPT damage modes that will likely require placement of new sensors for improved detection. For the reasons cited above for HPT air seal internal leakage, the same failure mode in the LPT is not likely detectable with existing sensors. Critical external leakage from engine casings and ducts are detected by the FODS. To provide the earliest possible detection of fire, FODS sensors are typically located in the vicinity of the hottest gas path components, such as the combustor and HPT casings. LPT case or cooling air leaks typically do not risk fire outbreak due to a combination of (1) the lower gas temperatures prevalent in the LPT (relative to the combustor or HPT) and (2) the diluting effects of core compartment ventilation air, which usually exhausts aft over the LPT case in most propulsion system installations. Thus, the usual placement of FODS sensors is well forward of the LPT.

2.6.7 Nacelle Components Damage Modes (Tables 2-10 through 2-12).

Nacelle components include such structural items as the inlet, exhaust system, cowls, strut, and engine mounts. The thrust reverser was also assigned to this category. Damage to these nacelle components generally included cracked, missing, or loose portions of structure. These damage modes were most often detected by postflight visual inspection. While such damage can cause elevated vibration levels, detection and indication of this type of vibration depends on the AVM accelerometer location and signal processing concept. To meet the prescriptive regulations, the AVM system's primary task is to provide awareness of synchronous vibration arising from rotor imbalance. As such, the AVM algorithms are not specifically designed to capture nonsynchronous vibration that would typically be associated with nacelle structural damage.

The engine inlet includes the anti-ice system. Most anti-ice systems operate with hot bleed air piped from the HPC forward to the inlet lip. Anti-ice bleed air duct failures are sensed by the Duct Leak Overheat Detection System (DLODS). Anti-ice air is regulated through a shutoff valve. Shutoff valve failures are sensed by a dedicated position sensor.

The thrust reverser includes dedicated sensors to detect actuation and locking system failures.

2.6.8 Propulsion Subsystems: Bleed Air and Fire Protection System Damage Modes (Table 2-13).

Engine bleed air system component damage typically includes duct leaks or failures of the associated control valves. In both cases, existing sensors provide adequate detection of most

failures. Hot gas leakage is detected by the FODS. Exceptions include detection of low-temperature bleed air leaks such as fan air piped to active clearance control (ACC) manifolds. In this case, however, failure of the ACC system to function is confined to decreased EGT margin or slightly elevated fuel consumption, depending on the mission phase rather than an immediate operational consequence. Some bleed air valve failures are detected by internal position sensors.

Fire protection system components include both the FODS and fire-extinguishing systems. FODS incorporates fault checking intended to distinguish failed sensors from a fire or overheat condition. The fire-extinguishing system monitors extinguishing agent storage and alerts if leaks are detected.

2.6.9 Propulsion Subsystems: Lubrication System Damage Modes (Table 2-14).

The lubrication system is one of the most problematic in terms of UERs and IFSDs, but lubrication system damage is not a strong contributor to ICR. As noted in table 2-1, the lubrication system directly accounts for 7% of all UERs and ~14% of IFSDs. Acknowledgement of this system's susceptibility to damage is reflected in the large amount of prescriptive sensors dedicated to lubrication system health (refer to table 2-3). These existing sensors generally target leaks, debris generation, and overheat conditions and provide good coverage for the vast majority of lubrication system failures.

2.6.10 Propulsion Subsystems: Lubricated Components Damage Modes (Table 2-15).

Failures of lubricated components, such as gearboxes, bearings, and bearing seals, account for a relatively large portion of UERs and IFSDs (~10% and 12%, respectively). Damage to gearboxes includes shaft and gear failures, housing cracks, and internal bearing failures. Apart from housing cracks, which are generally discovered during postflight visual inspections, gearbox internal failures usually result in an uncommanded shutdown if the main fuel pump drive is compromised or a loss of oil pressure if the lube pump drive fails.

Complete failures of main shaft roller or ball bearings also usually result in uncommanded shutdown. Bearing failures may culminate in an EGT rise or compressor surge, but are often preceded by increased vibration (at bearing frequency) and some form of oil system indication such as high filter differential pressure or oil debris monitor/metallic chip detector-sensed debris.

With the exception of bearing seals, lubricated component damage was assessed to have potential for improved detection via integration of vibration and oil system sensors. Bearing seal failures generally become initially evident as smoke or odor in the cabin and later may degrade into measurable oil loss. New sensors would be required to provide odor detection. Significant oil quantity loss is currently detectable in the same manner as lubrication system plumbing leaks—via the oil quantity sensor.

Table 2-15. Engine Damage Mode Assessment (Lubricated Components)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Lubricated Components																																			
Shafts	Cracks				Component teardown																														
Bearings	Excessive wear / impending failure	5.13%	3.39%		Component teardown; debris monitor, vibration monitor					✓															X	✓								
Bearings	Complete failure				Component teardown; debris monitor	X			*	*					*			*				*			*	*								*
Seals	Excessive Leakage	0.75%	2.70%		Oil pressure sensor; Oil Quantity Indicator				✓										*							✓								
Gearboxes	Excessive wear / impending failure	5.57%	3.23%		Component teardown; debris monitor				X	X															X	X								
Gearboxes	Failed gear teeth				Component teardown; debris monitor				✓	✓					✓							✓			X	X								*
Gearboxes	Failed shaft				Component teardown; debris monitor				*	✓					*							*			X	*								*
VSCF / IDG																																			
Shafts	Failed	0.87%	0.14%		VSCF/IDG BIT				✓																	X			*					
Mounting System	Failed				Engine Oil System Sensors				✓																	X			✓					
Lube System	Leaks				VSCF/IDG lube sensors (pressure, level, etc.)				✓																	X			✓					

No main shaft failures were noted during the 6-year study period. However, in the rare event of such failures, uncommanded shutdown results through a combination of protective features either in the mechanical design (e.g., rotating parts clash) or control system detection and accommodation.

Table 2-16 also lists failure modes relating to engine-driven electrical generators. Such generators include constant speed drive, integrated drive generator, or variable speed constant frequency designs. Irrespective of the design, these generators are driven by an engine-mounted gearbox and are usually lubricated by oil systems independent of the engine lubrication system. These generators are equipped with dedicated electrical, mechanical, and oil system failure detectors.

Table 2-16. Engine Damage Mode Assessment (Fuel Supply and Controls)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Fuel Supply System																																				
Boost Pumps	Internal Leak / low output		0.30%	0.00%	Fuel pressure sensor									✓								✓														
Fuel Spar Valve	Failure (closed)		0.53%	0.02%	Position Sensor									*								*														*
Tubing / Hoses	Leaks				Visual									*						✓		*					✓									
Couplings	Loose / Missing				Post-flight visual																															
Filters	Clogged / Bypass		0.08%	0.00%	Delta-P switch																															✓
Flow Meter	In or out-of-range failure				Error comparison to tank sensors			✓																											✓	
Main Fuel Pump	Internal Leak / low output		0.51%							X				✓							✓	✓														
Main Fuel Pump	Complete failure		0.92%	0.21%						X				*							✓	*														
Hydro-Mechanical Unit / Fuel Controller	High Output / Internal Leak		2.79%	0.20%	Detected by higher-order engine effects (flameout, thrust												*				X		*	✓												
Hydro-Mechanical Unit / Fuel Controller	Internal Leak / low output		↓	↓										✓							✓	✓														
Propulsion Control System & Sensors																																				
FADEC	FADEC failure		1.54%	0.11%	internal BIT										*						*	*														*
Throttle	Stuck or jammed throttle		0.64%	0.01%													*																			
Pneumatic System	Control Line Leak		2.33%	0.46%	internal BIT										✓	✓					✓	✓	✓				X									
PMA	Failure		0.94%	0.14%					X																	X										✓
AVM	False Reading		0.45%	0.05%						*															✓											
Sensor Failure	In or out-of-range failure		7.04%	0.79%	sensor BIT	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	✓		✓		X	X	X	X	X				

2.6.11 Propulsion Subsystems: Fuel Supply and Control System Components Damage Modes (Table 2-16).

Fuel supply component damage consists of plumbing leaks (both external and internal) and failures of pumps, valves, and other components. External leaks cause a loss of fuel from the system (i.e., overboard), while internal leaks generally occur across valves and pump seals. Depending on the location, large external leaks may be detectable by existing sensors (e.g., disparity between aircraft fuel tank sensors and engine fuel flowmeter totalization). Fuel system damage upstream of the main fuel filter that results in debris generation is currently detectable with the prescribed filter bypass sensor. Failures of the main fuel pump may be detectable by difficulty in starting or failure to achieve rated thrust. In general, however, internal leaks associated with fuel valves or pumps are difficult to detect and probably will require new sensor technology.

2.6.12 Propulsion Subsystems: Other Aircraft System Components Damage Modes.

Table 2-17 lists the principal damage modes of the engine start system and hydraulic system components usually located in the propulsion nacelle. Both of these systems are generally equipped with dedicated existing sensors for their principal failure modes.

Table 2-17. Engine Damage Mode Assessment (Other Aircraft Systems)

Symbology:	
Highly Likely	*
Likely	✓
Possible	X
Unlikely	

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Relative Frequency of Occurrence: % of all IFSD's	Relative Frequency of Occurrence: % of all Unscheduled Removals	Existing Sensor Means of Detection	Existing Engine Indications: EPR/N1/N2/N3 High/Low/Fluctuation	Existing Engine Indications: EGT High/Low/Fluctuation	Existing Engine Indications: Fuel Flow Shift/Fluctuation	Existing Engine Indications: Oil System Indication (P, T, Qty, Filter Dp)	Existing Engine Indications: Indicated Vibration High	Other Existing Indications/Symptoms: Surge/Stall (Unrecoverable)	Other Existing Indications/Symptoms: Surge (single recoverable)	Other Existing Indications/Symptoms: Surge (continuous/multiple)	Other Existing Indications/Symptoms: Flameout	Other Existing Indications/Symptoms: Powerloss (Subidle) / Uncommanded Shutdown	Other Existing Indications/Symptoms: Powerloss (above idle - Partial Thrust Loss or Rollback)	Other Existing Indications/Symptoms: No Response to Throttle (Overthrust)	Other Existing Indications/Symptoms: Sensible/Audible Airframe Vibration	Other Existing Indications/Symptoms: Smoke (Flt Deck or Cabin)	Other Existing Indications/Symptoms: Visible FireVisible Leak	Other Existing Indications/Symptoms: Failure to Start or Restart	Existing Alerts/Annunciations: Eng Subidle Alert	Existing Alerts/Annunciations: Eng Thrust High/Low Alert	Existing Alerts/Annunciations: Eng Limit Exceedance Alert (High/Low)	Existing Alerts/Annunciations: Vibration Exceedance Annuncuation	Existing Alerts/Annunciations: Eng Oil (T, P, or Q) Alert or Annunciation	Existing Alerts/Annunciations: Fire/Overheat Alert/Ann	Existing Alerts/Annunciations: Anti-Ice Alert/Ann	Existing Alerts/Annunciations: CSD / IDG Alert/Ann	Existing Alerts/Annunciations: Reverser Unlock Alert/Ann	Existing Alerts/Annunciations: Start System Alert	Existing Alerts/Annunciations: Fuel Imbalance	Existing Alerts/Annunciations: Other	Usually Causes Downstream Damage?
Start System																																				
	Start Turbine / shaft	blade / shaft /clutch failure	1.20%	0.07%	Starter speed sensor				✓	X								X			✓				X	✓										
	Starter Air Valve	Failure to function (open or			Valve BIT																✓										*					
	Starter	Oil Leak			Engine lube system sensors (if shared oil system); otherwise - post-flight visual				✓																	X										
	Position / Pressure Sensor	In or out-of-range failure			Sensor BIT																✓										X				
Hydraulic System (Propulsion Portion)																																				
	Engine-Driven Pump	External Leak	0.30%	0.12%	Hydraulic Reservoir Level																						X									
	Engine-Driven Pump	Seized Shaft			Pump pressure				X	X															X	X									✓
	Engine-Driven Pump	Internal Failure			Pump pressure				X	X															X	X									✓
	Tubing / Hoses	Leaks			Hydraulic Reservoir Level															X							X								
	Filters	Clogged / Bypass			Filter Dp (maintenance display?)																														X
	Couplings	Loose / Missing			Hydraulic Reservoir Level															X							X								

2.6.13 Indeterminate Damage Modes.

Tables 2-3 through 2-17 include relative rates of occurrence for both UERs and IFSDs. Since the in-service data also reflects events attributable to indeterminate and nonengine damage-related causes, the percentage sums need to be corrected as shown in table 2-18 to achieve 100% totals for both event types.

Table 2-18. Percentage of Sums of ISFDs and UERs

	Percent of All IFSDs	Percent of All Unplanned Removals
Sum of data from tables 2-4 through 2-17	75.6	82.8
Excluded items (i.e., indeterminate and nonengine damage-related)	24.4	17.2
Total	100	100

2.6.14 Potential New Coverage Provided by Sensor Fusion.

For each engine damage mode, tables 2-3 through 2-17 provided assessment of:

- The probability of setting existing indications, alerts, annunciations, and other symptoms.
- The damage mode's detectability detected by existing sensors, sensor fusion, or whether new sensors would likely be required.

In an effort to gauge the potential benefit of new sensor fusion-based damage detection, the damage modes considered highly likely or likely to trigger existing alerts were grouped according to UER and IFSD frequency. Figures 2-17 and 2-18 compare the component damage occurrences correlated against baseline annunciations for UERs and IFSDs, respectively. As these figures show, most potential new coverage is for lubricated component damage, followed by gas path component damage[*]. Overall, the potential new coverage is in the 16%-20% range, depending on the damaged component group.

[*] Excluding other components such as control, sensors, nacelle structure, etc., which were not a focus of this study.

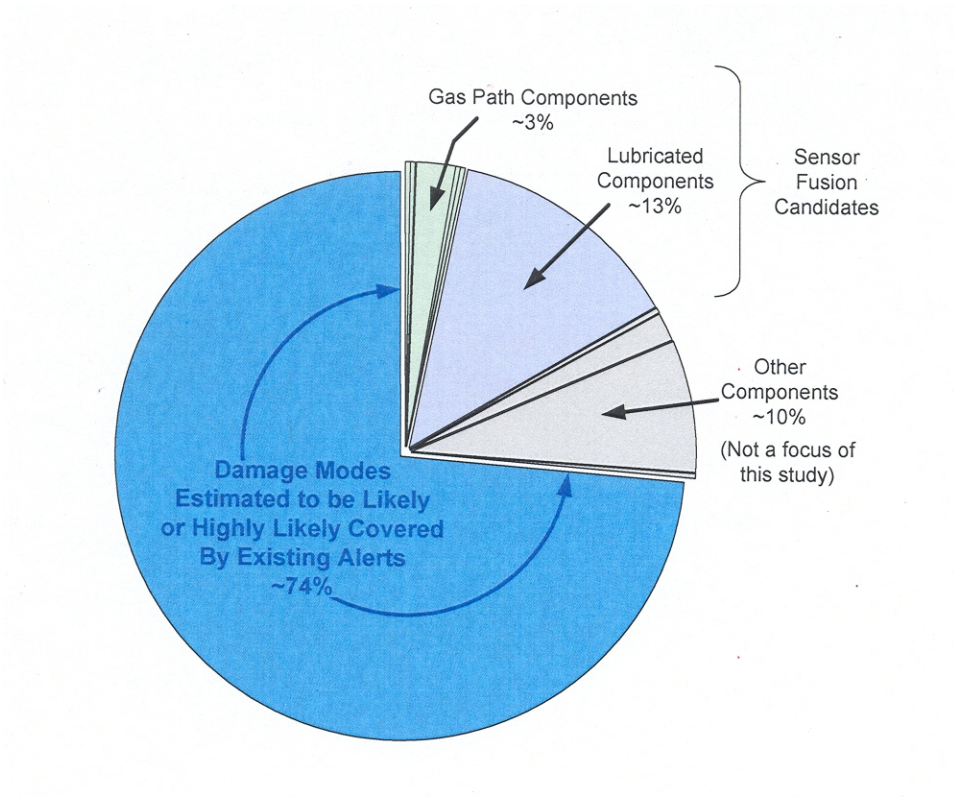


Figure 2-17. Estimated Baseline Annunciation Coverage for IFSDs

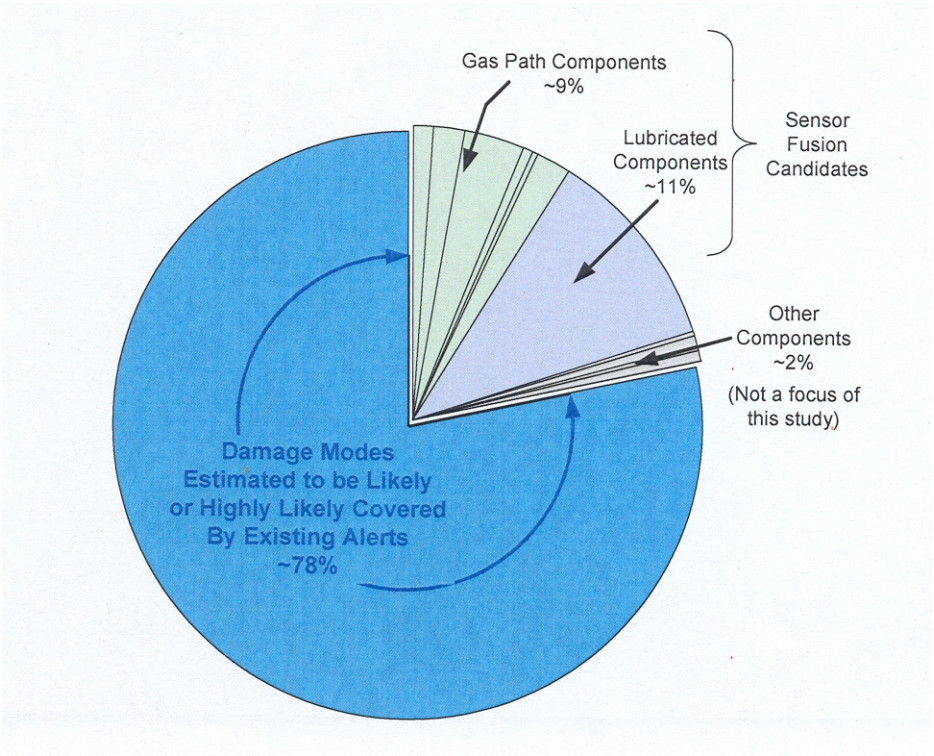


Figure 2-18. Estimated Baseline Annunciation Coverage for UERs

2.7 IN-SERVICE DATA APPLICATION.

The in-service data collected and analyzed in Task 1 was used in successive Phase 3 research tasks for a variety of applications. The distillation of UER and IFSD events in the Task 1 analysis and subsequent tasks is shown in figures 2-19 and 2-20. Engine damage events where the engine both continued to operate with damage and registered flight deck effects were assessed to have the greatest potential applicability for new damage detection.

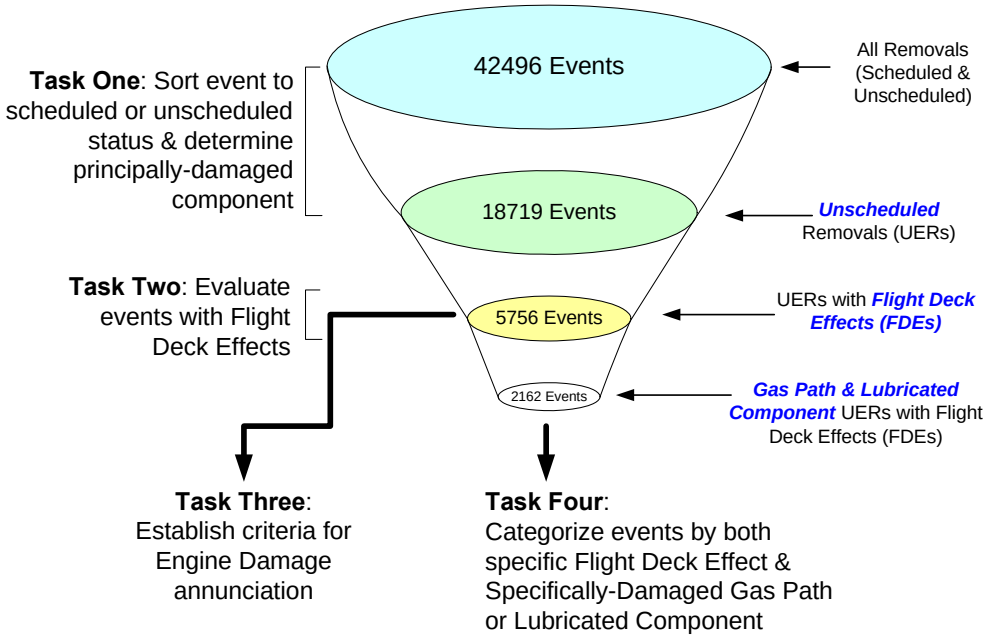


Figure 2-19. Removal Event Distillation

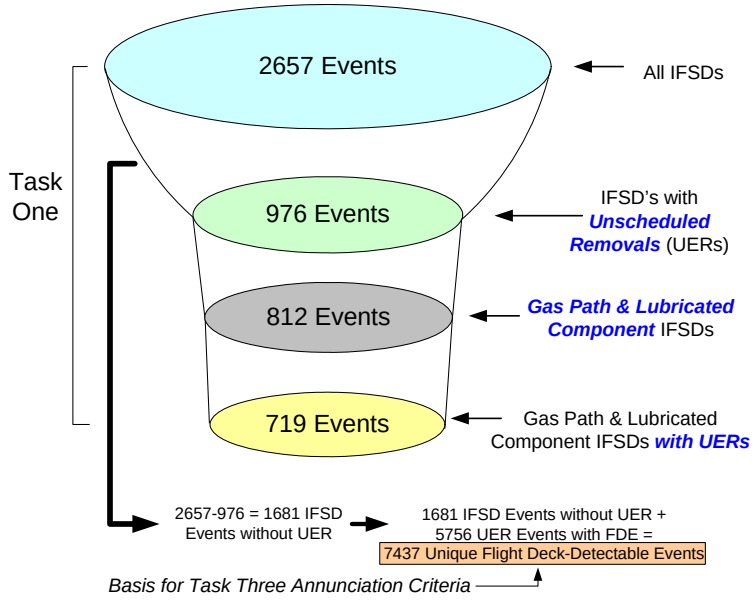


Figure 2-20. Event Distillation of IFSD

2.8 ENGINE DAMAGE DURING ICR EVENTS.

References 1 and 2 documented 80 PSM events where ICR occurred. These 80 events were reviewed as a part of the Task 1 effort to determine what role, if any, engine damage played in these events. This assessment applied the Phase 3 definition of engine damage (i.e., all propulsion nacelle components were included). The assessed breakdown of the events was as follows:

- Fifty-five events had documented damage to the propulsion system. (Note: This includes one example of a sensor shift and seven instances of "stuck throttle.") The results of the review in terms of number of events versus specifically damaged components are provided in figure 2-21. Gas path, control system, and lubrication system components dominated the distribution. All engine damage modes recorded during these events were consistent with the descriptions previously documented under Task 1.

- Seventeen events did not contain enough information to specifically identify engine damage participation, but damage was potentially present.

- Eight events either involved an engine abnormality with no apparent damage or the crew erroneously thought an engine malfunction had occurred. Examples include:

  - bird ingestion that resulted in no apparent damage,
  - water ingestion resulting in thrust loss but no damage,
  - water on runway resulting in slow airplane acceleration, or
  - recoverable surge caused by engine deterioration, without specific damage.

Damage Distribution	
Principally-Damaged Component	**# of Events**
Spinner	2
Fan Blades	8
Fan Case	1
HPC Blades	6
Turbine Blade	6
Turbine Seal	1
Disk	5
Indeterminate - Gaspath-related	3
Indeterminate - Gas path or Lubricated Component Related	2
Bearing	2
Lube System	1
Gearbox	1
Bleed Air System	2
Fuel System	1
Sensor	1
Pneumatic System	2
Thrust Lever System	7
Thrust Reverser	2
Indeterminate - Fire Warning	1
Indeterminate - Insufficient Info	1
Total:	55

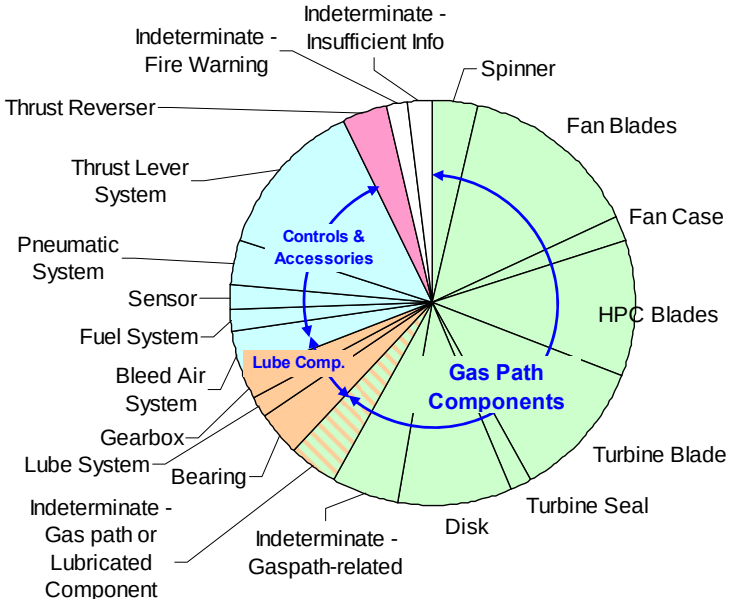


Figure 2-21. Engine Damage During PSM+ICR Events

The 80 events were further analyzed in terms of prevention potential and engine malfunction annunciation, as shown in figure 2-22.

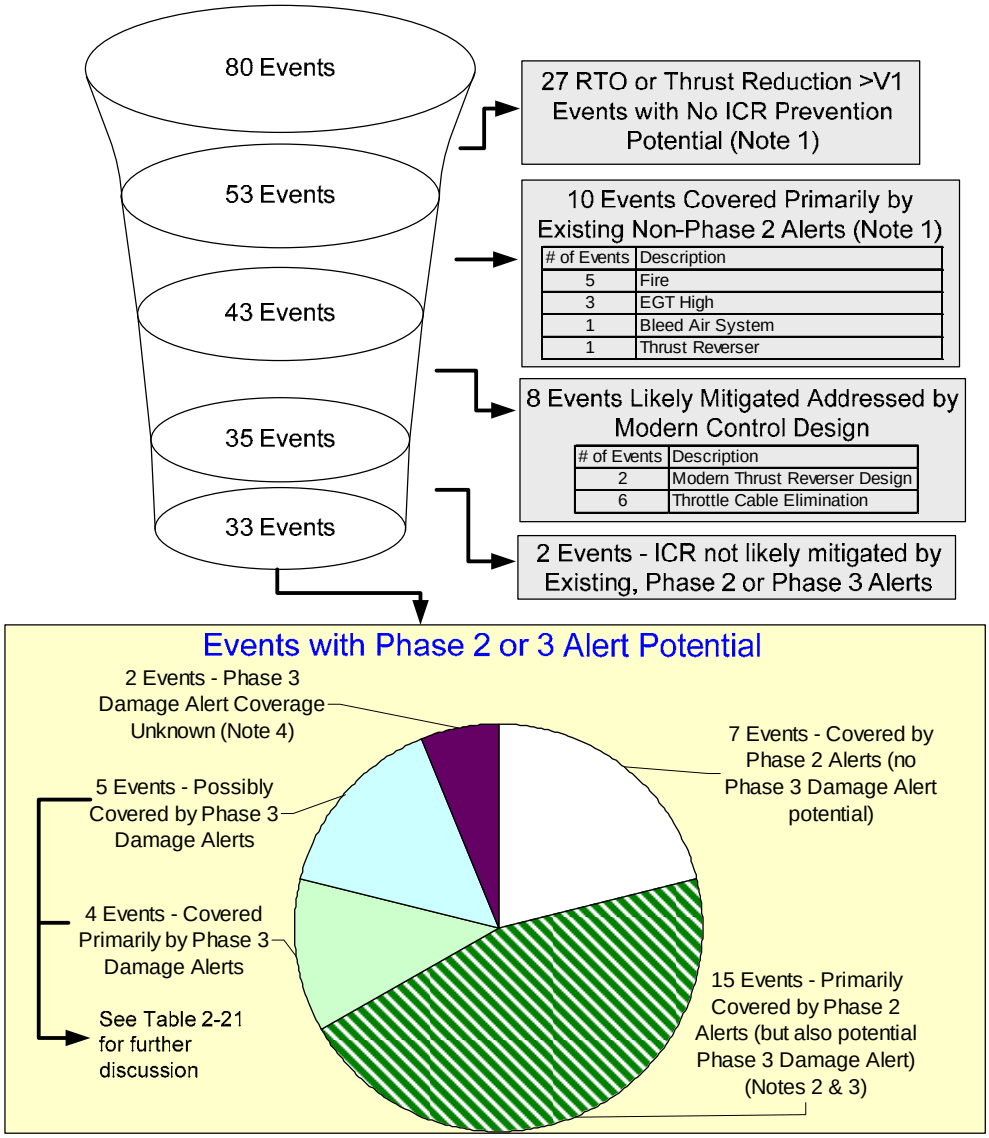
- Twenty-nine events were refused takeoff (RTO) RTO>V1 or thrust lever reduction >V1. Of these, 27 events were considered not to have prevention potential.

- As a part of Phase 3, these events were reanalyzed to determine how far below V1 the damage was incurred, and whether an annunciation would have prompted proper pilot response before V1. For example, if engine damage can be annunciated below 80 knots, the pilot has sufficient time to determine the appropriate course of action. Without this early annunciation capability, the pilot typically has no time to detect and interpret the data, which may result in an RTO above V1 (decision speed). Similarly, timely awareness of damage may prevent other ICR, such as allowing aircraft reconfiguration for engine inoperative landing with engine damage on approach or prior to go-around.

- In one RTO>V1 event, high vibration was noted during engine run-up, so it is likely an engine damage alert could have prevented this event (included as one of the five events "Possibly covered by Phase 3 Damage Alerts" in figure 2-22). In another event, continuous multiple surging was detected in the previous flight, and so it is likely that a continuous/multiple surge or engine damage alert could have prevented this event (included as one of the 15 events "Primarily Covered by Phase 2 Alert (but also potential Phase 3 Alert)" in figure 2-22).

- Eighteen events were likely addressable by alerts that exist on modern aircraft (e.g., fire alert, bleed air malfunction, EGT exceedance, etc.) or have been mitigated through modern design (i.e., throttle cable elimination or improved thrust reverser control redundancy).

- Two events would not likely have mitigated the ICR through any alert (existing, Phase 2, or Phase 3), but rather, were airmanship-related.



Note 1: Unknown prevention potential possibly exists for some events through Phase 3 damage alerting (if damage can be detected and annunciated sufficiently prior either to V1 or setting an existing alert)
Note 2: Includes some events with unknown engine damage
Note 3: "Primarily Covered by Phase 2 Alerts" refers to events covered by (1) existing certified sub-idle and thrust disagree alerts; or (2) a continuous/multiple surge alert. In these cases, the Phase 2 alerts are more operationally appropriate and feasible to implement.
Note 4: Events with engine "deterioration" listed as a contributing factor.

Figure 2-22. The PSM+ICR Event Assessment

As indicated in figure 2-22, the above filtration left 33 events with Phase 2 or Phase 3 alerting potential. These 33 events were further categorized as follows.

- Seven events were primarily covered by Phase 2 alerts. These events included (1) six scenarios where the Phase 2 and Phase 3 alerts would have been near simultaneous and, thus, the Phase 2 alert would have been preferable by providing a deterministic condition or response and (2) one scenario where the Phase 3 engine damage alert would not have detected the anomaly.

- Fifteen events were assessed to have either Phase 2 or Phase 3 alert potential. However, these events were further evaluated to be primarily covered by Phase 2 alerts in that they were either covered by (1) existing certified subidle or thrust disagree alerts or (2) a continuous/multiple surge alert (for which reference 3 defined a more operationally appropriate deterministic condition or response). Also included in this category were two events where engine damage may have been present, but insufficient information was available from the write-up.

- Nine events potentially covered by a Phase 3 engine damage alert.

  Four events were determined to have clear ICR prevention potential. Three of the four events involved shutdown good engine (SDGE), one event had hull loss and fatalities (the reference 4 event), and the other two were incidents only (no hull loss or fatalities). The fourth event was an RTO<V1 due to noise and vibration, and the ICR was Other—malfunction misidentification (the pilot thought it was a damaged tire rather than engine damage).

  The remaining five events had possible prevention potential. Table 2-19 provides specific details on these nine events.

- Two events with engine deterioration recorded as a contributing factor were categorized as having unknown Phase 3 damage alert potential. If the deterioration occurred over numerous flights prior to the ICR event, it is likely that the parameter shift during the ICR event would not have been significant enough to trigger the damage alerts described in section 5.

In summary, the PSM+ICR event review concluded that engine damage annunciation had clear ICR prevention potential in at least 5% and perhaps as much as 11% of the historical PSM+ICR events. Engine damage annunciation is, thus, complementary to the Phase 2 STA detection. Specifically, engine damage detection provides additional new coverage and may improve existing engine malfunction detection and annunciation. Note that six engine damage events involved continuous/multiple surge, which would be covered by Phase 2 STA detection and annunciation.

Table 2-19. The PSM+ICR Event Analysis: Damage Alerting ICR Prevention Potential

Reference 1 Event No.	Reference 1 ID No.	Event Class	Prevention Potential	Event Description
53	89/MNB/2/HF	Hull Loss/ Fatalities	Yes	Recoverable surge, SDGE
42	85/MWB/2/I	Incident	Yes	Recoverable surge, SDGE
68	94/2ND/3/I	Incident	Yes	Recoverable surge, SDGE
57	91/2ND/3/I	Incident	Yes	Pilot had right response. RRO<V1 due to vibration and noise, but pilot thought it was damaged tire rather than damaged engine
81	96/1ST/4/HF	Hull Loss/ Fatalities	Possible	Not enough information. Likely thrust loss on two engines before V1, but pilot continued takeoff and hit tower. Likely thrust loss on engine 4, but perhaps damage (cowl loss) on engine #3
63	93/WEB/4/I-2	Incident	Possible	Pilot shutdown two engines. Both engines had EGT exceedances, but only on was damaged.
41	85/EWB/4/I-2	Incident	Possible	Subidle alert for engine #3. Thrust lever pullback (and engine parameter reduction) caused confusion and shutdown of engine #4. Perhaps lack of engine damage alert would address.
32/33	82/EWB/4/I	Incident	Possible	Correct engine was identified by high vibe warning light, but engineer (three crew) shutdown wrong engine
56	56: 91/MNB/2/I	Incident	Possible	RTO > V1, but high vibration noted during engine runup.

2.9 TASK 1 CONCLUSIONS.

The Task 1 evaluation of in-service events identified the engine damage modes that drive both UERs and IFSDs. Conclusions related to specific component failures include the following:

- Gas path components are the principal driver for unscheduled removals and are also a strong contributor to IFSDs. Within the gas path, the HPC and HPT stand out as the most frequently damaged components. For the HPC, this is generally due to the large "target" presented by the HPC to incoming foreign objects (i.e., large number of stages and rapid rotation rate relative to the upstream fan and LPC). For the HPT, the high gas temperatures presented to these components provide a challenging oxidation and creep environment.

- Lubrication system and lubricated components stand out as a strong contributor to both IFSDs and UERs. As expected, failures of LRUs, such as sensors, drove a greater proportion of IFSDs than UERs.

- Indeterminate causes accounted for a significant portion of both IFSDs and UERs. However, upon examination of the table 2-1 data, only 4% of either event category was

indeterminate due to insufficient information. The remaining events, while not documented in adequate detail to reveal the primary damaged engine component, did contain sufficient information to categorize the symptoms according to one of three categories:

- High vibration—indicated or sensible (tactile)
- Lubrication system or lubricated component-related
- Performance or operability-related—compressor surge or EGT exceedance noted

These results suggest that improved damage detection for gas path and lubricated components would also address the majority of the indeterminate cause events.

The Task 1 propulsion system failure analysis results complemented the findings from the in-service report review. This failure analysis revealed which damage modes were

- adequately served by existing detection or annunciation methods (either sensor or visual inspection-based),
- candidates for improved damage detection using combinations of existing sensors, or
- likely to require introduction of new sensors.

Within the sensor fusion category, gas path and lubricated components are the greatest potential opportunity for new detection and annunciation. Conversely, examples of propulsion system components adequately covered by existing sensors are the lubrication, fuel supply, and control systems. Such damage as internal fluid system leaks and nacelle structural damage will likely require application of new sensor technology.

A review of the 80 historical PSM + ICR Phase 1 events indicates engine damage was present in the majority of these events. Further, the nature and relative frequency of the PSM+ICR engine damage events were consistent with the Phase 3 Task 1 engine damage mode definitions and service data review findings. The review specifically concluded that damage annunciation may have had primary ICR prevention potential in at least 5% and, potentially, 11% of the 80 events. Approximately 20% of the 80 events had ICR prevention potential through either Phase 2 STA or Phase 3 engine damage alerting, but the study assessed that the Phase 2 alerts would have been more feasible to implement either because they were based on existing certified designs or were more likely to provide a deterministic condition or response. Refer to further discussion on alert response determinism in section 4.14. Over half of the 80 events were assessed as not covered by either Phase 2 STA or Phase 3 engine damage alerts since these events involved either (1) RTO or thrust reduction above V1, (2) were already covered by existing alerts, (3) were most likely mitigated by modern controls design, or (4) were primarily airmanship-related.

3. TASK 2: ENGINE DAMAGE MODES ASSESSMENT FOR PILOT AWARENESS AND ACTION.

Task 2 established the types of damage-related performance information a flight crew would desire, determined damaged engine performance characteristics, developed detection categories appropriate for crew awareness and action, and identified what response could be associated with each damage detection category. Specifically evaluated within this task were:

- For each engine module, an assessment of potential operational effects as a result of damage.
- The preferred damage annunciation methods from both desired response and dispatch-related maintenance awareness perspectives.
- Available methods to determine damaged engine power capability.
- For each major engine module, the minimum state of mechanical integrity necessary to support restart and the associated available indications.

The first two considerations jointly established the engine damage detection fidelity criteria.

3.1 TASK 2 OBJECTIVES.

The overall approach to Task 2 execution is illustrated in figure 3-1. Task 2 sought to determine the usefulness of engine damage annunciation from a pilot perspective. Further, the preferred form of damage annunciation was to be assessed. This task included an evaluation of damaged engine restartability prerequisites and power range capability.

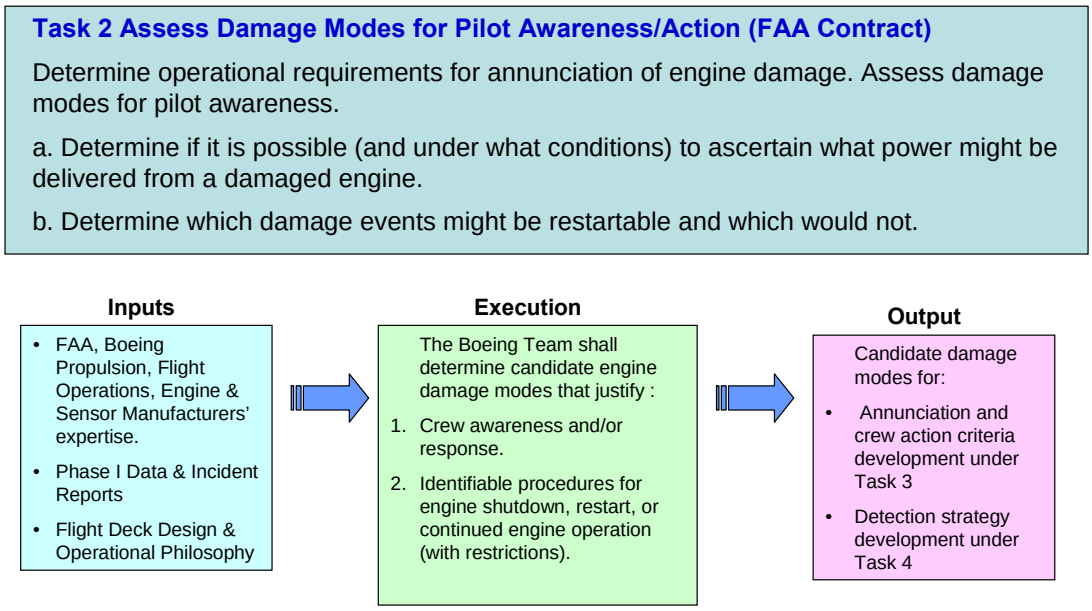


Figure 3-1. Task 2 Approach

3.2 TASK 2 RESULTS SUMMARY.

Task 2 categorized the engine damage for common response characteristics' unique categories. In increasing order of operational significance, these categories were:

- Awareness Only
- Isolate Bleed Air—covered by existing detection, annunciation, and procedures
- Restrict Thrust
- Shutdown
- Immediate Shutdown—covered by existing fire detection, annunciation, and procedures

Based on the commonality of ensuing responses and the operational requirement to minimize the number of alerts, Task 2 further concluded that the awareness only and restrict thrust categories should be merged.

For purposes of dispatch-related maintenance awareness, engine damage annunciation was classified to a major engine module level.

Since commanded engine shutdown, and to a lesser extent thrust restriction, incurs potentially significant operational consequences, Task 2 evaluated the detailed considerations for these actions. Both operational and economic reasons for these responses were evaluated.

Task 2 undertook an assessment of the requirements to restart a damaged engine—both in terms of minimum hardware integrity and the attendant indications. As well, Task 2 documented the current procedure for determination of a damaged engine's power capability. Pilots participating in this research expressed a desire for automatic determination of these capabilities for a damaged engine. However, designing these features into a sensor fusion-based damage detection system is likely to be very challenging (covered in further detail in section 5).

3.3 ENGINE DAMAGE ANNUNCIATION CONCEPTS.

Engine damage annunciation is useful for two purposes: (1) to provide crew awareness that potentially prevents ICR or otherwise informs the flight crew of the appropriate response action that preserves maximum operational flexibility within safe operating limits and (2) to identify critical maintenance action prior to subsequent dispatch. Categorization of appropriate response requires only that engine damage be identified to a common response group. For modern turbofan engines equipped with bleed air extraction for cabin air conditioning, there are a limited range of pilot actions that directly affect the engine:

- Bleed air isolation: The pilot can directly close shutoff valves that direct engine bleed air to the air conditioning or anti-ice systems.

- Thrust lever placement: Once disengaged from the autothrottles, the engine thrust is controllable at the pilot's discretion from idle to maximum power settings.

- Engine shutdown: The engine may be shutdown by placing the fuel control switch to cutoff or pulling the fire handle. Two engine damage categories were considered: one for immediate shutdown (where memorized action as in the case of fire), and one for shutdown (where memorized action was not required). In both cases, shutdown is only advised after completion of a current critical flight phase.

Identification of dispatch-critical maintenance requires a higher damage isolation fidelity than categorization of appropriate response. Virtually all modern turbofan engine designs incorporate some form of fault detection and annunciation through aircraft maintenance displays. Often, this fault detection system is capable of isolating the damage to a specific engine subcomponent. This research did not seek to duplicate this existing capability, but rather, focused on detection requirements sufficient to isolate damage to the most affected major module or subsystem.

A detailed assessment of desired response against specific component failure modes is provided in tables 3-1 through 3-9. The goal of this effort was to group detailed component failures into common response categories. To this end, detailed failure modes previously evaluated in Task 1 were used for the response assessment. In evaluating the initial response to specific damage, these tables employed the response categories listed below. Note: This research recognized that damage modes may progress from one response state to another (e.g., an awareness event may cascade to restrict thrust and culminate in shutdown or immediate shutdown. Listed in these tables is the initial response. Further considerations regarding cascading effects are provided in section 5.7.

- Awareness—Pilot awareness of the specifically damaged engine is warranted. In some cases, awareness only without a specific response was considered appropriate. In other cases, awareness in combination with a preferred response was recommended.

- Isolate Bleed Air—Engine damage to either the compression system or the bleed air components may allow this response in lieu of a thrust reduction, thrust restriction, or engine shutdown. Note: Existing alerts and procedures for smoke in the cabin, nacelle overheat, or detected bleed air duct leak were determined to adequately cover all the damage modes in this response category, and thus, additional damage detection improvements were not undertaken.

- Restrict Thrust—Damage is such that the continued engine operation at lower thrust is possible. Reducing the engine thrust setting is expected to limit the damage progression yet maintain idle-or-above engine operation. In general, gas path component damage comprised this response category. Exceptions to this rule included (1) combustor damage where case burn-through and resulting fire were probable, (2) selected subsystem failures, and (3) nacelle damage modes influenced by engine power setting. In addition to thrust reduction, thrust rate of change was considered.

- Shutdown—Damage is such that the engine should be shutdown to avoid severe damage or uncommanded shutdown. Delays in shutting down the engine are acceptable. Even for the more severe damage events, a delay in executing the pilot-commanded shutdown is acceptable to first allow completion of high pilot workload flight phases, such as takeoff or landing. Additional delays may be acceptable, with operation of the engine at idle.

The allowable delay time prior to commanded shutdown depends on the following considerations:

- The specific engine design.

- The actual damage scenario. As an example, bearing damage alone may allow substantially longer continued operation than bearing damage coupled with an immediate loss of oil pressure.

Both of the above considerations require further evaluation to precisely establish any allowable shutdown times.

Engine damage types contributing to this response category were lubricated components where continued operation would likely lead to severe damage (refer to section 3.4 for further discussion). Note: This phase's research applied the shutdown response category to encompass only detected lubricated component damage; the existing procedures for oil alerts (i.e., lubrication system damage) are very similar. Phase 3 research determined that these existing oil alert procedures are adequate, but improvements are possible for lubricated component damage. The detailed integration of existing oil alert procedures and the new shutdown response category is recommended for future research, section 8.3.

- Immediate Shutdown—Damage requires prompt engine shutdown to avoid degradation of safety margins. This category was limited to engine damage modes that risked uncontrolled fire (e.g., high-pressure flammable fluid leaks or combustor burn-through). Current prescriptive fire detection instruments and associated existing alerts and procedures were deemed to adequately cover these damage modes. Similar to isolate bleed air, additional damage detection improvements were not undertaken for components assigned to the immediate shutdown category.

Table 3-1. Initial Response to Detected Damage: Fan Components

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Initial Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
Fan								
	Blade	Missing Section			✓			Continued operation at reduced fan speed may be possible if vibration is acceptable.
	Blade	Bent Blade	✓		✓			Same as above for missing blade section. Awareness benefit: full thrust may not be available from damaged engine.
	Blade	Crack (beyond service limits)						
	Spinner	Liberation, Distortion, or Missing Section	✓		✓			Continued operation at reduced power setting may prevent surge or complete liberation. Awareness benefit: distinction of affected engine.
	Platforms / Annulus Fller	Missing Section	✓		✓			Continued operation at reduced power setting may prevent surge or progrssion of damage. Awareness benefit: distinction of affected engine.
	Hub/Disk	Missing Section						Uncommanded engine shutdown is the most likely outcome from fan disk failure. Awareness covered by existing engine failure alert.
	Hub/Disk	Crack (beyond service limits)						
	Case	Crack (beyond service limits)						
	Abradable	Missing Section	✓		✓			Continued operation at reduced power setting may prevent surge or progression of further damage. Awareness benefit: distinction of affected engine.
	Fan Hub Frame	Crack						
	Fan Hub Frame	Missing Section	✓					Awareness benefit: distinction of affected engine.
	Outlet Guide Vanes / Fan Case Struts	Missing Section	✓		✓			Same as above for missing blade section. Awareness benefit: full thrust may not be available from damaged engine.
	Outlet Guide Vanes / Fan Case Struts	Crack (beyond service limits)						

Table 3-2. Initial Response to Detected Damage: LPC Components

Study Emphasis:
This Phase's Focus
Existing Detection Adequate
Not a Focus of this Study / New Sensors Required
Detectable post-flight

Major Module	Component or Subsystem	Type of Damage	Initial Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
Booster / LPC / IPC								
	Blade / Vane	Missing Section	✓		✓			Continued operation at reduced power setting may prevent surge or damage progression. Awareness benefit: distinction of affected engine.
	Blade / Vane	Bent Blade	✓		✓			
	Blade / Vane	Crack (beyond service limits)						
	Hub / Rotor	Crack (beyond service limits)						
	Hub / Rotor /Drum	Missing Section						Uncommanded engine shutdown is the most likely outcome from LPC disk failure. Awareness covered by existing engine failure alert.
	Air Seal	Excessive Leakage	✓		✓			Continued operation at reduced power setting may prevent surge or damage progression. Awareness benefit: distinction of affected engine.
	Air Seal	Missing Section	✓		✓			
	Air Seal	Crack (beyond service limits)						
	Case	Crack (beyond service limits)						
	Case	Leak						
	Stability Control System (Variable Bypass / Stability Bleed)	Air Leak						
	Stability Control System (Variable Bypass / Stability Bleed)	Jammed or failed actuator (failed closed)	✓		✓			Continued operation at reduced power setting may prevent surge or damage progression. Awareness benefit: distinction of affected engine.
	Stability Control System (Variable Bypass / Stability Bleed)	Failed Open	✓		✓			

Table 3-3. Initial Response to Detected Damage: HPC Components

Study Emphasis:	
This Phase's Focus	
Existing Detection Adequate	
Not a Focus of this Study / New Sensors Required	
Detectable post-flight	

Major Module	Component or Subsystem	Type of Damage	Initial Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
HPC								
	Blade / Vane	Missing Section	✓		✓			Continued operation at reduced power setting may prevent surge or damage progression. Awareness benefit: distinction of affected engine.
	Blade / Vane	Bent Blade	✓		✓			
	Blade / Vane	Crack (beyond service limits)						
	Hub / Rotor	Missing Section						Uncommanded engine shutdown is the most likely outcome from HPC disk failure. Awareness covered by existing engine failure alert.
	Hub / Rotor	Crack (beyond service limits)						
	Case	Crack (beyond service limits)						
	Case	Leak			✓		✓	Fire / Overheat Detection System will likely trigger. If overheat only: restrict throttle is appropriate. If fire threshold is exceeded: immediate shutdown.
	Air Seal	Excessive Internal Leakage	✓		✓			Continued operation at reduced power setting may prevent surge or damage progression. Awareness benefit: distinction of affected engine.
	Air Seal	Missing Section	✓		✓			
	Air Seal	Crack (beyond service limits)						
	Actuation (IGV's / VSV's)	Excessive freeplay	✓		✓			Continued operation at reduced power setting may prevent surge or damage progression. Awareness benefit: distinction of affected engine.
	Actuation (IGV's / VSV's)	Lever arm / linkage system failure	✓		✓			
	Actuation (IGV's / VSV's)	Jammed or failed actuator (failed closed)	✓		✓			
	Actuation (IGV's / VSV's)	Jammed or failed actuator (failed open)	✓		✓			

Table 3-4. Initial Response to Detected Damage: Combustor and Ignition System Components

Study Emphasis:
This Phase's Focus
Existing Detection Adequate
Not a Focus of this Study / New Sensors Required
Detectable post-flight

Major Module	Component or Subsystem	Type of Damage	Initial Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
Combustor / Diffuser								
	Liner	Crack (beyond service limits)						
	Liner	Missing Section	✓		✓			Continued operation at reduced power setting may prevent EGT Limit Exceedance. Awareness benefit: distinction of affected engine.
	Case	Crack (beyond service limits)						
	Case	Leak					✓	Fire Detection System will likely trigger requiring immediate shutdown response.
	Fuel Manifold / Nozzles	Internal Leak	✓		✓			Continued operation at reduced power setting may prevent EGT Limit Exceedance. Awareness benefit: distinction of affected engine.
	Fuel Manifold / Nozzles	Clogged Nozzle	✓		✓			
	Fuel Manifold / Nozzles	External Leak					✓	Fire Detection System will likely trigger requiring immediate shutdown response.
Engine Ignition System								
	Exciter	Failure to function						Engine will fail to start. Failure self-evident.
	Wiring	Break						
	Ignitors	Failure to function						

Table 3-5. Initial Response to Detected Damage: HPT Components

Study Emphasis:
This Phase's Focus
Existing Detection Adequate
Not a Focus of this Study / New Sensors Required
Detectable post-flight

Major Module	Component or Subsystem	Type of Damage	Initial Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
HPT / IPT								
	Blade / Vane	Crack (beyond service limits)						
	Blade / Vane	Excessive Erosion/Oxidation (beyond service limits)						
	Blade / Vane	Missing Section	✓		✓			Continued operation at reduced power setting may prevent EGT limit Exceedance and progression of further damage. Awareness benefit: distinction of affected engine.
	Shroud	Crack and/or erosion (beyond service limits)						
	Shroud	Missing section	✓		✓			Continued operation at reduced power setting may prevent EGT limit Exceedance and progression of further damage. Awareness benefit: distinction of affected engine.
	Air Seal	Excessive Leakage	✓		✓			
	Air Seal	Missing Section	✓		✓			
	Air Seal	Crack (beyond service limits)						
	Hub / Rotor	Fretting at blade root interface						
	Hub / Rotor	Crack (beyond service limits)						
	Hub / Rotor	Missing Section						Uncommanded engine shutdown is the most likely outcome from HPT disk or shaft failure. Awareness covered by existing engine failure alert.
	HPT Shaft	Complete failure						
	Cooling Air Supply	Blocked Passage \ Reduced Cooling Flow						
	Cooling Air Supply	External Leak			✓		✓	Fire / Overheat Detection System will likely trigger. If overheat only: restrict throttle is appropriate. If fire threshold is exceeded: immediate shutdown.
	Case/Frame	Crack (beyond service limits)						
	Case	Leak					✓	Fire Detection System will likely trigger requiring immediate shutdown response.

Table 3-6. Initial Response to Detected Damage: LPT Components

Study Emphasis:
This Phase's Focus
Existing Detection Adequate
Not a Focus of this Study / New Sensors Required
Detectable post-flight

Major Module	Component or Subsystem	Type of Damage	Initial Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
LPT								
	Blade / Vane	Crack (beyond service limits)						
	Blade / Vane	Excessive Erosion/Oxidation (beyond service limits)						
	Blade / Vane	Missing Section	✓		✓			Continued operation at reduced power setting may prevent EGT limit Exceedance and progression of further damage. Awareness benefit: distinction of affected engine (in particular - full thrust may not be available at higher power settings).
	Hub / Rotor	Fretting						
	Hub / Rotor	Crack (beyond service limits)						
	Hub / Rotor	Missing Section						Uncommanded engine shutdown is the most likely outcome from LPT disk or shaft failure. Awareness covered by existing engine failure alert.
	LPT Shaft	Complete failure						
	Air Seal	Excessive Leakage	✓		✓			Continued operation at reduced power setting may prevent EGT limit Exceedance and progression of further damage. Awareness benefit: distinction of affected engine.
	Air Seal	Crack (beyond service limits)						
	Shroud	Crack (beyond service limits)						
	Shroud	Excessive Erosion/Oxidation (beyond service limits)						
	Cooling Air Supply	Blocked Passage \ Reduced Cooling Flow						
	Cooling Air Supply	External Leak			✓		✓	Depending on individual sensor locations, Fire / Overheat Detection System may trigger. If overheat only: restrict throttle is appropriate. If fire threshold is exceeded: immediate shutdown.
	Frame	Crack (beyond service limits)						
	Case	Crack (beyond service limits)						
	Case	Leak					✓	Fire Detection System will likely trigger requiring immediate shutdown response.

Table 3-7. Initial Response to Detected Damage: Nacelle Components

Study Emphasis:
This Phase's Focus
Existing Detection Adequate
Not a Focus of this Study / New Sensors Required
Detectable post-flight

Major Module	Component or Subsystem	Type of Damage	Initial Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
Exhaust System								
	Primary Nozzle	Crack (beyond service limits)						
	Primary Nozzle	Missing Section	✓					Awareness benefit: distinction of affected engine.
	Primary Nozzle	Looseness	✓					
	Exhaust Shields	Thermal damage						
	Exhaust Shields	Crack (beyond service limits)						
	Exhaust Shields	Missing Section	✓		✓			Operation at reduced throttle settings may limit thermal damage to aircraft structure. Awareness benefit: distinction of affected engine.
Cowls								
	Powered Door Operating System	Failure to function						
	Powered Door Operating System	Leak						
	Cowls	Missing Section	✓		✓			Operation at reduced airspeeds may limit damage progression. Awareness benefit: distinction of affected engine.
	Cowls	Damaged or unsecured latch	✓		✓			
Inlet								
	Acoustic Liner	Missing Section	✓		✓			Operation at reduced throttle settings may prevent engine surge or damage progression. Awareness benefit: distinction of affected engine.
	Acoustic Liner	Impact damage	✓		✓			
	Inlet Structure	Impact damage	✓		✓			
	Anti-Ice System	Leak		✓				Covered by existing DLODS detection.
	Anti-Ice System	Failure to function	✓					Covered by existing fault messages.
	Anti-Ice System	Stuck open valve (system failed on)	✓					
Thrust Reverser								
	Cascades	Missing Section	✓					Awareness benefit: distinction of affected engine.
	Actuation & Indication System	Failure to function	✓					Covered by existing TR alerts and/or fault messages.
	Actuation & Indication System	Leak	✓					
	Blocker Doors	Missing Section	✓					Awareness benefit: distinction of affected engine.
	Inner or outer wall	Failure / Missing section	✓					
	Translating Sleeve	Jam	✓					Covered by existing TR alerts and/or fault messages.
	Translating Sleeve	Missing Section	✓					Awareness benefit: distinction of affected engine.
Nacelle Structure								
	Frames	Crack (beyond service limits)						
	Frames	Sealant damage						
	Frames	Thermal damage						
	Panels	Crack (beyond service limits)						
	Panels	Thermal damage						
	Panels	Looseness / missing fasteners						
	Panels	Missing Section						
	Drains	Clogs / Leaks						
	Engine Mounts / Thrust Links	Crack						
	Engine Mounts / Thrust Links	Complete failure	✓					Requires new sensors to isolate from uncommanded shutdown. If failure could be automatically identified, isolation of flammable fluids (fuel, hydraulics) is appropriate response.

Table 3-8. Initial Response to Detected Damage: Engine Subsystem Components

Study Emphasis:
This Phase's Focus
Existing Detection Adequate
Future Research Area
Detectable post-flight

Major Module	Component or Subsystem	Type of Damage	Preferred Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
Bleed Air								
	Offtakes	Cracks / Leaks		✓				Covered by existing nacelle overheat detection and duct leak detection systems.
	Ducts	Cracks / Leaks		✓				
	Couplings	Loose / Missing		✓				
	Valves	Failure to function (open or closed)		✓				
Fuel Supply System								
	Boost Pumps	Internal Leak / low output	✓		✓			Continued operation at lower altitudes and / or reduced throttle operation may prevent engine flameout during suction feed operation.
	Fuel Spar Valve	Failure (closed)	✓					Covered by existing valve BIT.
	Tubing / Hoses	Leaks					✓	If detectable (likely requires new sensors) and size of leak, immediate shutdown may be appropriate to prevent fire outbreak.
	Couplings	Loose / Missing						
	Filters	Clogged / Bypass	✓		✓			Covered by existing Alert
	Flow Meter	In or out-of-range failure	✓					Awareness benefit: distinction of sensor failure from fuel leak.
	Main Fuel Pump	Internal Leak / low output	✓		✓			Operation at reduced power (and thus reduced fuel flow) may enable continued engine operation.
	Main Fuel Pump	Complete failure						Likely result is uncommanded shutdown due to flameout
	Hydro-Mechanical Unit / Fuel Controller	High Output / Internal Leak	✓		✓			Operation at reduced power may enable continued engine operation. Awareness benefit: distinction of affected engine.
	Hydro-Mechanical Unit / Fuel Controller	Internal Leak / low output	✓		✓			
Propulsion Control System & Sensors								
	FADEC	FADEC failure	✓					Awareness benefit: distinction of affected engine.
	Throttle	Stuck or jammed throttle	✓					
	Pneumatic System	Control Line Leak	✓					
	PMA	Failure	✓					
	AVM	False Reading	✓					
	Sensor Failure	In or out-of-range failure	✓					
Hydraulic System (Propulsion Portion)								
	Engine-Driven Pump	External Leak	✓			✓		In general, covered by existing hydraulic system alerts and / or fault messages. In some cases, continued operation may risk damage to engine gearbox and / or lubrication system.
	Engine-Driven Pump	Seized Shaft	✓			✓		
	Engine-Driven Pump	Internal Failure	✓			✓		
	Tubing / Hoses	Leaks	✓			✓		
	Filters	Clogged / Bypass	✓			✓		
	Couplings	Loose / Missing	✓			✓		
Fire / Overheat Detection System								
	Sensors	Sensors Failure	✓					Covered by existing system BIT
	Duct Leak Detection System	False Alarm	✓					
Fire Extinguishing System								
	Plumbing	Leak						
	Bottle	Leak	✓					Covered by existing system BIT

Table 3-9. Initial Response to Detected Damage: Lubrication System and Lubricated Components

Study Emphasis:
This Phase's Focus
Existing Detection Adequate
Future Research Area
Detectable post-flight

Major Module	Component or Subsystem	Type of Damage	Preferred Response to Detected Damage: Awareness Only	Isolate Bleed Air	Restrict Thrust	Shutdown	Immediate Shutdown	Rationale
Engine Lube System								
	Reservoir	Leaks / low level				✓		Sustained operation will result in progression of ecnomic damage and/or eventual engine uncommanded shutdown. Awareness benefit: distinction of affected engine.
	Pumps	Low output				✓		
	Pumps	Failure				✓		
	Filters	Clogged / Bypass				✓		
	Tubing / Hoses	Leaks				✓		
	Tubing / Hoses	Collapsed liners				✓		
	Tubing / Hoses	Damaged sleeves						
	Coolers	Fouling				✓		Sustained operation will result in progression of economic damage and/or eventual engine uncommanded shutdown. Awareness benefit: distinction of affected engine.
	Coolers	Internal leaks				✓		
	Coolers	External leaks				✓		
	Couplings	Loose / Missing						
Lubricated Components								
	Shafts	Cracks						
	Bearings	Excessive wear / impending failure				✓		Sustained operation will result in progression of economic damage and/or eventual engine uncommanded shutdown. Awareness benefit: distinction of affected engine.
	Bearings	Complete failure				✓		
	Seals	Excessive Leakage				✓		
	Gearboxes	Excessive wear / impending failure				✓		
	Gearboxes	Failed gear teeth				✓		
	Gearboxes	Failed shaft				✓		
VSCF / IDG								
	Shafts	Failed				✓		If VSCF or IDG is not independently disconnectable, sustained operation will result in progression of economic damage or damage to engine oil system or gearbox. Awareness
	Mounting System	Failed				✓		
	Lube System	Leaks				✓		
Start System								
	Start Turbine / shaft	Blade / shaft /clutch failure				✓		Continued operation may result in progression of economic damage or possible uncommanded shutdown if starter turbine overspeeds. Awareness benefit: distinction of affected engine.
	Starter Air Valve	Failure to function (open or closed)				✓		
	Starter	Oil Leak				✓		Continued operation may result in progression of economic damage or damage to engine oil system (resulting in delayed shutdown). Awareness benefit: distinction of affected engine.
	Position / Pressure Sensor	In or out-of-range failure				✓		May be indistinguishable from starter air valve failure. Awareness benefit: distinction of affected engine.

The response assessment resulting from a consideration of each detailed failure mode was summarized at the module level and the results provided in table 3-10. In addition to grouping specific damage modes into common response groups, this summarization process considered the following factors.

- Principal Potential Operational Effects (Current or Future)–Potential operational effects included both symptoms that were present with the current level of damage and future effects that might ensue with change in operating conditions (i.e., throttle movement or altitude/airspeed/angle of attack) or continued operation.

- Reason for Damage Discrimination—Did the damage effect(s) justify a unique pilot awareness or response? Further, would awareness of this specific damage help prevent ICR?

Table 3-10. Engine Module Damage Response Summary

Damaged Major Module	Principal Potential Operational Effects (Current or Future)	Reason for Damage Discrimination	Appropriate Response Group	Principal Existing Annunciations
Fan	Unindicated Thrust Loss, Indeterminate Tactile Vibration	Continued operation of engine is possible, but commanded thrust may not be available (i.e., thrust/N1 affected). Tactile vibration is engine-related and due to a specific engine.	Awareness Only or Restrict Thrust	Indicated Vibration
LPC/Booster/HPC	Surge, Stall, Flameout	Thrust restriction may be desirable to prevent subsequent surge, stall, or flameout. Throttle pullback may be necessary to clear an existing continuous/multiple surge event. If shutdown, the engine may not restart.	Awareness Only or Restrict Thrust	Engine Failure Alert, EGT Indication
Combustor	Flameout, Overheat, Fire	Fire may break out.	Immediate Shutdown	Engine Failure and/or Fire/Overheat Alerts
Turbine	Uncommanded Shutdown	Continued operation of engine at low power may be possible, but full thrust may not be available. If shutdown, the engine may not restart.	Awareness Only or Restrict Thrust	Engine Failure Alert, EGT Indication
Accessories: Lube System / Lubricated Components	Lubricated Component (i.e., Bearing, Gear, Accessory Drivetrain) failure leading to uncommanded shutdown	Continued operation of engine at low power may be possible, but ***sustained*** full thrust may not be possible. Risk of continued operation leading to significant damage.	Shutdown	Eng Oil Pres, Eng Oil Temp, Eng Oil Filter Alerts
Accessories: Fuel System	Flameout, Fire	Fire may break out.	Immediate Shutdown	Fire/Overheat Alerts
Accessories: Fuel System	Thrust Limit; Flameout	Low Main Fuel Pump output scenario: continued operation at low power may be possible, but full thrust may not be available. If shutdown, the engine may not restart.	Awareness Only or Restrict Thrust	Engine Failure Alert, EGT Indication

Table 3-10. Engine Module Damage Response Summary (Continued)

Damaged Major Module	Principal Potential Operational Effects (Current or Future)	Reason for Damage Discrimination	Appropriate Response Group	Principal Existing Annunciations
Accessories: Bleed Air	Overheat/Fire; Smoke in Cabin (Oil leakage compressor)	Severe economic damage or fire may ensue. Passenger health or comfort may be affected.	Isolate Bleed Air	Duct Leak/ Overheat Alerts
Accessories: Controls/Sensors	Thrust Loss; Surge, Stall, Flameout, or Uncommanded Shutdown	Engine may not respond to throttle.	Awareness Only or Restrict Thrust	Engine Control Alerts
Nacelle Static Structure (Cowls, Inlet, Frames, Exhaust System, Thrust Reverser, etc.)	Engine FOD, Control Surface damage	Sensed or indicated vibration (broadband) is not related to engine rotation.	Awareness Only or Restrict Thrust	Indicated Vibration

Specific considerations for selected engine failure modes with table 3-10 included the following.

- Fan—In a high bypass turbofan, the fan is the principal thrust producer. The Task 2 research determined that scenarios may arise where fan damage compromises the indicated thrust accuracy (i.e., indicated thrust based on fan speed or engine pressure ratio may not reflect the actual engine thrust).

- Compression System—The Task 2 research acknowledged that compression system damage is likely to produce complex effects on engine operation. In general, thrust restriction is the appropriate response to compression system damage; however, the possibility exists that such failure effects as continuous multiple surges may drive a more sophisticated response than simple thrust restriction. Compression system damage may also cause an upper limit on power setting. Surge margin in damaged state may be different, depending on speed. Depending on where damage is present (low- or high-pressure compressor), the final restricted thrust setting may vary. General note: response potentially could be automated within FADEC, but in either case (automated or manual), pilot awareness may be desirable. As an example, while thrust rate of change could be achieved by pilot action, automatic control is also possible. If the engine damage detection system was FADEC-resident, the detected damage could be used to bias the acceleration/deceleration schedules as necessary to prevent surge or other engine limit exceedances for the remainder of the current flight.

- Combustor—In general, combustor damage was expected to produce one of two effects: (1) case burn-through, which would invoke an immediate shutdown desired response, or (2) liner damage, which may cause an EGT shift and possibly overtemperature at high engine power (in which case, a restrict thrust action would be appropriate).

- Turbine—Damage may force time at power limitations as well (e.g., creep damage to blades and nozzles, etc.). Thus, damage may be more pertinent to dispatch than the current flight.

Table 3-10 summarizes the response and maintenance-based distinctions. Also indicated in this table are this phase's focus areas for module damage detection: gas path and lubricated component damage. Engine subsystems, such as fuel supply, lubrication, bleed air, and controls, were assessed to have adequate existing annunciation and detection. Damage to nacelle structure was not a focus of this study.

A review of the desired types of restrict thrust responses determined that limited coverage of within-limits thrust restriction guidance could be provided using sensor fusion (the focus of this study). However, existing out-of-limits conditions (except high vibration) could be provided to the crew by existing (baseline) alerts or indications. This enabled merging of the awareness only and restrict thrust categories into a single category titled awareness/restrict thrust. This composite category would be used to trigger awareness of the affected engine (i.e., distinguish from other undamaged engine(s)). If required, subsequent thrust reduction or shutdown in response to the awareness/restrict thrust condition would be guided by additional symptoms and alerts:

- Unacceptable Tactile Vibration—Determined by pilot discretion (e.g., elevated tactile vibration levels which affect the pilot's ability to operate the aircraft or passenger comfort may necessitate thrust reduction or engine shutdown).

- Continuous Compressor Surging—Covered by the dedicated alert and procedure for this sustained thrust anomaly developed in the PSM+ICR Phase 2 research. If this alert is not implemented in the design, pilot discretion would be used to determine if thrust reduction is required.

- Limit Exceedance (EGT, Rotor Speed, etc.)—Covered by existing alerts and procedures. Note: Thrust reduction is not required for approach to limits (only limit exceedances) or nonsurge parameter fluctuation within limits.

- Oil System Limit—Covered by existing alerts and procedures.

- Fuel System Limit (filter high differential pressure)—Covered by existing alerts and procedures.

- Nacelle Overheat Indication—Covered by existing alerts and procedures.

The sequencing of the awareness/restrict thrust damage detection, alerting, and subsequent response is illustrated in figure 3-2.

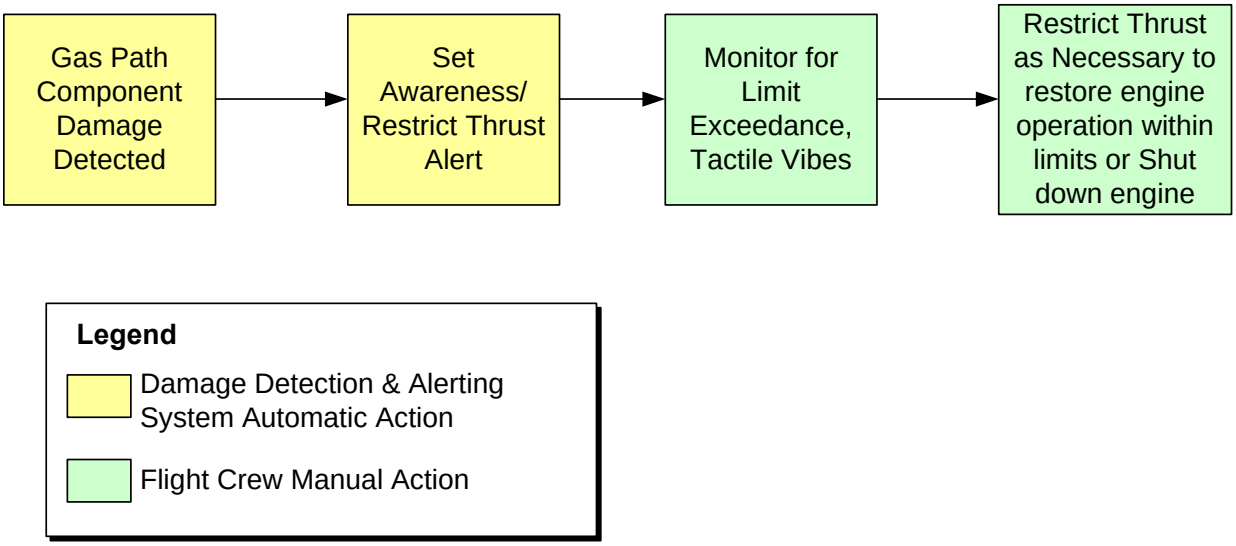


Figure 3-2. Awareness/Restrict Thrust Alert and Response Sequence

Once the engine components were assigned to a specific response group, the service reports were used next to develop failure rate information for later use in Task 3. Specifically, failure rates per engine flight hour were tabulated for engine component and grouped into the preferred response categories. The following specific rates were extracted from the service reports:

- UERs—The UER event count data previously provided in table 2-1 divided by the total engine flight hours for the period 1 January 1999 through 31 December 2005.

- IFSDs—The IFSD event count data provided in table 2-1 divided by the total engine flight hours for the same period.

- UERs with In-Flight Effects—The subset of UER events where in-flight effects such as high indicated vibration, EGT shift, or other flight deck-detectable effect occurred (see a more detailed discussion in section 5.3) divided by the total engine flight hours for the same period.

These rates are summarized by engine component and response group in figures 3-4 through 3-10. The overall rate sums for each response category are tabulated in table 3-11. Included in this table are the derived rates for both:

- UERs with In-Flight Effects and IFSD—The subset of UER events where in-flight effects as defined above which also included an IFSD divided by the total engine flight hours for the same period.

- UERs with In-Flight Effects and no IFSDs.

A Venn Diagram of the relationship between the various event categories is shown in figure 3-3. (Note: A pictorial subset of these data is later presented for those events related strictly to gas path and lubricated components in section 5.3.) While figure 3-3 includes all service events irrespective of cause or damaged component, the rate figures (3-4 through 3-9) and the summary table do not include those UER and IFSD events either unrelated to propulsion system damage (e.g., aircraft systems), indeterminate events, or not a focus of this research study (e.g., items such as nacelle structure, engine mounts, etc.).

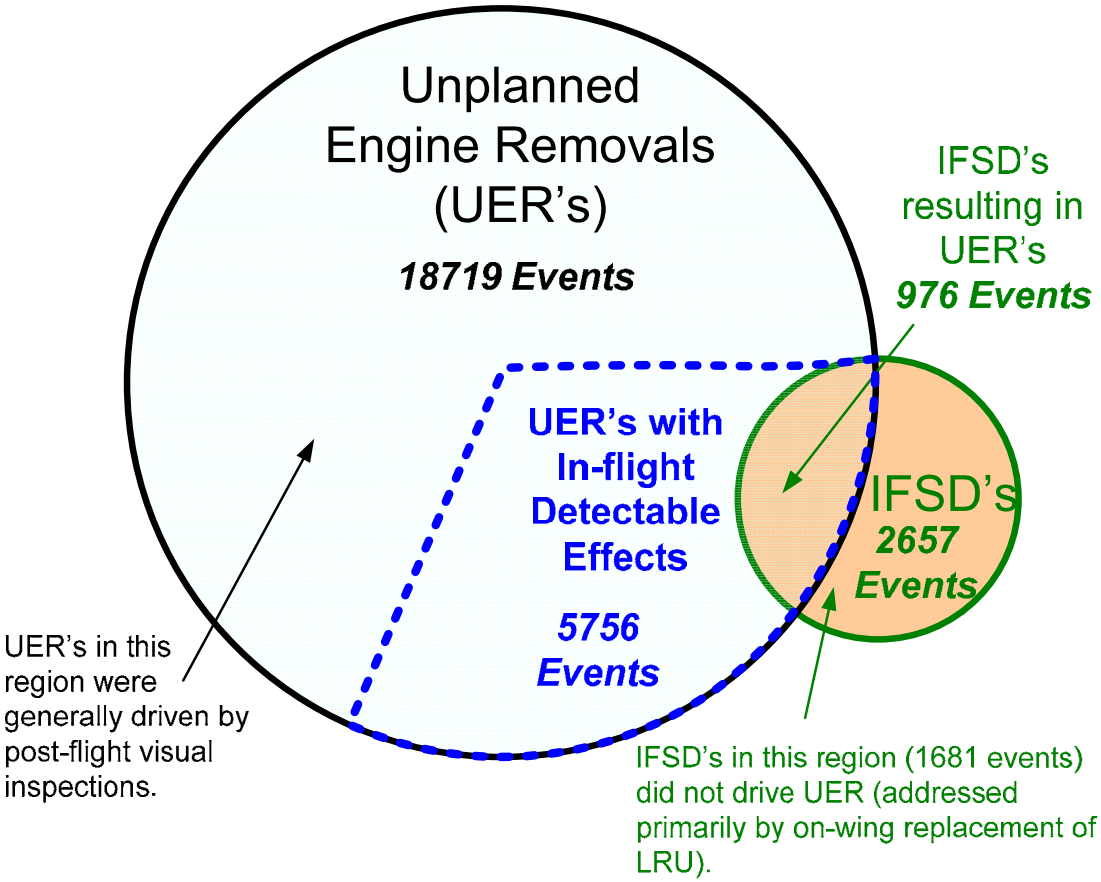


Figure 3-3. Relationship Between UERs, UERs With FDEs, and IFSDs

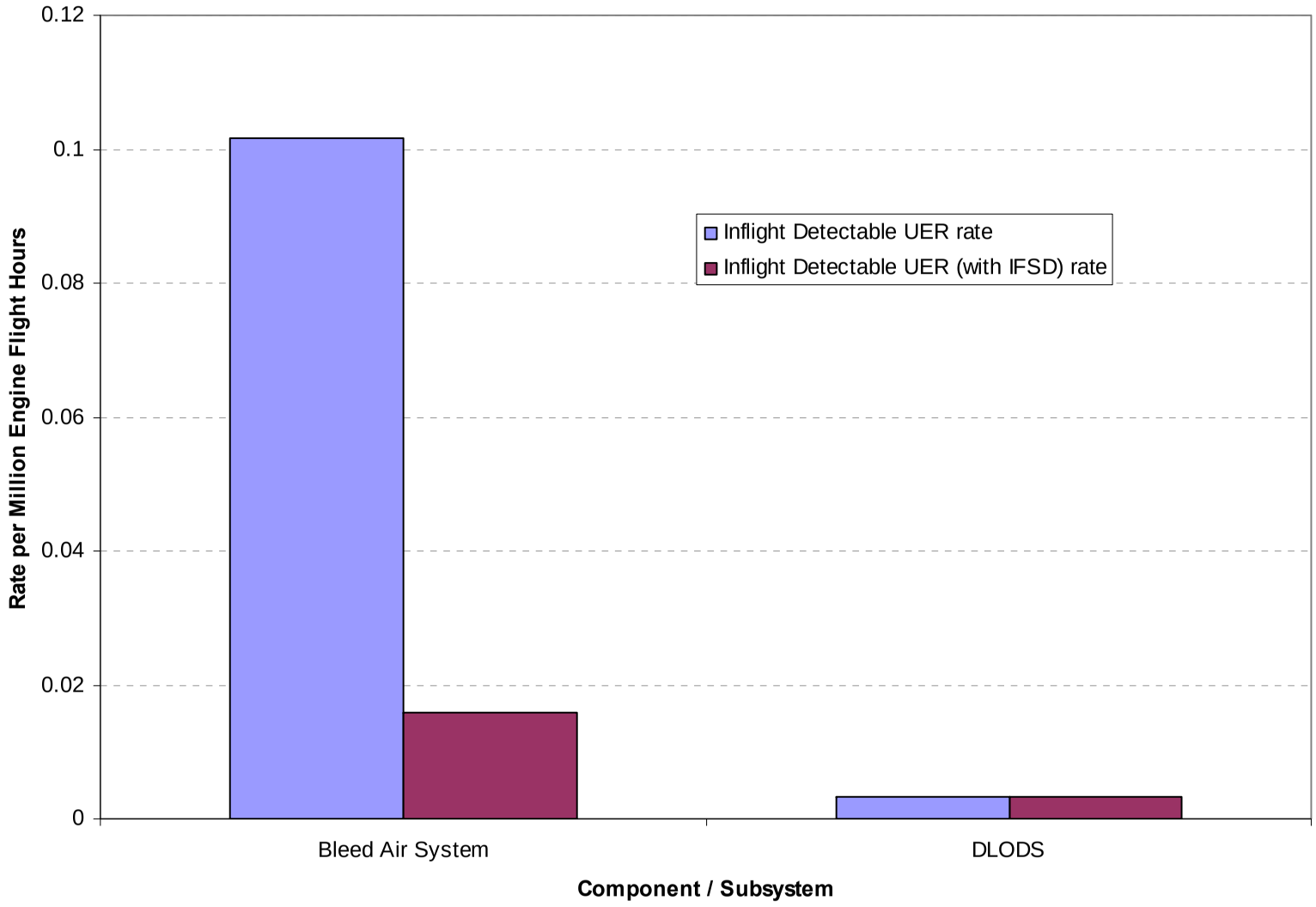


Figure 3-4. Engine Component Rates for Isolate Bleed Air Response Category

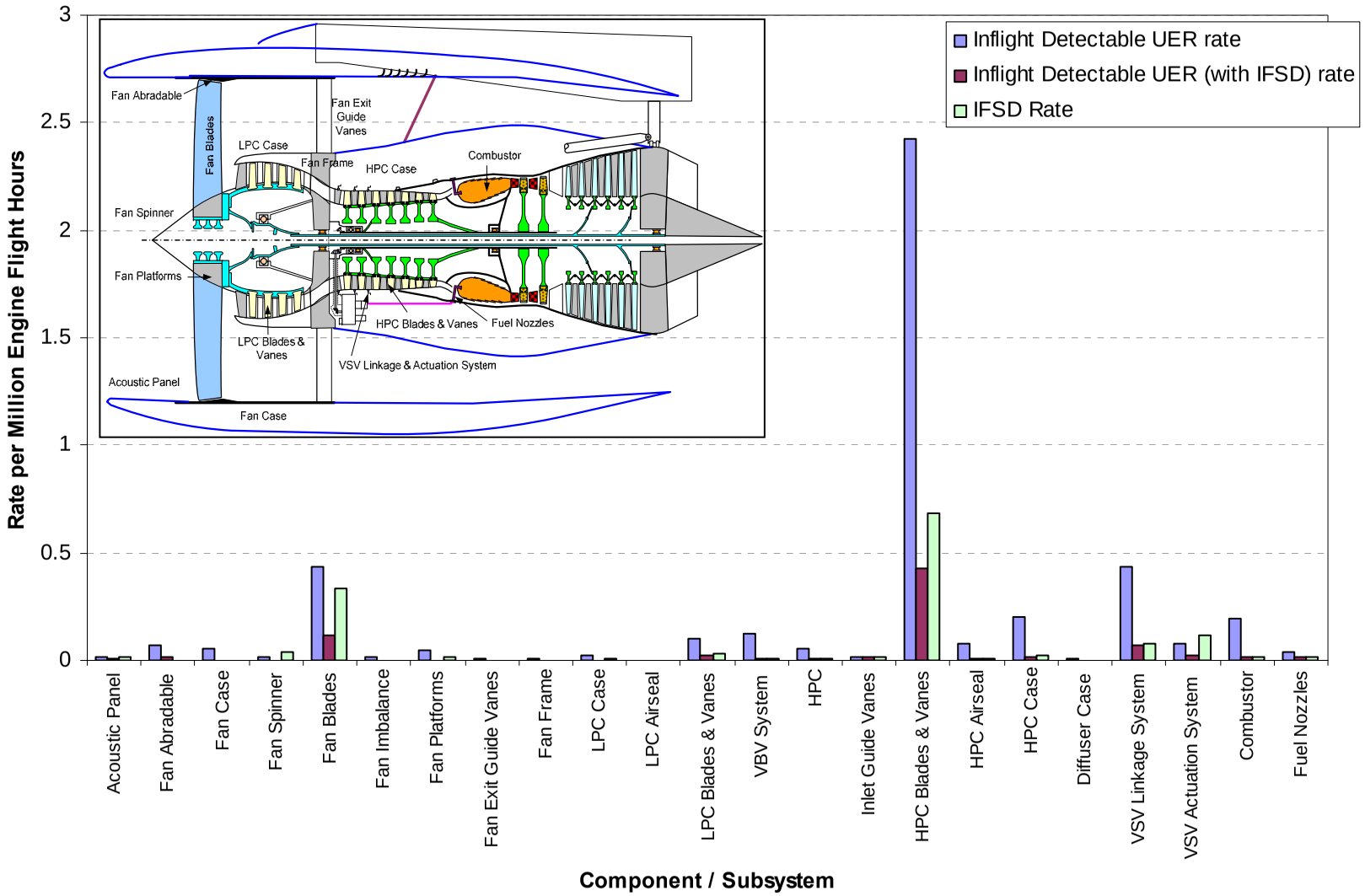


Figure 3-5. Engine Component Rates for Restrict Thrust Response Category

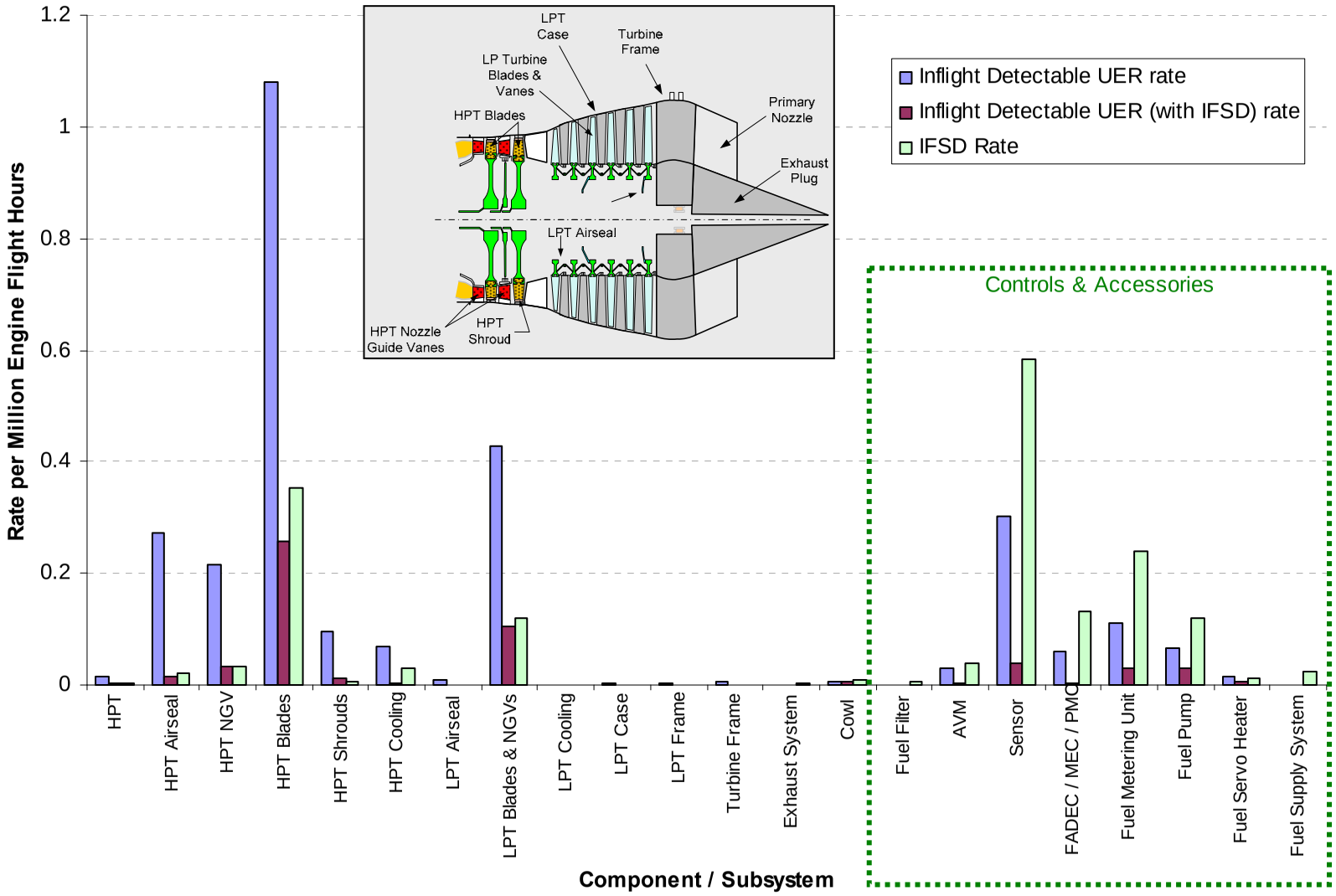


Figure 3-5. Engine Component Rates for Restrict Thrust Response Category (Continued)

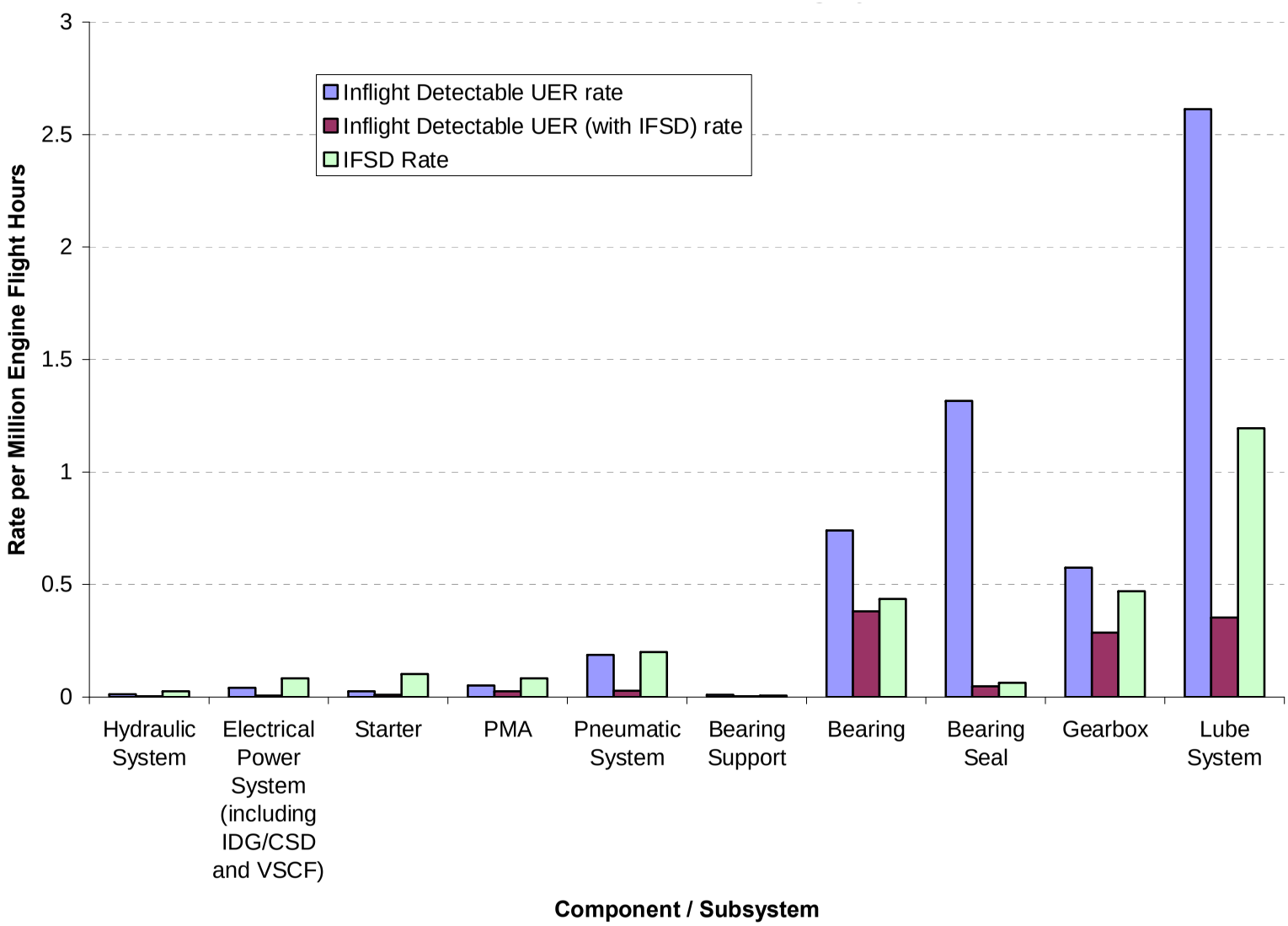


Figure 3-6. Engine Component Rates for Shutdown Response Category

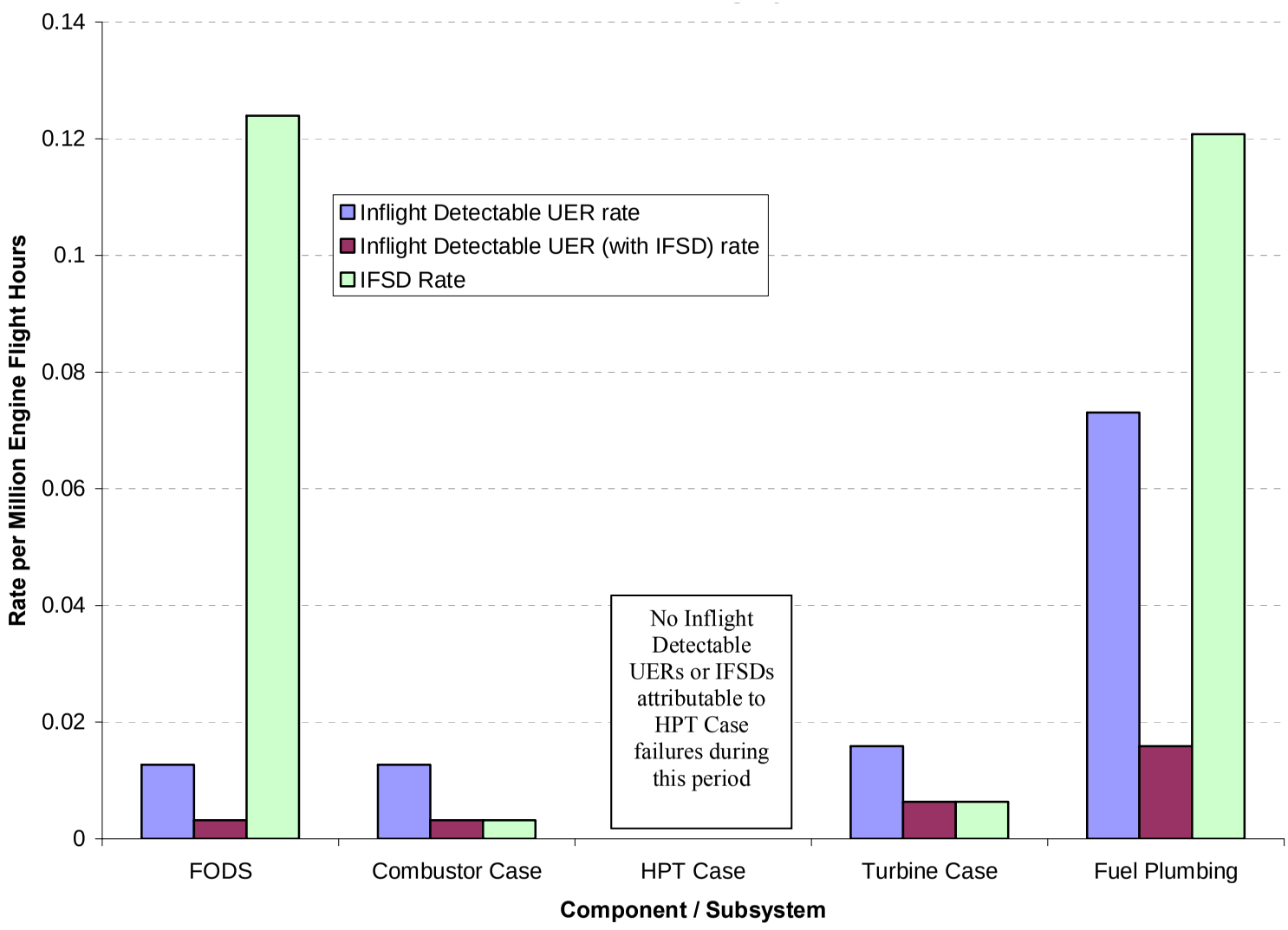


Figure 3-7. Engine Component Rates for Immediate Shutdown Category

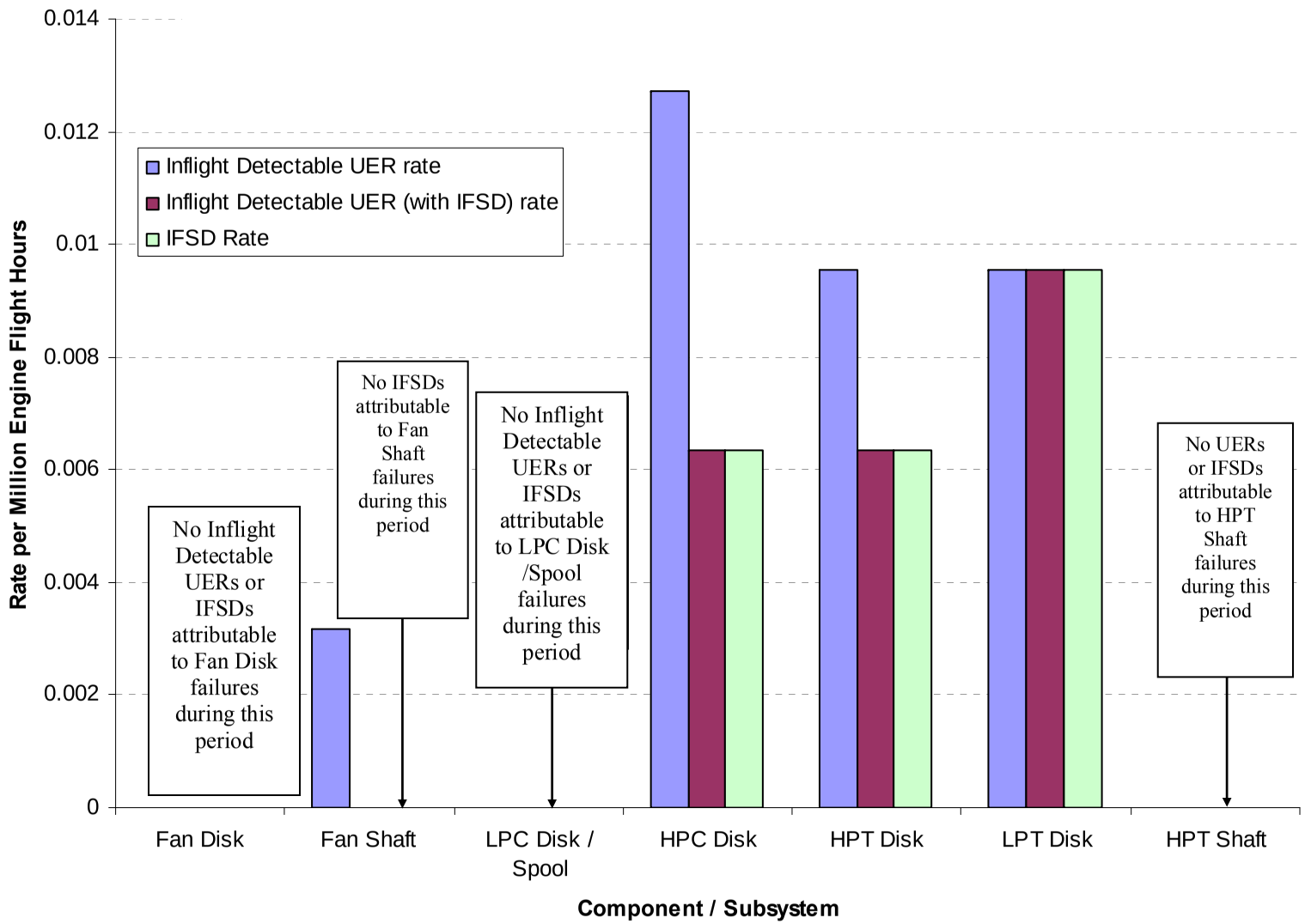


Figure 3-8. Engine Component Rates for Failures Leading to Uncommanded Shutdown

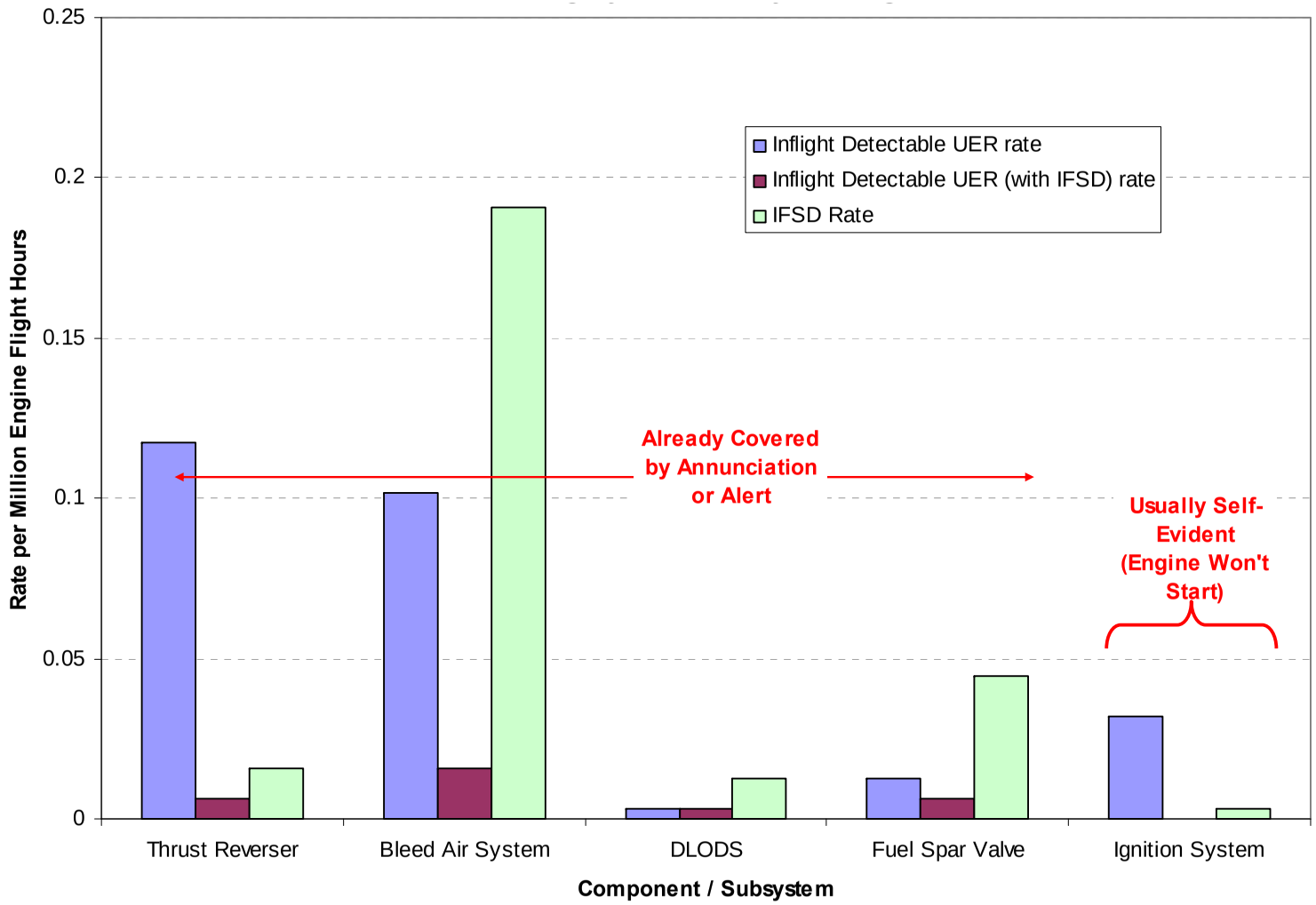


Figure 3-9. Engine Component Rates for Failures Already Covered by Existing Annunciations or Alerts

Table 3-11. Rate Summary by Response Category

Rates per ***Engine*** Flight Hour Response Category	UER Rate	Inflight Detectable UER Rate	Inflight Detectable UER (with IFSD) Rate	Inflight Detectable UER (no IFSD) Rate	Total IFSD Rate	Total In-Flt Rate
Awareness/Restrict Thrust (Note 1)	3.73E-05	7.49E-06	1.36E-06	6.14E-06	3.35E-06	**9.49E-06**
Shutdown (Caution)	1.01E-05	5.38E-06	1.12E-06	4.27E-06	2.46E-06	**6.73E-06**
Immediate Shutdown (Warning)	covered	covered	covered	covered	covered	covered
Uncommanded Shutdown	covered	covered	covered	covered	covered	covered
Isolate Bleed Air	covered	covered	covered	covered	covered	covered
Totals	**4.74E-05**	**1.29E-05**	**2.47E-06**	**1.04E-05**	**5.82E-06**	**1.62E-05**

Rates per ***Aircraft*** Flight Hour Response Category	UER Rate	Inflight Detectable UER Rate	Inflight Detectable UER (with IFSD) Rate	Inflight Detectable UER (no IFSD) Rate	Total IFSD Rate	Total In-Flt Rate
Awareness/Restrict Thrust (Note 1)	8.84E-05	1.78E-05	3.22E-06	1.46E-05	7.96E-06	**2.25E-05**
Shutdown (Caution)	2.40E-05	1.28E-05	2.65E-06	1.01E-05	5.84E-06	**1.60E-05**
Immediate Shutdown (Warning)	covered	covered	covered	covered	covered	covered
Uncommanded Shutdown	covered	covered	covered	covered	covered	covered
Isolate Bleed Air	covered	covered	covered	covered	covered	covered
Totals	**1.12E-04**	**3.06E-05**	**5.87E-06**	**2.47E-05**	**1.38E-05**	**3.85E-05**

Notes:

(1) Awareness/restrict thrust reflects the merging of the awareness only and restrict thrust categories.

The rates shown above for the awareness/restrict thrust and shutdown categories are conservative because these rate data also contain events where uncommanded shutdown occurred.

Rates are depicted in terms of both engine and aircraft flight hours. Since the service data is dominated by twin-engine aircraft, but also includes information for four-engine aircraft, the overall aircraft hour-to-engine-hour ratio is ~ 2.4:1.

Covered indicates that existing alerts and procedures cover these response categories.

3.4 RESPONSE TO ENGINE DAMAGE: OPERATIONAL VERSUS ECONOMIC EFFECTS.

Commanded engine shutdown or thrust restriction in response to annunciated engine damage are flight crew actions with consequences to continuation of the originally planned flight. Of the two, commanded engine shutdown is the most significant because it reduces safety margins (number of operating engines) and may require a diversion. Restricted thrust allows more crew discretion. Depending on the nature of engine damage, both operational and economic reasons may necessitate such action. Task 2, therefore, undertook an assessment of specific engine damage modes that may warrant such actions.

In general, the operational reasons for commanded engine shutdown or thrust restriction were such that continued operation with existing damage could substantially degrade safety margins that were necessary to

- prevent uncontrolled fire. Avoid conditions likely to cause nacelle fires or result in engine separation including high-pressure flammable fluid leaks in close proximity to an ignition source, or hot section case burnthrough.

- maintain aircraft control during extreme tactile vibration, uncontrolled high thrust events, or critical flight phases (e.g., approach).

Avoidance of high economic damage resulting from continued operation at the existing power setting was acknowledged as a potential reason for commanded shutdown or thrust restriction. In this context, economic damage was defined as propulsion system damage that may increase or propagate to other portions of the engine, nacelle, or aircraft but would not significantly hazard the airplane. However, the propagated damage would likely require unscheduled engine removal and/or repair of major nacelle components.

Operational and economic reasons for commanded engine shutdown or thrust restriction were assessed for each engine damage mode. The results are shown in tables 3-12 through 3-14. For each engine damage mode, the potential propulsion system end effects were assigned to one of the following categories: uncommanded engine shutdown, significant thrust loss, commanded shutdown, or thrust restriction. If the latter two actions were possible, a further subdistinction of why such an action might be taken was provided:

- Operational Reasons: Prevent uncontrolled fire, preserve structural integrity, or maintain aircraft control. Damage modes that affect structural integrity, such as disk or engine mount failures, generally experience immediate uncommanded engine shutdown and, as such, were not considered candidates for continued operation (even at reduced thrust).

- Economic Reasons: Avoid the spread of damage through the following means:

  - Fatigue failure induced by elevated vibration associated with rotor imbalance or other sources.

  - Thermally induced failure arising from elevated gas path temperatures.

  - Liberation of gas path components and ingestion by downstream components (e.g., foreign or domestic object damage).

  - Lubricated component debris spread to other elements of the lubrication system.

  - Loss of engine exhaust shielding and associated thermal damage to other structure.

The Task 2 research recognized the significant consequences of liberation of nacelle structural components or engine separation and the associated possibility of aircraft structural or flight control surface damage. However, in the case of nacelle structural component liberation, it is likely that aircraft operating speed has more influence on propagation of damage than continued engine operation. Engine separation is a rare event (only one recorded instance during the 6-year study period). Engine separation could possibly be detected by existing sensors, but this damage mode was not a focus of this study. Thus, engine separation was excluded from consideration in the table 3-12 through 3-14 results.

Table 3-12. Propulsion System End Effects: Compression System Components

Symbology:	
Highly Likely	*
Likely	✓
Possible	X

Major Module	Component or Subsystem	Type of Damage	Propulsion System End Effect								
					Commanded Shutdown or Throttle Restriction:						
					Operational Reasons:		Economic Reasons (Avoid Damage):				
			Uncommanded Engine Shutdown	Significant Thrust Loss	Prevent Uncontrolled Fire	Maintain Aircraft Control	Vibration-Induced	Hot Gas-Induced	Gaspath Component	Lubricated Components	Nacelle Structure
Inlet											
	Acoustic Liner	Missing Section							X		
Fan											
	Blade	Missing Section	X	*		X	✓		X		X
	Blade	Bent Blade		X							
	Spinner	Liberation, Distortion, or Missing Section	X	*					X		X
	Platforms / Annulus Fller	Missing Section		X					X		X
	Abradable	Missing Section									
	Fan Hub Frame	Missing Section							X		
	Outlet Guide Vanes / Fan Case	Missing Section									X
	Hub/Disk	Missing Section	*								
Booster / LPC / IPC											
	Blade / Vane	Missing Section	X				✓		✓		
	Blade / Vane	Bent Blade					X				
	Hub / Rotor /Drum	Missing Section	*								
	Stability Control System	Jammed or failed actuator (failed closed)									
	(Variable Bypass / Stability	Failed Open		X							
HPC											
	Blade / Vane	Missing Section	X	X			✓		✓		
	Blade / Vane	Bent Blade					X				
	Disk	Missing Section	*								
	Actuation (IGVs / VSVs)	Leak						✓			
		Excessive freeplay							✓		
		Lever arm / linkage system failure									
		Jammed or failed actuator (failed closed)		✓							
		Jammed or failed actuator (failed open)	✓								

Table 3-13. Propulsion System End Effects: Hot Section Components

Symbology:	
Highly Likely	*
Likely	✓
Possible	X

Major Module	Component or Subsystem	Type of Damage	Propulsion System End Effect								
			Uncommanded Engine Shutdown	Significant Thrust Loss	Commanded Shutdown or Throttle Restriction: Operational Reasons: Prevent Uncontrolled Fire	Commanded Shutdown or Throttle Restriction: Operational Reasons: Maintain Aircraft Control	Commanded Shutdown or Throttle Restriction: Economic Reasons (Avoid Damage): Vibration-Induced	Commanded Shutdown or Throttle Restriction: Economic Reasons (Avoid Damage): Hot Gas-Induced	Commanded Shutdown or Throttle Restriction: Economic Reasons (Avoid Damage): Gaspath Component	Commanded Shutdown or Throttle Restriction: Economic Reasons (Avoid Damage): Lubricated Components	Commanded Shutdown or Throttle Restriction: Economic Reasons (Avoid Damage): Nacelle Structure
Combustor / Diffuser											
	Liner	Missing Section							✓		
	Case	Leak			*			✓			
	Fuel Manifold / Nozzles	Internal Leak		X					✓		
		Clogged / Malfunctioning Nozzle		X					✓		
		External Leak			✓			✓			
HPT / IPT											
	Blade / Vane	Missing Section	X				X	✓	✓		
	Air Seal	Excessive Leakage						X			
		Missing Section	*								
	Disk	Missing Section	*								
	HPT Shaft	Complete Failure	*								
	Cooling Air Supply	External Leak						✓			
	Case	Leak						✓			
LPT											
	Blade / Vane	Missing Section	X	X			✓		✓		
	Disk	Missing Section	*								
	LPT Shaft	Complete Failure	*								
	Cooling Air Supply	External Leak						✓			
	Case	Leak						✓			
Exhaust System											
	Exhaust Shields	Missing Section									✓

Table 3-14. Propulsion System End Effects: Engine Subsystems Components

Symbology:	
Highly Likely	*
Likely	✓
Possible	X

Major Module	Component or Subsystem	Type of Damage	Propulsion System End Effect								
					Commanded Shutdown or Throttle Restriction:						
					Operational Reasons:		Economic Reasons (Avoid Damage):				
			Uncommanded Engine Shutdown	Significant Thrust Loss	Prevent Uncontrolled Fire	Maintain Aircraft Control	Vibration-Induced	Hot Gas-Induced	Gaspath Component	Lubricated Components	Nacelle Structure
Engine Lube System											
	Reservoir	Leaks / low level			X					✓	
	Pumps	Low output			X					↓	
		Failure			X						
	Filters	Clogged / Bypass			X				X		
	Tubing / Hoses	Leaks			X						
		Collapsed liners			X						
	Coolers	Fouling			X					X	
Lubricated Components											
	Bearings	Excessive deterioration / impending failure			X				✓	✓	
		Complete failure	*		X				✓	↓	
	Seals	Excessive Leakage			X						
	Gearboxes	Failed gear teeth / gear shaft	✓								
		Failed quill shaft	*								
Start System											
	Starter	Oil Leak								X	
Fuel Supply System											
	Tubing / Hoses	Leaks			*						
	Filters	Clogged / Bypass							✓		
Bleed Air											
	Offtakes	Leaks						*			
	Ducts	Leaks						↓			
	Couplings	Loose / Missing									

3.5 CONTINUED ENGINE OPERATION WITH KNOWN DAMAGE.

Section 3.4 documented the operational and economic considerations for shutting down or restricting the thrust on a damaged engine. Task 2 also considered the converse case: why would a pilot want to continue operating an engine with known damage? The Task 2 research assessed that continued operation (with potential restrictions) allows the following.

- Preservation of Systems Redundancy—While thrust may be compromised, the damaged engine may still be able to supply electrical, hydraulic, and/or pneumatic power to the aircraft.

- Preservation of Safety Margins—Damage may be such that engine will not restart; however, continued operation retains some level of thrust from the damaged engine and the possibility of additional thrust in emergency situations.

In summary, continued operation with known engine damage may be desirable under circumstances where the damage does not propagate, risk degradation of available safety margins or cause high crew workload in terms of continued monitoring.

3.6 ENGINE RESTARTABILITY ASSESSMENT.

Another objective of Task 2 was to evaluate the restartability of a damaged engine. This feature would enable a pilot to make informed decisions in the following situations:

- Should a damaged engine be left running if not restartable? For example, the pilot may elect to keep the engine running at idle if it was known to be unrestartable. Conversely, if the engine is restartable, then the option exists to shutdown and restart later in the flight.

- Should continued attempts be made to restart a damaged shutdown engine?

This evaluation included an assessment of the major engine components' minimum mechanical integrity necessary to ignite and accelerate the engine to idle. Further, the means available to the flight crew of verifying such mechanical integrity was also documented.

In general, engine restart is likely only possible with the following minimum engine mechanical integrity:

- The engine gas path must be intact to the extent that:

  - Surge-free operation is possible, at least during starting and at idle.

  - LPC stability bleed system is functional up to idle.

  - VSVs are not failed open.

  - Combustor is lightable and operable through idle without risk of overtemperature.

- No hot section case leaks are present.
- Compressor and turbine casings sufficiently intact to prevent hard rubs against blades.

- Shafts and bearings are free to rotate.
- The engine control system is functional on at least one channel.
- Engine subsystems can operate without risk of igniting a fire (e.g., no significant flammable fluid system or bleed air system leaks). If the engine was previously shutdown in response to a detected fire, attempted restart is inadvisable.

Specific requirements by major module and associated components are given in tables 3-15 through 3-18. Note: The context of these tables is continued operation within a given flight only (not dispatched with known damage). Also listed in these tables are the potential sensor-based indications to the flight crew to verify the specific component's mechanical integrity. Highlighted in these tables are the components for which no verification means is available with existing sensors. For many of the component damage modes listed as verifiable via sensor means, calibration of the degree of damage versus the sensed effect would be required to ensure a reliably predictive system.

Integrating an automated restartability assessment into a damage detection system is likely to be very complex. As indicated in tables 3-15 through 3-18, there is currently no sensor-based means that can likely detect several necessary prerequisites for restartability. Although discussed further in section 5, it is expected that such capability is not feasible for a sensor fusion-based damage detection system. Note: The sensor-based means of detecting restartability is listed as "Indicated Vibration (Advanced Signal Processing)" for several components in tables 3-15 through 3-18. This implies AVM signal processing beyond basic one-per-revolution filtering that is currently done to satisfy 14 CFR 25.1305(d)(3). Refer to section 5.5.4 for further discussion.

Table 3-15. Minimum Requirements for Engine Restart (Compression System Components)

Major Module Components	Minimum Requirements for Restart	Potential Sensor-Based Verification Means Prior to Restart Attempt
Fan		
Fan Blades	Blade dents and nicks acceptable, but no missing major blade portions	Indicated Vibration
Spinner	Not required, but if liberated, should not be blocking core flowpath	None (Visual Only)
Outlet Guide Vanes/Struts	Must be intact enough to provide structural support for fan case	Indicated Vibration (with Advanced Signal Processing)
Case	No damage that would cause hard rubs of fan blades	N1 Rotation
Hub/Disc	No missing major portions	N1 Rotation
Abradable	Limited damage acceptable	None (Visual Only)
Fan Hub Frame	Intact to the extent that core gas path and fan structural support is preserved.	Indicated Vibration (with Advanced Signal Processing)
Annulus Filler	Not required, but if liberated, should not be blocking core flowpath	None (Visual Only)
Shaft	Intact and free to rotate without excessive vibration.	N1 Rotation
Booster/LPC/IPC		
Blades and Vanes	Blade dents, nicks, and tears acceptable, but no missing entire blades	Indicated Vibration
Hub/Rotor/Drum	No damage present that might result in blade liberation or excessive vibration	N1 Rotation
Air Seals	Limited damage is acceptable as long as surge margin is not severely compromised.	None (Visual Only)
Case	No damage that would cause hard rubs of LPC blades	Indicated Vibration
Stability Control System	Functional through start and idle operating regimes.	Component fault detection
HPC		
Blades and Vanes	Blade dents, nicks, and tears acceptable, but no missing entire blades	Indicated Vibration
Discs	No damage present that might result in blade liberation or excessive vibration	N2 Rotation
Air Seals	Limited damage is acceptable as long as surge margin is not severely compromised.	None (Visual Only)
Case	No damage that would cause hard rubs of HPC blades	N2 Rotation
VSV Linkage System	Intact. Limited freeplay is acceptable, but no broken lever arms, etc.	None (Visual Only)
VSV Actuation System	Not failed open.	Existing position sensors

Table 3-16. Minimum Requirements for Engine Restart (Hot Section Components)

Major Module Components	Minimum Requirements for Restart	Potential Sensor-Based Verification Means Prior to Restart Attempt
Combustor/Diffuser/Engine Ignition System		
Diffuser and Liner	Cracks acceptable, but gas path through to HPT NGV must be intact	None (Visual Only)
Case	No significant leaks that might risk fire outbreak	No prior Fire Warning
Fuel Manifold/Nozzles	No externals leaks. Some degradation of fuel nozzle spray pattern is acceptable.	No prior Fire Warning
Engine Ignition System	Functional on at least one channel	None (Visual Only)
HPT/IPT		
Nozzle Guide Vanes	Cracks/Severe Oxidation damage OK, but intact enough to preserve gas path through to blades	None (Visual Only)
Blades	Most of the airfoils intact (enough to provide power to compressor and avoid excessive vibration)	Indicated Vibration
Shrouds	Heavy damage is acceptable as long as HPT rotation is not compromised (i.e., no heavy rubs, etc.) No severe leaks that might allow hot gas intrusion into bearing sumps or other vulnerable areas. Also intact enough to avoid excessive vibration.	N2 Rotation
Air Seals	No severe leaks that might allow hot gas intrusion into bearing sumps or other vulnerable areas. Also intact enough to avoid excessive vibration.	None (Visual Only)
Hub/Rotor	No damage present that might result in blade liberation or excessive vibration	N2/N3 Rotation
HPT Shaft	Intact and free to rotate without excessive vibration.	N2/N3 Rotation
Cooling Air Supply	No significant leaks (that might risk fire outbreak)	No prior Fire Warning
Case/Frame	No significant leaks (that might risk fire outbreak)	No prior Fire Warning
LPT		
Nozzle Guide Vanes	Cracks/Severe Oxidation damage OK, but intact enough to preserve gas path through to blades	None (Visual Only)
Blades	Most of the airfoils intact (enough to provide power to LP compressor/fan and avoid excessive vibration)	Indicated Vibration
Hub/Rotor	No damage present that might result in blade liberation or excessive vibration	N1 Rotation
LPT Shaft	Intact and free to rotate without excessive vibration.	N2 Rotation

Table 3-16. Minimum Requirements for Engine Restart (Hot Section Components) (Continued)

Major Module Components	Minimum Requirements for Restart	Potential Sensor-Based Verification Means Prior to Restart Attempt
Combustor/Diffuser/Engine Ignition System		
LPT (Continued)		
Air Seal/Shroud	No severe leaks that might allow hot gas intrusion into bearing sumps or other vulnerable areas. Also intact enough to avoid excessive vibration.	None (Visual Only)
Cooling Air Supply	No significant leaks (that might risk fire outbreak)	No prior Fire Warning
Case/Frame	No significant leaks (that might risk fire outbreak)	No prior Fire Warning

Table 3-17. Minimum Requirements for Engine Restart (Exhaust System and Nacelle Structure)

Major Module Components	Minimum Requirements for Restart	Potential Sensor-Based Verification Means Prior to Restart Attempt
Exhaust System		
Primary Nozzle	Heavy damage acceptable (or even complete absence) as long as there is no excessive vibration associated with engine operation.	Indicated Vibration (with Advanced Signal Processing)
Exhaust Plug	Heavy damage acceptable (or even complete absence) as long as there is no excessive vibration associated with engine operation.	Indicated Vibration (with Advanced Signal Processing)
Nacelle Structure		
Cowls	Not required, but should be intact enough to preserve fan flow path and prevent excessive tactile vibration.	None (Visual Only)
Inlet	Intact enough to provide unseparated flow to the fan.	None (Visual Only)
Thrust Reverser/Firewall	Not required to be functional, but inner and outer walls should be intact enough to support engine operation without excessive vibration. Inner wall/firewall should be intact enough to preserve firewall protection to aircraft.	Thrust Reverser Functionality: No Thrust Reverser Alerts Other: None
Strut	Intact enough to support engine operation without excessive engine vibration.	Indicated Vibration (with Advanced Signal Processing)
Engine Mounts/Load Path	Intact enough to support engine operation without excessive engine vibration or risk of engine separation.	Indicated Vibration (with Advanced Signal Processing)

Table 3-18. Minimum Requirements for Engine Restart (Engine Subsystems Components)

Major Module Components	Minimum Requirements for Restart	Potential Sensor-Based Verification Means Prior to Restart Attempt
Engine Lube System/Lubricated Components		
Lube Storage, Supply, and Filtration System	Not required for short-term operation if severe economic damage is an acceptable tradeoff against operational concerns. However, extended operation without oil flow cannot risk sump fire and associated possibility of failing high-energy parts (e.g., shaft or disk).	Oil System Indications
Bearings	Free to rotate without excessive vibration or heat generation.	N1, N2, and N3 Rotation, Indicated Vibration (with Advanced Signal Processing)
Seals	Some leakage acceptable, but must not allow excessive oil intrusion into gas path such that pervasive compressor surge occurs.	None (Visual Only)
Gearboxes	Intact and free to rotate without excessive vibration through to critical shaft-driven accessories (MFP, HMU).	N2, N3 Rotation or Gear-driven Accessory faults. Indicated Vibration (with Advanced Signal Processing)
Bleed Air	Customer bleed not required, but damage must not compromise ability to develop burner pressure. Also, uncontrollable leaks must not be present which might risk fire outbreak.	Existing Fault Detection
Fuel Supply System		
Boost Pumps	Not required (suction feed restart and operation with altitude restrictions is possible).	Fuel System Alert(s)
Spar Valve	Not failed closed	Fuel System Alert(s)
Plumbing	Intact from tank through to fuel manifold. No significant leaks that might risk fire outbreak.	Fuel Imbalance
Main Fuel Pump	Functional enough to provide lightoff and acceleration to idle fuel flow capability.	None (Visual Only)
Miscellaneous Systems		
Propulsion Control System and Sensors	Functional on at least one FADEC channel	Existing Fault Detection
Start System	Functionality not required for windmill starts. Hardware must be intact enough to not compromise engine oil system integrity or accessory gearbox rotation.	Starter Alert
Hydraulic System (Propulsion Portion)	Functionality not required. Hardware must be intact enough to not compromise engine oil system integrity or accessory gearbox rotation, or risk significant leakage of flammable fluids.	N2 Rotation
Fire/Overheat Detection System	Functionality not required.	FODS Alert
Fire Extinguishing System	Functionality not required.	Fire Extinguishing Alert

Table 3-18. Minimum Requirements for Engine Restart (Engine Subsystems Components) (Continued)

Major Module Components	Minimum Requirements for Restart	Potential Sensor-Based Verification Means Prior to Restart Attempt
Miscellaneous Systems (Continued)		
VSCF/IDG	Functionality not required. Hardware must be intact enough to not compromise engine oil system integrity or accessory gearbox rotation.	Dedicated Alerts

MFP = Main Fuel Pump
HMU = Hydro-Mechanical Unit (Fuel Controller)

3.7 DAMAGED ENGINE POWER CAPABILITY DETERMINATION.

During the research, pilots expressed a desire for automatic detection and annunciation of damaged engine thrust capability. A further desire was expressed for a prediction of how long a damaged engine would operate as a function of power level. Modern turbofan installations do not currently offer this capability. Rather, this determination is usually made through pilot action and monitoring of engine indications and alerts. The current factors (either automated or manually set), which may dictate the maximum allowable thrust setting, include:

- Acceptable tactile or indicated vibration level. (Note: The means to discriminate between engine damage and icing is separately discussed in section 5.5.4.4)
- EGT and rotor speeds operating within limits.
- Absence of continuous multiple surging.
- Avoidance of out-of-limits oil system indications (e.g., pressure, temperature, filter Δp, etc.).
- Avoidance of out-of-limits fuel system indications (severe fuel imbalance or high filter Δp).
- Absence of nacelle overheat alert.

With these considerations, the standard procedure for determining available thrust following sensed engine damage is as follows:

1. Pull thrust lever to idle. Note: Assumes modern FADEC with automated stall recovery logic (i.e., commanded engine shutdown is not necessary to clear stall).
2. Advance thrust lever until limits described above are determined.

Replicating the above power capability determination in an automated fashion is likely to be very challenging. Characterization of the damaged engine performance requires information from

more than one thrust lever setting. Automating this characterization process would require automated thrust variation that may be inconsistent with pilot-commanded thrust. As a result, the damage detection system would likely require degree-of-damage assessment capability without thrust change and would, thus, necessitate sophisticated real-time predictive models of damaged engine behavior. These challenges are addressed in more detail in section 5.

3.8 TASK 2 CONCLUSIONS.

Engine damage detection fidelity requirements are directly dependant on the intended usage. For direction of appropriate flight crew response, resolution to a general engine damage awareness level or common response groups is necessary. Presuming no other fault messages are available, identification of dispatch-critical maintenance likely demands resolution to the major module level. Within the response categorization of engine damage, one awareness and four specific responses seem appropriate: awareness only, isolate bleed air, restrict thrust, shutdown, and immediate shutdown.

Of these five categories, awareness only is generally not covered by existing alerts. Restrict thrust is generally covered (with the Phase 2 sustained anomaly alerts), with the exception of tactile vibes. Shutdown is partially covered by existing oil system alerts, but potential benefits arise from inclusion of lubricated components. Isolate bleed air and immediate shutdown are covered by existing alerts.

Further evaluation of the awareness only and restrict thrust categories determined that the response based on sensor fusion-based detection would be guided by subsequent symptoms for which existing alerts and annunciations already existed. This permitted the merging of the awareness only and restrict thrust into a common awareness/restrict thrust category. This damage detection, annunciation, and alerting strategy was carried forward for development in Tasks 3 and 4 and is summarized in figure 3-10.

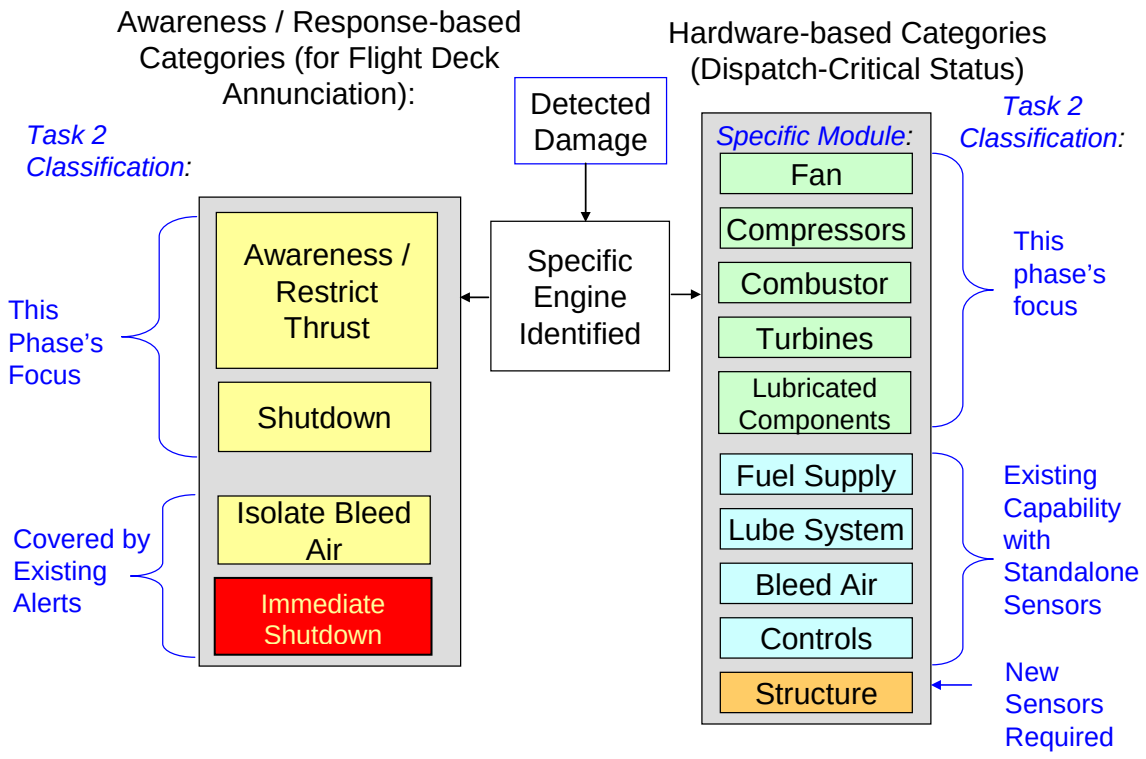


Figure 3-10. Damage Annunciation Categories

Once engine damage has been detected and annunciated, pilot-commanded thrust restriction or engine shutdown may be required, depending on the nature of the damage. In this regard, both operational and economic considerations apply. Conversely, there are scenarios where it may be both desirable and acceptable to maintain damaged engine operation in order to preserve systems redundancy, maximize available safety margins, or maintain operational flexibility.

Engine restartability depends both on the specifically damaged component and the degree of damage to this component. A pristine engine state is not required for restart, but minimum mechanical integrity is necessary for selected gas path, lubricated, subsystem, and control system components. In some (but not all) cases, existing indications are available to the flight crew to verify the minimum mechanical integrity of the damaged engine sufficient to support restart (e.g., rotation, indicated vibration, etc.).

Once engine damage has been detected and annunciated however, the means to determine the reliable thrust range of the engine is principally achieved through pilot action and continued monitoring of critical engine parameters. Pilots participating in this research effort have expressed a desire to incorporate damaged engine restartability and power capability determination as an integral component of engine damage detection. An integrated capability to detect all the prerequisites for restartability does not exist in today's propulsion system designs. Automating these features is likely to be very challenging for a sensor fusion-based damage detection system, and may not be feasible. The issues associated with incorporating these capabilities are discussed in more detail in section 5.

Task 2 determined that engine damage annunciation potentially provided both awareness and response benefits. Awareness-based benefits of engine damage detection and annunciation included:

- Providing advance knowledge of the engine's future capability for higher thrust operation, restart, and potential for possible uncommanded shutdown, and thus reducing the potential for ICR.

- Identifying damage to the specifically affected engine, and thus reducing the potential for shutting down a good engine.

Response-based benefits of engine damage annunciation included:

- Preservation of safety margins for potentially hazardous failures (e.g., prevention of uncontrolled fire, etc.).

- Reduction of high crew workload during critical flight phases (e.g., precautionary shutdown to preclude uncommanded shutdown on approach and, thus, avoid urgent reconfiguration and possible ICR).

- Limiting further severe economic damage (acknowledgement that this is a genuine consideration for airline operations).

While Task 2 identified these potential benefits for engine damage alerting, Task 3 provides a discussion on the drawbacks associated with nondeterministic detection and annunciation.

4. TASK 3: OPERATIONAL CRITERIA FOR DAMAGE DETECTION AND ANNUNCIATION.

4.1 TASK 3 OBJECTIVES.

The primary Phase 3 study goal was to identify engine damage modes requiring flight crew awareness or action. Flight crew awareness of such nonnormal conditions is provided by warning, caution, or advisory crew alerts, and by supporting engine indications and annunciations. Flight crew action is typically guided by paper or electronic nonnormal procedures corresponding to each alert.

A secondary Phase 3 study goal was to identify engine damage modes requiring near-term maintenance action. Typically, such awareness is provided to the maintenance and flight crew via discrete system status indicators or annunciators, or as a separate part of a centralized crew alerting system (e.g., a system status message page), or some combination of the two. Centralized crew alerting system status messages are checked before each flight to determine aircraft dispatchability.

Task 3 focused primarily on the development of engine damage-related annunciation and procedure strategies (e.g., alerts, flight deck display indications, and annunciations and crew checklist procedures) for modern, new, and future aircraft. Task 3 objectives included development of

- an engine damage annunciation strategy based on Task 1 and Task 2 assessments, and
- operational criteria for engine damage detection and annunciation.

4.2 TASK 3 RESULTS.

Task 3 documented engine damage-related alert reliability and availability criteria, alert procedures, and supporting engine indications and other annunciations. Task 3 also included an overview of typical existing modern commercial aircraft flight deck displays, indications, and alerting.

Task 3 specifically developed an alert strategy: messages, levels, supporting indications, procedures, and associated availability and reliability criteria for flight crew annunciations corresponding to the Task 2 engine damage response categories awareness/restrict thrust, and shutdown. Task 3 also developed annunciation criteria for dispatch-related engine damage. Such annunciations may be provided alone or in conjunction with alerts. The overall approach to Task 3 is illustrated in figure 4-1.

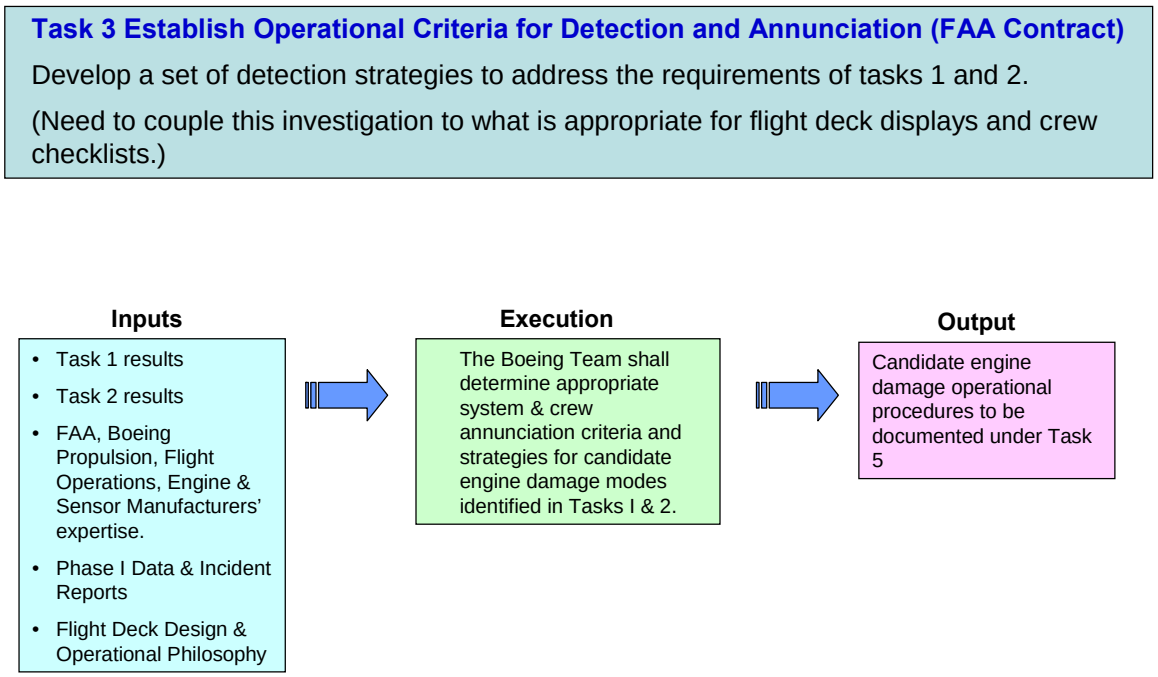


Figure 4-1. Task 3 Approach

In addition to developing engine damage annunciation strategy, operational criteria, and associated crew procedures, Task 3 also included a discussion of

- typical modern commercial transport flight deck displays, engine indications, and engine controls;
- crew alerting and checklist procedure displays;
- crew alerting-related awareness and response considerations; and
- ICR considerations.

These considerations provided the context for new engine damage annunciation.

Task 3 determined that immediate crew awareness would be justified for all Task 2 engine damage response categories. The combined engine damage awareness only and the restrict thrust response category may or may not require subsequent crew response. The shutdown common response category requires a specific crew response. Caution level alerting was, therefore, determined appropriate for all response categories.

Task 3 engine damage annunciation criteria are based on the operational (both safety and economic) consequences of failure to alert and false alerting. Operational criteria applicable to

detection and annunciation require consideration of the following event probabilities and the associated operational consequences for each Task 2 response group:

- The probability of actual engine damage
- The probability of failure to detect engine damage
- The probability of false detection of engine damage

The reference 1 PSM+ICR Phase 1 report concluded that "Malfunction annunciations have little or no potential to prevent Rejected Takeoff above V1 (RTO>V1)." However, Phase 3 Task 3 concluded that damage detection and annunciation early in the takeoff roll has RTO>V1 ICR prevention potential.

The Task 3 assessment concluded that a potential benefit for annunciation of engine damage exists. However, in the absence of engine damage detection thresholds and a correlation of engine damage to engine affect, the ICR benefit of engine damage annunciation cannot be currently quantified or predicted. Although annunciation of engine damage is beneficial in identifying the affected engine, the benefit is realized only if the annunciation is reliable (meaning, it meets the failure to alert and false alerting operational criteria). In addition, the operational benefit and feasibility of engine damage detection and annunciation is proportional to the level of determinism in the detection and annunciation strategies.

4.3 FLIGHT DECK OVERVIEW OF DISPLAYS, CONTROLS, AND ALERTING.

Alert, as used in this section and throughout this document, refers to red or amber message text or inscribed indicator lights whose text describes the alert condition (e.g., ENG FIRE L(R), ENG FAIL L(R), etc.). These alert indicator lights or messages are typically accompanied by attention-getting aurals (e.g., siren or voice) and separate red or amber visual attention-getting lights (labeled WARNING or CAUTION) mounted in the forward primary field of view. Such attention-getting lights and aurals, are designed to alert the crew to the presence and level of a nonnormal aircraft or operational condition that requires their awareness or action. The alert message text or inscribed indicator lights (and in some cases, the alert aural or voice) are designed to provide crew awareness of the specific nonnormal condition and lead to a supporting information and procedure that promotes understanding and guide crew response.

The following figures and tables provide an overview of flight deck displays, controls, and indications with particular focus on engine and alerting displays, controls, and indications. The intent is to provide context for the Task 3 discussion of crew annunciation and alerting in general, and engine damage annunciation, alerting, and crew procedures in particular.

Figure 4-2 illustrates a typical modern commercial transport two-crew flight deck panel and display layout. Each pilot has a dedicated primary flight display (PFD) and navigation display (ND). In the figure, the NDs are multifunction displays (MFDs) that can display other formats such as an electronic checklist or dynamic graphical schematics of aircraft systems such as fuel, hydraulic, electrical, air, door, and flight controls. Note: electronic flight bag (EFB) is an optional side display.

The center upper and lower displays are typically shared by both pilots. In figure 4-2, the upper center display provides Engine Indication and Crew Alerting System (EICAS) indications, while the lower center display is a third MFD. Display control panels allow the pilots to interact with the MFDs. Engine controls (e.g., throttles and fuel control switches) are typically located on the center control stand.

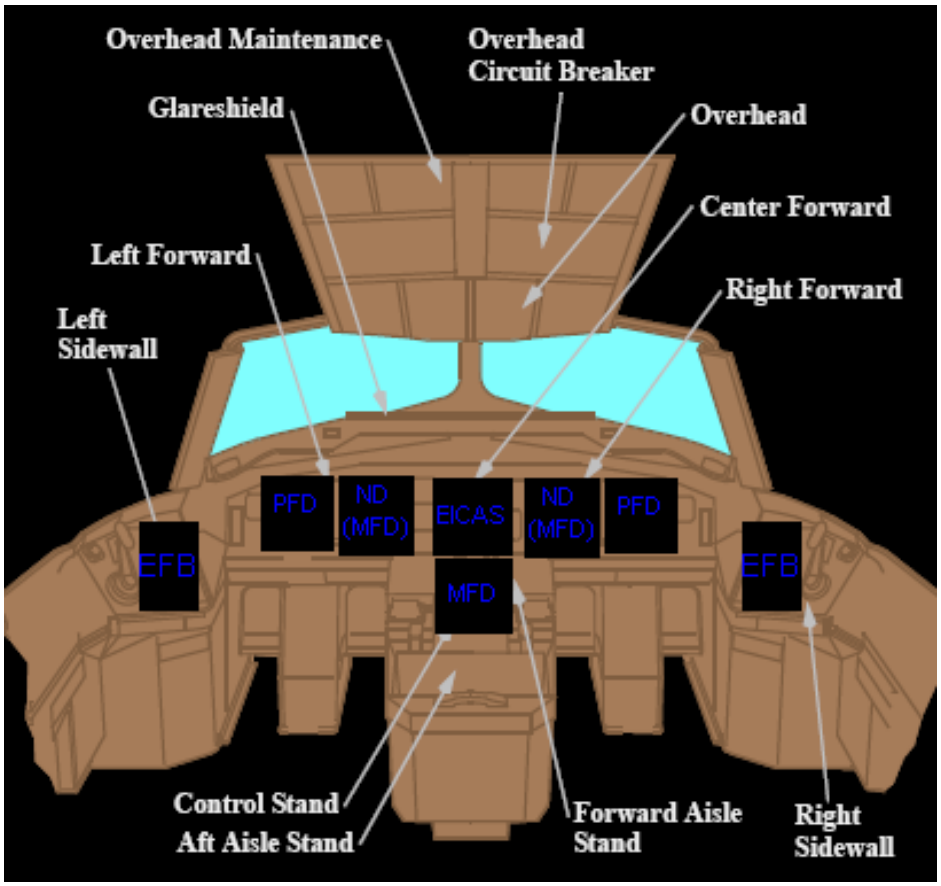


Figure 4-2. Typical Modern Commercial Transport Flight Deck

Figure 4-3 illustrates the glareshield integrated master warning and caution alert lights; upper center EICAS display; the left, right, and lower center MFDs; and the throttle quadrant. The master warning and caution alert lights are integrated with reset switches and are located in front of each pilot. These lights illuminate whenever a warning or caution alert is first displayed. The lights reset when either the left or right switch is pushed. Primary engine indications, alert messages, and other aircraft systems indications (e.g., memo messages, fuel quantity, and gear and flap position) are displayed on the EICAS. The secondary engine indications displays are shown on the lower center MFD. The electronic checklist display is shown on the left MFD. A status page display is shown on the right MFD. Left and right cursor control devices are provided for each pilot to interface with the interactive displays. Among other controls, the throttle quadrant shown provides thrust and reverse thrust levers, and below those, fuel control switches for each engine.

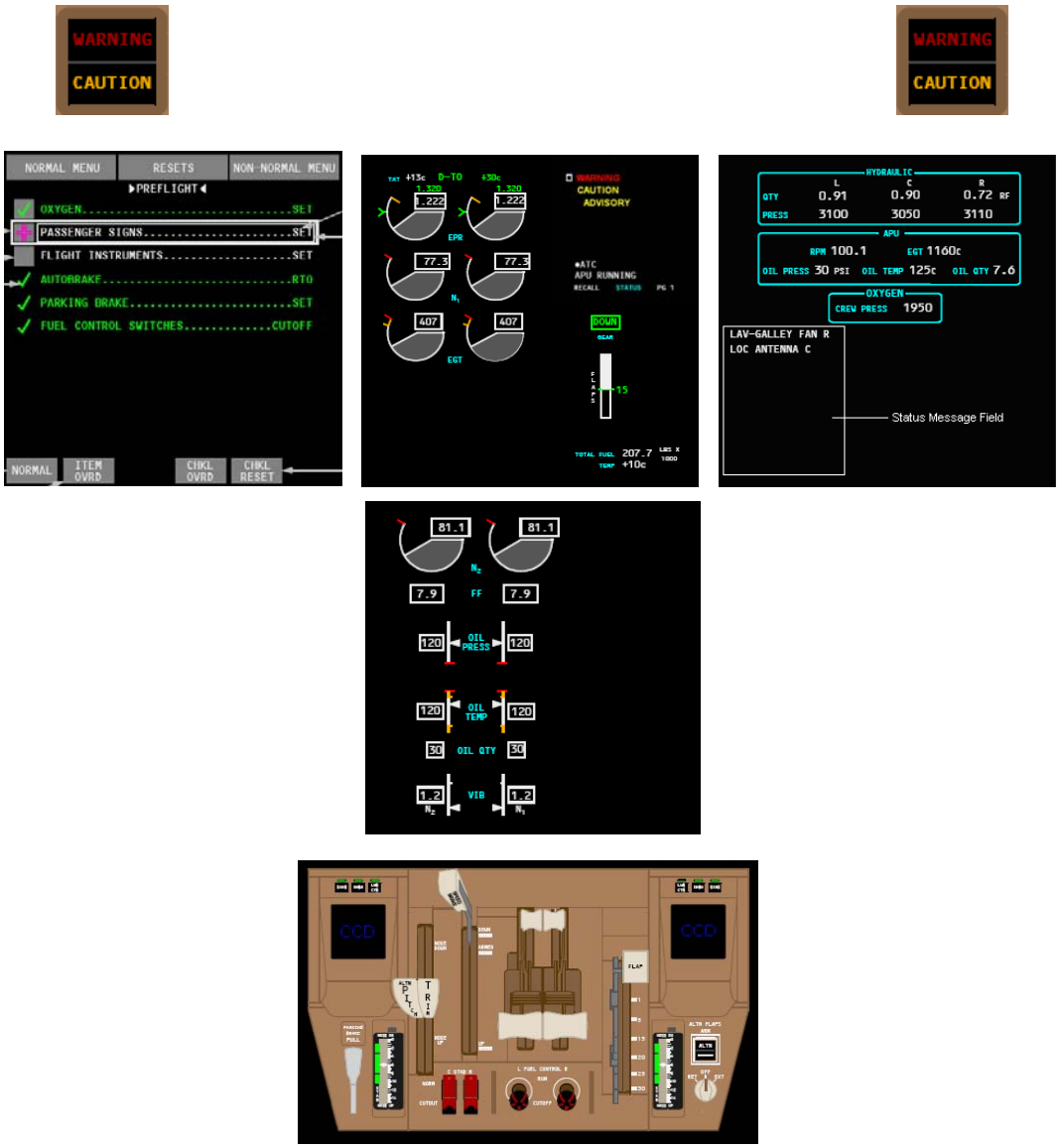


Figure 4-3. Typical Commercial Transport Flight Deck Displays and Controls

Table 4-1 defines and describes one possible implementation of flight deck alerting and messaging—i.e., alert, memo, status, and maintenance messages. These definitions were used to develop and define the Task 3 engine damage annunciation strategy.

Table 4-1. Message Types, Levels, Implementations, and Definitions

Message Type	Message Level[1]	Display Location	Visuals and Aurals	Message Definition/Description/Use
Alert	Warning	EICAS (Upper Center Display)	Red visual components—e.g., red attention-getting lights and red message/condition text. Aural tone or voice.	Operational or aircraft system condition that requires immediate crew awareness and timely corrective or compensatory crew action.
	Caution		Amber visual components—e.g., amber attention-getting lights and amber message/condition text. Aural tone or voice.	Operational or aircraft system condition that requires immediate crew awareness. Compensatory or corrective action may be required.
	Advisory		Visual components of advisories should be amber[2] or some other color sufficient to differentiate advisories from normal conditions and annunciations. No aural component.	Operational or aircraft system condition that requires crew awareness. Compensatory or corrective action may be required.
Nonalert	Memo		White message text.[3] No aural component. Memo messages should be collocated, but not intermixed with alert messages.	Normal indication of current state of manually, and certain automatically, configured airplane systems—e.g., Parking Brake Set, APU Running, Autobrake, etc.
	Comm		White message text[3] with preceding bullet. Chime.	Normal indication of incoming data link and other communications.
	Status	MFD Status Page (L, C, or R MFD)	White message text. Cyan STATUS cue displayed below EICAS message field. No aural component.	Airplane system condition affecting airplane dispatch. Required/used to determine aircraft dispatchability. No Dispatch or Time Limited Dispatch per Master Minimum Equipment List and Dispatch Deviation Guide.
	Maintenance	Maintenance Access Terminal—Aft Flt Deck or Remote	White message text. No aural component.	Airplane system fault condition. Not required/used to operate aircraft or determine dispatchability. Used for scheduled and unscheduled maintenance. Supports maintenance operations. Maintenance messages generally correlate with alert and status messages.

[1]Alert level and alerting means should be based on the time criticality of awareness and response. The more time-critical the condition, the more the need to use higher alert levels and redundant alerting modes. Visual, tactile, or auditory alerting are available means to ensure awareness and response.
[2]Amber advisories may not be allowed in the future, at the time of this writing 14 CFR 25.1322 is being revised.
[3]Other colors may be used provided they are suitably validated.

4.4 GENERAL CREW ANNUNCIATION AND ALERTING CONSIDERATIONS.

Flight crew alerting may consist of noncentralized alerting (e.g., discrete indicators and annunciators), or a centralized crew alerting system. In either case, various combinations of aurals and visuals are used to get crew attention, communicate that a nonnormal alert condition exists, identify the specific nonnormal condition and urgency or criticality, and direct the crew to an appropriate nonnormal procedure. Supporting engine indications and annunciations are also typically provided and, in some instances, may be necessary to accomplish the crew procedure. Indication, annunciation, and alerting can be accomplished in many different and equally effective ways.

As shown in figure 4-3, modern commercial transport flight decks typically provide a centralized alerting system designed to ensure timely crew awareness of nonnormal conditions and appropriate crew response. This is accomplished using a combination of visual and aural stimuli designed to attract crew attention and orient the crew to the presence of a nonnormal condition that requires their awareness and possible response. Centralized alerting systems typically provide warning, caution, and advisory alert message levels related to awareness and response criticality, and provide supporting system indications and annunciations. Alert message text typically provides explicit condition awareness (e.g., ENG FAIL L) and leads the crew to a corresponding nonnormal checklist procedure that guides crew response and promotes the crew's understanding of the condition and its operational effects on the system, aircraft, and flight. Centralized alerting or maintenance systems also typically provide other messages that annunciate conditions affecting aircraft dispatch.

As used in this report:

- Annunciations refer to a broad category of normal and nonnormal indications and/or aurals designed to draw or focus crew attention and to support crew awareness or action. For engine damage alerting strategy, annunciations refer to visual enhancements of affected engine indications.

- Alerts are a subset of annunciations and refer to a nonnormal malfunction-specific or nonnormal condition-specific annunciation requiring crew awareness or action. As described in table 4-1, there are various alert levels, visuals and aurals—all typically designed to ensure appropriate crew awareness and/or response, and lead to an appropriate crew procedure. For engine damage alerting strategy, alerts refer to text messages accompanied by attention-getting lights and aurals unique to each alert level.

An annunciation is displayed or occurs when its corresponding event or condition occurs and typically persists for as long as the condition exists. Nonnormal annunciations are generally differentiated from normal annunciations by using aural and visual attention-getting components, color-coded indications or messages designed to provide appropriate crew awareness and understanding and elicit appropriate crew response by linking to a specific nonnormal procedure. As described in previous paragraphs and illustrated in figures 4-1 and 4-2, alerts are typically displayed in a centralized location. Alerts are often accompanied by corresponding alert-related annunciations that are displayed on the PFD, ND, engine, and other display formats.

A Flight Deck Effect (FDE) is a crew-detectable display indication or annunciation, or a crew-sensible condition (e.g., visual, aural, tactile, or odor). Engine damage that produces an FDE is considered flight crew detectable.

Table 4-1 describes typical alert (nonnormal) and nonalert (normal) implementations. Specific implementations will be similar, but differ somewhat by aircraft manufacturer. Regardless, the spirit and intent of all implementations is the same—to ensure and promote appropriate crew awareness and response.

The objective of any integrated alerting system solution is to assure timely and appropriate crew awareness and response. Alerting must be designed to communicate the criticality and nature of the specific nonnormal condition. Related alert procedures must be designed to ensure appropriate crew response. Crew awareness and response is accomplished via various alert levels—each of which is uniquely defined in terms of awareness and response requirements. This is accomplished through the use of visual, aural, and tactile alerting, alone or in combination. Because multiple alerting means may satisfy a given alerting requirement, the final integrated alerting solution can take alternative forms.

4.5 CREW ALERTING-RELATED AWARENESS AND RESPONSE CONSIDERATIONS.

The selection of an alert level and alerting method should be based primarily on crew awareness and response considerations. A demonstrable need for crew awareness or response should exist. The time criticality of the condition, the specific aircraft type and model, and the total sensory loads for visual, audible, and tactile signals for the specific aircraft should also be considered. The more critical the alert condition, the more the need to use redundant alerting modes. Visual, tactile, or auditory alerting are available means to ensure appropriate pilot awareness and response. Warnings are used where immediate awareness and response are required. Cautions are used where immediate awareness and possible response are required. Where response is time-critical, memorized crew action may be desired or required. Note, flying the aircraft takes priority over immediate response to alerts. Flight crews are trained to stabilize the aircraft, ensure flight path control, and complete the critical flight phase prior to responding to a warning alert (e.g., delayed response to engine fire may be warranted).

Immediate crew awareness is typically provided by redundant visual and aural attentions. Warning and caution visual attentions are placed in the forward primary field of view. At a minimum, aurals are typically unique to the alert level (e.g., warning or caution). Often, aurals are unique to specific conditions—particularly warning level conditions. Fault or alert conditions requiring immediate time-critical crew action are typically annunciated with aural alert voices. The crew is informed of an alert condition by specific graphical and/or alphanumeric (alert message text) indications.

Voice alerts are the most efficient method of transferring high-priority information, primarily because they minimize the number of information transfer steps. But voice alerts are typically used only where pilot response time is critical, and where the actual or potential time delays associated with other methods of alerting are insufficient. Voice alerts should be limited to events where immediate, memorized, flight path-related or tactical, time-critical crew action is required.

The number and nature of time-critical warning and warning level alerts are intentionally limited to critical conditions having very low probability of occurrence, where the warning can be provided reliably and not falsely or inappropriately, and where crew response is necessary, simple, and invariant. The low likelihood of existing warnings limits the potential for distraction. The criticality of existing warnings must justify any potential for crew distraction. All alerts, regardless of level, should be implemented with consideration for the potential and consequences of false alerting against the potential and consequences of failure to alert.

4.6 NONNORMAL CHECKLIST CONSIDERATIONS.

The aircraft is operated through normal and nonnormal checklist procedures. Nonnormal checklists are provided for abnormal conditions affecting aircraft operation. Nonnormal checklists should include a condition statement, and typically begin with steps to correct the situation or condition. Nonnormal checklist use commences when the airplane flight path and configuration are properly established. Only a few situations require an immediate response (such as stall warning, ground proximity and wind shear warnings, and rejected takeoff). Usually, time is available to assess the situation before corrective action is initiated. All actions should then be coordinated under the captain's supervision and performed in a deliberate, systematic manner. Flight path control should never be compromised.

While every attempt should be made to establish necessary nonnormal checklists, it is not possible to develop checklists for all conceivable situations, especially those involving multiple failures. In certain unrelated multiple failure situations, the flight crew may have to combine elements of more than one checklist and/or exercise judgment to determine the safest course of action.

Information for planning the remainder of the flight is typically included. Checklists prescribing an engine shutdown should be evaluated by the captain to ascertain whether an actual shutdown or operation at reduced thrust is the safest course of action. Consideration must be given to probable effects if the engine is left running at minimum required thrust.

Typically, there are no nonnormal checklists associated with the loss of an engine indication or with an automatic display of the secondary engine indications. The crew should operate the engine normally unless an alert message displays or a limit is exceeded.

Both pilots should agree before moving critical controls in flight, such as:

- the thrust lever of a failed engine
- a fuel control switch
- an engine or APU fire switch or cargo fire-arming switch
- a generator drive disconnect switch

After moving the control, the crewmember taking the action should also state the checklist response. Action is taken by the pilot flying and the pilot monitoring based on the crewmember's area of responsibility.

During engine start and prior to takeoff, the appropriate nonnormal checklist is accomplished if a nonnormal annunciation is displayed. Upon completion of the checklist, the dispatchability of the aircraft should be assessed before departure.

4.7 INAPPROPRIATE CREW RESPONSE CONSIDERATIONS.

There are four categories of ICR: rejected takeoff above V1 (RTO>V1), Loss of Control (LOC), Shut Down Good Engine (SDGE), and Other. Other predominantly consists of nonnormal procedure errors (e.g., selecting or accomplishing the wrong procedure or selecting the correct procedure but not accomplishing it correctly).

Typically, in PSM+ICR events, the crew does not initially recognize that a malfunction exists or is engine-related, does not correctly identify the malfunction or the affected engine, or does not correctly select or accomplish the appropriate nonnormal procedure. High workload, limited time for assessment, autothrottle or autopilot engagement, and poor crew communication or resource management are often among the contributing factors. Therefore, annunciations that provide affected engine awareness have ICR prevention potential.

LOC events account for the majority of fatal PSM+ICR events and most fatalities. SDGE and Other events account for nearly all the remaining fatal events and fatalities. SDGE typically result from lack of awareness of the affected engine, or a crew tendency to indict the engine at lowest power when presented with two engines at different power settings.

In general, errors typically occur when the crew must monitor, detect, and interpret the malfunction and then select from two or more procedures. Detection and interpretation tasks require substantial flight crew knowledge, effort, and time to identify and understand the malfunction and formulate an appropriate response. Consequently, detection and interpretation tasks increase the potential for crew error. Even when significant changes in airplane performance or engine parameters are detected, it can be challenging to interpret or understand those changes and determine how to respond. Ideally, the flight deck interface design and associated procedures should be as error-proof as possible and aid the flight crew transition from malfunction detection to an appropriate response. To minimize the potential for crew error or ICR, crew system monitoring, detection, and interpretation tasks should be eliminated or minimized to the maximum extent feasible. Where a malfunction can be reliably detected, the crew should be alerted to the malfunction via a central alerting function such as EICAS, which should improve the flight crew's understanding of the malfunction at airplane system and mission levels.

4.8 OPERATIONAL ANALYSIS.

Phase 2 PSM+ICR work addressed Sustained Thrust Anomaly (STA) PSMs. Consequently, the primary Phase 3 focus was on detection and annunciation of engine damage that does not cause an STA. However, because engine damage is the root cause of many engine malfunctions, engine damage detection may significantly overlap existing or proposed malfunction detection such as engine failure, limit exceedance, thrust disagree, engine surge, oil system, and other malfunctions. This requires that engine damage detection and annunciation be well integrated with other engine malfunction detection and alerting. For obvious reasons, multiple alerts for the

same condition are typically avoided by alert-inhibiting in the display design (i.e., display of only the highest priority alert).

Damage-related SDGE is the Phase 3 ICR of primary operational concern. Other nonnormal procedure errors are ICRs of secondary Phase 3 concern. Also included in the Other category are undesired pilot responses that must be considered. These include continuing takeoff when RTO is appropriate, unnecessary engine shut down, air turn-back, and diversion. The risk of such undesired pilot responses is proportional to the level of determinism in the detection and alerting strategy. As such, alerts provided for awareness only which result in subsequent pilot monitoring or interpretation of engine parameters are nondeterministic. Such nondeterministic alerts may present increased risk for highly subjective, variable, and thus, undesired crew interpretation and response. In developing and implementing engine damage alerting, it must be assured that the alerting does not induce more inappropriate or undesired pilot response than it prevents.

The PSM+ICR Phase 1 report [1] concluded that "Malfunction annunciations have little or no potential to prevent Rejected Takeoff above V1 (RTO>V1). Above V1, malfunction annunciations increase the risk of causing RTO>V1 events." However, further review and analysis of the Phase 1 PSM+ICR events suggests that damage detection and annunciation before V1, and particularly early in the takeoff roll below 80 knots after takeoff thrust has been set and stabilized, may have RTO>V1 ICR prevention potential. This limited potential was discussed in section 2.8.

It should be noted that PSM+ICR events cannot and should not be addressed solely by 14 CFR Part 25 design and certification of PSM alerts and procedures. As reference 1 acknowledged or inferred, 14 CFR Part 121 operational approvals of airline policies, practices, and procedures can have an equally positive and potentially greater impact on ICR prevention and mitigation. PSM+ICR prevention and reduction potential is possible through policies, practices, and procedures that promote PSM-related crew training and crew resource management (e.g., coordinated assessment and response), foster PSM recognition and understanding, and minimize unnecessary IFSDs.

4.9 OPERATIONAL ANNUNCIATION CRITERIA.

The objective of integrated alerting is to ensure appropriate crew awareness and response for all expected conditions and circumstances. A combination of visual, tactile, and auditory alerting stimuli are typically necessary to ensure appropriate pilot awareness and response. It was determined that immediate crew awareness was justified for all three Task 2 engine damage response categories. The combined engine damage awareness restrict thrust response category may or may not require subsequent crew response. The shutdown common response category requires a specific crew response. Neither category requires immediate crew action. Therefore, caution level alerting was determined appropriate for all three response categories.

Proposed engine damage detection and alerting assumes that separate detection, annunciation, and corresponding crew procedures pre-exist for all STAs, engine failure, all parameter limit exceedances, and all detectable conditions requiring immediate engine shutdown. Examples include thrust disagree (commanded and indicated thrust disagree), engine subidle, EGT

exceedance, engine speed exceedance, continuous multiple surge, and engine fire. Where automatic detection and annunciation are not provided, it is assumed that unannunciated crew procedures predicated on crew detection are provided.

Task 3 engine damage annunciation criteria are based on the operational (both safety and economic) consequences of failure to alert and false alerting. In general, the probability of a false alert should be at least an order of magnitude less than the probability of the malfunction itself. False alerting and failure to alert are both undesirable. But a trade between the two must typically be made. For engine damage, frequently or even sporadically occurring false alerting has more undesirable or unacceptable operational consequences than a rare failure to alert. Engine damage operational criteria are therefore biased to minimize false alerting, and to accept failure to alert because other existing annunciations ensure sufficient and appropriate crew awareness and response.

Operational criteria are specified in terms of percent of events and categorized as low, medium, high, and very high. These criteria are defined below.

- P (True Detection/Alert) is the probability or likelihood that the PSM will be detected and alerted when it actually exists: low (~90%), medium (~99%), high (~99.9%), and very high (~99.99%). 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/or thrust asymmetry) and the lower the altitude (closer the ground), the higher the desired reliability.

- P (Failure to Detect/Alert) is the probability or likelihood that the PSM will not be detected and alerted when it actually exists: high (~10%), medium (~1%), low (~0.1%), and 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 that significantly affects thrust, thrust control, or risks engine damage if crew action is not taken.

- P (False Detection/Alert) is the probability or likelihood that normal engine operation, or a minor insignificant engine anomaly, will be detected and alerted as a sustained and/or meaningful engine malfunction. This is also known as the annunciation reliability.

4.10 FAILURE TO ALERT VERSUS FALSE ALERT CONSIDERATIONS.

The engine damage detection and annunciation criteria established herein are based on the operational (both safety and economic) consequences of failure to alert and false alerting. In the case of engine damage detection/annunciation, which is considered an improvement to already acceptable levels of safety, false alerting is more critical than failure to alert.

The operational impact of false engine damage alerting includes possible air turn-back, diversion, IFSD, and increased crew workload—all of which decrease operational safety margins. Significant economic costs associated with unplanned flight diversions and

maintenance may also result. False alerts should be minimized, and accepted only on a case-by-case basis when other, more critical, considerations rule.

Specifically, the probability of false alerting should be at least an order of magnitude less than the probability of the malfunction itself. 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. In addition, in cases where the alert procedure involves pilot-commanded engine shutdown, the probability of false alerting should be very low, e.g., on the order of 1E-7 (single engine) to 1E-9 (dual engine) per flight hour or less.

Where the consequences of false alerting exceed those of the failure to alert, false alerting criteria must be stringent and validated. False alerting may have undesirable effects (e.g., falsely inducing engine shutdown inherently increases risk for a diversion and landing at an unfamiliar airport). But where the consequences of failure to alert are high and exceed the relative consequences of false alerting, a greater level of false alerting is justified (meaning, the operational criteria for false alerting will be less stringent). Fire detection annunciation is an example. The consequences of failure to alert to fire are unacceptable (potential loss of aircraft and lives). The consequences of false fire alerting (unnecessary engine shutdown and diversion) are accepted to ensure continued safe flight. Therefore, to prevent failure to alert, very low levels of failure to alert fire are allowed, and consequently, larger levels of false alerting are accepted.

Regarding failure to alert, it is important to note that the absence of a known alert (e.g., engine damage or some other alert identifying the affected engine and condition) could lead or otherwise misdirect the crew to believe that engine damage is not present, when in fact it is. Thus, for a given alert or set of alerts, a high degree of coverage is desirable.

However, even where the operational consequences of failure to alert are acceptable, economic considerations may drive levels of false alerting to a one, two, or greater order of magnitude less than the probability of the nonnormal event involved. A false alert could result in an unnecessary engine shutdown and subsequent diversion. Diversions have a significant economic penalty to the airlines (i.e., schedule interruptions, passenger accommodations, and the additional maintenance burden).

4.11 ANNUNCIATION/ALERTING CRITERIA.

Table 4-2 documents preliminary alert message text, alert level, and alert procedure for each Task 2 detection strategy response category. Operational criteria for availability, failure to alert, and false alerting are listed for each response category. The table 4-2 criteria reflect that the pilot action associated with false damage annunciation (thrust reduction) is not operationally critical (i.e., it is easily recoverable and does not significantly affect operational performance capability or safety margins). The pilot action associated with false damage annunciation (engine shutdown) is operationally critical (i.e., it significantly affects operational performance capability or safety margins).

Table 4-2. Proposed Annunciation Strategy and Criteria

Annunciation Category	Nonnormal Condition	Alert Message and Level	Procedure[1]
Awareness/ Restrict Thrust	Engine damage or degradation is suspected. Engine capability may, or may not, be affected. Available engine thrust may be limited. Restricted thrust operation may be necessary to maintain acceptable engine operation or prevent further damage. Engine shutdown may be required.	ENG GAS PATH L/R Caution level alert. Immediate awareness and possible crew action required.	- Autothrottle OFF. Retard throttle as required to maintain acceptable level of tactile vibration or engine indications within limits. - Shutdown engine if tactile vibration is unacceptable or engine parameter(s) exceed a limit.[2]
Ops Criteria:	P (True Det/Alert): 99% to 90% (99/100 to 9/10)	P (Failure to Det/Alert): ~1% to ~10% (1/100 to 1/10 misses)	P (False Det/Alert): ~1E-7 (<1/10 million flt hrs)
Shutdown	Engine is damaged or degraded. Continued operation at idle is acceptable, but uncommanded shutdown and extensive economic damage are likely to occur. Continued operation above idle could potentially affect safety. At crew discretion, engine shutdown may be temporarily delayed.	ENG LUBE SYS L/R Caution level alert. Immediate awareness required. Subsequent crew action required.	- Autothrottle OFF. Reduce thrust to idle. Do not operate engine above idle power. - Engine shutdown is recommended to prevent or limit further damage. - Shutdown engine if tactile vibration is unacceptable or engine parameter(s) exceed a limit.
Ops Criteria:	P (True Det/Alert): 99.99% - 99.9% (9999/10,000 to 999/1000)	P (Failure to Det/Alert): 0.01% - 0.1% (1/10,000 to 1/1000 misses)	P (False Det/Alert): 1E-8 to 1E-7(<1/100 million - 1/10 million flt hrs)
Dispatch	Engine damage or degradation affects aircraft dispatch.	ENG L/R[3] Status level annunciation.	Maintenance inspection disposition required before dispatch. If dispatch is time-limited, maintenance and/or operational dispatch limitations may apply.
Ops Criteria:	P (True Det/Alert): Same probability as corresponding alert.	P (Failure to Det/Alert): Same probability as corresponding alert.	P (False Det/Alert): Same probability as corresponding alert.

[1] In general, continued operation with high indicated vibration only is acceptable. If engine separation is suspected, shutdown and secure engine.
[2] Continued operation at normal or reduced thrust is acceptable, provided engine indications remain within limits and tactile vibration level is acceptable.
[3] Separate status messages would be required for no dispatch and time limited dispatch conditions.

4.12 SUPPORTING ENGINE INDICATIONS.

Task 2 documented an operational desire to know the thrust capability of a damaged engine. While alerting is an effective means of providing crew awareness and a documented procedural response, it is not an effective means of communicating dynamic information such as a variable thrust restriction. Supporting engine indications and annunciations are more effective means of conveying variable and dynamic information.

An alert that displays and clears as a function of thrust level and degree of engine damage is not an efficient or effective implementation (i.e., an alert that displays and clears when thrust changes). This is particularly true when the alert provides awareness of engine damage, which once it occurs, does not clear or self-heal. An alert for engine damage must persist. An alert for restricted thrust level that displays and clears could become a nuisance. Supporting graphical indications are an effective means to provide dynamic information to the crew.

Engine damage-related parameter shifts may be counterintuitive, subtle, or otherwise difficult to detect. Engine damage alerting and supporting indications (e.g., color coding, highlighting, etc.) should ensure crew awareness of the affected parameters and guard against counterintuitive changes that could delay, confuse, or misdirect the flight crew.

Where manual instead of automatic thrust limiting is implemented, supporting graphical indications are the best means to provide dynamic information such as thrust caution or warning operating ranges.

4.13 NEW ENGINE DAMAGE ALERTS.

An assessment was made regarding how new engine damage-related alerts would integrate with existing flight deck alerts and displays. The details of such integration primarily involve resolution of the overlap of new damage alerting with existing alerting, such as engine failure, limit exceedance, thrust disagree, engine surge, oil system, and other malfunctions. The primary objective of such integration is to prevent the display of multiple alerts (and procedures) for the same condition. When a condition may trigger multiple alerts, the most appropriate alert is selected for display, and it will typically inhibit the display of other alerts triggered by the same condition. Exceptions are made on a case-by-case basis.

Currently, it is envisioned that the engine damage alert would only be displayed for events without sustained thrust anomalies. However, engine damage detection capability could be used to improve existing alerting, particularly if it is more deterministic than the existing alerting.

While integration of new engine damage-related alerts with existing alerts depends on the detection capability, such alerts are compatible with existing alerts and consistent with the existing alerting paradigm.

4.13.1 Engine Gas Path L/R (Awareness/Restrict Thrust).

The gas path-related alert and supporting engine indication would be displayed when significant engine damage or degradation is detected. Engine damage would be such that crew awareness or

restricted thrust operation is justified to maintain acceptable engine operation or prevent further economic damage—i.e., to preserve operational capability, to ensure continued safe engine operation, or to ensure engine parameters remain within acceptable limits or at operationally acceptable levels. Engine shutdown may be required if engine parameters or airframe vibration cannot be maintained at an acceptable level.

It is operationally desirable that the thrust restriction be automatically determined and graphically displayed to the crew via supporting engine indications. Note: this capability was determined to not be readily achievable, as discussed in section 5. This relieves the crew of nonnormal system monitoring and interpretation tasks and minimizes the potential for crew error, misinterpretation, and ICR.

Figure 4-4 shows the engine damage alert set for awareness only (no thrust restriction). Figure 4-5 shows the engine damage alert set for awareness and a thrust restriction. The thrust restriction is indicated graphically on the affected engine thrust display and may be presented as an amber caution zone, as a red stay-out zone, or as a combination of the two, as shown in figure 4-5. Note that these implementations are conceptual and are intended only to illustrate possible supporting indications. Note also that such indications require a supporting detection system that can determine the thrust restriction.

Other baseline (i.e., existing or proposed) alerts and supporting indications, or unacceptable tactile vibration, would provide pilot awareness and guide further pilot response (e.g., thrust reduction or engine shutdown).

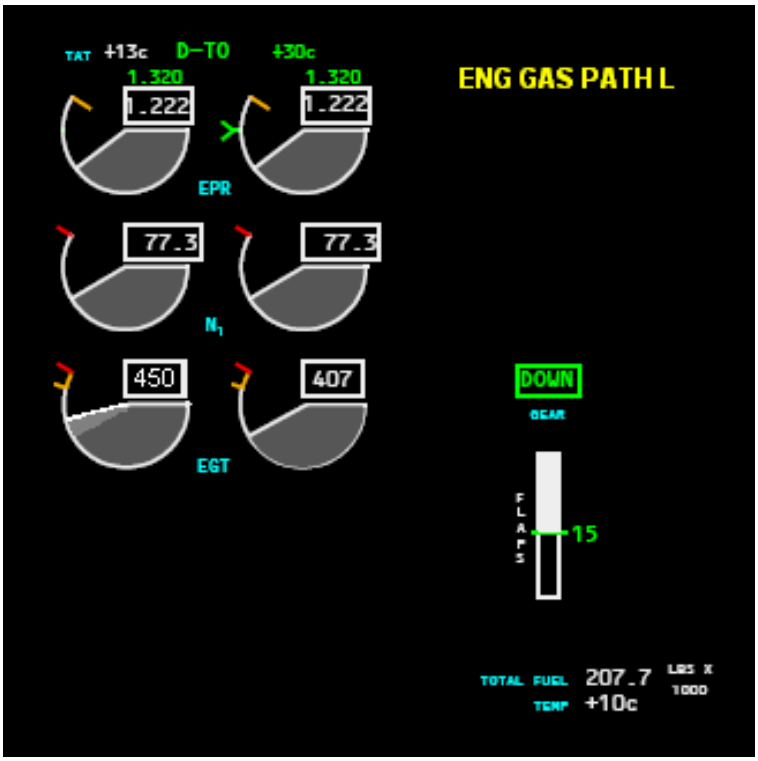


Figure 4-4. Engine Gas Path Damage Annunciation, No Indicated Thrust Restriction

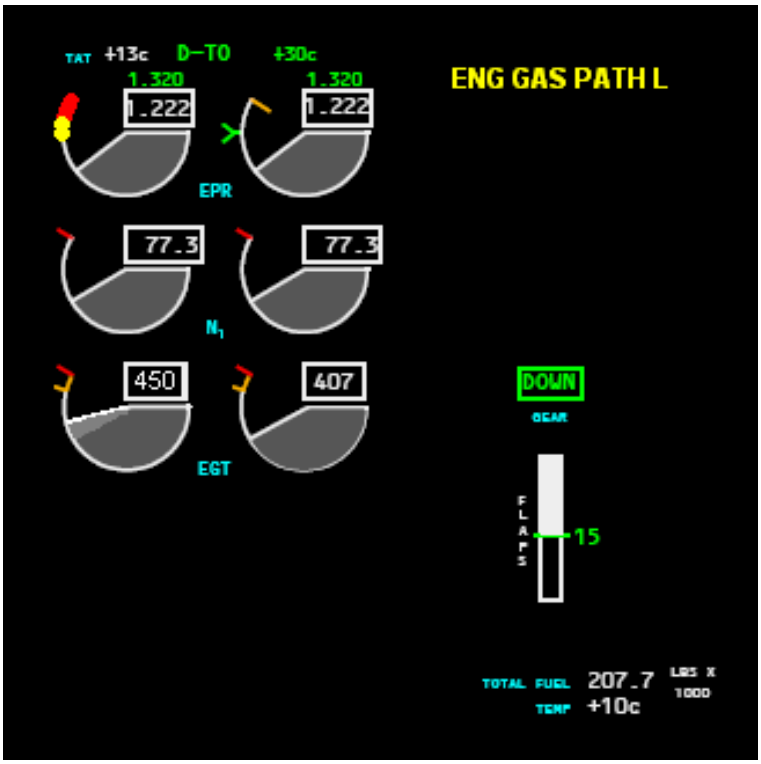


Figure 4-5. Engine Gas Path Damage Annunciation, Indicated Thrust Restriction

4.13.2 Engine Lubrication Systems L/R (Shutdown).

This alert is provided for detected damage to lubricated components. The alert and supporting engine indications are displayed when lubricated engine component damage and/or symptoms are such that idle operation is required, and subsequent engine shutdown is necessary to prevent severe damage.

As shown in figure 4-6, when the engine lubricated components alert is displayed, a thrust restriction is indicated graphically on the affected engine thrust display. The thrust restriction in figure 4-6 is shown as a red stay-out zone intended to prompt the crew to command idle thrust and to avoid operation above idle thrust.

Other baseline (i.e., current/existing or proposed) alerts and supporting indications, or unacceptable tactile vibration, would provide pilot awareness and guide further/additional pilot response (e.g., immediate engine shutdown).

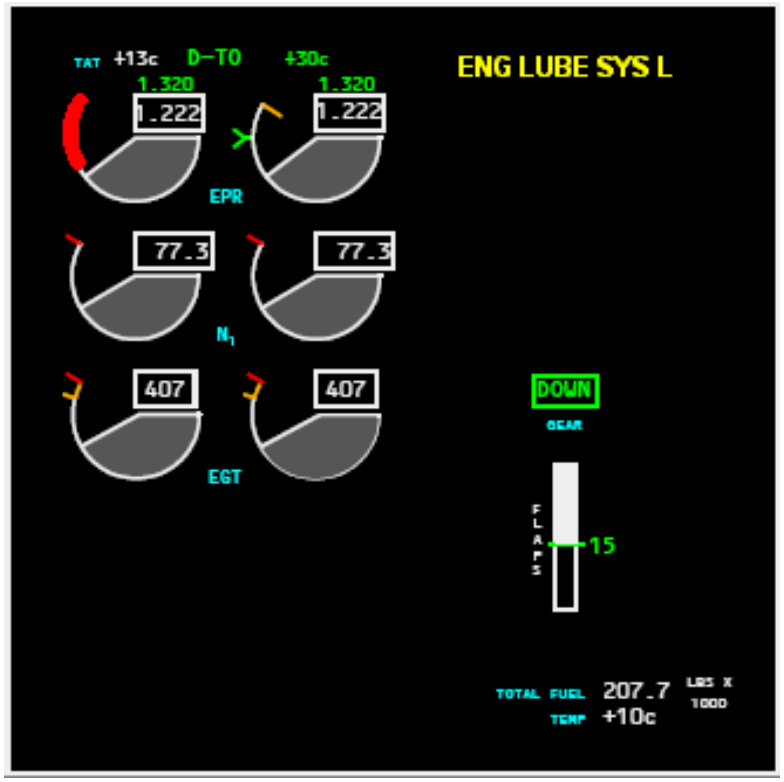


Figure 4-6. Engine Lubrication System Alert

4.14 DETECTION AND ANNUNCIATION DETERMINISM.

The level of determinism inherent in any damage detection and annunciation strategy reflects the underlying detection strategy's capability to accurately and reliably determine the operational effects of the detected damage and the required crew response. This, in turn, determines the required level of crew interpretation. Automated detection and annunciation of engine damage provides desired crew awareness, which relieves the crew of engine monitoring and damage detection. However, if the detection capability cannot determine the degree of engine damage and its effect on engine capability, the burden of assessment (i.e., interpretation) and determination of what action to take falls to the flight crew. This increases the potential for crew error. Three levels of determinism are defined below and are provided for later correlation to the spectrum of possible detection and annunciation strategies.

- Nondeterministic detection and annunciation strategies place all the interpretation and procedure-related burden on the crew.

- Semi-deterministic detection and annunciation strategies place most of the interpretation and procedure-related burden on the crew.

- Deterministic detection and annunciation strategies relieve the crew of most or all of the interpretation and procedure-related activity. This means that the crew must only consider applicable situational knowledge and context when formulating and executing the higher priority mission level decisions.

Specifically, determinism is the level with which the detection strategy can determine the operational impact of the damage and the effectiveness with which the annunciation strategy can communicate that knowledge to the crew. The level of determinism provided by any detection strategy directly affects the level of crew awareness and guidance that can be imparted through alerting and supporting indications and, consequently, the level of required crew interpretation workload activity. As noted in previous phases and in this section, monitoring, detection, and interpretation tasks are undesirable because they increase crew workload and error potential.

When alert-level annunciation is not feasible because of operational concerns, such as increased potential for unnecessary turn-back, diversion, or engine shutdown, it may be feasible instead to annunciate the detected engine damage at the status level where it will not affect the current flight, but will require maintenance assessment and disposition before the next flight. However, if the detection thresholds are set too low, increased unnecessary maintenance would result and, thus, negate the benefit of the new engine damage status message.

4.15 TASK 3 CONCLUSIONS.

Phase 3 damage detection and annunciation provide some new potential coverage, but is mostly complimentary to baseline[1] PSM detection and annunciation. Overall, the potential new coverage provided by engine damage alerting is relatively modest.

Enhanced engine indications, not alerting, is a more efficient and effective method of communicating thrust restrictions or limitations to the flight crew. Alerting should be used to provide initial crew awareness and formal procedural guidance. Alerting is not an efficient or effective way to provide dynamic system situational awareness such as engine capability or dynamic operating restrictions.

Damage-related SDGE was the primary Phase 3 ICR operational issue. The primary consideration was safety; and the secondary considerations were economic, 14 CFR Part 25 design strategies and certification, and 14 CFR Part 121 policies, practices, and procedures. For the purposes of mitigating ICR, procedures and operational approvals should be focused on slowing down, preventing, and otherwise minimizing a rush or bias towards engine shutdown. The crew bias should be against or away from engine shutdown in general and rushed engine shutdown in particular. As established in Task 2, the need for immediate shutdown is presently covered by fire, overheat, and other response-critical warning alerts.

To minimize the potential for ICR when FDEs attend a PSM wherever possible, the following should be provided:

- Specific crew awareness (regarding the nature and effect of the malfunction)
- Procedural guidance (as to the appropriate crew response)

The operational criteria for engine damage annunciation are very stringent. This stringency is necessary because such annunciation would only be an improvement and complimentary to the baseline detection and annunciation, which already provides an adequate and very acceptable

[1]Baseline reflects a modern aircraft annunciation suite and the Phase 2 STA detection and annunciation.

level of safety. Potential benefit exists, but the actual benefit of new engine damage detection and annunciation must be demonstrated and validated, and the operational risks associated with its implementation must be minimized. The potential for false alerting in particular must be minimized—even if it entails failure to alert.

In summary, care must taken to avoid over-focus on specific ICR events at the expense of risking other unintended consequences, which could include unnecessary IFSDs, diversions, air turn-backs, and additional maintenance.

5. TASK 4: DAMAGE DETECTION STRATEGIES.

Task 4 integrated the results from Tasks 1 through 3 to develop engine damage detection strategies. Task 4 evaluated the full spectrum of potential strategies ranging from existing single-parameter limit exceedance systems to advanced concepts fully integrated with engine health monitoring. However, the principal Task 4 emphasis was placed on detection strategies derived from fusion of existing sensors. Further, such sensor fusion strategies were targeted at gas path and lubricated component failures, as Tasks 1 through 3 had revealed the greatest potential operational benefit for these systems.

5.1 TASK 4 OBJECTIVES.

Task 4 sought to develop damage detection strategies that addressed the requirements and considerations previously identified in Tasks 1 through 3. A block diagram of the Task 4 approach is provided in figure 5-1. Task 4 specifically emphasized the development of damage detection strategies within the sensor fusion paradigm. In this regard, sensor fusion was defined to include correlation of existing parameter shifts to provide damage awareness and support appropriate crew response. Considered within this sensor fusion context were the potential benefits gained from correlating the parameter shifts against models of undamaged engine expected behavior. For each detection strategy, Task 4 developed the considerations associated with the specifically selected sensors as well as the corresponding annunciation concept. Task 4 also documented the benefits and limitations of the sensor fusion detection strategies relative to currently fielded systems and future strategies beyond the scope of Phase 3.

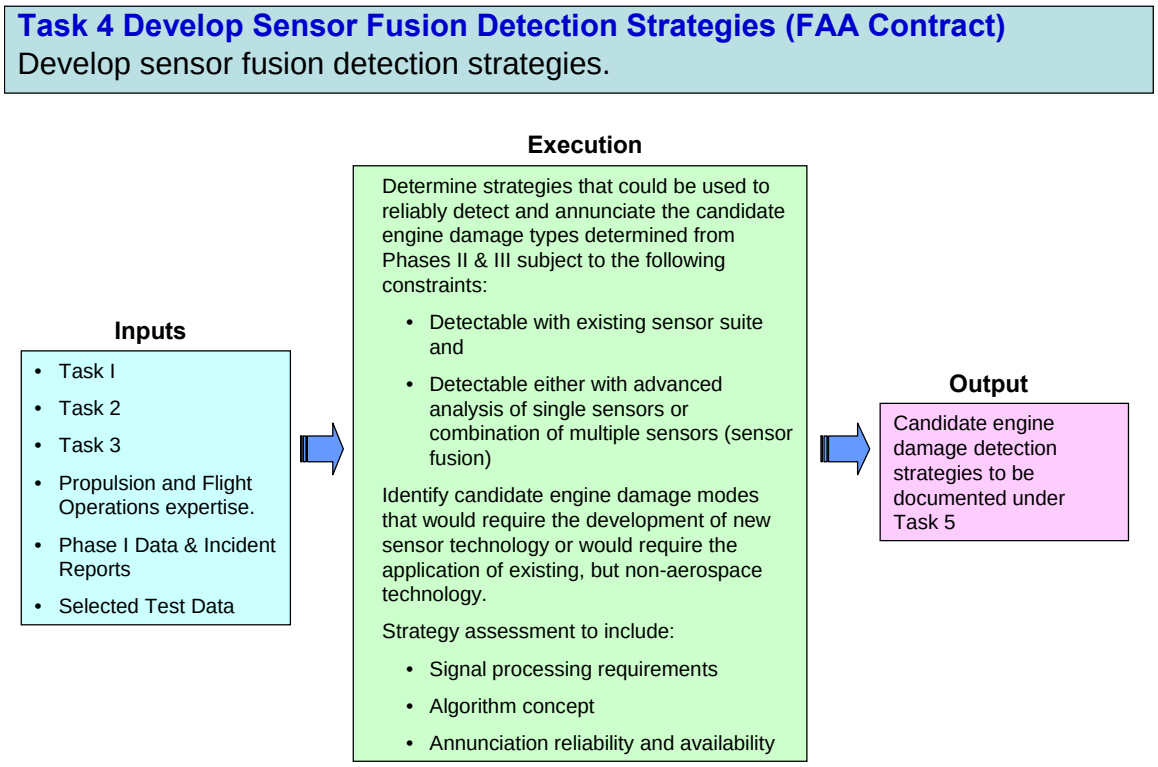


Figure 5-1. Task 4 Approach

Task 4 employed the following specific steps in developing sensor fusion damage detection strategies:

- Review of in-service reports to correlate engine parameter shifts to gas path and lubricated component damage.
- Assess considerations associated with using existing sensors to detect specific damage modes (i.e., determine damage signatures).
- Assign candidate existing sensors to previously identified (Task 1) expanded use or sensor fusion damage modes.
- Lay out basic methods of damage detection to desired level: response category (flight crew) or module group (maintenance).
- Evaluate the enhancements available from parameter shift correlation with models.
- Develop the annunciation considerations (display, alerting, and procedural) attending the strategies.
- Assess implementation issues:
    - Additional specificity necessary to establish general design requirements.
    - Certification considerations associated with qualifying AVM to higher software levels and reliability.
    - Cost, risks, and benefit evaluation, as well as the likelihood of meeting operational criteria.

5.2 TASK 4 RESULTS SUMMARY.

Task 4 accomplished a detailed in-service report review of the in-flight effects from gas path and lubricated component damage. These data validated that sensible parameter shifts accompanied such engine damage. EGT and indicated vibration shifts were found to be the most consistent effects common to all gas path components. For lubricated components, oil system parameters shifts were predominant, but indicated vibration shifts were relatively frequent as well. Shifts in at least two parameters were determined to be necessary to meet the Task 3 damage annunciation reliability criteria established in section 4.

Prior to the detailed development of damage detection strategies, Task 4 first considered the available spectrum of damage detection concepts. These concepts ranged from existing single-parameter limit exceedance systems to future systems fully integrated with engine health monitoring and equipped with new sensors specifically targeted at engine damage detection.

Task 4 developed damage detection strategies available through fusion of existing sensors. Four sensor fusion strategies were developed in Task 4:

- Strategy 1: A two-parameter shift detection with the engine at steady thrust. Shift detection would be provided for EGT and indicated vibration (for gas path components), or an oil system indication and indicated vibration (for lubricated components).

- Strategy 2: Strategy 1 supplemented with additional engine sensors to permit damage isolation to the module level.

- Strategy 3: Strategy 1 or 2 supplemented with a performance model to allow detection of damage for scenarios where the engine stabilized (post-damage) at a different thrust setting than where the damage initially occurred. Such a model potentially removes the steady-state, thrust-setting damage detection limitation associated with Strategy 1 or 2.

- Strategy 4: Strategy 1 or 2 supplemented with a trend-based model of expected undamaged engine behavior. Similar to Strategy 3, such a model potentially removes the fixed thrust-setting damage detection limitation associated with Strategy 1 or 2.

Second, Task 4 considered the operational crew awareness and response requirements associated with the new damage alerting. The Task 2 damage response categories (awareness only, restrict thrust, and shutdown) were merged into two response categories: awareness/restrict thrust and shutdown. The awareness/restrict thrust alert provides initial awareness for gas path component damage and relies on further pilot monitoring and interpretation to determine if thrust reduction is required. The shutdown alert provides awareness and procedural guidance for lubricated component damage. The proposed detection and annunciation strategy allows for automatic transition between these two damage alerts (i.e., gas path component damage propagation into lubricated components permits a previously displayed awareness/restrict thrust alert to be superseded by shutdown).

All damage detection strategies developed in Task 4 had significant limitations from an operational implementation perspective.

- Alert latching is required. While sometimes necessary and operationally acceptable, alert or other annunciation latching is not a preferred practice.

- The engine damage detection and annunciation strategy is not deterministic in the desired response when the engine is operating within limits. Crew monitoring and interpretation is required to determine

    - the acceptability of continued operation of the damaged engine at the current and other (higher or lower) power settings.

    - whether thrust restriction or subsequent shutdown is required.

    - the appropriate amount of thrust restriction or the capability for continued engine operation.

- Automatic determination of damaged engine power, restart capability, or capability for continued operation is not possible.

Third, as an alternative to the proposed sensor fusion detection strategies, alerting for high indicated vibrations was evaluated for potential operational and ICR benefits. This alternative has significant limitations and is discussed in further detail in section 6.1.

5.3 IN-SERVICE REPORT REVIEW.

Task 4 sought to develop damage detection strategies that provided flight crew awareness of

- engine damage significant enough to justify crew awareness or response, and
- potential or impending uncommanded engine shutdown.

The pursuit of these objectives first necessitated a revisitation of the service reports to determine the relative distribution between damage detected strictly by postflight inspection versus damage with in-flight effects apparent to the flight crew. To focus this effort on damage detectable through sensor fusion (the principal objective of Task 4), the Task 1 damage detection assessment results were sorted against the UER causes. The results are shown in figure 5-2, which indicates that ~13% are covered by existing sensors and ~60% of total UERs were caused by damage to gas path or lubricated components and hence principal candidates for sensor fusion. Note: UERs were given priority over IFSDs in this evaluation because events where sustained operation with engine damage occurred were assessed to have the highest potential benefit for damage annunciation (i.e., most service reports for IFSDs only detailed the events immediately preceding the commanded or uncommanded shutdown).

Two forms of in-service data were desired for the Task 4 development of engine damage detection strategies:

- Time histories of specific events where in-flight effects occurred and the effects were subsequently traced to a specific damaged engine component—Desired data included flight data recorder (FDR) or airplane health monitoring (AHM) information recorded on service aircraft. FDR and AHM data include the principal engine parameters such as EGT, indicated vibration, and oil system parameters. Specifically desired were events where the engine continued to run for a lengthy period following the initial damage event (parameter shift) and thus might allow for the validation of the detection strategies and the development of algorithm considerations. (Note that this type of data is essential for the development of a robust detection algorithm.)

- The event descriptions that attended the removal data described in section 2.5—Although these event descriptions often did not contain detailed quantitative information on the magnitude of parameter shifts in response to engine damage, sufficient data were generally available to list the type of indication change or annunciation triggered by the damage.

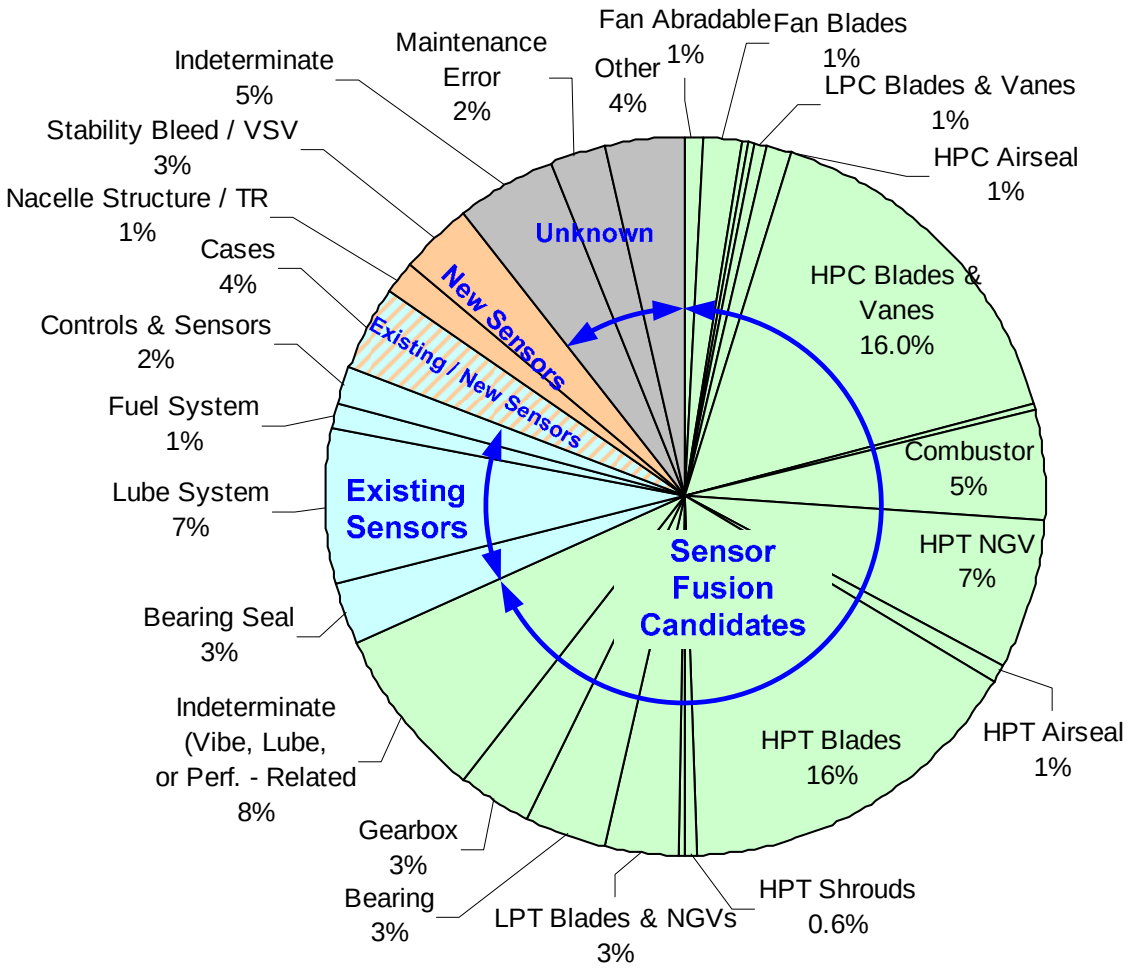


Figure 5-2. Unplanned Engine Removal Distribution vs Potential Damage Detection Means

A review of time history data available at The Boeing Company and the engine companies revealed that, while such data were available, the events were generally limited to IFSDs and, as such, did not fulfill the criterion of prolonged operation with damage. Although the engine companies also retained damage event data sufficient to calibrate proprietary EHM algorithms, these data pertained to subtle deterioration within the engine operating limits. Figure 5-3 illustrates the time history of failure progression. Discussions with personnel from various airlines indicated that FDR or quick access recorder data were not typically retained for engine damage events preceding an unscheduled removal. As a result, collection of engine damage data sufficient to calibrate damage detection and annunciation concepts was determined to be a necessary future research activity through a dedicated in-service program (refer to section 8.1).

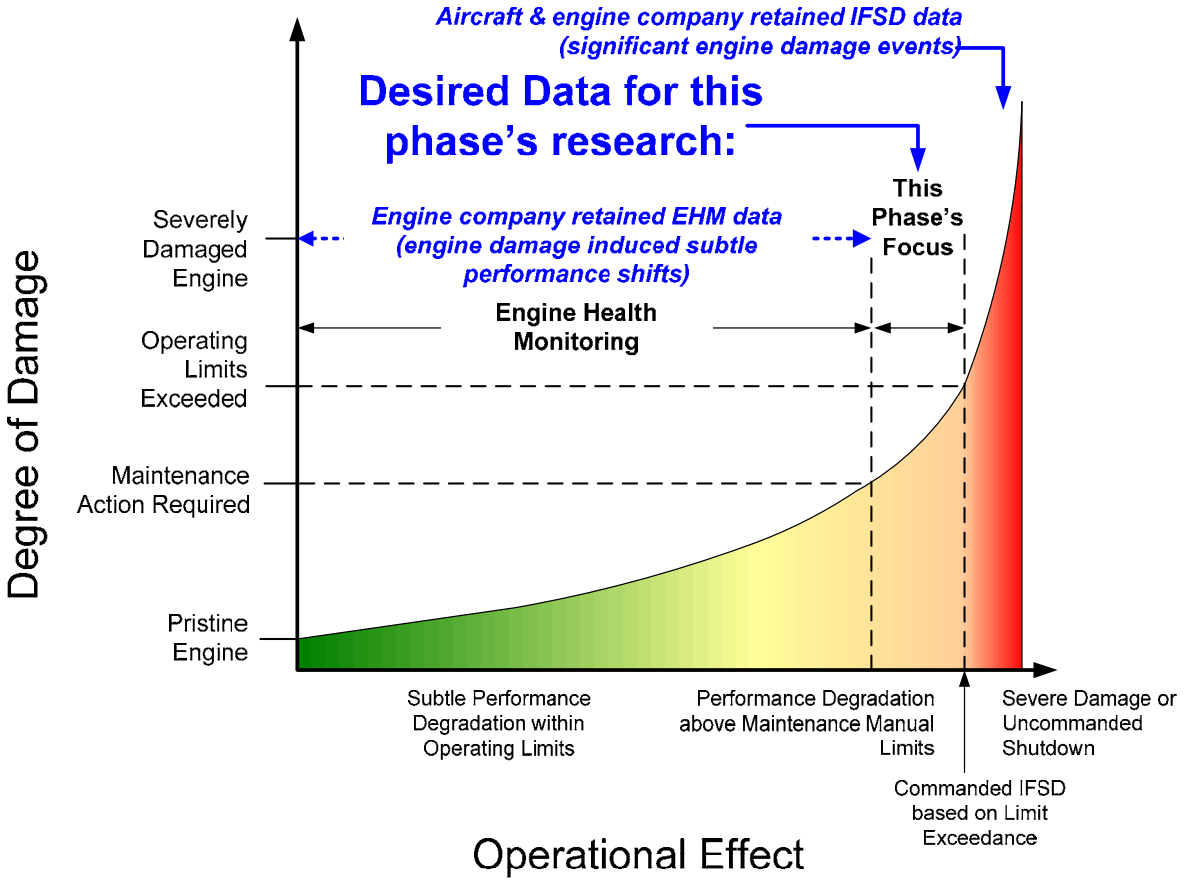


Figure 5-3. Desired Engine Damage Time History Data

However, the UER event description data did provide a relatively rich source of information on the frequency of indications that attended specific engine damage types. A first step in the review of these data was to cull those events where the engine damage was detected primarily through postflight inspection (and thus not a candidate for detection through fusion of existing sensors). Table 5-1 provides the results of this screening effort for the focus of this study—gas path and lubricated components. The table 5-1 results show that, on average, ~19% of these components cause unscheduled removals through in-flight effects. Figure 5-4 presents the engine damage subset of interest to this phase's research in terms of all gas path and lubricated component unscheduled removals and IFSDs. Note: The relative relationship between events in figure 5-4 (gas path and lubricated components) is different than in figure 3-3 (all components). Notable in figure 5-4 are the following:

- Nearly all IFSDs that also caused UERs were attributable to gas path and lubricated components.
- The subset of IFSDs that did not drive UERs is relatively small.
- The majority of events (~64%) with FDEs did not result in an IFSD (i.e., the engine continued to operate with damage). Note: 64% is a conservatively low assessment

because in an indeterminate number of events, the engine might have continued to operate if the pilot had not shut it down.

Table 5-1. Gas Path and Lubricated Component Engine Damage Detected Through Postflight Inspection and In-Flight Effects

Components	Total UER	UERs Due to Inspection	UERs Due to In-Flight Effects	Percent Due to Inspection	Percent Due to In-Flight Effects
Gas Path Components					
Fan Module:					
Fan Spinner	11	6	5	55	45
Fan Abradable	147	127	20	86	14
Fan Platforms	23	9	14	39	61
Fan Blades	275	109	166	40	60
Fan Exit Guide Vanes	37	35	2	95	5
Fan Disk	47	47	0	100	0
LPC Module:					
LPC Airseal	6	5	1	83	17
LPC Disk/Spool	6	6	0	100	0
LPC Blades and Vanes	122	90	32	74	26
HPC Module:					
HPC Airseal	234	209	25	89	11
HPC Blades and Vanes	2998	2237	761	75	25
HPC Disk	44	40	4	89	11
Combustor (including fuel nozzles)	983	901	82	92	8
HPT Module:					
HPT NGV	1272	1204	68	95	5
HPT Airseal	140	86	54	61	39
HPT Blades	2973	2631	342	88	12
HPT Shrouds	115	85	30	74	26
HPT Disk	27	24	3	89	11
LPT Module:					
LPT Blades and NGVs	655	520	135	79	21
LPT Disk	6	3	3	50	50
Lubricated Components					
Bearing	642	409	233	64	36
Gearbox	611	426	182	70	30
Total	11374	9209	2162	81	19

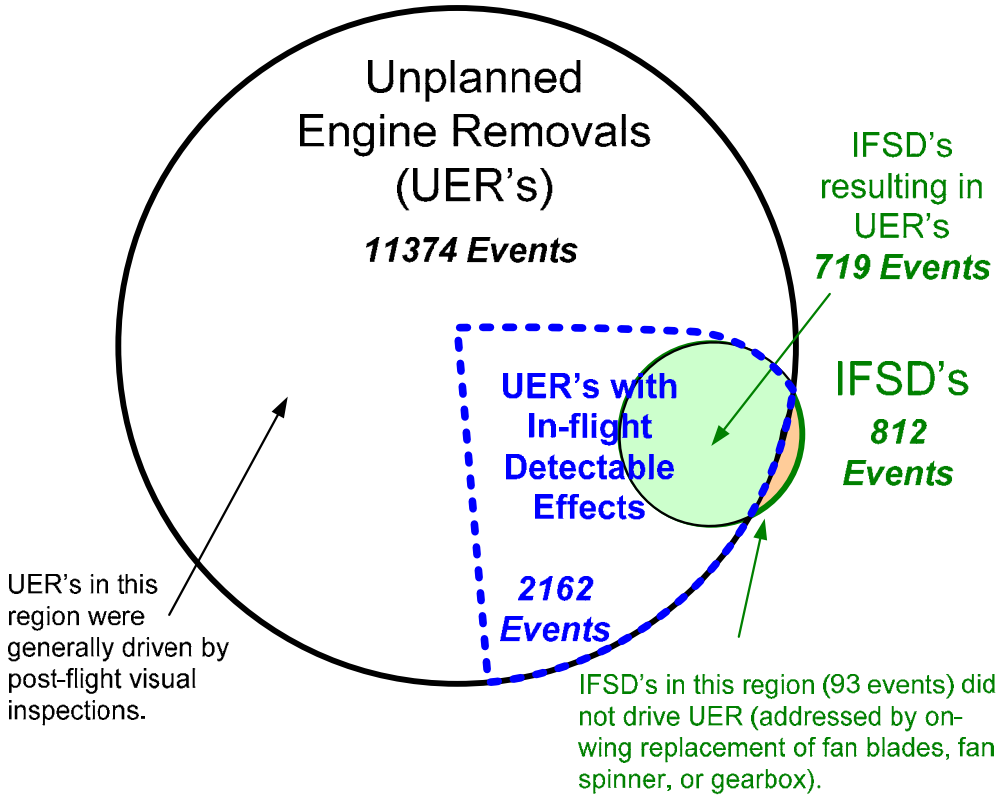


Figure 5-4. Unscheduled Engine Removals With In-Flight Detectable Effects (Gas Path and Lubricated Components Only)

Once the population of UERs with in-flight effects was isolated, these events were then characterized by the indications that attended the events. Indications were categorized as follows:

- Oil System Indication—Low oil pressure, high oil temperature, filter bypass impending, or low quantity indication.
- High Indicated or Tactile Vibration—Refer to section 5.5.4.2 for a more detailed discussion on AVM signal processing methods.
- Surge—Audibly detected compressor surge (usually a loud bang).
- EGT Shift—Significant change in EGT (within operating limits) or EGT limit exceedance.
- Fire Warning—Nacelle fire or overheat warning.
- Flameout—Extinguishment of combustor flame (noted through EGT indication).
- Fuel Flow Shift—Demonstrable change in fuel flow (usually noted by comparison to opposite engine when operating at the same throttle setting).

- Slow to Accelerate—Combustor remains lit, but rotor speeds respond slowly to throttle increase (distinct from stuck throttle condition, however). This category was also used to describe events when the engine started slowly.

- Other—Palpable effects not reflected in cockpit indications (e.g., visible sparks or flames, smoke in the cabin, etc.).

- N1 or N2 Fluctuation or Off-Schedule—Rotor speed variation or differences between engines at common throttle setting.

- Rollback or Thrust Loss—Uncommanded engine power loss, but engine remains operating at above idle power.

- Engine Pressure Ratio (EPR—Thrust Control Parameter) Low—Low indicated EPR when compared to opposite engine at same throttle setting (for engines using EPR control).

- Autoshutdown—Uncommanded engine shutdown.

The results of this FDE categorization for each gas path or lubricated component are shown in figures 5-5 through 5-19 and are discussed below. The data in these figures require consideration of the source, quality, and degree of detail in the reports. Specifically, the amount of narrative of the in-service reports was found to vary substantially between airline operators and engine models. Thus, the recorded FDEs may not necessarily be comprehensive for a given event, but rather, just those effects noteworthy to the flight crew (and ultimately transcribed by the report processors). These figures provide an overview of the FDE counts. Since all perceived indications for a given event are listed, there are more FDEs than events. Within limits, parameter shifts may also have occurred, which the flight crews either did not detect or did not consider significant enough to report. Thus, the data were considered indicative of the potential for individual FDE assertion, but not necessarily representative of all the effects that occurred in each event or conclusive for determining simultaneous effects.

- Fan Spinner (figure 5-5)—Since spinner damage or liberation principally altered inlet flow at the fan hub, the principal result of such damage was disruption of the airflow into the core. Consequently, compressor surge was the most frequent flight deck-observable effect.

- Fan Abradable (figure 5-6)—The dominant recorded effects for fan abradable damage were high vibration and surge. These effects occur due to (1) asymmetric increased blade tip clearance, which in turn, promotes elevated vibration (indicated and tactile) and (2) fan blade tip rub, which mismatches the LP and HP spools resulting in surge or EGT excursion. Nonsynchronous vibration resulting from this failure mode may have also been reported as tactile vibration.

- Fan Blades (figure 5-7)—The principal effects associated with fan damage were high vibration and bird strike. While bird strike is somewhat nebulous as to the actual observed FDE, most likely high indicated or tactile vibration occurred during the bird

strike events. Fan blade damage in high bypass turbofans usually induces significant changes in indicated vibration and sometimes tactile vibration. Such vibration effects result from the large amount of imbalance imparted by fan blade damage. Further, if the blade shape is significantly altered as a result of foreign object ingestion, an EGT shift and nonsynchronous vibration may also be apparent. If the fan blade damage involves debris shedding or flow disruption into the core, the compressor may surge.

- Fan Exit Guide Vanes (figure 5-8)—Fan exit guide vane damage was rarely detected through in-flight effects (only 5% of all cases). However, when such damage was detectable in-flight, high vibration (may have been tactile rather than indicated) was the reported effect. Since the fan exit guide vanes typically form the structural support for the fan module, damage to this component can affect low-speed rotor dynamics and register as high indicated or tactile vibration.

- Fan, Compressor, and Turbine Disks (figure 5-9)—Disk failures are extremely rare. When such events do occur, they generally resulted in uncommanded engine shutdown. Depending on the energy and location of any released parts, damage to the hot section casings and/or nearby flammable fluid lines may trigger a fire warning. The service reports indicate that main disk failures are not preceded by elevated indicated vibration, but rather degenerate rapidly into uncommanded engine shutdown. However, disk assembly failures that do not result in the liberation of high-energy parts (e.g., damage to an adjoining heat shield or other part bolted to the main disk) may register as an indicated or tactile vibration increase. Although an extremely rare event, if such a disk assembly failure compromises gas path sealing, compressor surge, EGT shift, or smoke in the cabin may result.

- LPC Blades and Vanes (figure 5-10)—The principal effects noted for LPC blade and vane damage were high vibration, surge, and EGT shift. Damage to the LPC blades and vanes generally disrupts the airflow throughout the engine core, resulting in a compressor surge. Blade damage generally increases the system imbalance, resulting in increased indicated vibration. If the core airflow is sufficiently disrupted by the LPC airfoil damage, an EGT shift may be induced.

- HPC Blades and Vanes (figure 5-11)—In over half the recorded cases with in-flight effects, damage to the HPC airfoils was either induced or accompanied by a surge. The reduced efficiency of the damaged HPC airfoils often produced an EGT shift and, in high damage cases, was sufficient to cause visible tailpipe flames, smoke, or combustor flameout. Since most current aircraft designs bleed air from one or more stages of the HPC for cabin pressurization environmental control system (ECS), damage to this module often registers as either a fault in an ECS component fault message or smoke in the cabin.

  Behind surge, the second most frequent HPC damage effect was high indicated vibration. Since the high-speed rotor, indicated vibration levels reported to the cockpit are usually filtered to reflect the one per revolution amplitude, this indication reports rotor imbalance. Thus, high indicated vibration associated with HPC damage most commonly reflects damage to the HPC blades rather than the vanes (static components). Further, the

blades generally realize a higher damage rate than vanes. Two factors combine to increase blade damage sensitivity: (1) the relative air velocity entering a blade row is higher than a vane row, thus any foreign object impact velocity is generally higher to a blade than a vane. (2) For performance reasons (minimization of shock losses), blade leading-edge thickness tends to be thinner than for a corresponding vane.

- HPC Air Seals (figure 5-12)—The HPC air seal damage effects were similar in distribution to the HPC blades and vanes; however, the high indicated vibration frequency was reduced for the air seals, as the damage in this category was predominately to static seals. Thus, high-speed rotor imbalance was less often affected than HPC blade damage.

- Combustor (figure 5-13)—The damage effects for this module were reported for the combustor liner and fuel nozzle subcomponents. The principal effect of damage to this hardware was an EGT shift due to distortion in the gas temperature profile exiting the combustor. High vibration was sometimes associated with loose combustor liners or liner support struts (likely, tactile nonsynchronous rather than indicated vibration). Other symptoms associated with an underperforming combustion process were also noted (fuel flow shift, flameout, and visible smoke).

- HPT Nozzle Guide Vanes (figure 5-14)—The vast majority of HPT NGV damage was discovered through postflight inspection (95%). For the failures of this component with in-flight effects, EGT shift was the most common. In this regard, HPT NGV damage resulted in a distortion of the gas temperature profile into the HPT blades and downstream LPT where EGT is sensed. HPT NGV damage sometimes resulted in high indicated N2 vibration—often as a result of interactive effects with the rotating blades. Since HPT NGV geometry influences the flow-limiting area for the HPC, damage that altered this area sometimes produced a surge.

- HPT Air Seals and Shrouds (figure 5-15)—Damage to the HPT air seals and shrouds overwhelmingly registered as an EGT shift. Secondary effects included fuel flow or high rotor speed (N2) shifts, as damage to this component affected HPT efficiency. High vibration was generally present when rotating air seal damage occurred.

- HPT Blades (figure 5-16)—HPT blade damage effects were dominated by high vibration and EGT shifts. Compressor surge occurred somewhat less frequently as HPT blade damage can disrupt the speed relationship between the high and low rotors and, thus, interrupt the compressor airflow. In some cases, the HPT blade damage was significant enough either through direct impact or severe imbalance loads to damage nearby portions of the lubrication system and trigger an oil system alert. Thrust loss was noted for a handful of HPT damage events.

- LPT Blades and NGVs (figure 5-17)—The distribution of LPT blade and vane damage effects was quite similar to HPT blades—namely, high vibration and EGT shift principally, and to a lesser extent, surge.

- Bearings (figure 5-18)—Bearing damage influences both the gas path and lubrication system. Not surprisingly, high vibration was a common effect for bearing damage. Similar to high indicated vibration, bearing damage was also noted to produce an audible rumble in many cases. Since bearing damage can drive higher frictional torque, an upward shift in EGT may occur. The most frequent effect associated with bearing damage was either loss of oil pressure or oil filter high differential pressure (i.e., due to the filter becoming clogged with bearing debris).

- Gearboxes (figure 5-19)—Gearbox damage produced similar effects to bearings (i.e., oil system indications predominated). However, gearbox damage also frequently resulted in a failure to transmit power to a critical gear-driven accessory such as a fuel pump, hydro-mechanical unit, or FADEC alternator. In these cases, sometimes a dedicated EICAS message would annunciate to indicate the accessory fault.

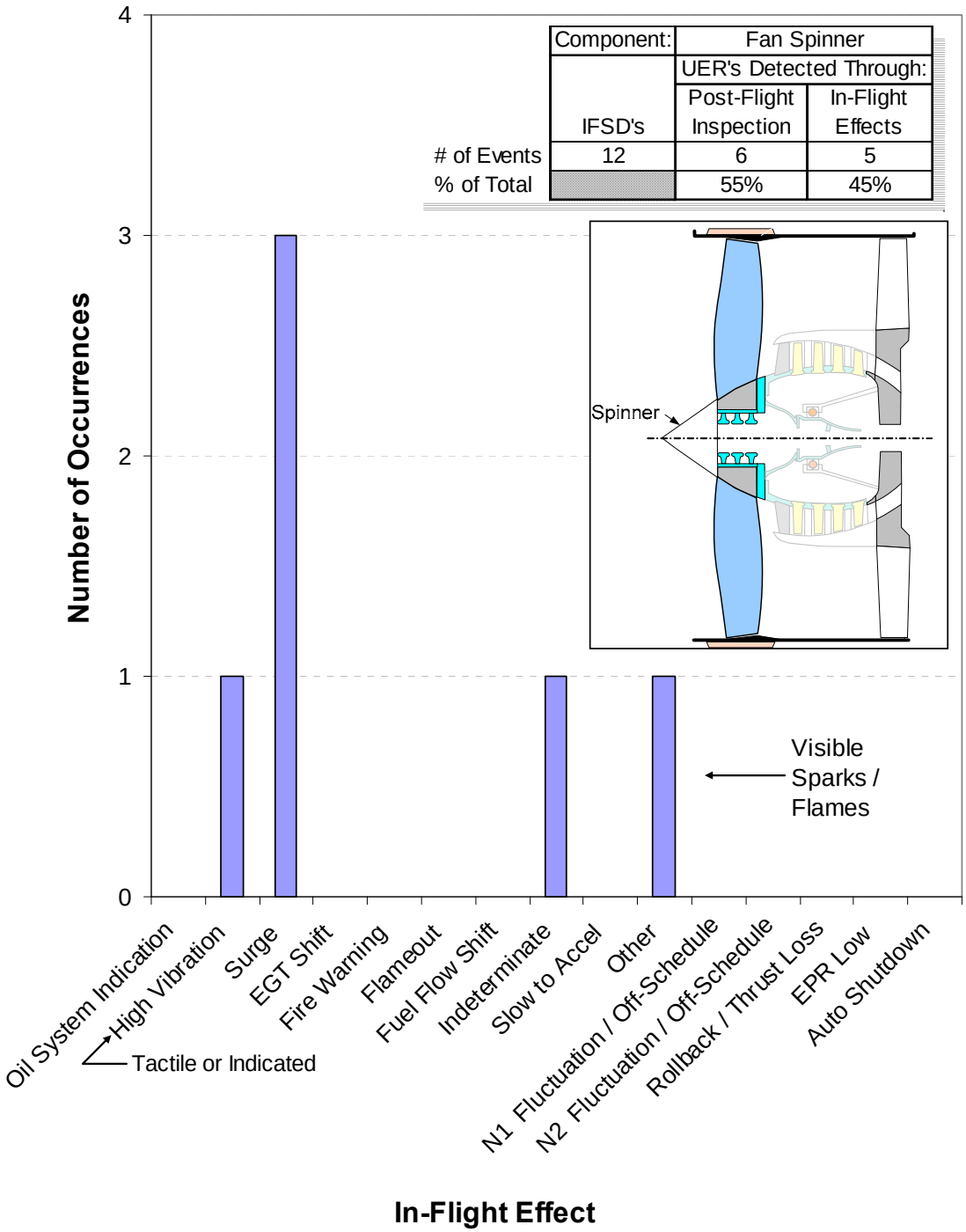


Figure 5-5. Fan Spinner Damage In-Flight Effects

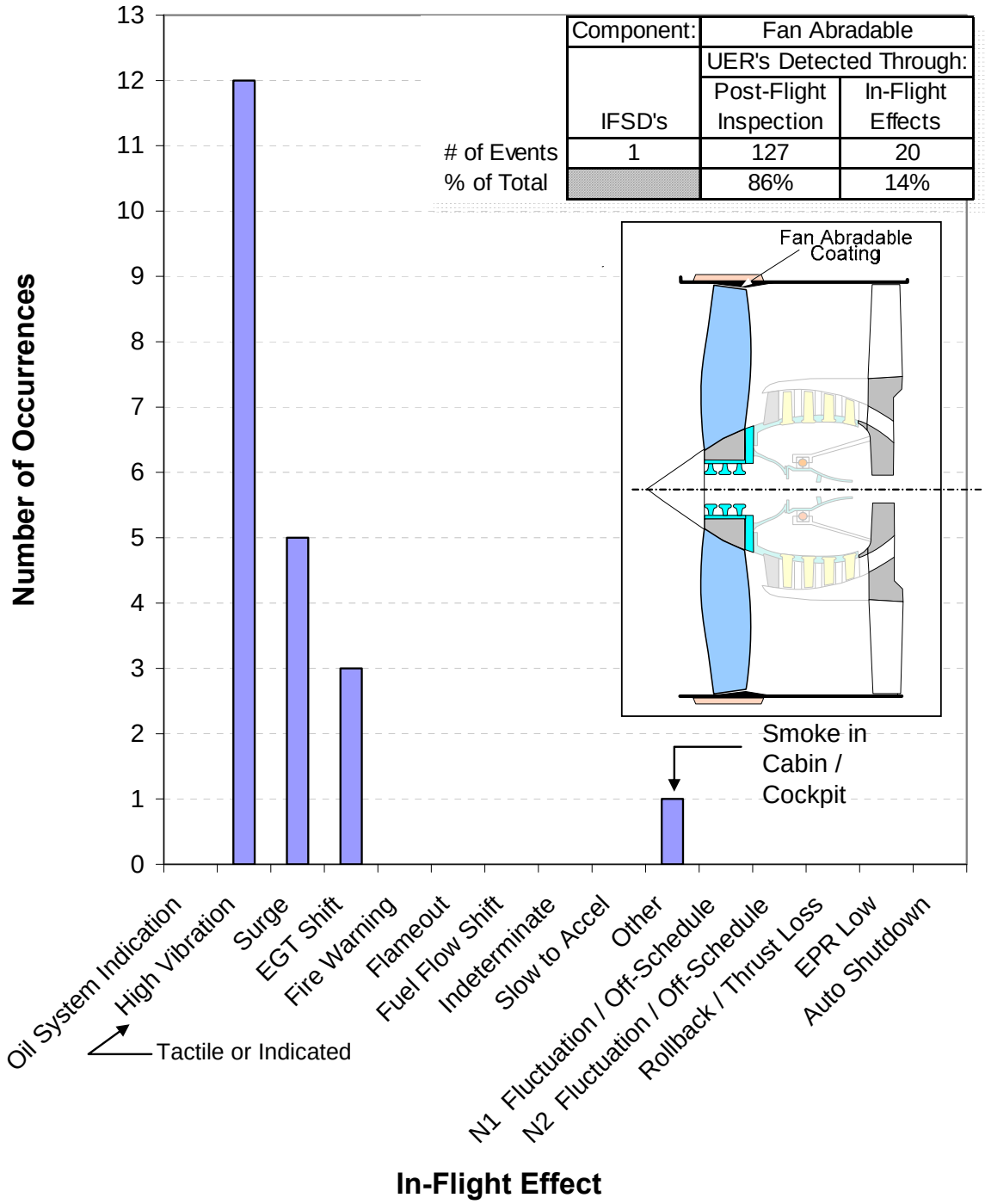


Figure 5-6. Fan Abradable Damage In-Flight Effects

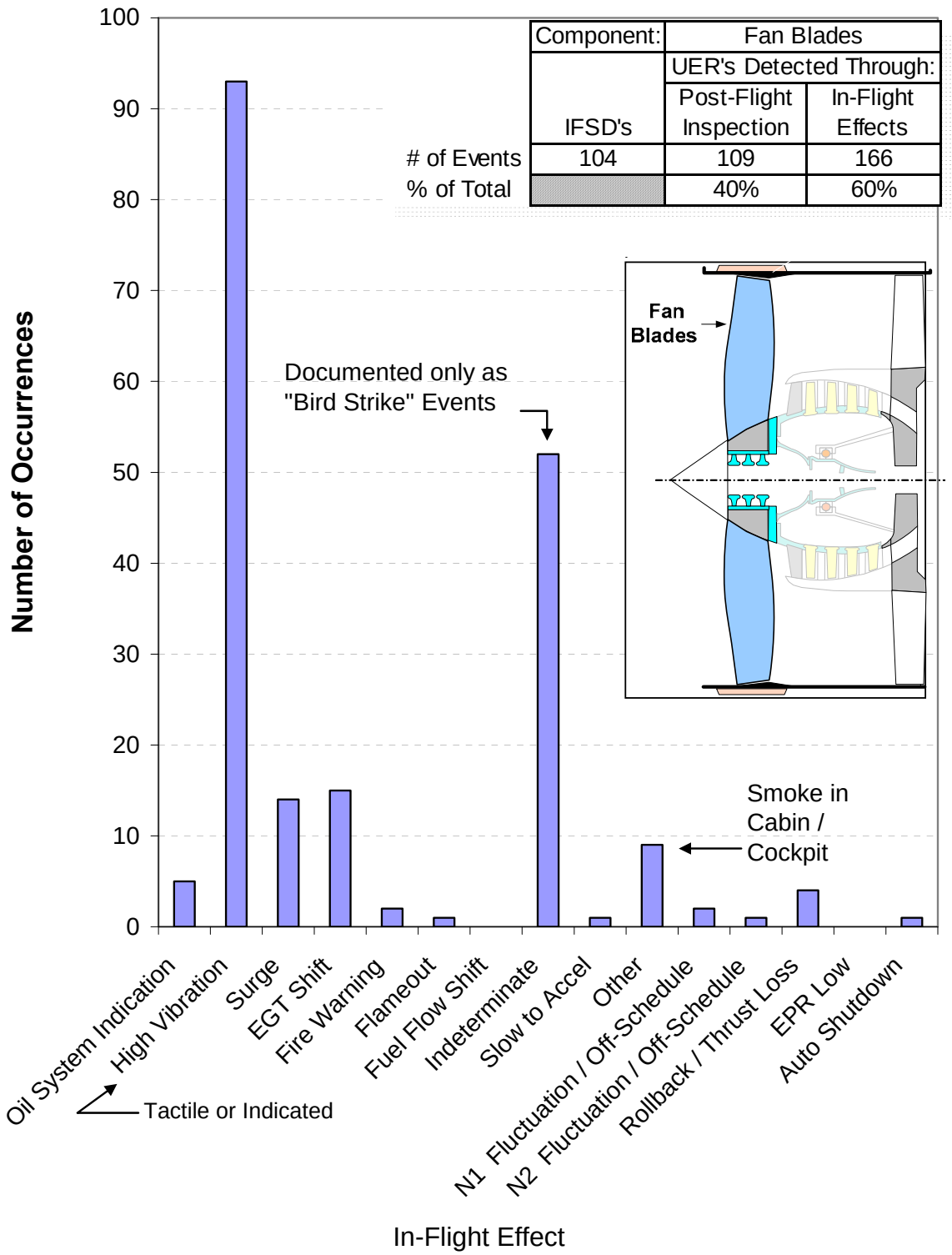


Figure 5-7. Fan Blades Damage In-Flight Effects

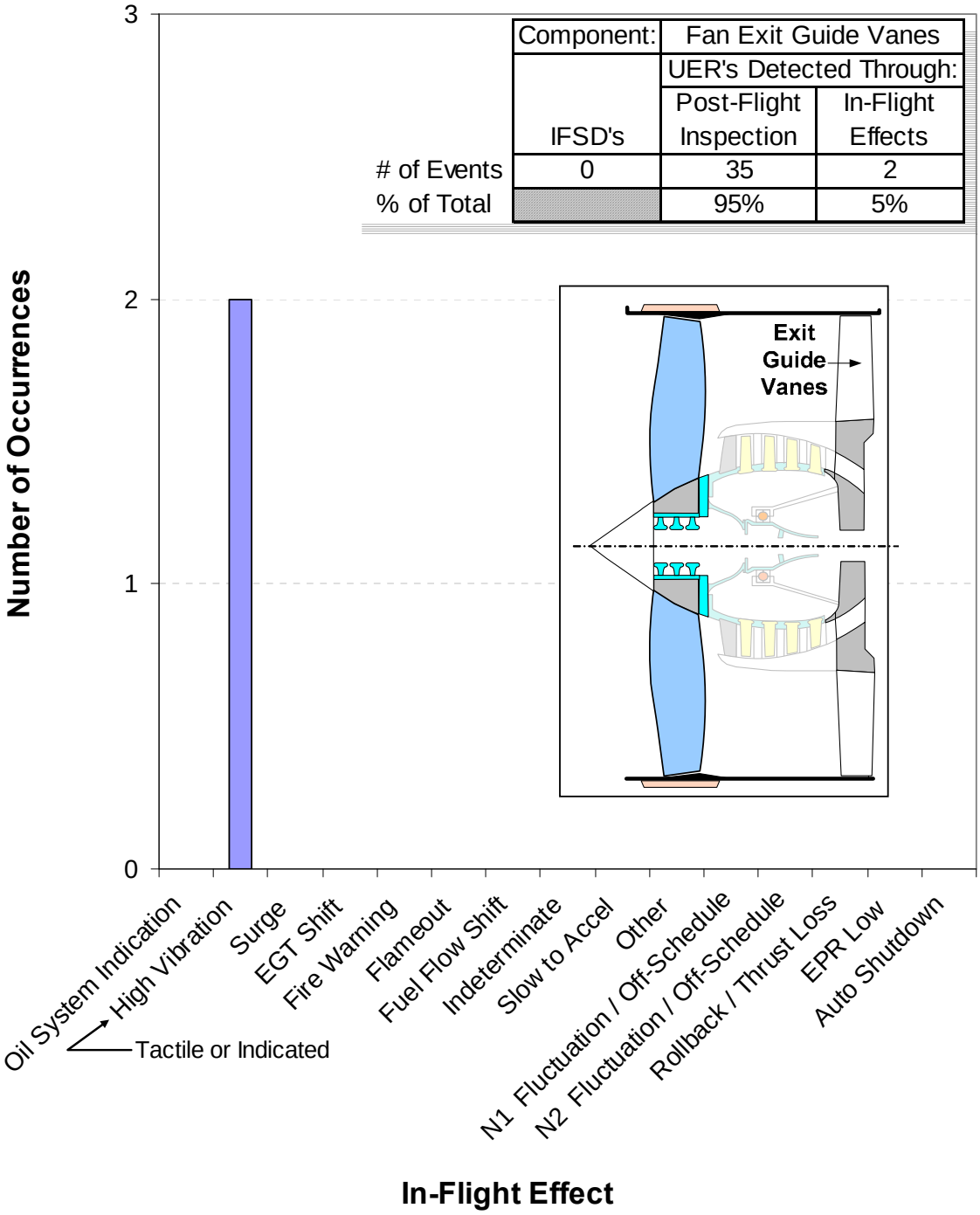
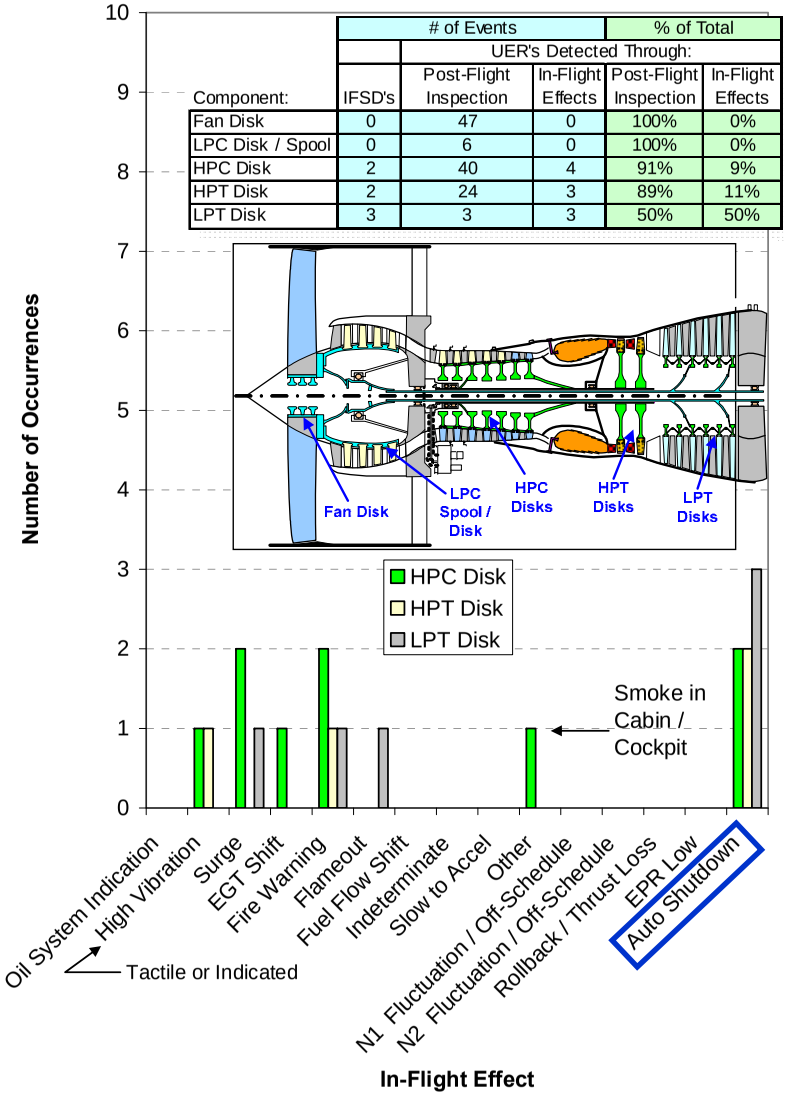


Figure 5-8. Fan Exit Guide Vanes Damage In-Flight Effects

Component:	# of Events			% of Total	
		UER's Detected Through:			
	IFSD's	Post-Flight Inspection	In-Flight Effects	Post-Flight Inspection	In-Flight Effects
Fan Disk	0	47	0	100%	0%
LPC Disk / Spool	0	6	0	100%	0%
HPC Disk	2	40	4	91%	9%
HPT Disk	2	24	3	89%	11%
LPT Disk	3	3	3	50%	50%



Of Ten Total disk-related events with in-flight effects,

- Seven complete disk failures led to uncommanded shutdowns:

Disk Type	Events with FDEs	Events with Uncommanded S/D
Fan	0	0
LPC	0	0
HPC	4	2
HPT	3	2
LPT	3	3

- The remaining three disk-related events without uncommanded shutdown did not involve failure of main disk body:

Description	FDEs
Liberated HPC tiebolt keywasher tab (main disk not failed)	Fire warning + smoke in cabin
Stage 2 HPC Disk "undersized ID rabbet" (manufacturing defect, but no direct component failure)	High Indicated Vibration
Cracked adjoining thermal shield (main HPT disk body not failed)	High Indicated Vibration

Figure 5-9. Disk Damage In-Flight Effects

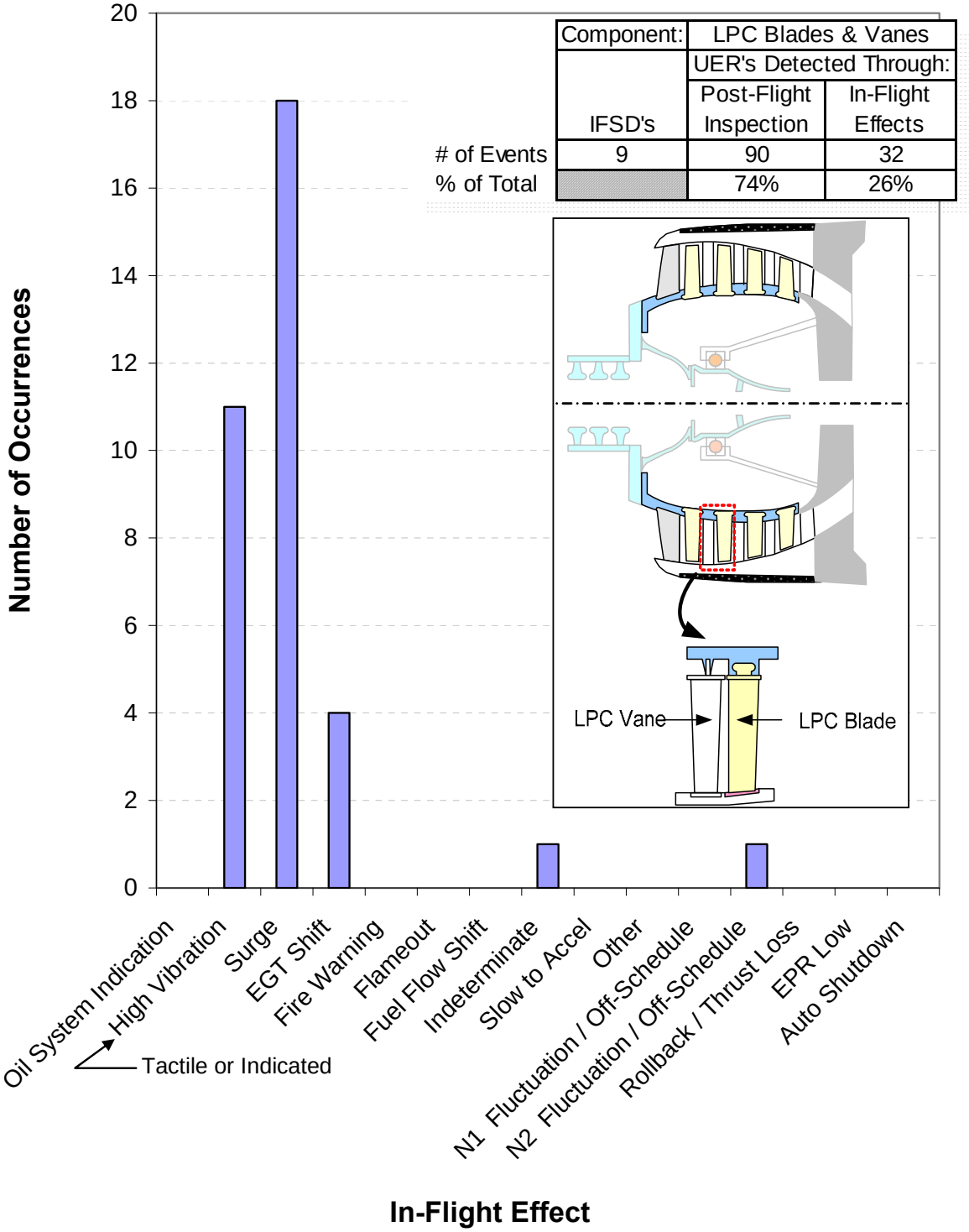


Figure 5-10. Low-Pressure Compressor Blades and Vanes Damage In-Flight Effects

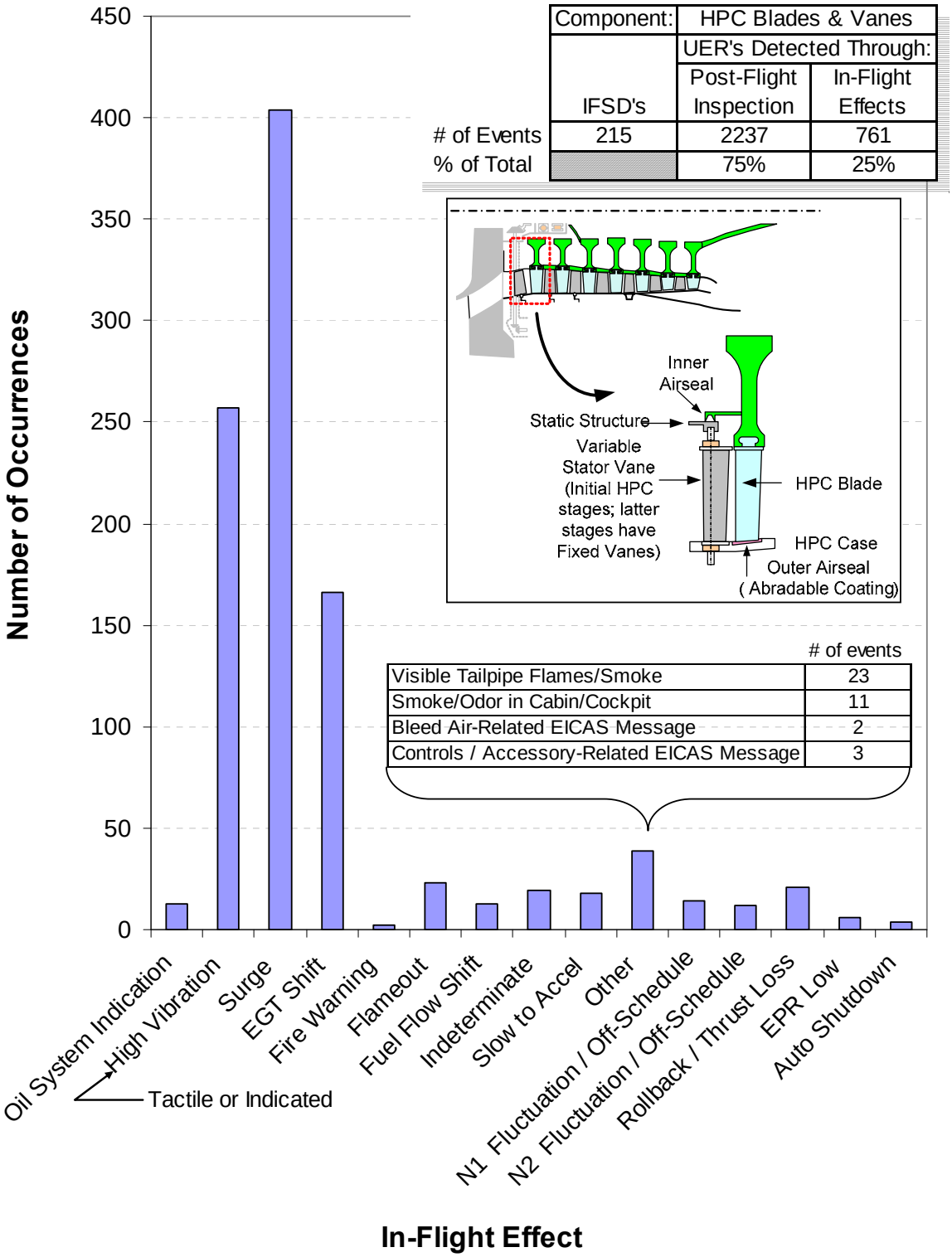


Figure 5-11. High-Pressure Compressor Blades and Vanes Damage In-Flight Effects

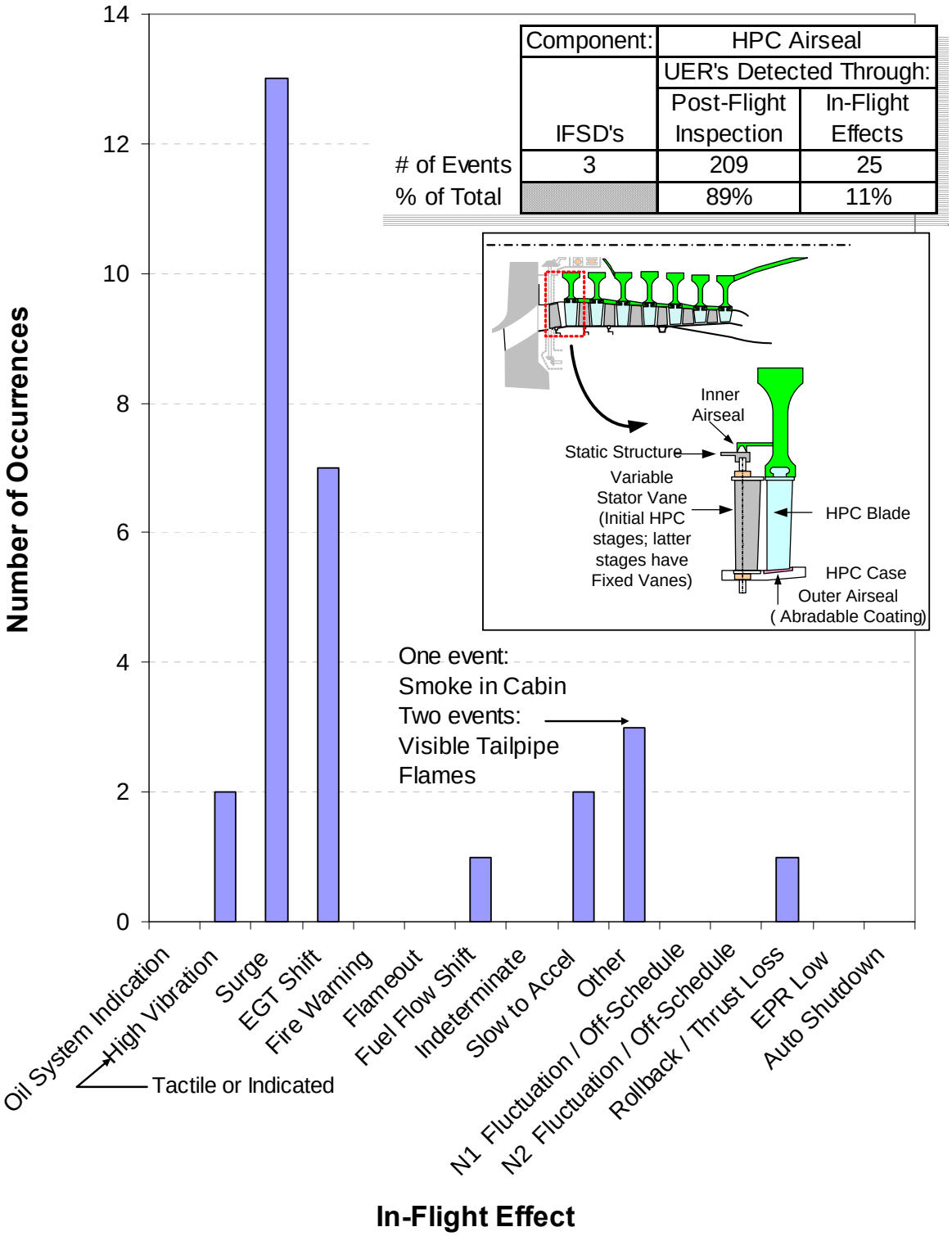


Figure 5-12. High-Pressure Compressor Air Seal Damage In-Flight Effects

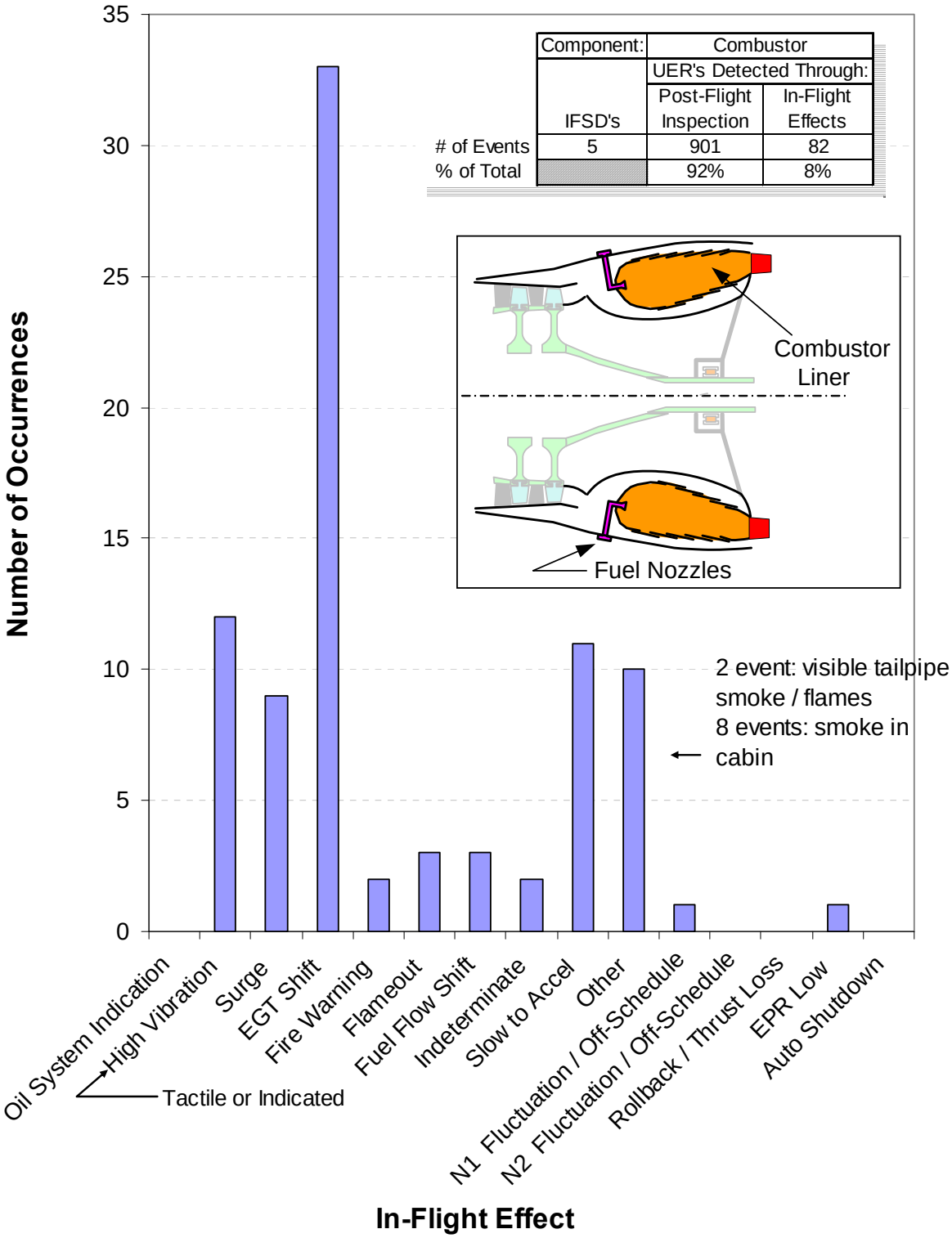


Figure 5-13. Combustor Damage In-Flight Effects

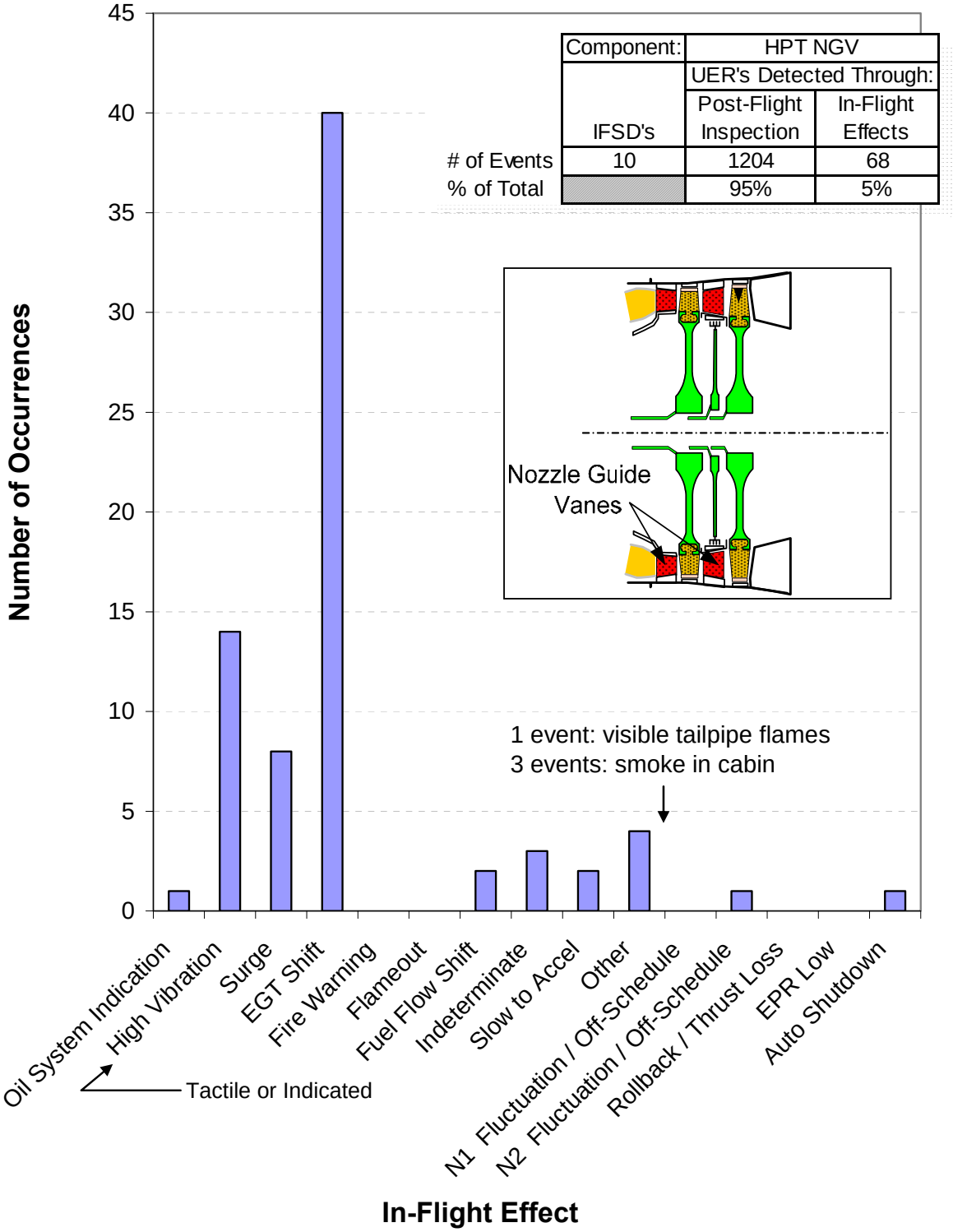


Figure 5-14. High-Pressure Turbine Nozzle Guide Vane Damage In-Flight Effects

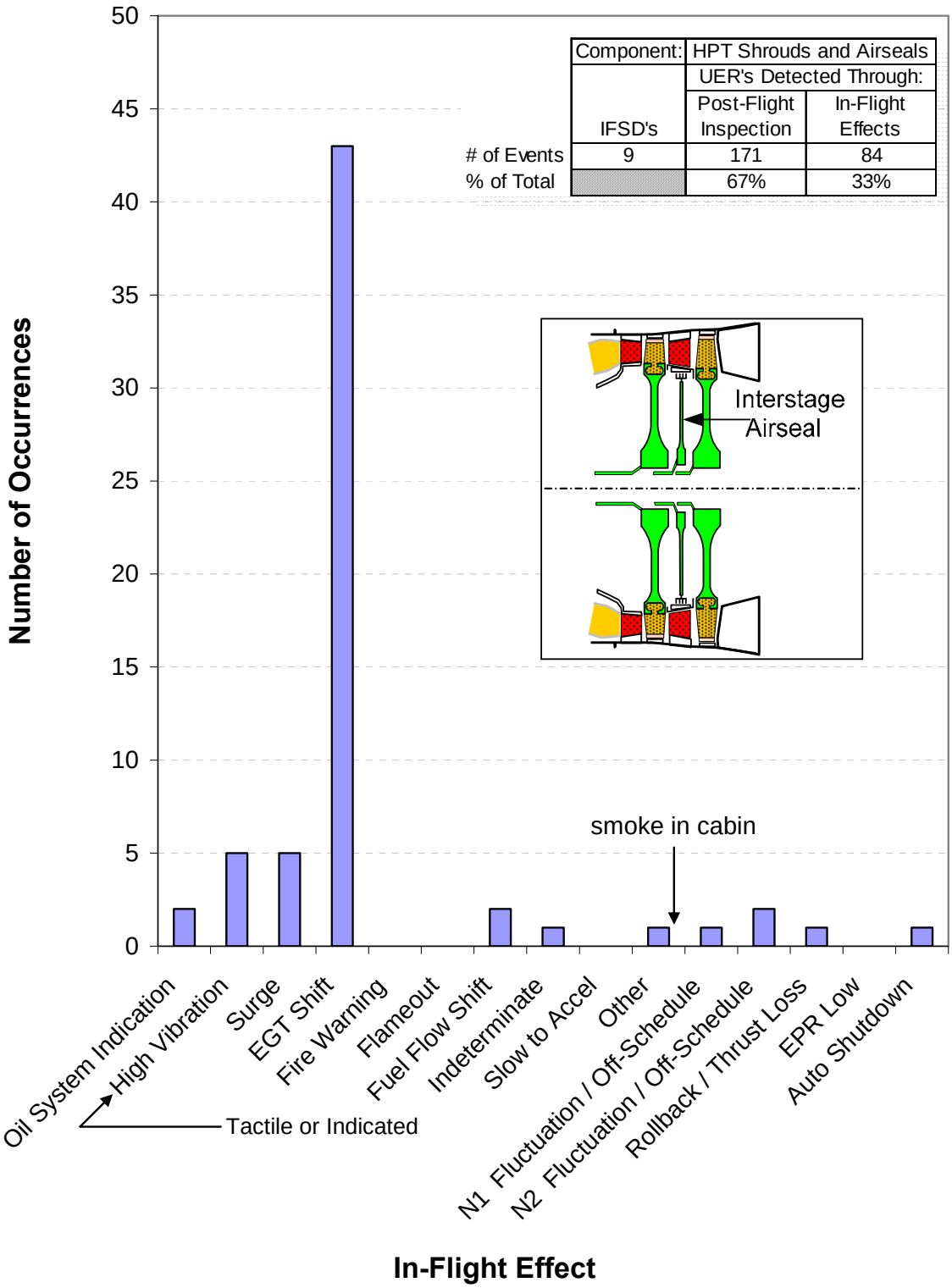


Figure 5-15. High-Pressure Turbine Air Seal and Shroud Damage In-Flight Effects

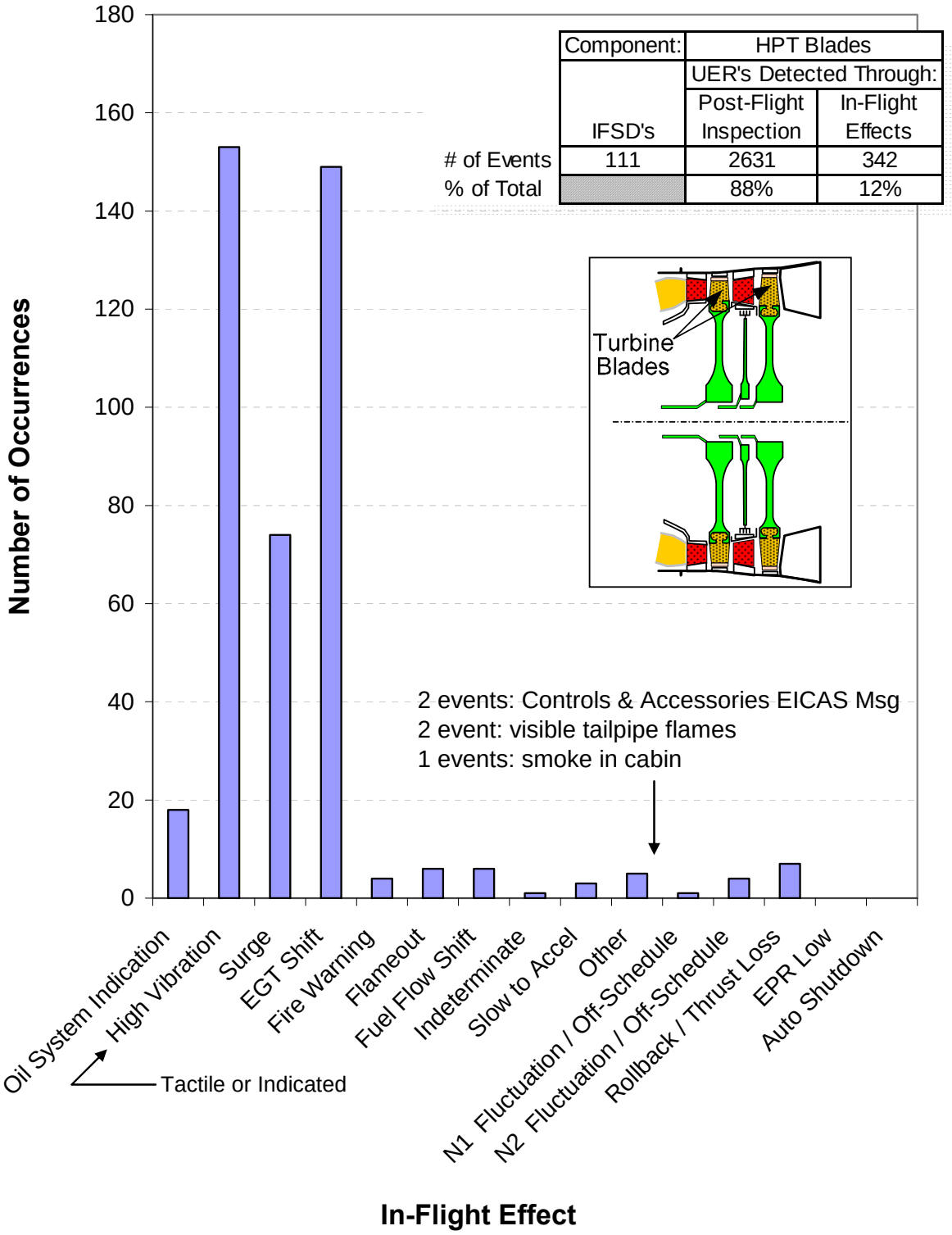


Figure 5-16. High-Pressure Turbine Blades Damage In-Flight Effects

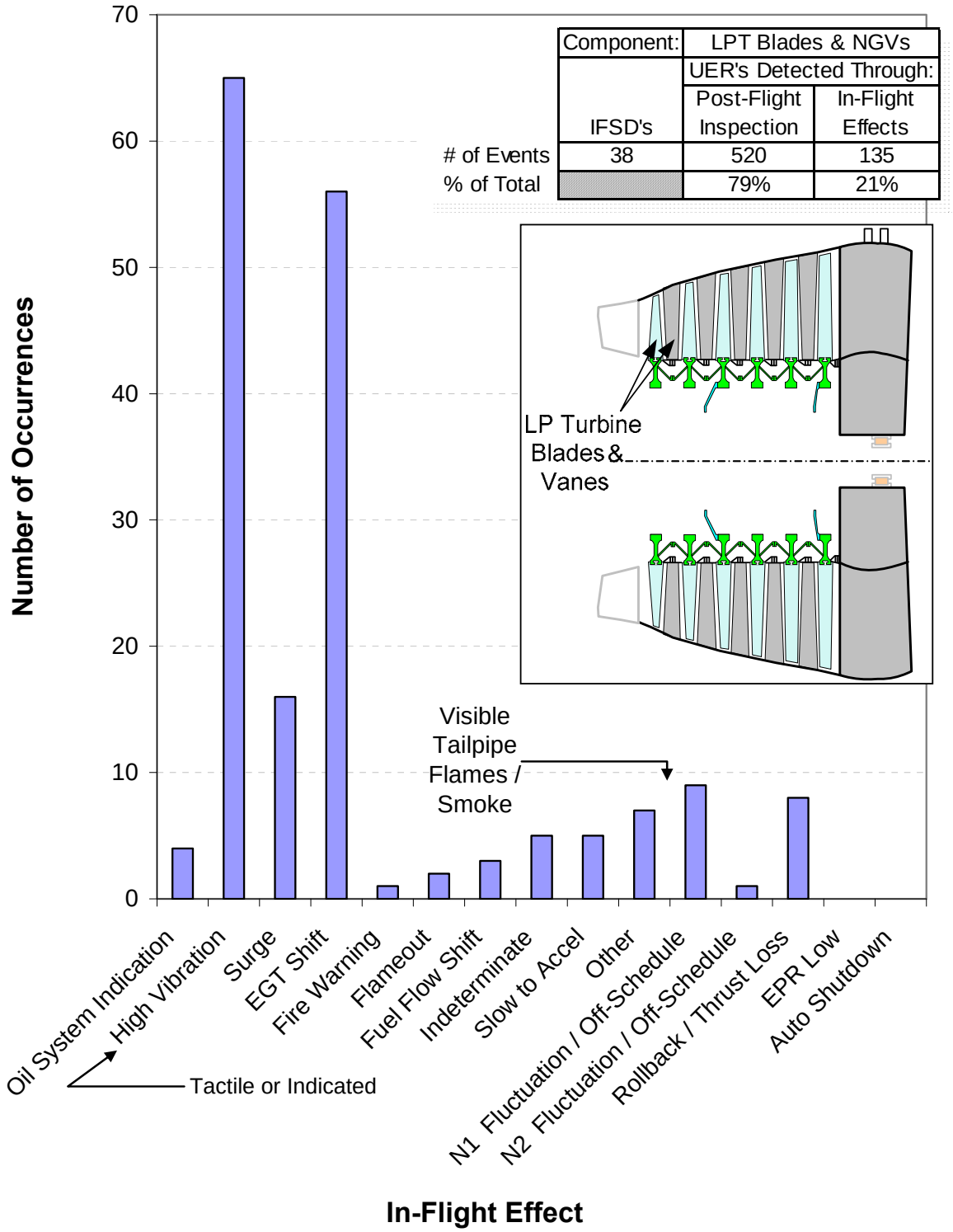


Figure 5-17. Low-Pressure Turbine Blade and Nozzle Guide Vane Damage In-Flight Effects

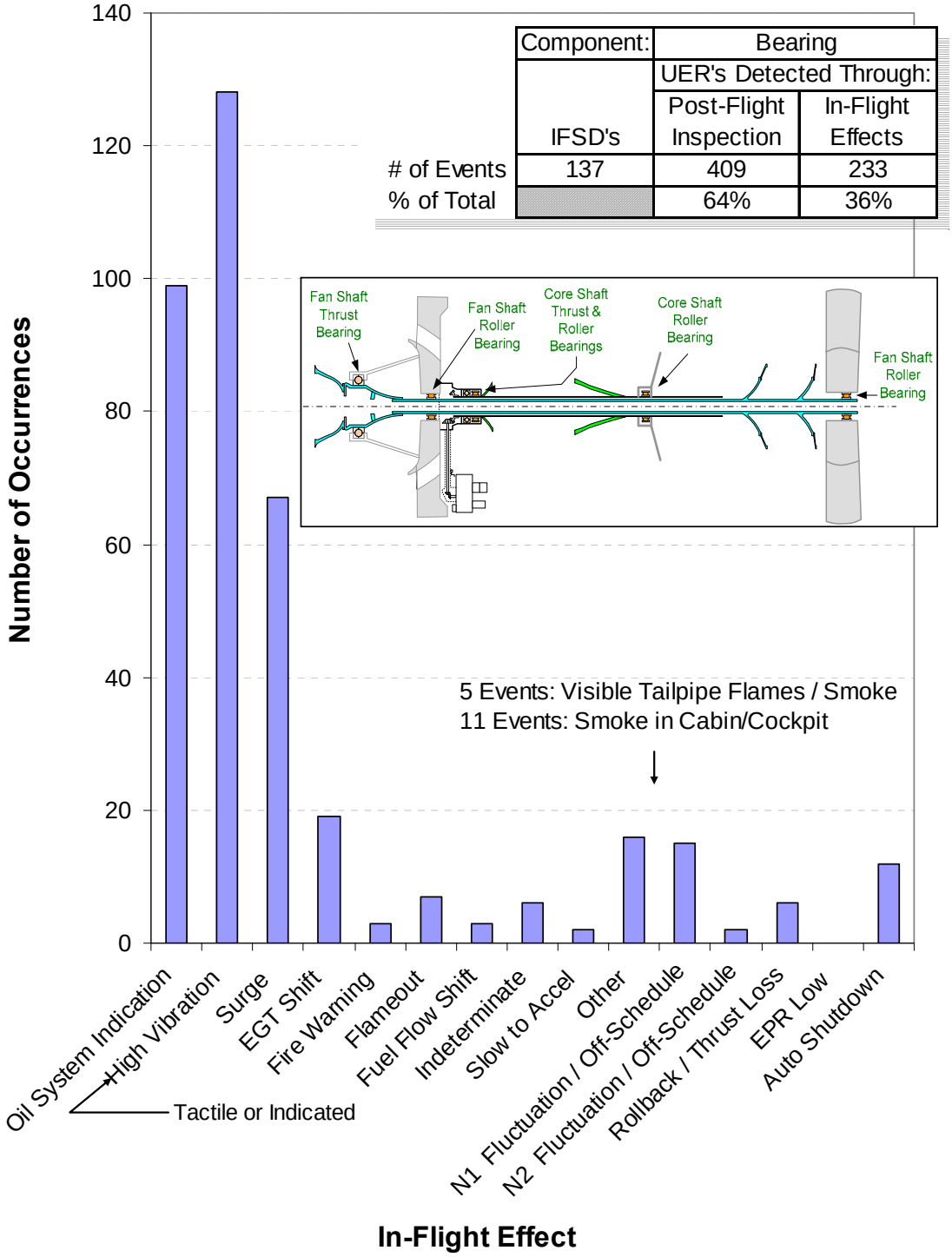


Figure 5-18. Bearing Damage In-Flight Effects

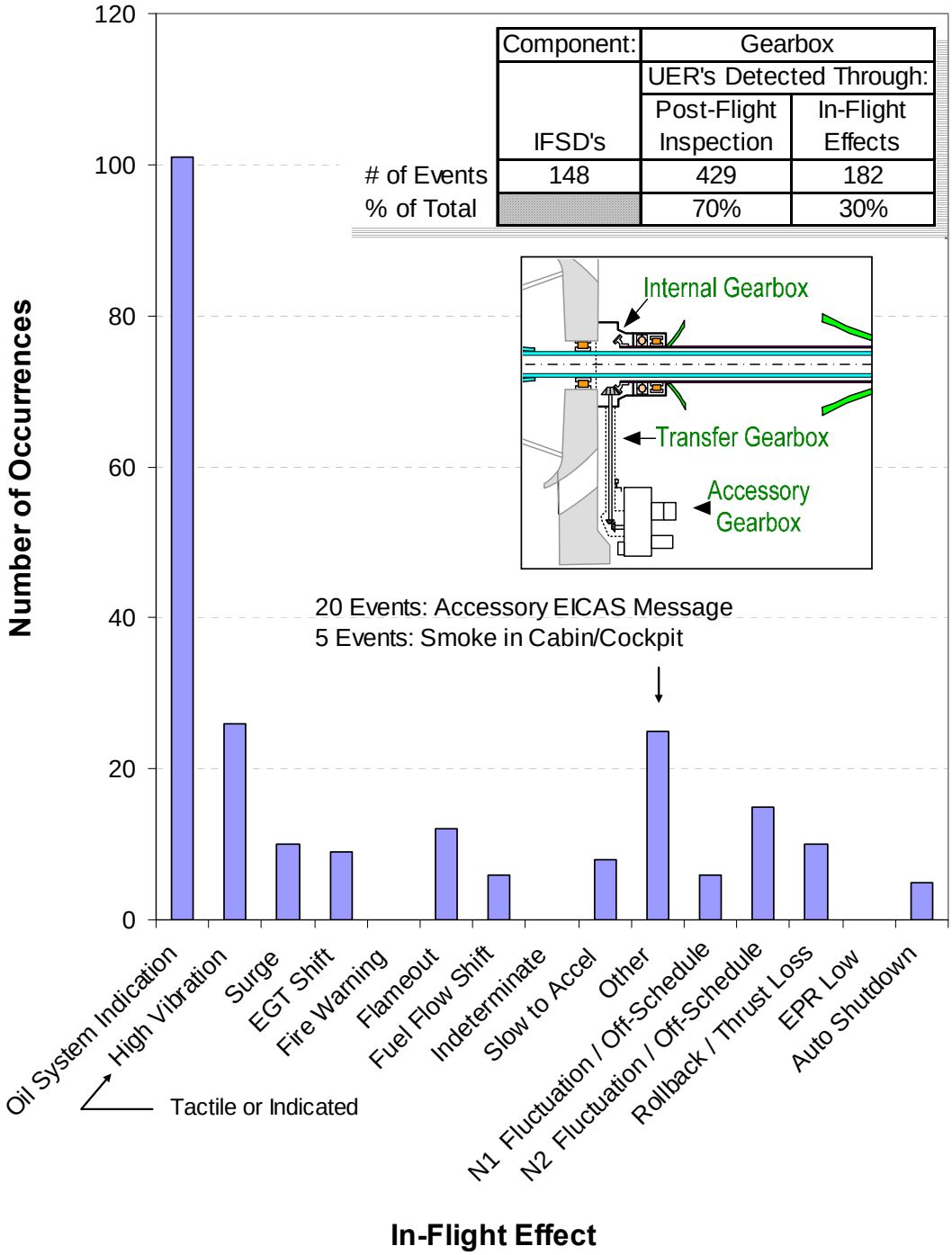


Figure 5-19. Gearbox Damage In-Flight Effects

The UER event descriptions provided a qualitative basis for selecting specific parameters to fuse for damage detection. Figures 5-5 through 5-19 indicate that multiple effects do occur for gas path and lubricated component damage events. Contrary to the commonly understood and accepted physics of such events, the data do not appear to include all the expected simultaneous effects in each event. Further, variations in the timing of multiple effects are not discernible from the service reports. This is explained by the data quality limitations previously discussed. Beyond the frequency of these effects, the event descriptions also provided anecdotal evidence that the magnitude of parameter shifts in response to the type of gas path and lubricated component damage that results in an IFSD or UER (and, hence, potentially an alert) is often significant and thus candidates for electronic monitoring, detection, and annunciation. As an example, the parameter shifts often occurred below alert limits, but were significant enough to be detected and reported by the flight crew.

It should be noted that the event descriptions were restricted to flight crew-detectable effects. As such, many additional engine parameters available to the FADEC, but not displayed in the cockpit (principally, compression system pressures and temperatures) were not discussed in the service reports. The sensor fusion strategies discussed in section 5.6 considered concepts where these FADEC-exclusive engine parameters would be available for damage detection.

5.4 AVAILABLE AND POTENTIAL DETECTION STRATEGIES.

Task 4 undertook the specific development of sensor fusion damage detection strategies. Consideration of the full spectrum of available damage detection and annunciation methods was necessary for a complete understanding of the potential for sensor fusion improvements relative to current concepts, and further, the limitations relative to future concepts. To this end, damage detection concepts were categorized according to the following criteria.

- Use of Models—Mathematical models of expected engine behavior may range from simple range-checking of sensors (i.e., reasonableness checking) to full transient thermodynamic models that predict the engine dynamic behavior under all operating conditions.

- Processing and Annunciation Concept—The simplest engine damage detection concepts process engine sensor information against fixed limits (i.e., oil temperature compared to an alarm limit) and do not retain trend information. More elaborate concepts correlate multiple sensor inputs to models and trend this information over multiple flights.

- System Capability—Damage detection ranges from discrete limit exceedance capability (current practice) to future systems with the capability to predict damaged engine restartability, available power range, and capability for continued operation.

Table 5-2 shows the damage detection system characteristics against distinct detection technologies: current single-parameter limit exceedance systems, sensor fusion systems (focus of this study), and future systems. While the characteristics assigned to current discrete exceedance and sensor fusion systems are readily classified as shown in table 5-2, the assignment of future systems' characteristics into the categories of enhanced fusion, complex fusion, or fully

integrated with EHM was somewhat arbitrary. However, these categories and the features that distinguish these future systems are expected to provide the capabilities listed in table 5-2.

Table 5-2. Damage Detection System Concepts and Capabilities

	Damage Detection and Annunciation Strategy				
	Single-Parameter Sensing	Sensor Fusion	Enhanced Fusion	Complex Fusion	Fully Integrated With EHM
	Current Practice	Focus of This Study	Candidates for Future Work		
Sensors	Existing			New + Existing	
Use of Models	Sensor fault checking (reasonableness checks) and limited fault accommodation for failed sensors	Emprical models of expected healthy engine operation		Self-tuning (adaptive) empirical or thermodynamic engine models	
Processing and Annunciation Concept	Individual sensors processed against fixed limits	Monitoring of multiple disparate sensor shifts. Limited correlation of sensor shifts against models	Full correlation of sensor shifts against models (at both transient and steady-state operating conditions across entire engine operating range)		Correlation of sensor shifts against models + longer-term trending (i.e., multiple flights)
System Capability	Baseline: Limit exceedance detection for selected failure modes	Gas path and lubricated components damage detection during steady-state operation (hold, cruise power, and above)	Throttle transients and low-power operation coverage. Improved isolation to specifically damaged component.		Predictive alerting (including thrust and restart capability determination with damage); progressive damage detection.

Increasing Capability, Cost, and Complexity

The principal potential benefit of a sensor fusion engine damage detection system beyond current limit exceedance systems is more comprehensive alerting for gas path or lubricated component damage modes. For gas path components, the damage-alerting capability inherent in a sensor fusion-based detection system is expected to be limited to awareness only for gas path component damage and response direction for lubricated component damage. As previously described in section 3.3, pilot monitoring and interpretation of existing engine indications, or the display of limit exceedance-based alerts, must guide any subsequent thrust reduction or other pilot response. To avoid potential issues caused by a damage awareness threshold set too low (i.e., unnecessary IFSDs, air turn-backs, diversions, or increased maintenance burden), it is essential that the awareness alert threshold be set such that limit exceedance or uncommanded shutdown is likely within the current flight. Figure 5-20 illustrates the relationship between the magnitude of sensible damage effect and annunciation or alerting capability.

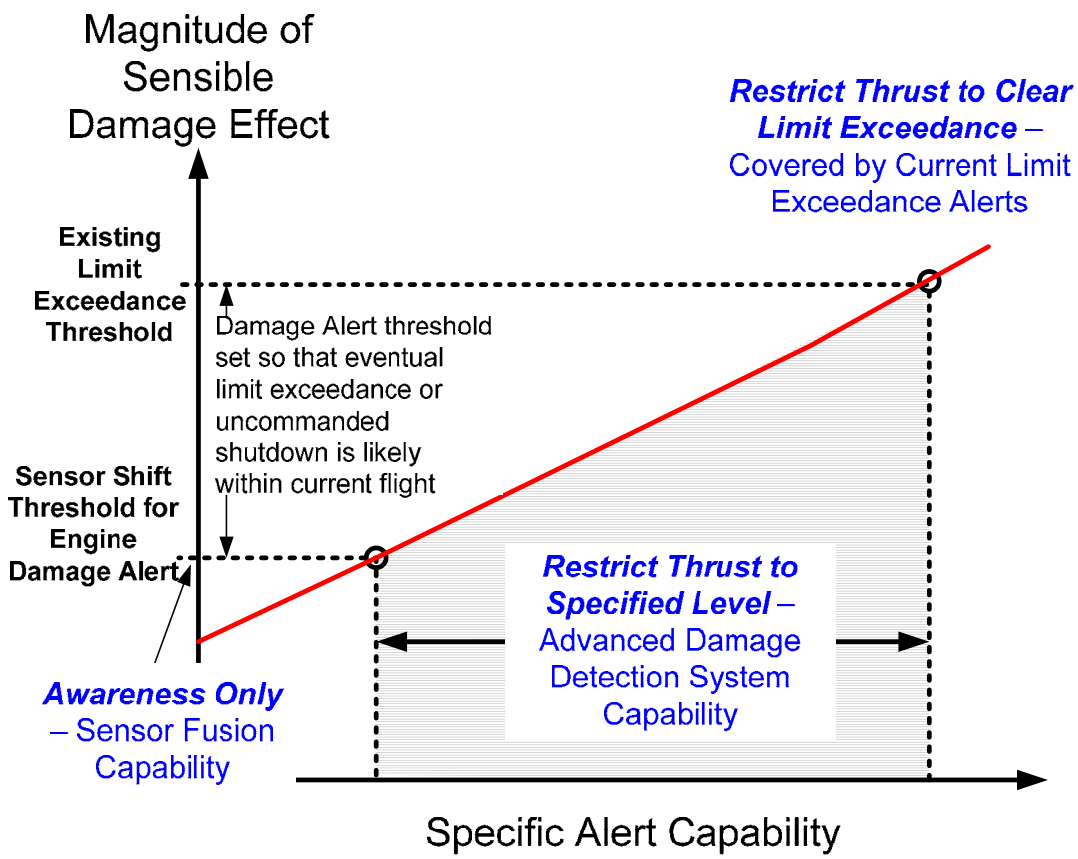


Figure 5-20. Sensor Fusion Annunciation Capability

5.5 SENSOR USAGE FOR DAMAGE DETECTION CONSIDERATIONS.

The existing baseline suite of engine sensors on modern aircraft has evolved to fulfill three basic requirements:

- Provide the basic propulsion health indications prescribed by CFRs (as listed in table 2-2).
- Maintain stable engine thrust control throughout all transient and steady-state operating regimes, including start, taxi, takeoff, climb, cruise, descent, approach, and go-around.
- Provide health monitoring for selected engine components and subsystems not otherwise prescribed by CFRs.

Integration or fusion of these sensors in an improved damage detection system necessitated the considerations described in the following sections.

5.5.1 Gas Path Pressures and Temperatures.

Pressures and temperatures are measured within the gas path primarily for use in fuel, VSV, and stability bleed scheduling. Figure 5-21 shows the typical arrangement of these sensors. As indicated in this figure, air pressure and temperature are usually measured at the inlet and discharge of each major compression system module (fan, LPC, and HPC). Engines that control thrust via EPR also measure exhaust pressure (see P5 in figure 5-21). Some engines measure fan exit pressure (see P14 in figure 5-21) for performance health monitoring. All modern FADEC-controlled engines employ fault-checking for sensors, which can include open or shorted input verification and reasonableness checks (i.e., tests to ensure sensed values are within expected range). Most sensors used for control purposes have redundant wiring (one for each EEC channel) or multiple probes (typically the case for EGT probes)[2]. Overall, given the high reliability required for control system usage, this class of sensors is considered suitable for damage detection.

[2] For the multiple EGT probes, the probe measurements are typically averaged at the probe loop. However, with additional wiring and FADEC processing, individual probe measurement could be compared to each other to provide improved combustor damage detection (i.e., detection of pattern factor distortion).

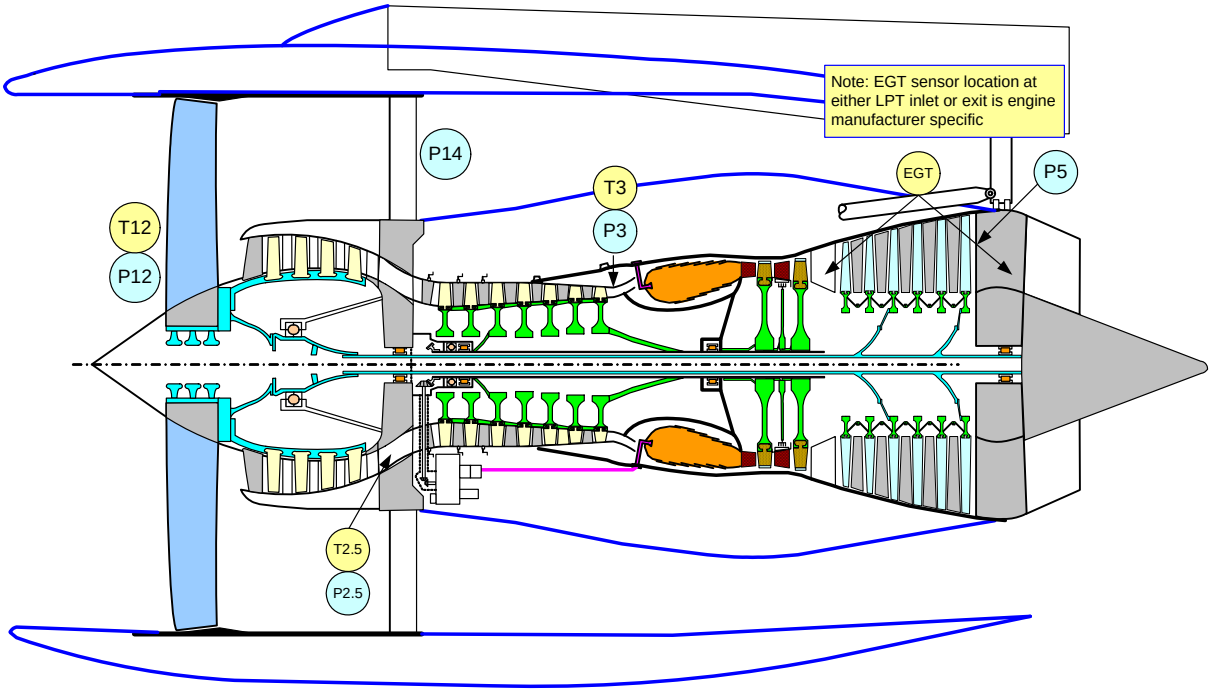


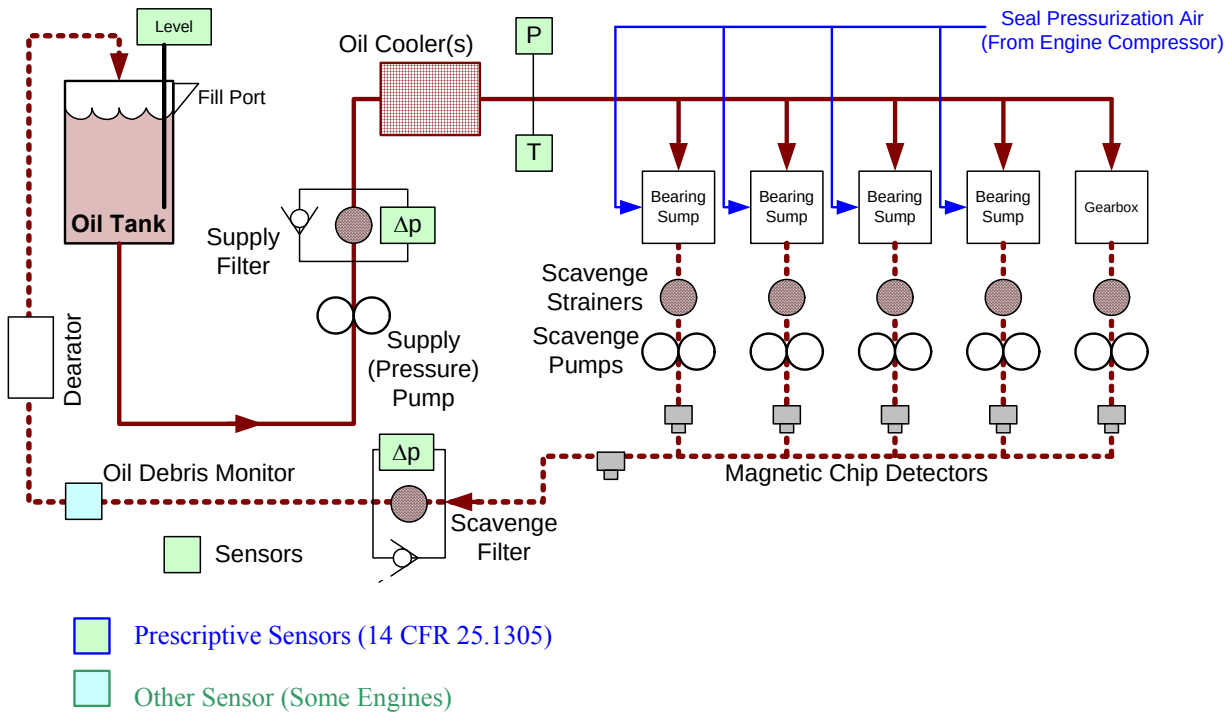
Figure 5-21. Gas Path Pressure and Temperature Sensors

5.5.2 Rotor Speeds.

Rotor speed measurement fulfills both the prescriptive requirements of 14 CFR 25.1305(c)(3) and the needs of the control system to set thrust, limit rotor acceleration, and prevent overspeed. Rotor speed is uniquely sensed for each main shaft. The most common form of rotor speed sensing is through a magnetic pickup combined with a toothed wheel either directly attached or geared to the main shaft. Because of the high criticality of the speed control function, rotor speed sensors are usually redundant and, thus, provide suitably high reliability for damage detection purposes.

5.5.3 Oil System Sensors.

Primarily due to prescriptive requirements, the engine oil system includes a large number of sensors relative to other engine subsystems. Virtually all oil system sensors are installed for system detection and annunciation of nonnormal alert or dispatch conditions. In limited applications, however, selected oil temperatures will be used to regulate air or fuel flow across an oil cooler. The typical arrangement of oil system sensors is shown in figure 5-22.



Notes:
(1) Only one oil filter Δp sensor is prescriptive
(2) Some engines comply with 14 CFR 25.1305 (a) (4) oil pressure and 25.1305 (a) (5) oil pressure warning requirements by installing separate a pressure sensor and low oil pressure switch. Other designs accomplish the functions strictly through oil pressure sensors.

Figure 5-22. Typical Oil System Sensor Configuration

Oil system sensor failures account for almost half of the sensor-related, IFSDs (or approximately 5% of all IFSDs). Since oil system sensors are not typically used for engine functions such as rotor speed or thrust control, the fault accommodation required for some control sensors has usually not been applied to oil system sensors. Thus, prior to expanded use for engine damage detection, consideration should be given to additional fault detection and/or redundancy for oil system sensors. Note, this research effort did not focus on the nature of such expanded fault accommodation, but rather, assumed that such additional robustness would be incorporated into the damage detection system design. In addition to improved lubrication system sensor fault detection, fusion of sensors within this well-instrumented system may serve to reduce sensor failure-related IFSDs. Specifically, oil pressure sensors and oil pressure switches offer a redundancy that could be correlated against other system parameters such as oil quantity, temperature, and/or filter differential pressure to detect sensor failures.

Oil debris monitors and electronic chip detectors have been introduced to recent turbofan designs as an early means of detecting lubricated component damage. These sensors typically monitor for ferrous debris entrained in the oil and offer early detection for excessive wear or failure of lubricated components. Oil debris monitors may support dispatch-related annunciations. Again, appropriate robustness is assumed if incorporated into a damage detection system design.

5.5.4 Airborne Vibration Monitor.

The service data described in section 5.3 showed that indicated vibration is associated with most gas path and lubricated component damage modes. Vibration detection, processing, and display are relatively complex compared to other engine parameters. Thus, vibration system application to damage detection should include a review of the current system installation and capability, and potential capability expansion.

5.5.4.1 Airborne Vibration Monitor: Current Installation Practice.

Indicated vibration is collected, processed, and displayed through the AVM system. AVMs are installed principally to satisfy the prescriptive 14 CFR 25.1305(d)(3):

> "The following are required powerplant instruments: … (d) For turbojet engine powered airplanes. In addition to the powerplant instruments required by paragraphs (a) and (c) of this section, the following powerplant instruments are required: … (3) An indicator to indicate rotor system unbalance."

A typical AVM system for a turbofan engine installation is shown in figure 5-23 and includes the following main elements: engine-mounted accelerometers (vibration pickups), shaft speed tachometers, signal conditioning, and displays. The most common type of vibration sensor in current use is an accelerometer. The locations and quantity of accelerometers are unique to each engine design, but in general, these sensors are installed to provide adequate sensitivity to rotor imbalance. A given accelerometer's response to either imbalance or engine damage is dependent on several factors:

- Degree of imbalance or damage
- Number and location of accelerometers
- Engine bearing support configuration (i.e., the arrangement and number of frames). Modern high bypass turbofan bearing support systems fall into three general categories:
    - A rotor with three main bearings (cantilevered fan)
    - A rotor with two main bearings (turbine and compressors may be cantilevered or straddle mounted)
    - Two rotors with bearings attached to case plus an intershaft bearing between shafts (shafts have historically been co-rotating but can be counter-rotating).

Figure 5-24 shows the typical arrangements of accelerometers and bearing supports for large commercial turbofan installations currently in service.

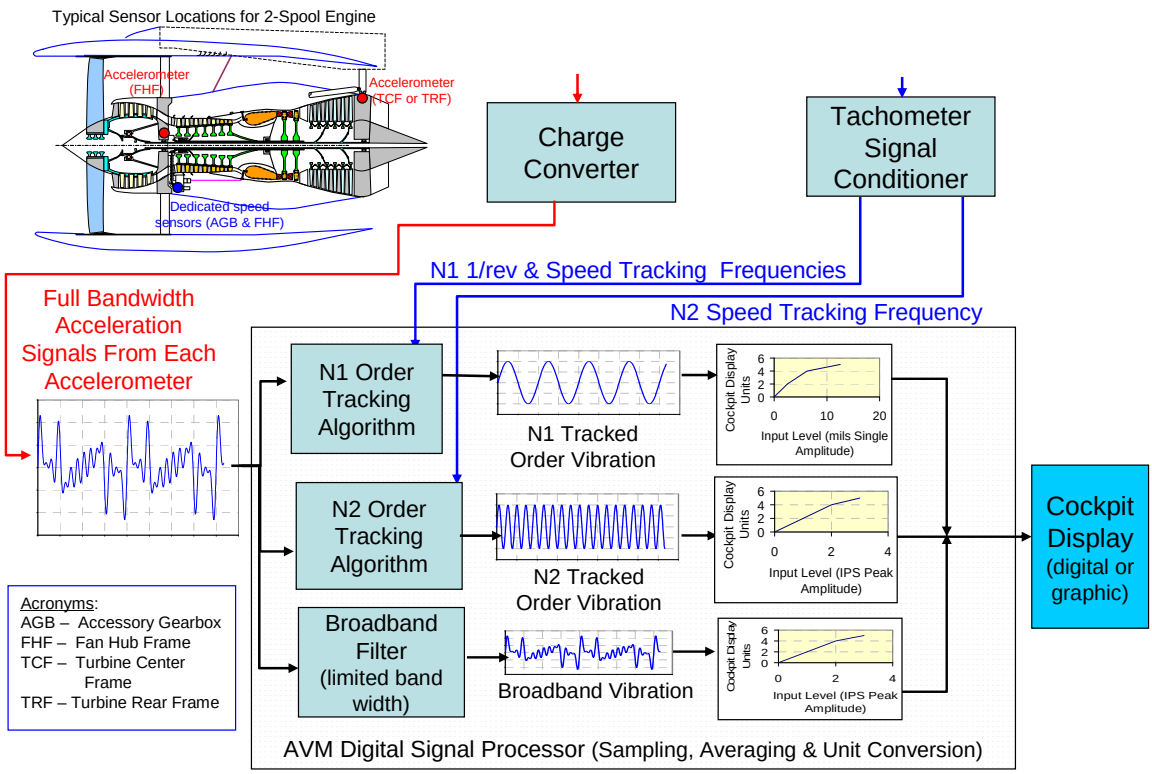


Figure 5-23. Airborne Vibration Monitor Installation and Signal Processing

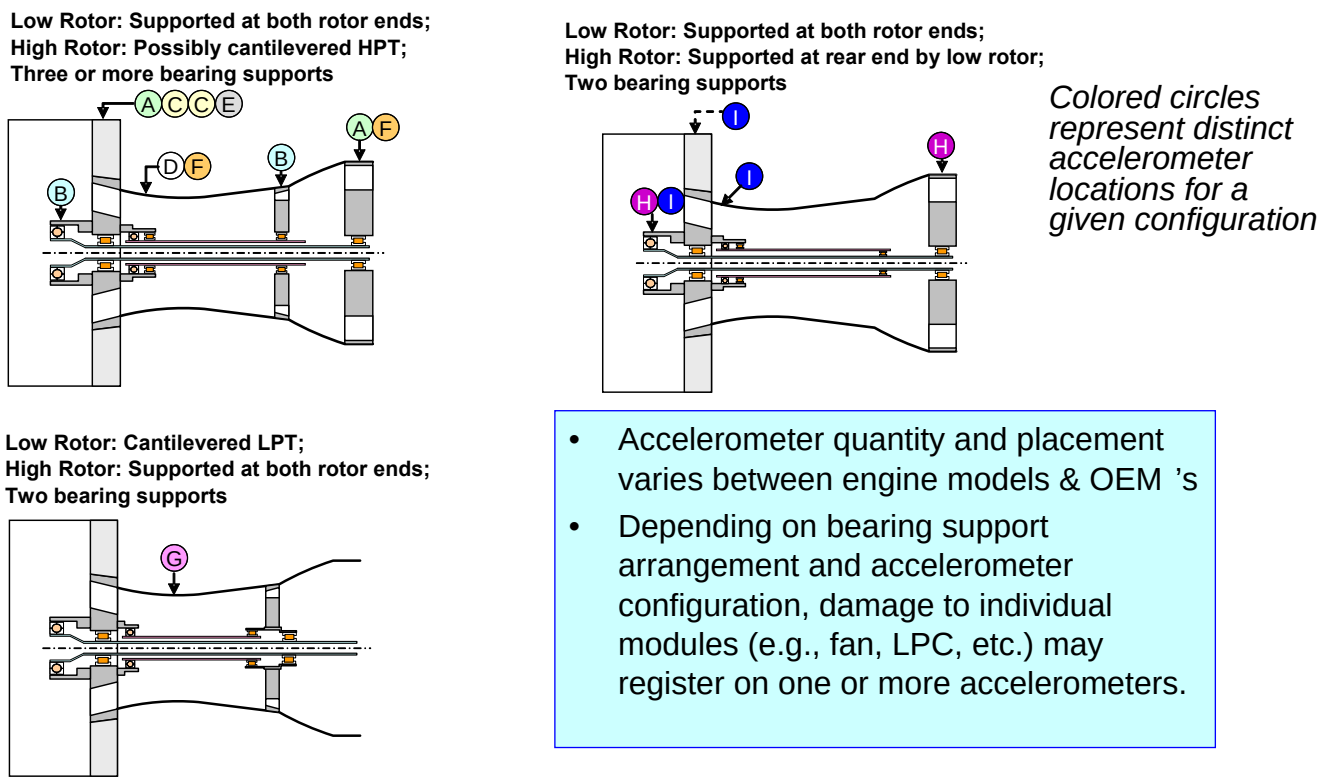


Figure 5-24. Accelerometer Locations and Bearing Support Arrangements

5.5.4.2 Airborne Vibration Monitor: Signal Processing and Display.

Rotor imbalance produces a one-per-revolution sinusoidal accelerometer response. In addition to simple rotor imbalance, the accelerometer signal also includes content from other sources, such as bearing rolling element passage and gear mesh frequencies, as well as flow-induced harmonic and random vibration. Strict compliance with 14 CFR 25.1305(d)(3) thus necessitates filtering the complex content broadband vibration signal to extract the one-per-revolution imbalance component. This filtering is accomplished through order-tracking algorithms resident in the AVM. The order-tracking algorithms use the rotor tachometer signals to establish the rotor frequencies for isolation of the vibration amplitudes associated with each main shaft rotor frequency. Once isolated, the one-per-revolution amplitudes are converted from dimensional vibration units to nondimensional cockpit units prior to display. As indicated in figure 5-23, the scaling between physical and cockpit units may be nonlinear to provide early awareness of increased vibration at lower amplitudes. The actual display format varies with each aircraft design, but commonly, the following features are included:

- Vibration source indication (rotor speed reference-N1, N2, etc.)—In some designs, if the tachometer signal is lost, or the order-tracking filter is faulty, an average broadband vibration level is displayed as an alternative to the one-per-revolution amplitude.

- Vibration-level cockpit units—Currently, most commercial transport aircraft do not employ alerting, per se, for high vibration. In general, with a few exceptions, this is because indicated vibration limits are not established. Some systems distinguish between a normal operating range and elevated levels by changing the color of the displayed units. Indicated vibration alone is not generally considered an unacceptable condition, but rather, is provided for supplemental crew awareness. Refer to section 6.1 for a discussion of vibration alerting considerations.

5.5.4.3 The AVM Usage for Engine Damage Detection.

The service reports review (section 5.3) found that elevated indicated vibration levels are a commonly reported FDE attending engine damage. Given that indicated vibration is filtered to one-per-revolution order-tracked amplitude (synchronous vibration), the simple conclusion is that gas path and lubricated component damage commonly induces rotor imbalance. In addition to indicated vibration, the unfiltered vibration signal may contain information revealing the specific engine component or module that is damaged. Table 5-3 lists the vibration signal characteristics for various types of engine damage. Modern EHM systems typically decode the unfiltered vibration signal to resolve these constituents and often detect subtle shifts indicative of early engine degradation.

Table 5-3. Vibration Signal Content

Vibration Excitation Source	Signature	Signature Characteristics
Rotor Imbalance*	One per rotor revolution frequency tone	Synchronous
Damaged Gear or Bearing	Gear mesh or rolling element passage frequency tone	Harmonic of shaft speed
Damaged Airfoil (no significant imbalance)	Blade passage frequency tone	Numerous possibilities: Harmonic of rotor speed, synchronous with vane/static structure passage rate, etc.
	Blade resonant frequency	Nonsynchronous
Rotor Whirl (instability, friction, or aerodynamically induced)	Tone + harmonics at whirl frequency	Usually subsynchronous
Loose Static Structure	Usually random	Nonsynchronous
Impact (FOD, bird strike, etc.)	Tone + broadband response (decays with time depending on level of system damping)	Nonsynchronous
Surge		

*Required by 14 CFR 25.1305(d)(3)

Definitions:

Imbalance—Radial displacement of rotor center of gravity from center of rotation
Tone—Discrete Frequency
Synchronous—Equal to shaft rotation speed
Harmonic—Integer multiple or fraction of shaft rotation speed
Subsynchronous—Fraction (<1) of shaft rotation speed
Nonsynchronous—Frequency is independent of shaft speed

A damage detection possibility, which was beyond the resources of this study to develop, includes sophisticated processing of the AVM signals in a manner that compares amplitudes of different frequencies. Such a concept may be adept at detecting certain types of airfoil distortion or structural damage that registers as nonsynchronous rather than one-per-revolution vibration. Further, this advanced form of signal processing may offer improved correlation between pilot-sensed tactile and indicated vibration.

5.5.4.4 Engine Damage Distinction From Fan Icing.

14 CFR 25.1093 requires commercial turbofan engines to operate in icing conditions "…without the accumulation of ice on the engine, inlet system components, or airframe components that

would adversely affect engine operation or cause a serious loss of power or thrust…". Compliance with this requirement is generally satisfied by two means:

- Dedicated anti-icing for the inlet lip. This is traditionally accomplished by piping warm engine compressor air through a regulation valve to warm the lip above the ice melting temperature.

- Procedures to shed ice from the fan and spinner. Operation in cold, moist air may subject the fan rotating components to ice accretion. This usually occurs at low fan speed when the centrifugal forces are insufficient to shed the accreted ice. Procedures are included to elevate the fan speed at prescribed intervals to shed the ice. Since the ice may shed asymmetrically, fan imbalance can result. An example time history ice accretion and shedding event is shown in figure 5-25.

Fan Ice Accretion is characterized by unsteady low rotor tracked-order vibration amplitude variation due to asymmetric ice accretion & sheds:

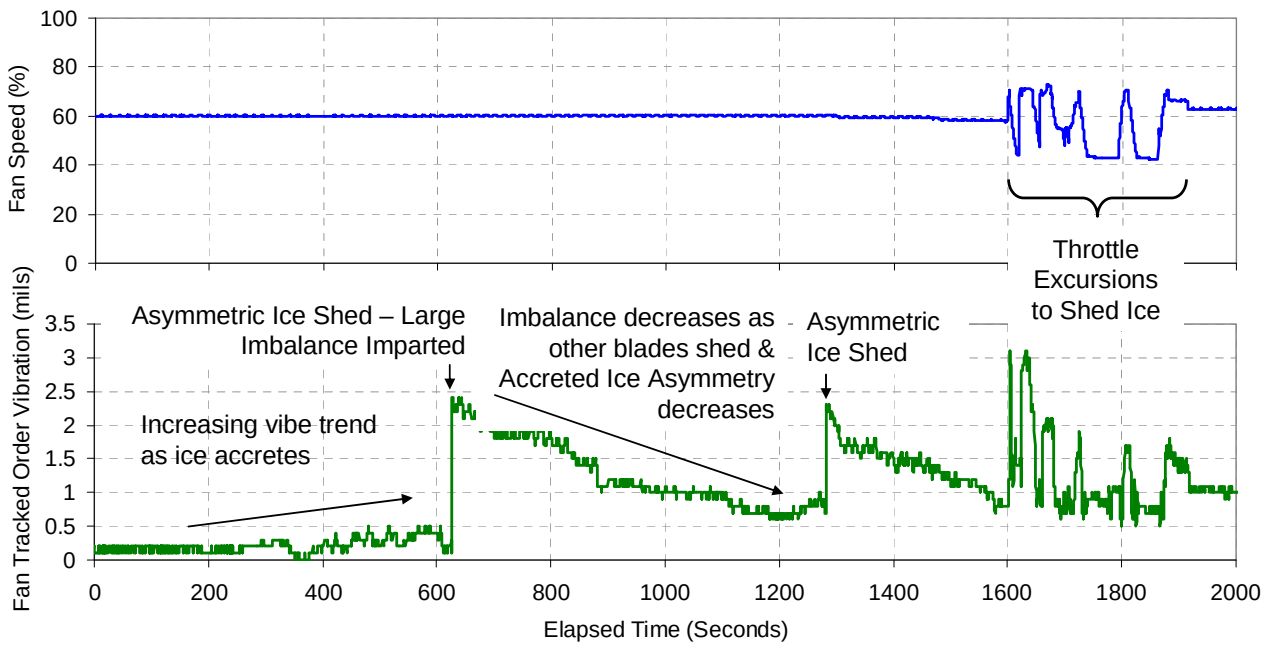


Figure 5-25. Fan Blade Icing Time History

Any engine damage detection system that incorporates indicated vibration with fan speed content should distinguish imbalance due to icing from genuine engine damage. Further evaluation of the information shown in figure 5-25 reveals the following characteristics of icing events:

- Fan blade icing occurs at relatively low fan speed.

- Fan blade icing produces fluctuating tracked-order indicated vibration (vibration amplitude rises and falls as the ice sheds asymmetrically and then re-accretes), although the rate of change can be slow.

- Above a threshold fan speed, ice is shed and vibratory characteristics return to normal steady levels.

Engine damage, however, exhibits different vibration characteristics:

- The indicated vibration amplitude does not usually fluctuate at constant fan speed.
- Indicated vibration will not likely subside at high fan speed.
- Fan blade damage may produce nonsynchronous vibration associate with bladed disk modes excited by distorted airflow.

The expected differences between fan icing and engine damage are summarized in figure 5-26. However, these differences and any potential thresholds must be substantiated with in-service data of the same fidelity required to develop engine damage detection algorithms. While additional data processing may be required to provide automatic distinction of the vibration signature differences, the influence of icing on indicated vibration may not be a significant impediment to indicated vibration-based damage detection. Although not evaluated in the development of the sensor fusion strategies discussed in the following, it is presumed that any engine damage detection strategy would also incorporate some form of icing discrimination.

Scenario	Occurs:	Characteristics:
Fan Blade Icing	Limited to descent, approach and ground idle power operation in icing conditions (fan speeds below 60-70% depending on engine model). Higher fan speeds impart centrifugal forces sufficient to shed accreted ice.	Unsteady low rotor tracked-order vibration amplitude due to asymmetric ice accretion & sheds.
Fan Blade Damage	Not limited to any flight phase or engine power setting (although most fan blade damage occurs due to bird strike events at lower altitudes).	Step change in low rotor tracked-order vibration amplitude. Also, often accompanied by off order excitation of bladed disc modes (see sketch).

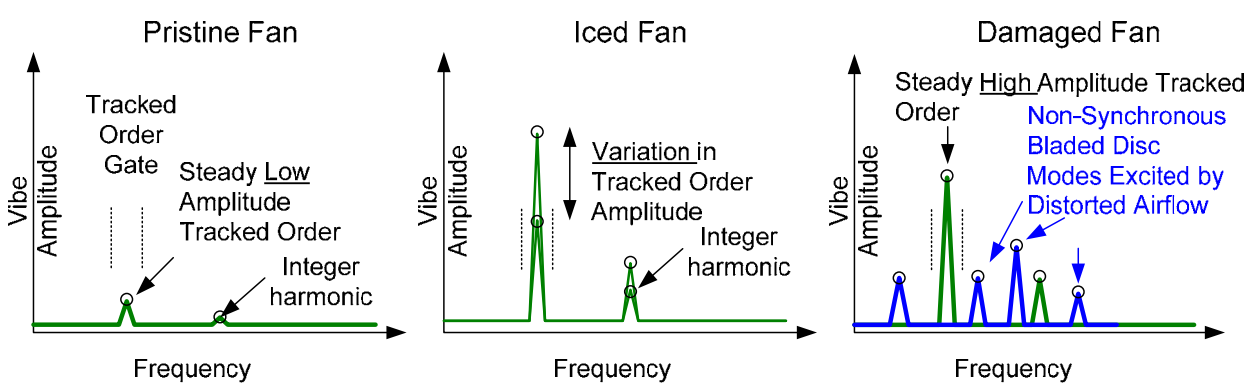


Figure 5-26. Vibration Characteristics: Fan Blade Icing vs Damage

5.6 SENSOR FUSION DAMAGE DETECTION STRATEGIES.

Task 4 developed four distinct damage detection strategies based on sensor fusion. In order of increasing complexity, these strategies were (1) two-parameter shift detection; (2) two-parameter shift detection enhanced with additional engine sensors; (3) shift detection enhanced with generic models of undamaged engine performance; and (4) shift detection enhanced with trend-based models[3] of undamaged engine performance. Common features pertinent to all four strategies are discussed in section 5.6.1. The principal distinct features, benefits, and limitations associated with each of the separate strategies are discussed in sections 5.6.2 through 5.6.5.

5.6.1 Sensor Fusion Strategy Common Features.

All four strategies evaluated in this research were fundamentally parameter shift detection schemes. The simplest strategies (1 and 2) monitored for shifts at constant thrust setting, while the more complex strategies (3 and 4) incorporated engine performance models as an alternative reference for shift detection. Irrespective of the undamaged engine baseline (measured or modeled), the basic shift detection scheme adopted for all strategies is shown in figure 5-27. The figure scheme reflects two major considerations:

- Shift Detection Processing—Shift detection occurs through a two-step process. The damage detection is armed on the first parameter shift and latched on the second parameter shift.

- Surge Accommodation—The service report review (section 5.3) found that compressor surge commonly accompanied or was induced by engine gas path or lubricated component damage. Since engine surge typically causes transient excursions in both EGT and rotor speeds (and, thus, indicated vibration), any damage detection scheme must be able to accommodate the surge event. The two-parameter shift detection strategy, thus, assumed the existence of automated engine surge detection (true for the modern turbofan engines under consideration in this research). Damage detection system accommodation of surge considered two scenarios:

    1. EEC-detected surge with autorecovery logic—The surge detection flag is used to freeze the last healthy baseline and temporarily deactivate sampling until surge is recovered and thrust has reacquired presurge setting. This scenario fundamentally assumed that the pilot does not move the throttles in response to surge[4].

    2. EEC-detected surge with pilot throttle action—Same as above, except sampling reactivates once surge is recovered and stable thrust setting is established. This scenario provided for manual throttle movement, but assumed that the original presurge thrust setting was re-established within a short period.

[3] Trend-based models are adaptable to both the specific engine design and engine serial number.
[4] Nonmovement of the throttles or rapid restoration of the throttles to the original presurge thrust setting is a questionable assumption. Hence, development of Strategies 3 and 4 was undertaken to address this steady thrust limitation.

Simple trend shift monitoring at steady state conditions:

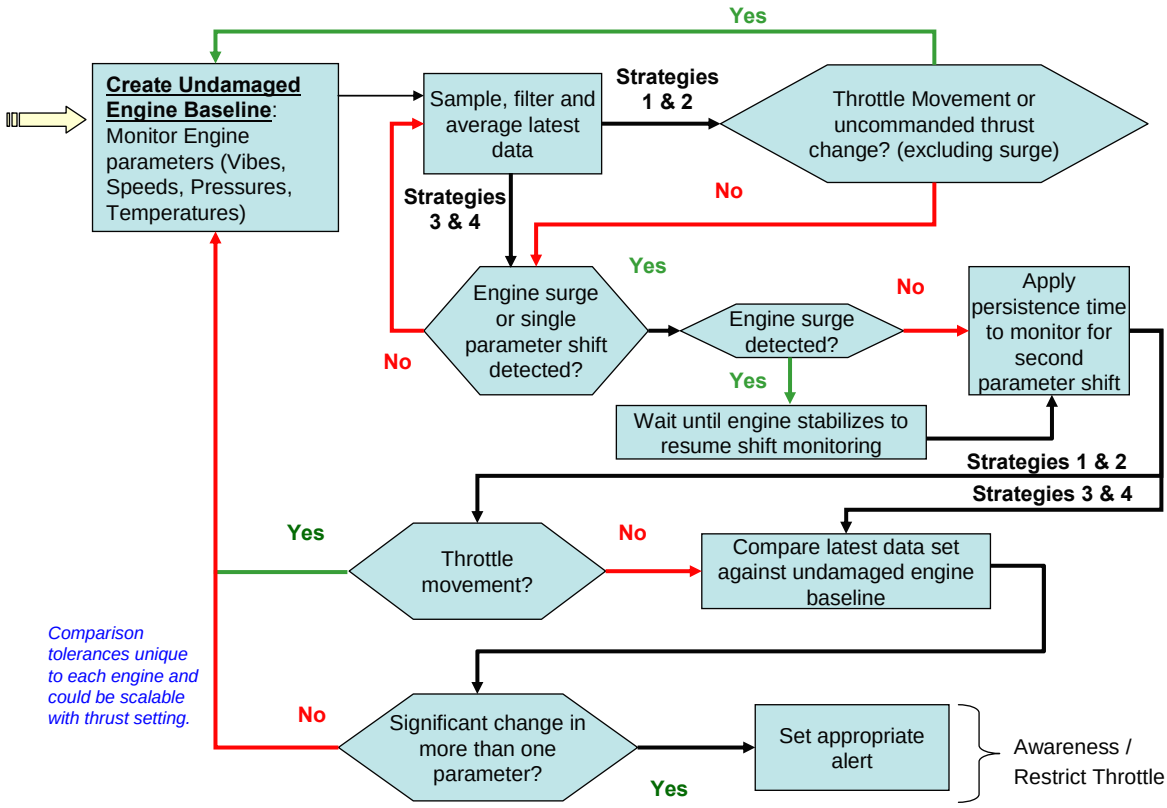


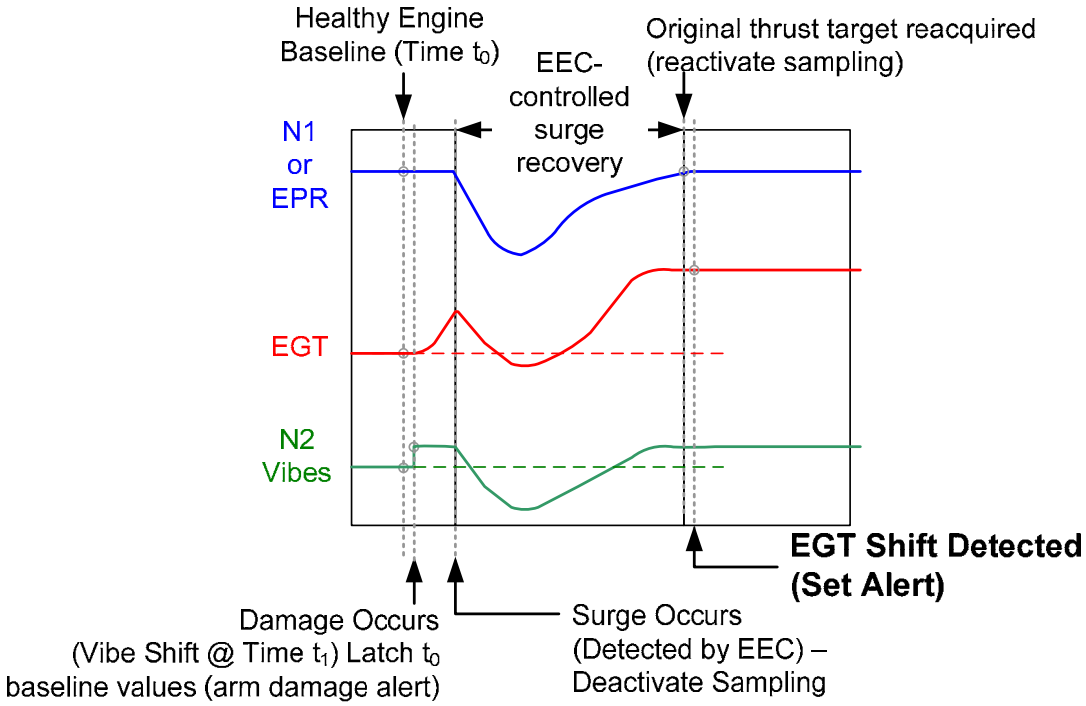
Figure 5-27. Trend Shift Monitoring Top-Level Concept

In both scenarios, monitoring for parameter shift detection must be suspended during the surge transient and, hence, would result an annunciation delay. Proper accounting for surges that might occur as a result of the damage event necessitated the monitoring sequence described in table 5-4 and figure 5-28.

Table 5-4. Damage Detection Surge Accommodation Scheme

Scenario	Latch Undamaged Engine Baseline (Arm Alert)	Deactivate Monitoring	Reactivate Monitoring	Set Alert
Damage Detection Occurs Prior to or After Surge	First parameter shift	Not applicable		Second parameter shift
Damage Detection Spans the Surge	Surge flag set		Stable postsurge thrust setting established	Second parameter shift

Damage occurs prior to an auto-recovered surge (no throttle action):



Damage occurs prior to a surge (with throttle action):

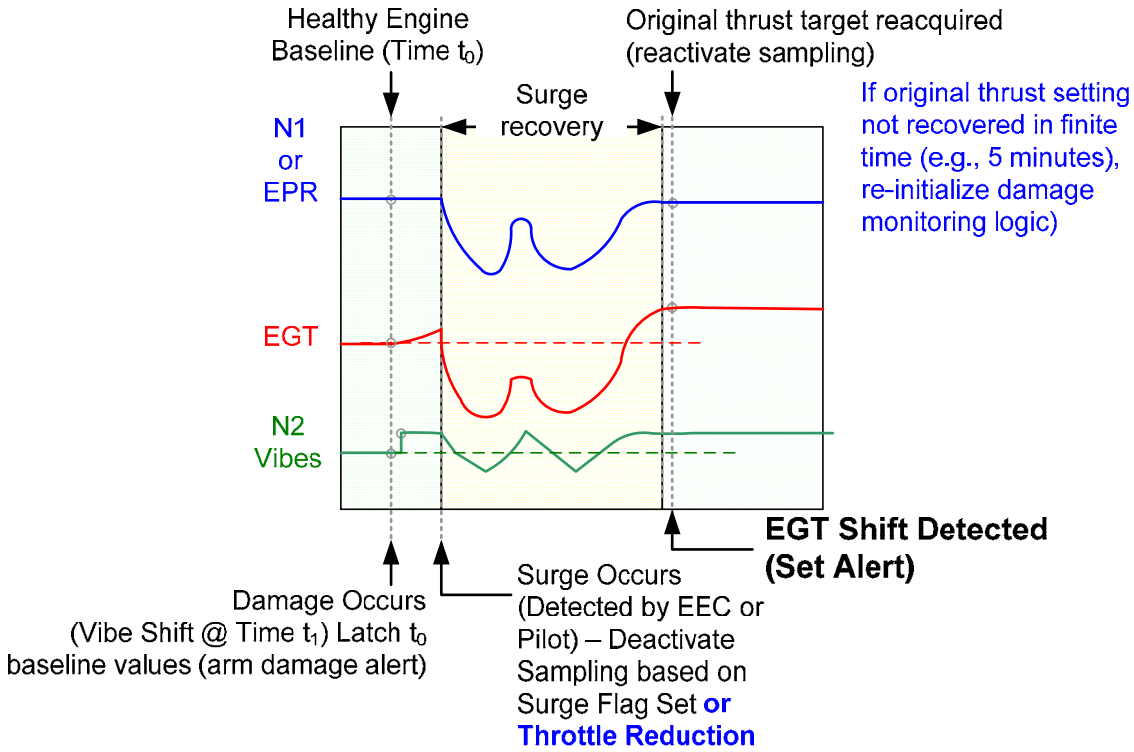


Figure 5-28. Sensor Fusion Surge Accommodation

5.6.2 Strategy 1: Two-Parameter Shift Detection.

The service reports review (section 5.3) found that, for most gas path damage modes, sensible shifts occurred for both exhaust gas temperature and indicated vibration. Conversely, lubricated component damage generally asserted as shifts in one or more oil systems indications with limited occurrences of indicated vibration shifts[5]. The high standard of false detection reliability established by Task 3 mandated that at least two sensor inputs be used to validate engine damage prior to cockpit annunciation. Thus, the most basic sensor fusion concept that fulfills these requirements is a system that monitors for simultaneous (or near simultaneous) shifts in at least two parameters at a constant thrust setting. Unique features of this concept include the following:

- Use of Models—Models were limited to sensor validation only (i.e., fault-checking, reasonableness checks, etc.) via simple table-lookup methods.

- Steady-State Thrust Operation—Limiting model use to only sensor validation meant that the baseline from which shifts were detected had to be based entirely on the previous operating condition. To distinguish changes due to thrust lever movement from genuine engine damage, this concept fundamentally restricted the damage detection to steady-state thrust operating conditions. Such a restriction implies that both parameter shifts had to occur at the same thrust setting and further, that a parameter change caused by a thrust change (manual or automatic) would not trigger false detection.

The basic two-parameter shift engine detection of Strategy 1 did not employ nonvolatile memory. As a result, this approach is the least consumptive of memory resources, but does not retain damage information between flights. As such, the concept presumes that the engine starts the flight undamaged and remains so until damage is detected. Once the damage is detected, this state is latched.

The two-parameter shift damage detection system outlined above represents the most basic form of sensor fusion and is, thus, expected to be the easiest to implement from an engine-processing and memory resource perspective. The ability of this concept to detect significant engine damage was assessed against the reference 4 service mishap. During this event, a fan blade failure on engine 1 was incorrectly interpreted as an engine 2 event, and as a result, the undamaged engine 2 was incorrectly shutdown. FDR time history data extracted from reference 4 for this event are plotted in figure 5-29. The following conclusions were made from these data:

- Relatively significant near-simultaneous upward shifts in engine 1 EGT and N1 tracked-order vibration amplitude as well as a large downward shift in fuel flow attended the engine 1 fan blade failure. Engine 1 continued to operate at reduced thrust until later in the flight when it suffered an uncommanded shutdown.

- Corresponding shifts did not occur on the undamaged engine 2.

[5] This research presumes that the application of advanced vibration processing (beyond current tracked order filtering) to detect gear mesh and/or rolling element passage frequencies would provide expanded gearbox and bearing damage detection capability.

- The crew retarded the throttle on the undamaged engine 2. The crew later shutdown the undamaged engine 2 (at an elapsed time of ~3.5 minutes).

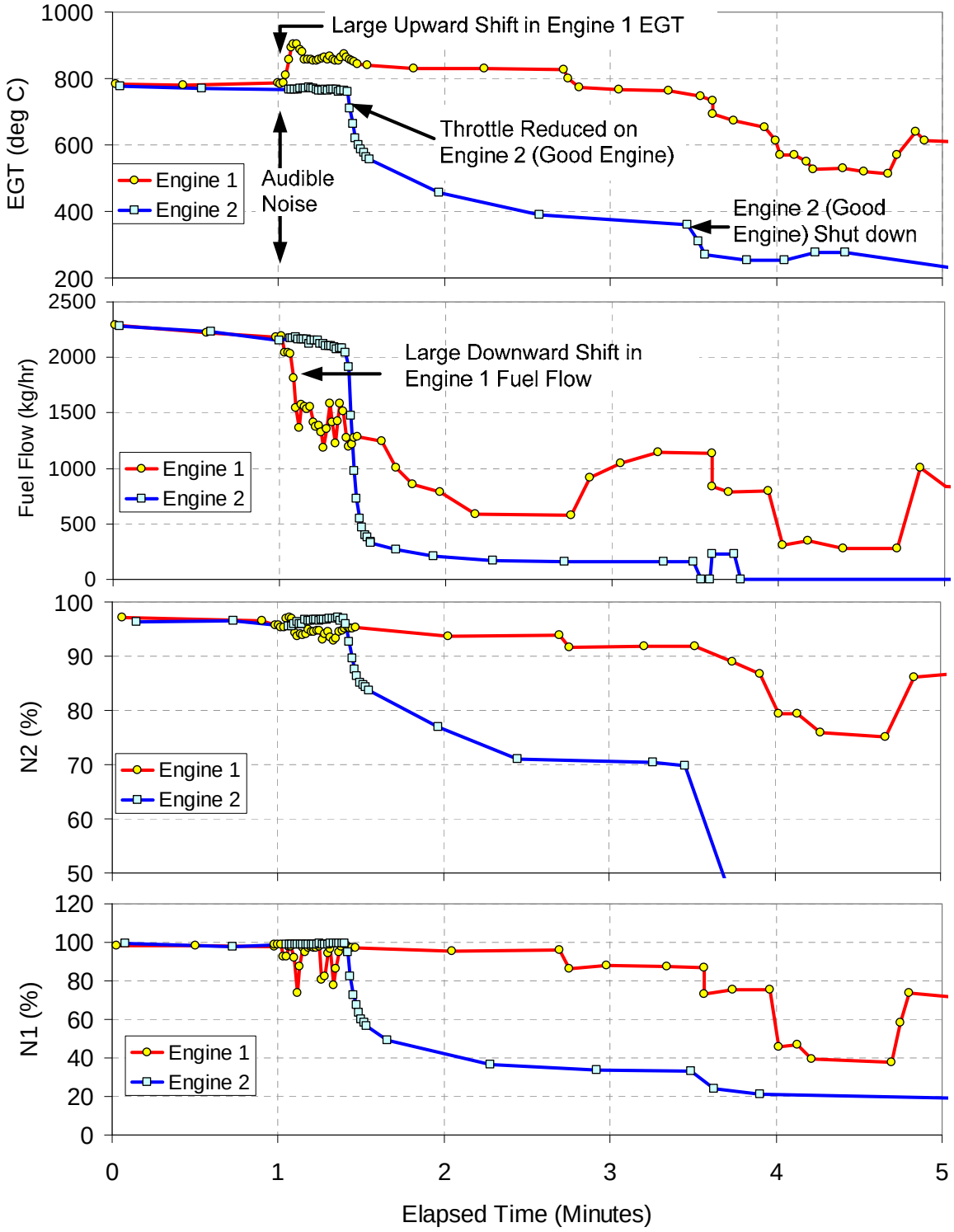


Figure 5-29. Reference 4 Service Mishap Time History Data

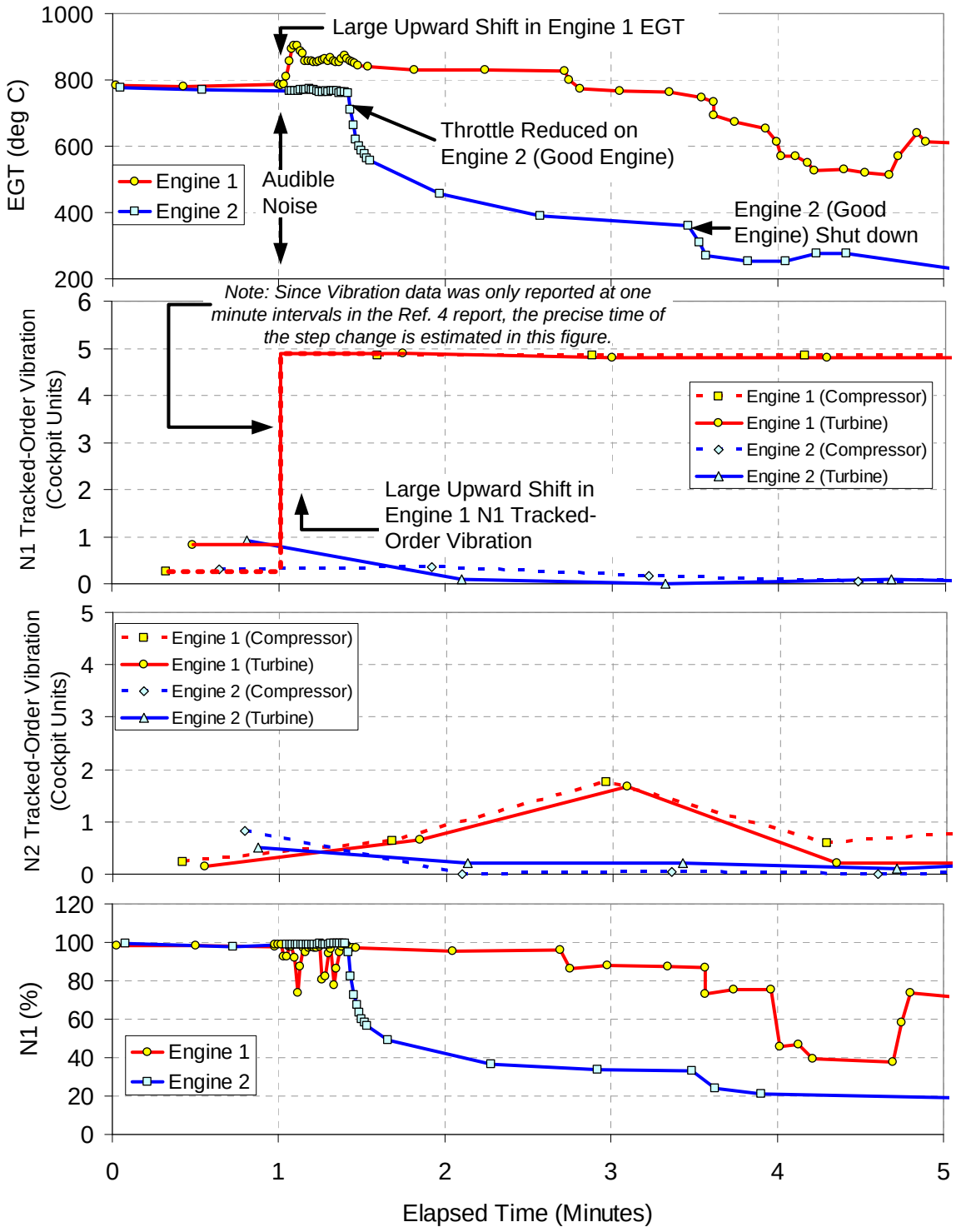


Figure 5-29. Reference 4 Service Mishap Time History Data (Continued)

The simplicity inherent in the Strategy 1 concept incurs significant operational limitations, which include the following:

- Coverage is excluded for normal thrust transients (e.g., acceleration to takeoff power, go-around, climb, descent, etc.). Further, this concept does not provide damage detection capability for thrust settings other than where damage was initially detected (i.e., the thrust at which the first parameter shift was detected). As a steady-state system, the concept does not detect damage if the throttle is moved before both parameters change. Further, this concept may not detect damage that occurs during a surge event where the autothrottle or crew reacts with thrust reduction and subsequent restoration to a thrust setting different than the presurge value. Note, these steady throttle limitations are addressed in the model-supplemented sensor fusion schemes described in sections 5.6.3 and 5.6.4.

- Damage alert latching is required because detection is inferred from relative step changes in parameter values, not absolute limits or thresholds. From a flight operations perspective, latching is not a preferred practice, but is acceptable on a case-by-case basis where the benefit justifies the risk of latching a false alert and implementing means to unlatch the alert.

- As defined above, Strategy 1 is limited to two states: damaged versus undamaged (gas path components) or shutdown versus undamaged (lubricated components). Although an alerting system that progresses to more severe response states if the damage deteriorates (i.e., from awareness only to restrict thrust and ultimately, to shutdown) is not theoretically excluded from this concept, such capability requires distinct shift thresholds for each alert level and may further vary, depending on the damaged component. Without the introduction of relatively sophisticated models, it is unlikely that resolution to anything beyond the preferred initial response (awareness/restrict thrust or shutdown) is achievable with this concept. As well, the secondary objective of isolating damage to the affected module level (for dispatch-critical maintenance) is not expected to be possible without correlation of additional sensors (the basis of Strategy 2 is described in section 5.6.3).

- Degree of damage detection and engine power/restart capability determination are not likely to be achievable with this detection scheme. These capabilities are expected to require the incorporation of both relatively complex models and, likely, the introduction of new sensors.

5.6.3 Strategy 2: Shift Detection Supplemented With Other Engine Parameters.

The two-parameter strategy outlined in section 5.6.2 relies on EGT and indicated vibration for gas path component or indicated vibration and oil system parameters for lubricated component damage detection. While these sensor choices are likely adequate for response category crew alerting, isolation of the affected major module is probably not possible without the introduction of additional existing engine sensors into the shift detection monitoring strategy.

Table 5-5 summarizes the benefits associated with adding additional sensors for damage detection. As indicated in this table, the principal benefit of the additional sensors is isolation of damage to the most affected module or subsystem. An assessment of the sensors that would likely register a shift in response to gas path or lubricated component damage was completed. Since no direct service data was available beyond that described in section 5.3, this assessment was based primarily on propulsion engineering and engine company expertise and ranked the effects on a likelihood basis. The results of this assessment are provided in figure 5-30.

Table 5-5. Strategy 2 Comparison to Strategy 1

		Strategy 1 Capability With EGT + Vibration or Vibration + Oil System Paramaters Alone		Strategy 2 Required Additional Sensors	
Response Group	Module	Response Alert	Module Maintenance Message	Response Alert	Module Maintenance Message
Awareness Only or Restrict Thrust	Fan	Good coverage	Ambiguous to LPT/LPC damage	None	Possibly separate discrimination of aft- and rear-mounted accelerometers. P14 (if installed)
	LPC		Ambiguous to Fan/LPT damage		Surge, P2.5, P3
	HPC		Ambiguous to HPT damage		Surge, P3, possibly separate discrimination of LPT and fan-mounted accelerometers
	Combustor	Reasonable coverage for damage modes with loose internal parts (which assert with high indicated vibration)	Likely not covered without additional parameter monitoring	Fuel flow, possibly P3 and P5	
	HPT	Good coverage	Ambiguous to HPC damage	None	Fuel flow, possibly separate discrimination of LPT and fan-mounted accelerometers
	LPT		Ambiguous to Fan/LPC damage		
Shutdown*	Lubricated Components	Good coverage	May be insufficient to resolve main bearing from gearbox damage	Oil System	Advanced AVM (higher frequency processing beyond N1 and N2 tracked order)

*Shutdown Response Group also includes lube system component damage, which is detected by existing standalone sensors.

*	Highly Likely
✓	Likely
X	Possible

Component	Speed			Pressure					Temperature				Vibration			Oil System					Fuel
	LP Shaft	IP Shaft	HP Shaft	P14	P2	P2.5	P3	P5	T2	T2.5	T3	EGT	LP Shaft	IP Shaft	HP Shaft	Temp	Pres	Quantity	Filter Dp	ODMS	Flow
Gas path*:																					
Fan Spinner	X			X		X							*								
Fan Abradable	X			X		X						X	*								
Fan Platforms	X			X		X						X	*								
Fan Blades	✓	X	X	✓		✓						✓	*								X
Fan Exit Guide Vanes	X			X		X							✓								
LPC Blades and Vanes	X	X				✓	X			✓	X	✓	*	*							X
HPC Airseal							✓	X			✓	✓			X	X					X
HPC Blades and Vanes			*			X	✓	X		X	✓	*			*						✓
Combustor												*									✓
HPT NGVs		X	X			X	X	X		X	X	*			X						✓
HPT Blades		X	X			X	X	X		X	X	*			*						✓
HPT Airseal						X	X	X		X	X	*			✓						X
HPT Shrouds		X	X				X	X			X	*			X						✓
LPT Blades and NGVs	✓					X		X		X		*	*								✓
Lubricated Components:																					
Bearing	X	X	X									X	*	*	*	✓	✓	X	*	*	X
Gearbox			✓									X			X	✓	*	X	*	*	✓

*Note: LPC Airseal excluded due to low frequency of failure

Figure 5-30. Component Damage Correlated to Sensor Effects

The introduction of the additional sensors in Strategy 2 does not alter the fundamental "sample and hold" approach inherent in Strategy 1 and described in figure 5-27, table 5-4, and figure 5-28. Relative to Strategy 1, Strategy 2 increases the processing resource requirements because of the additional sensors to be monitored. The Strategy 1 limitations associated with isolation of damage to the module level are potentially overcome with Strategy 2, but the operational limitations associated with steady thrust damage detection, alert latching, and the inability to detect degree of damage or determine restartability were not improved.

5.6.4 Strategy 3: Shift Detection Enhanced With Performance Model.

A significant limitation of both Strategy 1 and 2 is the inability to correlate parameter shifts that occur at different thrust settings. The first evaluated approach to overcoming this limitation was to supplement the parameter shift scheme described in figures 5-27 and 5-28, and table 5-4 with a model of expected engine operation. To meet the detection reliability requirements established by Task 3, such a model must account for engine-to-engine performance variation and the actual deterioration and imbalance state of the undamaged engine. As shown in figure 5-27, Strategy 3 bypasses the checks for commanded thrust change and instead uses the performance model to provide the reference for second parameter shift at a different thrust setting.

One possible approach to achieving such adaptive capability is to normalize the variation of the monitored sensor with a primary independent parameter. An example of such an approach is depicted in figure 5-31. In this example, normalized indicated vibration is modeled as directly dependent on rotor speed (a reasonable first-order approximation). The model is adaptive because it uses the actual (undamaged) vibration level at the current rotor speed in combination with a model-determined scalar to predict the expected undamaged level at another rotor speed. As indicated in figure 5-31, the allowable range of extrapolation would depend on the model fidelity (i.e., the repeatability of the normalized trend) and the threshold selected for shift detection.

One consideration for modeling vibration in this manner is that extrapolation "keep-out" zones may be necessary regions where expected response is highly variable. As an example, a vibration response variation can occur at conditions where axial loads reverse across a thrust bearing.

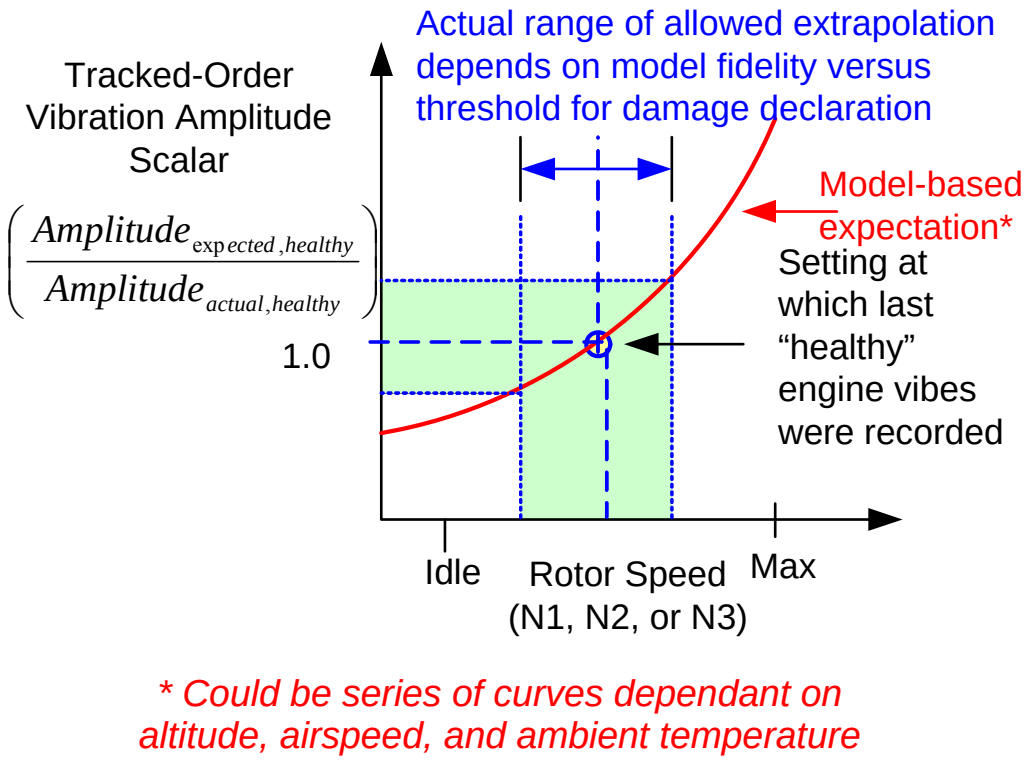


Figure 5-31. Vibration Trend Model

Developing a similar model for EGT is more complicated than indicated vibration because EGT is a multivariate function of flight condition (i.e., altitude, ambient temperature, and airspeed) as well as throttle setting and secondary power extraction. As indicated in figure 5-32, this multivariate dependency does not necessarily prevent implementation of the concept, but rather, forces a more complex model and may impose narrower limits on the available extrapolation range.

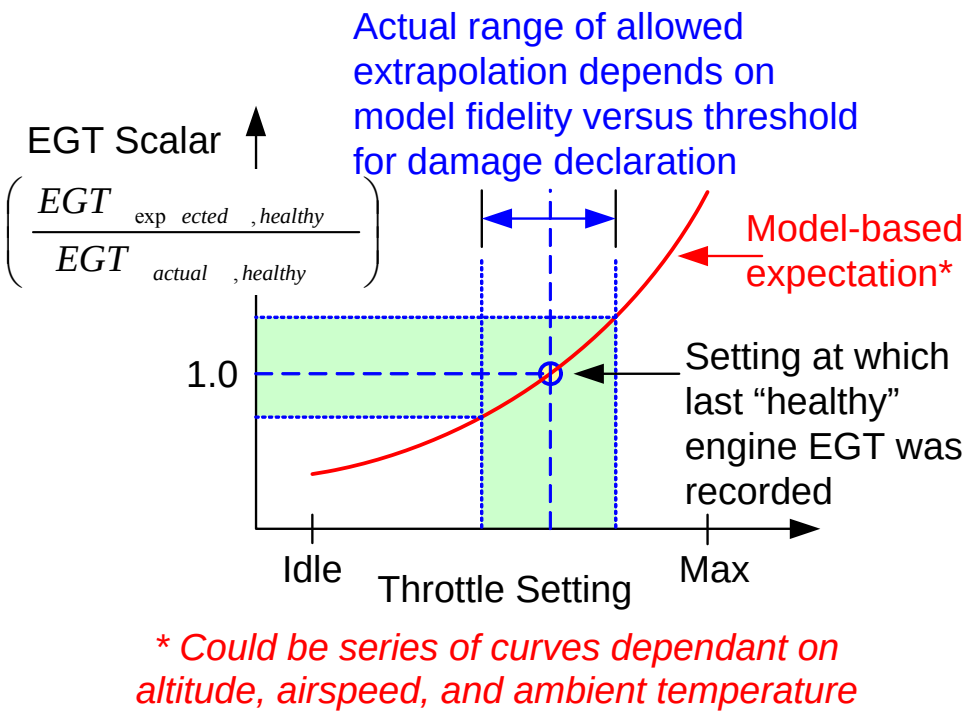


Figure 5-32. The EGT Trend Model

Strategy 3 potentially eliminates the constant thrust damage detection limitation. The other limitations associated with Strategies 1 and 2 remain:

- Damage latching is required
- Cascading alerts would be difficult to implement
- Degree of damage detection, available power capability, and restartability are not addressed

5.6.5 Strategy 4: Shift Detection Enhanced With Trend-Based Model.

A potentially more robust approach to establishing the undamaged engine signature across a broad range of power settings is to trend the sensor readings over multiple flights. Such a concept formed the basis for Strategy 4. Unlike the previously described strategies, such a concept would require nonvolatile memory. However, this requirement is not necessarily technologically prohibitive and in fact is a limited form of existing EHM systems currently in service with selected engine models and airlines. While such EHM systems are usually ground-based, nonvolatile memory is used to store the information on the aircraft until download or transmission to the ground computer. The difficulties associated with developing this concept would primarily be associated with both (1) the extensive data collection required for establishing both the specific engine baseline and (2) ensuring that a wide enough range of operating conditions were trendable over the period of interest.

The concept proposed under Strategy 4 would replace Strategy 3's predetermined normalized models of undamaged engine behavior with a trend established by sampling the engine parameters being monitored for damage (e.g., indicated vibration or EGT) over a limited number of recent flights. Trend establishment for indicated vibration is expected to be fairly straightforward and predominantly a function of rotor speed. As shown in figure 5-33, an envelope of the undamaged engine indicated vibration trend would be established over a limited number of recent flights and directly compared to the real-time level for damage detection. Another possibility with tracked-order vibration amplitude trending is to monitor the on-board balancing system available with modern AVMs. This system allows the rotor imbalance to be directly determined and, thus, eliminates frequency dependence potentially inherent in amplitude trending.

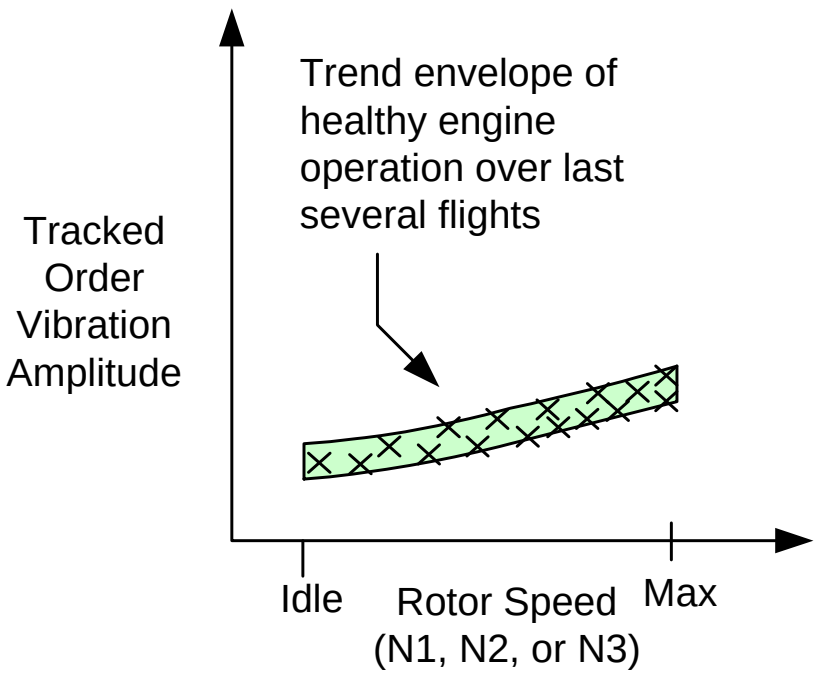


Figure 5-33. Indicated Vibration Trending

As with Strategy 3, development of an expected level of EGT for an undamaged engine is more complex than indicated vibration. The multivariate dependency of EGT can be reduced somewhat by correcting EGT to standard day conditions, as shown in figure 5-34, but corrected EGT would remain a four-dimensional function of ambient pressure, flight Mach, and rotor speed.

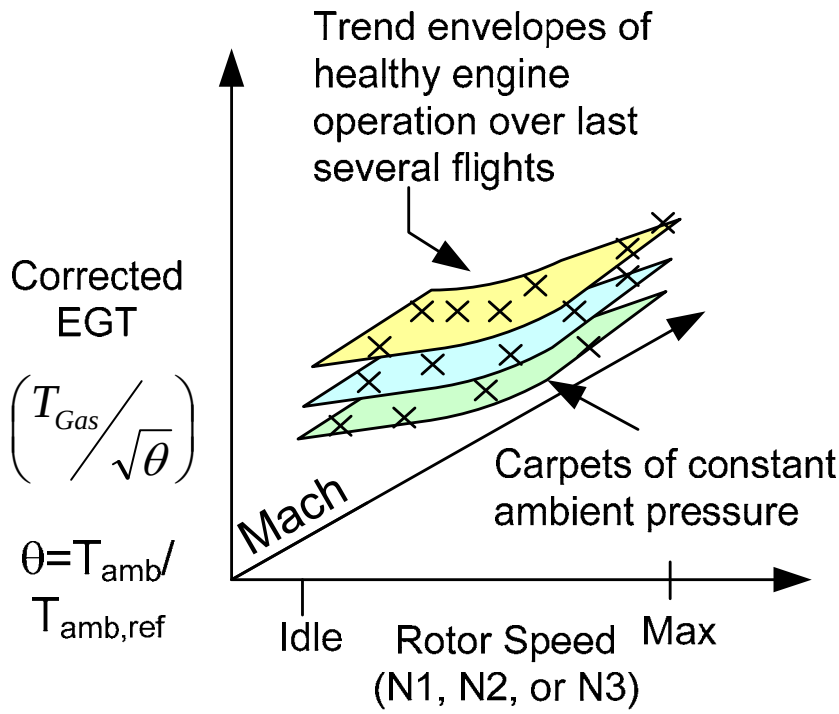


Figure 5-34. Engine Gas Temperature Trending

Relative to Strategy 3, Strategy 4 gains additional robustness in overcoming the constant thrust detection limitation of Strategies 1 and 2, at the expense of more complexity, and issues such as the time required to acquire the complete carpet, and loss of specific engine data with EEC replacement. Strategy 4 also retains the basic operational limitations cited for Strategy 3 (i.e., damage alert latching, alert cascading with progressive damage, and an inability to forecast restartability or available power range). Further discussion of the consequences and considerations associated with these limitations is discussed in section 5.7.

5.7 SENSOR FUSION ANNUNCIATION AND RESPONSE CONSIDERATIONS.

5.7.1 Annunciation and Alert Latching.

All the sensor fusion strategies outlined in sections 5.3 through 5.6 are expected to require latching of the damage alert. From a propulsion system perspective, this latching is necessary for at least two reasons:

- The damage typically does not self-heal. As such, the parameter shifts are expected to remain until a postflight correction action is taken. Under a Strategy 3 or 4 concept, clearing the damage alert potentially renders subsequent damage detection unreliable (i.e., pre-existing damage potentially invalidates the expected undamaged trends) and violates the reliability detection requirements.

- Only significant damage justifying crew awareness is proposed to be detected and alerted with any of the sensor fusion concepts. To avoid inappropriate flight crew response at

some future point in the flight where elevated power might otherwise be desired, indication of the damaged state should persist for the remainder of the flight and until dispositioned by maintenance.

This alert-latching approach is consistent with existing practice for status messages. As with existing dispatch-critical status messages, the damage alert is expected to be cleared on the ground after maintenance procedure.

5.7.2 Potential Consolidation and Cascading of Engine Damage Alerts.

The four strategies outlined above fundamentally segregate engine behavior into two states: damaged versus undamaged. Once damage is detected, the appropriate response category alert is set and latched. After a review of the correlation between the potential alerts and the engine damage modes associated with each alert, two generalizations could be made.

- Both the awareness only and the restrict thrust response categories would be set by gas path damage and could be combined in a single alert.

- A gas path engine damage mode only would transition from an engine damage alert to a shutdown alert if the damage increased to affect the lubrication system.

As discussed in section 3.3, the awareness only and restrict thrust categories were merged into a common awareness/restrict thrust category.

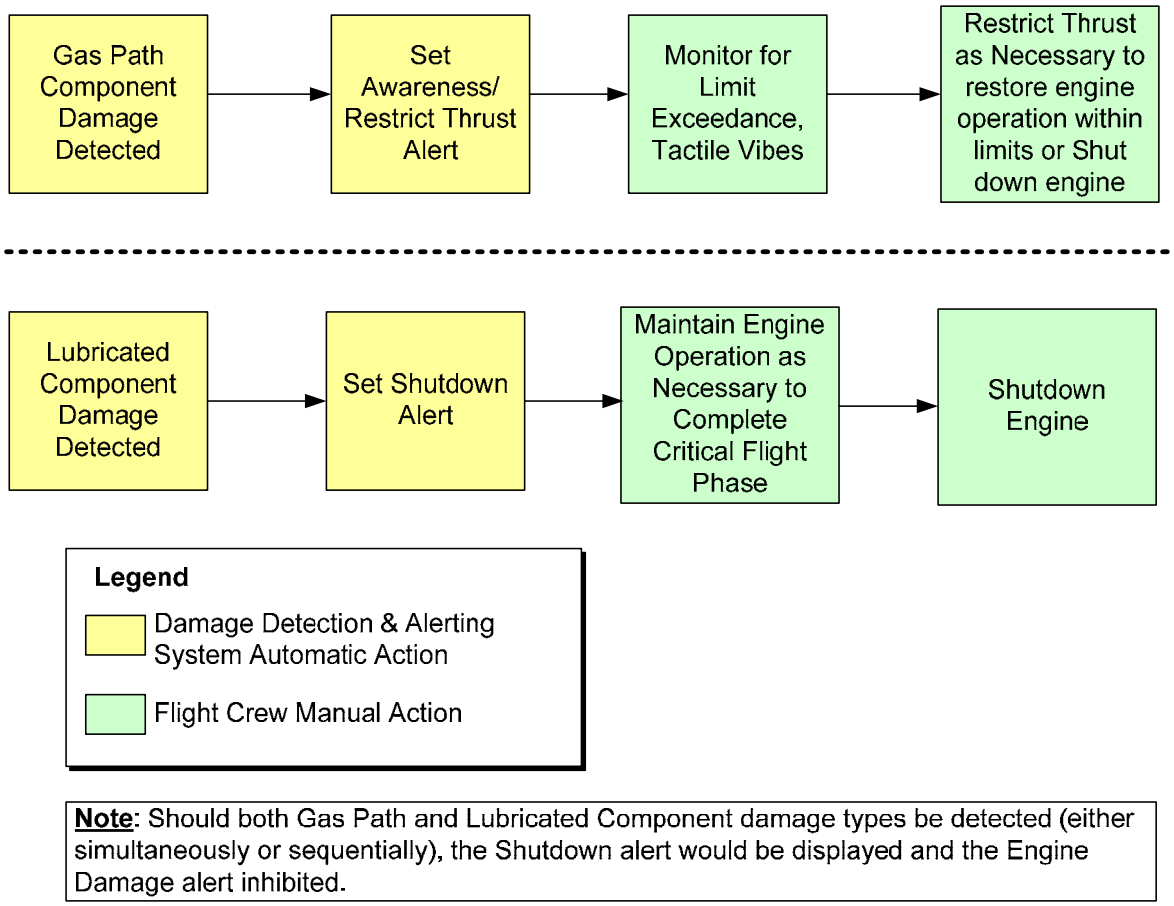
Shutdown was retained as a distinct response category and alert because the component damage is separate from gas path and justifies unique crew awareness and response:

- Engine has damage that may progress to an uncommanded shutdown with extensive economic damage.

- Limited continued operation is acceptable, but engine should be shut down as soon as possible.

Note that neither isolate bleed air nor immediate shutdown are proposed as new alerts as these damage conditions are already covered by existing duct leak and fire alerts.

When gas path damage precedes lubricated component damage, the initial gas path damage alert is latched and further gas path damage monitoring is suspended. Automated monitoring for additional parameter shifts would continue for those conditions where the damage spreads from gas path to lubricated components. For this case, the engine damage/restrict thrust alert would be cleared and replaced by the shutdown alert. When gas path and lubricated component damage are coincident or lubricated component damage occurs first, only the lubricated component shutdown alert would be displayed. Figure 5-35 illustrates this alert and response sequencing for detected gas path and lubricated damage.



Note: Should both Gas Path and Lubricated Component damage types be detected (either simultaneously or sequentially), the Shutdown alert would be displayed and the Engine Damage alert inhibited.

Figure 5-35. Alert and Response Sequencing

5.8 TASK 4 CONCLUSIONS.

The feasibility of a sensor fusion-based damage detection system was assessed by a review of available service data for in-flight damage effects correlated to specific gas path and lubricated component damage modes. While further detailed data are required to calibrate the specific thresholds for damage annunciation, the existing data analyzed in Task 4 revealed the most likely affected parameters associated with these damage modes. Collection of detailed in-service time history data is identified as a potential follow-on research objective in section 8.

Task 4 applied the damage effects data from Task 1, the detection fidelity requirements from Task 2, and the alerting reliability annunciation criteria from Task 3 to develop four distinct sensor fusion damage detection strategies. These detection strategies have the potential to provide benefits for ICR primarily by improving awareness of the specifically affected engine. The degree of benefit beyond existing single-parameter limit exceedance damage detection systems depends on the level of additional new coverage it provides, and the complexity of the adopted scheme:

- Strategy 1 (two-parameter shift detection) is the simplest to implement, but is limited to constant thrust setting damage detection, which does not provide sufficient operational

robustness, and is not expected to fulfill this research's secondary objective of identifying dispatch-critical maintenance requirements.

- Strategy 2 (multiple-parameter shift detection) retains the constant thrust limitation of Strategy 1, which does not provide sufficient operational robustness, but does provide improved damage isolation (to the affected major module or subsystem). As such, it better fulfills the requirement to identify dispatch-critical maintenance.

- Strategy 3 (two- or multiple-parameter shift detection enhanced with performance models) introduces additional complexity to overcome the constant thrust limitation of Strategies 1 or 2.

- Strategy 4 (two- or multiple-parameter shift detection enhanced with trend-based models) provides a potentially broader damage detection range (i.e., across a wider range of engine power settings) than Strategy 3. This increased capability requires the use of nonvolatile memory to store engine data between flights.

A principal challenge associated with developing any of the four sensor fusion strategies is establishing the appropriate thresholds for damage annunciation. Setting the threshold too low would invite the problems previously cited: increased risk of unnecessary IFSDs, diversions, air turn-backs, and additional maintenance. Setting the threshold too high reduces the coverage and availability and hence, the intended benefit. To reap the potential benefits for ICR prevention, the awareness/restrict thrust (gas path component damage) annunciation threshold should be set such that a near-term (i.e., within the current flight) limit exceedance or uncommanded shutdown is likely. In any case, an extensive in-service data collection effort is required and must include all engine-aircraft design combinations for which the concept is intended. A risk versus benefit assessment associated with implementing these strategies is provided in section 6. The potential benefits of alerting for excessive or abnormal indicated vibration are also discussed in section 6.

None of the Task 4-evaluated strategies are expected to provide degree-of-damage detection capability. Rather, these concepts are expected to resolve the engine condition to a damaged or undamaged state only and, in the case of lubricated component damage, provide a recommended response. Sensor fusion-based damage detection is expected to result in two potential new alerts: awareness/restrict thrust—an awareness alert for gas path component damage and shutdown—a preferred response alert for lubricated component damage. The awareness/restrict thrust alert depends upon subsequent pilot monitoring of other symptoms and alerts to determine if thrust reduction is required.

A Task 2 goal of this research was to determine if automated available power range or restartability detection capability could be provided with sensor fusion. Task 4 concluded that these features would likely be well beyond the capability of sensor fusion and would require the introduction of sophisticated models of damaged engine behavior and/or new sensor technology. An example challenge for restartability determination is validating gas path air seal integrity while the engine is windmilling (shutdown). Examples of the expected requirements for automated determination of damaged engine power capability are outlined in table 5-6.

Table 5-6. Example Damaged Engine Automated Power Determination Requirements

Module	Example Prediction Capability Required in Damaged Mode
Fan	Actual thrust versus control parameter (N1 or EPR)
Compressors	Real-time surge margin
Combustor	Lean blowout limit and maximum temperature capability
Turbines	Available EGT margin to redline
Lubricated Components	Available time margin to complete failure

In summary, sensor fusion-based damage detection systems are considered potentially feasible with current technology and principally provide potential improvements for damage awareness and avoidance of ICR to PSM. Implementation of robust algorithms requires the acquisition of extensive engine damage data to be able to set damage detection thresholds to meet flight deck alert availability and reliability criteria. Further, the data would have to be collected for each certified engine-airplane combination. As such, there are questions as to whether new engine designs would be able to field the capability at entry into service or have to wait until they have accumulated sufficient service baseline data. Additionally, the development of capabilities beyond basic awareness of the damaged engine and identification of dispatch-critical maintenance requires further research, which may necessitate the introduction of complex real-time models or new sensor technology.

6. DAMAGE DETECTION IMPLEMENTATION CONSIDERATIONS.

Introduction of new damage detection and annunciation requires a consideration of the service benefits versus the risks of development and implementation. This section documents both the incremental improvements available from and the implementation considerations for the Task 4-developed damage detection strategies. The risks and potential benefits for each Task 4 strategy are compared against the baseline detection and annunciation as well as improved annunciation for indicated vibration.

6.1 INDICATED VIBRATION ANNUNCIATION.

14 CFR 25.1305 requirements for turbojet engine-powered airplane power plant instruments include "an indicator to indicate rotor system unbalance." Aircraft manufacturers have typically satisfied this requirement by the tracked-order vibration detection and display schemes described in section 5.5.4. Such display systems typically do not include centralized alerting of excessive vibration beyond simple means to increase awareness of the current indicated vibration level. Examples of such awareness techniques include changing the color or blinking the vibration indication when a specific threshold is exceeded.

The current indicated vibration display philosophy has evolved for a variety of reasons:

- Early AVMs suffered from low reliability and thus low credibility.
- Typically, no operational limits exist for high vibration.
- Vibration levels are not strictly related to damage, nor does damage strictly correlate to high vibration. As described in section 5.5.4, high indicated vibration can be also caused by non-damage-related rotor imbalance or ice accretion. Variations in airline operator engine balancing practices result in a wide range of indicated vibration levels during normal undamaged engine operation. Lastly, high indicated vibration may attend normal engine speed regions or flight phases, such as takeoff or landing.

Although modern AVM systems have greatly improved reliability and expanded capability, the other ambiguities cited above result in no one procedure that is suitable in all high vibration circumstances.

As part of the assessment of the spectrum of detection schemes (current to future), this research considered alerting excessive indicated vibration as an alternative to the awareness only damage alert discussed in sections 4 and 5. In this concept, the indicated vibration display would be complemented with an alert message when a threshold vibration level was exceeded. Like the engine damage alert, an excess vibration alert would identify the specifically affected engine and provide a procedure. The subsequent pilot response would be guided by other engine indications or alerts as described in sections 4 and 5. Note, the concept was not fully developed because single-sensor damage detection and alerting was not a primary focus of this research. However, consideration of excessive indicated vibration alerting is warranted to evaluate the full potential scope of annunciation strategies.

Indicated vibration alerting would likely realize the same drawback associated with a sensor fusion-based awareness/restrict thrust alert: namely, without specific procedural guidance, introduction of this alert may cause increased risk of IFSD, diversions, air turn-backs, and airline maintenance burden. In the case of indicated vibration alerting, these risks are likely much greater because, without the fusion of additional sensors for damage detection, the possibility of setting the alert for non-damage-related alert scenarios is much higher. Elevating a supplemental indication such as high indicated vibration to an alert creates an implied level of criticality that may be inappropriate.

During the reference 4 event, there was an indication of excessively high indicated vibration that did not appear to be detected or sufficiently considered by the crew. Even though an excessive vibration alert may have ensured crew awareness of the affected engine during this event and possibly prevented the shutdown of the good engine, the potential for overreaction to an indicated vibration alert during other more commonly encountered scenarios greatly limits the effectiveness of this alternative. As with an awareness/restrict thrust alert, the lack of specific procedural guidance for excessive indicated vibration alert necessitates further research to assess the implementation and human factors issues.

6.2 DAMAGE DETECTION SYSTEM BENEFIT COMPARISON.

Commercial turbofan engine damage events leading to unscheduled removal or IFSD are very infrequent. For modern FADEC-equipped engines, these rates are less than one in 10,000 engine hours for unscheduled removals and less than one in 100,000 engine hours for IFSDs. When coupled with the rarity of documented ICR events, new engine damage detection, annunciation, and alerting systems are expected to provide only modest improvements beyond current limit exceedance systems. However, depending on the desired extension of damage detection capability, a varying range of improvements may be possible in the future once an appropriate suite of data is collected. While new sensor fusion damage detection strategies appear feasible, validation of that feasibility and an assessment of potential coverage necessitate the empirical in-service damage event data that presently are not available.

Excess indicated vibration alerting and sensor fusion damage detection both provide better awareness than presently exists and both have ICR prevention potential for scenarios where distinguishing the damaged engine may be difficult (i.e., where the potential for crew misinterpretation or error exists). However, both concepts require crew monitoring and interpretation and fall short of providing deterministic operational information regarding the degree of engine damage, the engine module affected, and the damaged engine's capability. Ultimately, only a very advanced engine damage detection system that incorporates adaptive and prognostic engine models and possibly new sensors is likely to achieve the desired operational information: damaged engine thrust capability, capacity for continued/sustained operation, and restart capability prediction.

The specific benefits and limitations available from each type of damage detection, ranging from vibration alerting to advanced systems, are contrasted in table 6-1.

Table 6-1. Engine Damage Detection Benefits Comparison

Capability Relative to Existing Limit Exceedance System	Vibration Alerting	Sensor Fusion: Strategy 1	Sensor Fusion: Strategy 2	Sensor Fusion: Strategy 3	Sensor Fusion: Strategy 4	Advanced System
Improved Awareness of Selected Damage Modes	Able to identify specifically affected engine, but potentially prone to alerting for non-damage-related scenarios (i.e., high imbalance and icing). As such, vulnerable to increased unnecessary thrust restrictions, IFSDs, diversions, and air turn-backs.	Improved ability to distinguish engine damage from icing or non-damage-related rotor imbalance.				Resolvable to specifically affected engine component
			Resolvable to major engine module (depends on the number of fused sensors). Critical maintenance identification capability.			
Annunciation and Reponse Capability (Degree of Crew Awareness Provided and Assessment Required)	Nondeterministic: Inferrerence of possible engine damage. Awareness only. Appropriate response guided by pilot interpretation of other indications, alerts, annunciations, and symptoms.	Semideterministic: Reliable correlation that significant gas path or lubricated component damage is present. Gas Path Damage: Awareness only. Appropriate response guided by pilot interpretation of other indications, alerts, annunciations, and symptoms. Lubricated Components Damage: Alert provides advance detection prior to uncommanded shutdown. Crew assessment required for shutdown timing.				Deterministic. Potential detection of engine damage supplemented with power capability, restarability, and available operating duration information. Limited crew assessment required.
Damaged Engine Power Capability	Requires manual throttle action and pilot monitoring, assessment and interpretation of other indications, alerts, annunciations, and symptoms.					Potential capability
Damaged Engine Restart Capability	No projected capability	Limited capability for predicting inability to restart. Challenge is how to communicate this effectively and efficiently.				

6.3 DAMAGE DETECTION SYSTEM DEVELOPMENT RISK ASSESSMENT.

Implementation of the damage alerting strategies described in section 5 entails varying degrees of increased cost for both the aircraft and engine. While Strategy 4 may include increased hardware costs for expanded use of nonvolatile memory, all the proposed concepts potentially drive increased software complexity and therefore development and certification costs. Additional costs include continued updates with in-service events or resolution of implementation issues. Software is certified to a level consistent with its usage and potential effects. Software associated with critical engine functions, such as thrust control and critical action alert displays, are certified to higher levels than noncritical functions such as indicated vibration display. EHM functions are only required to be certified to the lowest levels. Most FADECs do not partition their software functions, so any software incorporated into the FADEC would likely be certified as critical, unless a software-partitioning scheme were introduced (at increased complexity to the FADEC design).

The damage detection strategies developed in Task 4 all include expanded use of indicated vibration. Use of indicated vibration for damage alerting may result in elevated software certification levels for vibration sensing and processing. However, since the proposed damage detection strategy involves the integration of at least two parameters, the potential exists that the use of an existing high-integrity signal (e.g., EGT) combined with one lower-integrity signal, such as vibration, may be acceptable, as long as it can be demonstrated that a failure of the lower-integrity signal alone will not have an unacceptable affect.

The potential implementation risks associated with each Task 4-developed sensor fusion damage detection strategy are compared with the development of vibration alerting and advanced engine damage detection systems in table 6-2. As indicated in this table, the expected development and operational risks are lowest with vibration alerting and are incrementally elevated with the added complexity inherent in the sensor fusion schemes. Not unexpectedly, the greatest development risk and cost would be associated with an advanced system that fulfills all the desired operational objectives, including damaged engine power, capability for continued operation, and restart capability prediction.

Table 6-2. Engine Damage Detection Implementation Risk Assessment

Concept	Relative Development Cost	Relative Operational Risk
High Indicated Vibration Alert: Alerting and procedure for existing indicated vibes exceedance.	Low: Limited to display software changes only.	High: Difficult to establish thresholds that are damage-related only and thus avoid any increased rate of unnecessary IFSDs, diversions, air turn-backs, and maintenance for nondamage events.
Sensor Fusion Strategy 1: Fused EGT and indicated vibration (gas path components) or oil system parameter (lubricated components) shift correlation without use of models.	Medium: Cost to collect necessary in-service damage signature data (but could entail lengthy collection period).	High: Risk of meeting operational requirements (due to steady thrust limitation). Medium risk of meeting reliability requirements (dependent on the degree of desired damage resolution (could be high)).
Sensor Fusion Strategy 2: Multiple (more than two) parameter shift correlation without the use of models.	Medium High: Elevated costs over Strategy 1 due to the inclusion of more parameters.	High: Same level of risk cited for Strategy 1 in terms of steady thrust limitation. Slightly reduced risk for increased unnecessary maintenance relative to Strategy 1 due to improved fidelity of damage resolution. Medium risk for meeting reliability requirements.
Sensor Fusion Strategy 3: Fused EGT and indicated vibration (gas path components) or oil system parameter (lubricated components) shift correlation against simple model.	Medium High: Same as above, including development of undamaged engine parameter models (trends) and minor engine adaptive capability. Higher risk than "no model" option to meet requirements due to additional complexity.	Medium: Lower operational risk than Strategy 1 or 2 (steady thrust limitation removed). Medium risk for meeting reliability requirements.
Sensor Fusion Strategy 4: Fused EGT and indicated vibration (gas path components) or oil system parameter (lubricated components) shift correlation against multiple-flight, trend-based models.	Medium High: Same as above, except nonvolatile memory expansion and more complex or adaptive trend monitoring/models capability addition required. Higher risk than "no model" option to meet requirements due to additional complexity.	Medium: Same as Strategy 3.
Advanced Damage Detection System: New sensors plus adaptive and prognostic models.	Very High: Development costs due to high software complexity (including model construction and calibration) and development of new sensor technology associated with damaged engine power and restart capability prediction.	Low: Expanded capabilities for damaged engine power and restart capability potentially provide for improved determinism in response direction.

7. CONCLUSIONS.

The focus of Phase 3 was improved damage detection and annunciation using fusion of existing sensors. Sensor fusion-based engine damage detection and annunciation appear to be feasible to implement; however, it provides only modest and limited operational benefits (awareness and guidance) over existing systems. Further collection of detailed time-history data for engine damage events correlated with inspection findings are required to establish the specific capability of sensor fusion damage detection and annunciation (refer to section 8.1 for further discussion of in-service data collection).

7.1 TASK 1 CONCLUSIONS.

Task 1 assessed all potential propulsion system damage modes significant enough to warrant annunciation for crew awareness or response. A comprehensive review of 6 years of in-flight shutdown (IFSD) and unplanned engine removal (UER) in-service reports was completed. This review included all events, even for non-Full Authority Digital Engine Control (FADEC) engines. For physical engine damage, this suite of events is statistically significant and appropriate.

The service report review identified the principal engine failure modes that cause both UERs and IFSDs. These failure modes were categorized against a generic physical model of a modern two-spool turbofan engine installation. Conclusions regarding specific component failures include the following:

- Damage to gas path components, such as airfoils and air seals, are the principal drivers for UERs. Due to higher sensitivity to ingested foreign objects, the high-pressure compressor (HPC) is the most frequently damaged compression system component. The high-pressure turbine (HPT) is the most frequently damaged hot section component due to high gas temperature exposure.

- Engine subsystem damage was the highest contributor to IFSDs. Within the engine subsystems category, lubrication system and lubricated components were the dominant failure items. Gas path components were the next strongest contributor—at about half the level of engine subsystem components. When gas path component damage caused an IFSD, in most cases, an UER also resulted.

- As expected, failures of line replaceable units (LRU), such as sensors, drove a far greater proportion of IFSDs than UERs (although there were some recorded cases of UERs precipitated by LRU failure). The IFSDs resulting from sensor failures were categorized according to specific sensor type. Lubrication system sensors, such as oil pressure, filter differential pressure, temperature, and oil reservoir quantity, accounted for nearly half of all sensor failure-related IFSDs. (Note that a marked reduction in sensor-related IFSDs was noted for newer electronically controlled engines.) The sensor fusion strategies developed later in Task 4 directly use these same engine sensors. Achieving the Task 3-established high standards for damage detection availability and reliability necessitates restricting the introduction of any new sensor-based damage detection systems to electronic control-equipped engines.

A propulsion system failure analysis complemented the findings from the in-service data review. This failure analysis assessed which damage modes were adequately covered by existing detection methods (either sensor- or visual inspection-based), required introduction of new sensors, or had the potential for improved damage detection using fusion of existing sensors. Within the sensor fusion category, detection of gas path and lubricated component damage offered the greatest potential benefit for inappropriate crew response (ICR) avoidance.

Task 1 re-examined the previously documented 80 propulsion system malfunction (PSM)+ICR events and ensured the Task 1 damage analysis encompassed the known events. At least 55 events were assessed to include engine damage. Further, the types of damage and associated indications were determined to be consistent with the Task 1 work. Engine damage annunciations were assessed to be a primary means of alerting in at least 5%, but not more than 11%, of the Phase 1 PSM+ICR events. Another 15 events (approximately 20% of the total) were assessed to be covered by either Phase 2 sustained thrust anomaly or Phase 3 alerts. However, in these 15 events, the Phase 2 alerts were assessed as more operationally appropriate and feasible to implement because they either already exist as certified designs or provide a more deterministic condition or response than engine damage alerts.

7.2 TASK 2 CONCLUSIONS.

Task 2 classified the principal economic and operational reasons for annunciating engine damage. For flight crew alerting purposes, engine damage was divided into five distinct groups: an awareness-only category and four distinct response categories—restrict thrust, shutdown, immediate shutdown, and isolate bleed air. Of these five categories, existing engine fire and bleed air leak procedures were determined to adequately cover the immediate shutdown and isolate bleed air response groups. The three remaining categories were reduced to two: awareness/restrict thrust and shutdown, which were assessed to correspond to gas path and lubricated component damage, respectively. All the potential new alerts were concluded to be feasible categories for the Task 4 development of engine damage detection using existing sensors.

Task 2 assessed the detection capability required to support two operational objectives for engine damage detection: damaged engine restartability and power capability. The minimum engine integrity requirements to support engine restart were assessed first. The indications available to detect this minimum integrity were then evaluated on a detailed engine component basis. While many engine components' integrity was sufficiently detectable with existing sensors, some components, such as gas path air seals, are expected to require new sensors to support restartability prediction. Similar to restartability, the current procedure for damaged engine power capability determination was assessed to require manual pilot action and, thus, unlikely to be replaceable by an automated system without the introduction of complex modeling or new sensor technology.

7.3 TASK 3 CONCLUSIONS.

The PSM detection and annunciation capability currently available on modern commercial transports provide considerable protection against ICR. Although ICR prevention enhancements are possible through expanded engine damage detection and annunciation, other unintended effects may arise without deterministic procedural requirements, such as: unnecessary IFSDs, air turn-backs, diversions, and increased maintenance.

A two-alert strategy was proposed that corresponded to gas path and lubricated component damage. These new alerts were determined to be compatible with existing engine alerting and annunciation systems.

Detection and annunciation criteria were characterized according to:

- Availability: ability to detect and alert genuine engine damage
- Unavailability: failure to detect and alert genuine engine damage
- Reliability: false detection and annunciation

Since new engine damage alerting is considered an enhancement only, priority was given to ensuring these new alerts would be operationally acceptable. Thus, high reliability standards were applied to the new damage alerts.

Task 3 also concluded that the benefits and feasibility of engine damage detection and annunciation were proportional to the level of procedural determinism associated with new engine damage detection and alerting. Detection and annunciations that limit the amount of crew interpretation and reduce variability in the associated response offer the greatest potential benefit. The lower the detection and annunciation determinism, the less desirable and feasible are the strategy and implementation.

While noting that improved damage detection and annunciation may offer ICR prevention potential, Task 3 also concluded: emphasis on improved Title 14 Code of Federal Regulations Part 121 operational oversight of airline policies, practices, and procedures can have an equally positive and potentially greater impact on ICR prevention and mitigation.

7.4 TASK 4 CONCLUSIONS.

The likelihood of sensible shifts in engine parameters during significant damage events was determined by expert opinion and the potential was established from a review of the available service reports. It was determined that the type of high-fidelity data required to develop and validate a reliable detection strategy was not available. The specific requirements for such high-fidelity data were for damage scenarios where

- the engine operates for a sufficient period to register operating sensible parameter shifts and

- the specific engine damage is established with postfailure inspection.

Damage events involving gas path and lubricated components were assessed and categorized for detection by either postflight inspection or in-flight effects. For those events detectable by in-flight effects, such effects were further categorized according to the specific indication shift(s), annunciation, alert, or other effect such as surge or uncommanded shutdown. The number of effects was then tabulated for each specifically damaged gas path or lubricated component to determine the relative likelihood of a sensible shift corresponding to the damaged component. The results of this process suggested that exhaust gas temperature shifts, surge, and indicated vibration shifts were most common for gas path component damage. Conversely, lubricated component damage was most frequently characterized by oil system indications (low pressure, high temperature, etc.) and indicated vibration shifts.

The focus of Phase 3 was to develop and assess engine damage detection and annunciation using existing sensors. Consistent with this criterion, Task 4 applied the damage effects data from Task 1, the detection fidelity requirements from Task 2, and the annunciation reliability criteria from Task 3 to develop four distinct sensor fusion damage detection strategies. In order of increasing complexity, these strategies included:

- Strategy 1 (two-parameter shift detection)—constant thrust-setting damage detection strategy that flagged a damage event when two parameters shifted beyond a pre-established threshold. Accommodation was provided to record damage coincident with compressor surge.

- Strategy 2 (multiple-parameter shift detection) added shift monitoring of additional gas path and oil system parameters to allow identification of the specifically damaged engine module for dispatch (maintenance). Such a strategy was determined to better fulfill the requirement for airline operations than Strategy 1 but still retained the constant thrust detection limitation.

- Strategy 3 (two- or multiple-parameter shift detection enhanced with performance models) introduced additional complexity through FADEC-resident models to overcome the constant throttle limitation of Strategies 1 or 2.

- Strategy 4 (two- or multiple-parameter shift detection enhanced with trend-based models) provided a potentially broader damage detection range (i.e., across a wider range of engine power settings) than Strategy 3 by trending undamaged engine behavior over several flights to establish a baseline for shift comparison. This strategy requires nonvolatile memory to store data between flights.

All the Task 4-developed strategies provide improved awareness of engine damage and, in cases of lubricated component damage, provide a recommended shutdown response. Strategies 1 and 2 were deemed operationally unacceptable due to constant thrust limitation. The variable thrust accommodation inherent in Strategies 3 and 4 was considered operationally acceptable. None of these strategies are believed to be capable of detecting degree-of-damage, available power range, or restart capability. The awareness/restrict thrust alert provides a benefit in terms of identifying the affected engine (and reduction of shutdown good engine (SDGE) ICR potential). Based on engine parameter data, sensor fusion would likely have appropriately identified the affected engine and possibly prevented the ICR that occurred during the January 8, 1989, Kegworth

event. To ensure appropriate sensitivity to an awareness-only alert (i.e., avoid overreaction to detected engine damage), the threshold for damage detection should be set relatively high: damage should be such that near-term limit exceedance or uncommanded shutdown (within the current flight) will likely occur. Establishing such a threshold will require a robust evaluation of potential fault data for each engine and aircraft combination targeted to incorporate such damage detection.

7.5 COST/BENEFIT CONCLUSIONS.

The benefits assessed in Phase 3 accrue primarily to new and future aircraft. Over 80% of the Aerospace Industries Association and European Association of Aerospace Industries PSM+ICR events occurred in older airplanes equipped with non-FADEC controls. Current modern aircraft system designs (e.g., FADEC) and aircraft capability (e.g., engine monitoring, datalink, satellite communications, etc.), and crew training reduce the potential for PSM+ICR. As an example, it is possible that high indicated vibration annunciation alone (such as is available in many modern commercial transport aircraft) may have been sufficient to have directed the crew to the affected engine in the event.

Human factors considerations and an integrated approach to PSM+ICR is warranted. In this regard, an integrated approach includes:

- Complementary design and operational policies, practices, and procedures, and improved training
- Synergy with higher-order airplane functionality such as control and navigation
- The appropriate combination of automatic and manual PSM accommodation
- Appropriate combination of airborne and ground-based capability

A detailed cost/benefit assessment of these strategies was not part of this research effort, but several issues were identified that would be needed to complete a comprehensive cost/benefit study. Primarily, a program to obtain the type of data required to develop and validate a reliable algorithm would be needed.

The cost of additional airborne damage detection and annunciation should be weighed against alternatives that expand the use of existing systems. As an example, aircraft health-monitoring data could be continuously transmitted to a ground station via an existing radio data link such as the Airborne Communications Addressing and Reporting System (ACARS). An interpretation, assessment, and response recommendation could be made by an expert ground team and communicated in real time back to the flight crew.

Another consideration is the known advancement in engine health monitoring (EHM). EHM offers the potential for early detection of engine damage prior to deterioration to operationally significant levels and is, thus, a potential alternative to improved damage annunciation. Sophisticated EHM engine performance deterioration algorithms that incorporate the basic concepts of the strategies presented in section 5 are known to have been implemented in a variety

of applications including military and commercial transport aircraft as well as ground-based and marine power applications. Currently, EHM primarily performs a maintenance cost reduction service by identifying necessary maintenance prior to the occurrence of widespread (and thus, economically expensive) deterioration. In such scenarios where undetected engine deterioration could otherwise lead to significant performance loss during an operational scenario, timely maintenance reduces the occurrence of PSM, and thus reduces the opportunity for ICR.

8. FUTURE WORK.

Phase 3 focused on engine damage detection and annunciation through fusion of existing sensors. Additional data is required to determine the quantitative levels of parameter shifts that attend significant engine damage events. Such data could be acquired through a dedicated in-service data collection effort, as described in section 8.1.

Operationally desired objectives for engine damage detection included automatic prediction of damaged engine power capability for continued engine operation and engine restartability. The feasibility of developing these capabilities requires further research into advanced damage detection sensors and performance models. An example of such modeling effort is described in section 8.2.

All the sensor fusion damage detection strategies for gas path damage, which do not trigger an existing alert, require pilot monitoring and interpretation to the appropriate response to engine damage. Sensor fusion damage detection capability is intended to supplement and compliment mostly prescriptive existing PSM detection and alerting. The potential benefits from integrating these prescriptive indications into an alternative display format are recommended by the research described in section 8.3.

8.1 DETAILED IN-SERVICE ENGINE DAMAGE DATA COLLECTION.

The available service data for in-flight effects correlatable to specifically damaged engine components is limited to qualitative event descriptions only. The appropriate thresholds for declaring damage from detected parameter shifts can only be established through a comprehensive review of quantitative data. Such quantitative data regarding the specific magnitudes of parameter shifts during engine damage events could be obtained by a focused in-service collection effort of either flight data recorder or other similar time-history data. Coupled with the existing available unplanned engine removal descriptions of the damaged components, the data collected from several aircraft over a sufficiently long period could provide an adequate database for damage detection threshold development. Further, the engine data should be correlated to pilot-reported effects such as tactile vibration and smoke/odor in the flight deck or cabin.

8.2 DAMAGE DETECTION TECHNOLOGY DEVELOPMENT.

Beyond the damage alerting evaluated in Phase 3, advanced engine damage detection and associated performance modeling offer other potential operational benefits. Specifically, damaged engine detection could enable:

- Adaptive controls that provide continued damaged engine operation (although at potentially lower thrust) for the remainder of the flight.

- Prediction of damaged engine power capability or restartability. Since automatic throttle movement to determine the specific trend of engine parameters is not an acceptable approach to achieving such capability, advanced models will be required that extrapolate the critical engine parameters to other throttle settings. An example requirement for such

performance models is prediction of available compressor surge margin. Schemes have been proposed for specific engine models that use dedicated compression path dynamic pressure sensors to monitor for pressure fluctuations along the compressor surge line. The feasibility of applying such schemes to a wide range of engines could be the focused topic of further research.

8.3 ADVANCED ENGINE DISPLAY PARADIGMS.

In the larger context of PSM+ICR, systems interface, and human factors considerations, further research is recommended into the development, demonstration, and validation of new normal and nonnormal engine display concepts. These concepts should support and facilitate pilot engine capability assessment and pilot decision making regarding continued engine operation, recovery, or shutdown. Beyond improved damage detection, sensor fusion is also an enabling technology for advanced information-based display concepts. Emphasis should be placed on developing information-based displays that relieve the flight crew of the engine parameter monitoring, detection, and interpretation tasks associated with current prescriptive displays. Integration with higher-order aircraft functionality or operational capability should be considered. Due to the quantity and nature of existing prescriptive instruments, an ideal candidate for such an information-based display is the engine lubrication system. It is recommended that a follow-on investigation focus on developing, demonstrating, and validating the benefits of certifiable alternatives to the current prescriptive data- (versus information) -based oil system indications.

9. DEFINITIONS.

Annunciations: A broad category of normal and nonnormal indications and/or aurals designed to draw or focus crew attention and to support crew awareness or action. For engine damage alerting strategy, annunciations refer to visual enhancements of affected engine indications.

Alerts: A subset of annunciations that relate to a nonnormal malfunction specific or nonnormal condition-specific annunciation requiring crew awareness or action. There are various alert levels, visuals and aurals, which are typically designed to ensure appropriate crew awareness and/or response, and lead to an appropriate crew procedure. For engine damage alerting strategy, alerts refer to text messages accompanied by attention-getting lights and aurals unique to each alert level.

Engine (or Aircraft) Health Monitoring: An engine (or aircraft) data collection and processing system that monitors trend changes in various operating and/or diagnostic parameters. The principal objective of the system is to provide timely notification of engine or aircraft maintenance requirement. Portions of the system may be both aircraft-resident and ground-based.

Gas Path Components: The engine components directly related to compression, combustion, and expansion of the inducted air.

Indicated Vibration: Engine vibration that is sensed, processed, and provided for cockpit display by the airborne vibration monitor. Typically, indicated vibration is processed to provide only tracked first order (i.e., once-per-shaft revolution) frequency content or, in some cases, broadband vibration.

Lubricated Components: Those components, such as gearboxes and bearings, that use the oil provided by the lubrication system.

Lubrication System: Those components that store, filter, and cool the oil provided to the lubricated components.

Sensor Fusion: The combination of discrete sensor outputs to provide higher-level system information.

Tactile (Sensible) Vibration: Aircraft vibration that is sensed by the flight crew or passengers. Tactile vibration may or may not correlate to indicated vibration.

Uncommanded Shutdown: An engine shutdown not directed by the flight crew (i.e., shutdown caused by engine damage or other external factors such as volcanic ash ingestion and bird strike).

Unplanned Engine Removal: An aircraft engine removal caused by circumstances other than scheduled overhaul, life-limited part removal, Service Bulletin or Airworthiness Directive compliance, performance margin expiration, or other reasons such as cycle-time stagger and lease expiration.

10. REFERENCES.

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4. UK Department of Transport Air Accidents Branch Air Accident Report 4/90, "Report on the Accident to Boeing 737-400 G-OBME Near Kegworth, Leicestershire on 8 January 1989," 31 August 1990.