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FLIGHT DECK ENGINE ADVISOR FINAL REPORT

W. D. Shontz
R. M. Records
D. R. Antonelli

Boeing Commercial Airplane Group
Flight Deck Research
Seattle, Washington

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NASA
National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23665-5225

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EXECUTIVE SUMMARY

The current project is part of a larger fault management research program funded by NASA-Langley. The focus of this project is on alerting pilots to impending events in such a way as to provide the additional time required for the crew to make critical decisions concerning non-normal operations. The project addresses pilots' need for support in diagnosis and trend monitoring of faults as they affect decisions that must be made within the context of the current flight.

Monitoring and diagnostic modules developed under the NASA Faultfinder program were restructured and enhanced using as inputs data from an engine model and real engine fault data. The model and data represent a current high by-pass turbofan engine. A total of eight (8) fault scenarios were prepared to support knowledge base development activities on the MONITAUR and DRAPhyS modules of Faultfinder. An analysis of the information requirements for fault management was included in each scenario. A conceptual framework was developed for systematic evaluation of the impact of context variables on pilot action alternatives as a function of event/fault combinations. A major effort on the project involved an attempt to reduce spurious symptoms in the output of the monitoring module. These spurious symptoms have been greatly reduced but not eliminated. The rule base in STAGE1 of DRAPhyS has been substantially enhanced based on fault data. STAGE2 of DRAPhyS has been modified to accept inputs directly from MONITAUR and suggestions for further enhancements to STAGE2 have been prepared.

Lesson learned include:

1. Solution of the spurious symptom problem with MONITAUR is imperative before proceeding much further with enhancement of diagnostic capability.

2. An adequate fault data base must be identified and accessed in order to support further feasibility testing of the Flight Deck Engine Advisor system.

3. The impact of context variables on the appropriateness of crew action alternatives in the face of event/fault combinations needs to be systematically evaluated.

4. The impact of current and anticipated levels of automation on fault management in general and on context/crew action relationships in particular should be determined.

A proposal submitted for follow-on activities in developing a Flight Deck Engine Advisor system addresses the above recommendations.

FLIGHT DECK ENGINE ADVISOR

FINAL REPORT

1.0 INTRODUCTION

In today's commercial airliner flight decks, a non-normal event must have occurred or a parameter threshold exceeded before an alert is evoked. This leaves the crew with little or no advanced warning when response decisions have to be made to events such as flame outs, thrust shortfall, or engine overspeed. The degree of automation now present in the subsystem interface on modern commercial airplanes can lead to situations where pilots are out of the loop until their intervention is required. This in turn can lead to a degradation in systems situational awareness and make the decision process more difficult with a higher probability of error.

Automated monitoring and integration/fusion of engine data and airplane information, for the purpose of diagnosing subtle faults or anticipating engine abnormalities, could provide the additional time required for the crew to make critical decisions concerning non-normal operations. This is especially applicable during periods of high workload or during situations where vigilance is reduced (e.g., long haul flights).

Single events (e.g., flame outs, etc) can be the result of many different faults. However, the action required by flight crews to maintain or guard against degradations in flight safety can vary as a function of both the fault and the context in which it occurs. This program addresses pilots' need for support in diagnosis or trend monitoring on faults <u>as they affect decisions that must be made within the context of the current flight</u>. Thus, aiding in diagnosis or trend analysis need only be taken to the level at which crew actions and/or decisions are affected.

1.1 Approach

The Engine Advisor development effort addresses issues from a pilot's perspective (as opposed to that of a maintenance technician). The focus is on the integration and correlation of flight deck information within the framework and foundation of the NASA Faultfinder Program (Refs. 1,2,3,4) and is guided by the constructs of crew-centered automation(Ref. 5). This effort builds upon the monitoring and diagnostic aspects of the Faultfinder program, augmenting and restructuring where necessary to accommodate new technologies, and adapting the Faultfinder modules to be consistent with current Boeing flight deck systems, operational requirements, and overall flight deck philosophy.

Figure 1 illustrates the relationship between relevant components of the Faultfinder concept and the contributions of Boeing and NASA-Langley on this project. The specific objectives which generate the inputs needed for this system are described in the following section.

The overall goal of the program is to provide air crews with information which will support timely and accurate response decisions on extant or developing engine faults.

This information will be generated by monitoring and diagnosis, correlated with the phase of flight, operational constraints, airplane state, and the pilot's overall flight objectives. Pilot expertise, flight operations manuals, flight deck engineers and propulsion experts are being used to address a range of situations and identify the information requirements.

1.2 Objectives

The multi-year goal of the program is to develop an expert system advisor which:

- assists the crew in system diagnosis (if appropriate) and recommends applicable procedures in response to the situation;

- advises the crew of inconsistencies, adverse performance trends, or non-normal situations before the condition becomes critical;

- monitors engine performance and displays critical information to the crew.

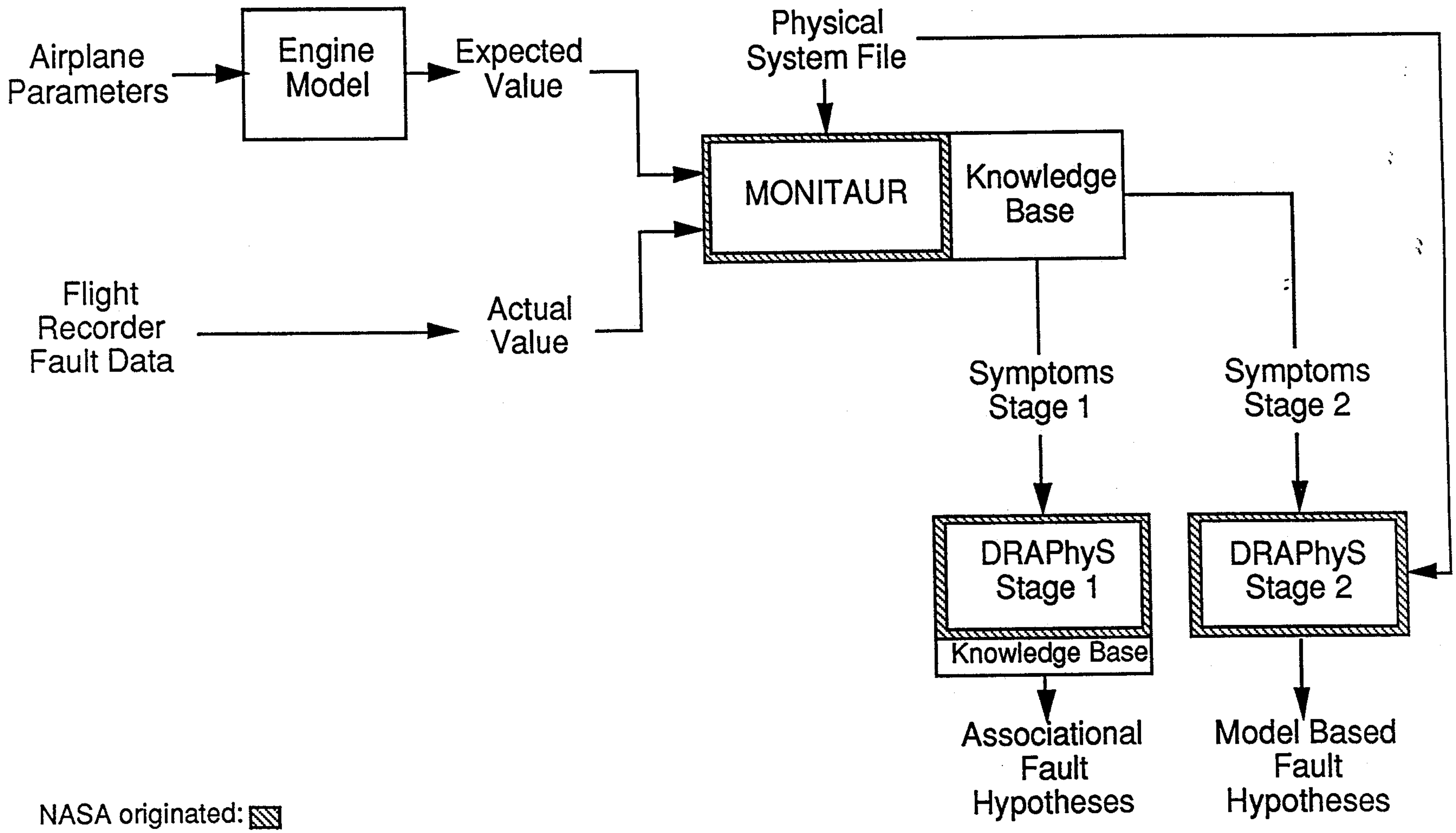

Figure 1. Flight Deck Engine Advisor Modules

Objectives for the first year effort include:

- Select a candidate engine with readily available, stand alone engine model and substantial real engine data;

- Select and employ hardware/software tool combination(s) with maximum utility and transportability;

- Develop a set of fault scenarios for use in knowledge base augmentation/restructuring and future testing;

- Develop a data base of pilot information requirements to accompany fault scenarios;

- Restructure and augment STAGE1 & STAGE2, respectively, of DRAPhyS portion of Faultfinder.

2.0 FLIGHT DECK ENGINE ADVISOR PROGRAM PROGRESS

2.1 TASK 1 - Program Plan Development

A Detailed Program Plan was developed and delivered as Boeing Document D6-55677 on May 3, 1990. A revised version was approved by June 1, 1990 and work began on implementing the plan to achieve first year objectives.

2.2 TASK 2 - Definition and Scope of Effort

The definition and scope of the current effort insofar as fault coverage is concerned involved four activities. These were:

- Define a sample of faults which would represent total possible faults;
- Determine sources and availability of fault propagation data;
- Determine approach and format for fault data representation;

- Conduct preliminary screening of candidate faults.

The first step in assembling a candidate fault pool involved canvassing the various sources of such information. These included: 1) faults used by NASA in evaluating Faultfinder modules and related research (Ref. 6); 2) ASRS incident reports; 3) Boeing safety data on Boeing planes with advanced cockpits; and 4) flight test data from Boeing propulsion groups. This produced a substantial list of events on which to carry out the initial screening task. For many of the events, particularly those taken from ASRS reports, information on the nature of the fault was so sketchy as to make the instance of no value for the project.

When faults were evaluated for availability of real engine data on which to base fault propagation, the candidate pool quickly shrank to those faults identified by Boeing propulsion groups. No other source could provide both real engine fault data plus matching normal simulated data generated under the same flight conditions. Both these types of data are required to test the monitoring and diagnostic modules. Thus, a much reduced but realistic candidate fault pool was generated.

Initially, a quantitative approach to fault symptom representation was planned. However, proprietary issues, which are dealt with later in this report, precluded the inclusion of quantitative data as a part of the deliverable reports on the project. Therefore, the quantitative engine data was used as input to MONITAUR in module development and testing but only qualitative representations are included in the deliverables.

The scoping process as defined above was carried out over several months rather than the originally scheduled one month period in order to include all possible faults for which data sources could be identified. This did not affect progress on the project because an iterative approach to fault scenario development was employed. Implementation of the iterative approach meant that data gathering, scenario development, and information requirements analysis activities could proceed in parallel without having to wait on the completion of any one task.

The Technical Monitor was kept apprised of the progress and results of activities in this task and had the opportunity to provide inputs regarding specific priorities and preferences.

2.3 TASK 3 - Hardware/Software Selection

Several potential candidate hardware platforms were evaluated for the Flight Deck Engine Advisor. These included

PC 386
Apollo Workstation
Symbolics
McIvory Workstation
MacII

In addition, Common LISP and NEXPERT OBJECT were considered as software development environments. Each component of Faultfinder (MONITAUR, DRAPhyS STAGE1 and STAGE2) was evaluated separately because they were originally developed with differing dependencies. The goal was to be able to link all three modules for a run-time version at project completion. Criteria for selection (as discussed in the Detailed Program Plan) included:

Portability from NASA to Boeing
Interface with Simulator
Interface with Engine Model
Real Time Performance/Response
Cost to Implement at Boeing
Cost to Implement at NASA
Impact on Productivity

Each applicable criterion will be discussed in context with the specific module discussed.

2.3.1 MONITAUR Development

The development of enhancements to MONITAUR was performed on a 386 PC using GCLISP Developer software. This development was completed using the 3.1 version of the GCLISP Developer. A 4.0 version of the GCLISP Developer became available during the first quarter 1991, but this was too late to be utilized effectively on this contract. There are several advantages to both NASA and Boeing in the choice of development environment. These are summarized below.

NASA advantages include the following:

1. NASA has a GCLISP implementation hosted on a PC in their experimental airplane. This will facilitate the transition to inflight testing.

2. A greater number of potential users will be able to utilize the PC version since more engineers have PCs on their desks than LISP Workstations. This will facilitate dissemination of the product of this study.

3. GCLISP boasts a Steele compatibility and is upward portable to other Common LISP environments.

4. No additional expense will be incurred, since NASA already owns GCLISP.

5. GCLISP is available in both interpretive and compiled mode to allow both efficient development and better run-time performance.

6. Porting MONITAUR from Genera Common LISP to GCLISP was relatively straight forward since few special Genera features have been used in MONITAUR. This allowed more time for fault information development.

Boeing advantages include:

1. Boeing owns GCLISP so no additional costs will be incurred.

2. GCLISP on a 386 PC is compatible with Flight Deck Research's MicroCab architecture so the Engine Advisor can be integrated with existing applications

3. GCLISP is portable to other Common LISP environments used at Boeing.

4. GCLISP is available in both interpretive and compiled mode to allow both efficient development and better run-time performance.

5. Porting MONITAUR from Genera Common LISP to GCLISP was relatively straight forward since few special Genera features have been used in MONITAUR. This allowed more time for fault information development.

There are some disadvantages in the selection as well. Most important among these is run-time performance. Even using the compiled form of GCLISP, execution times on a 33Mhz PC will not be in the order of real time processing unless time slices are taken several seconds apart. A second disadvantage of selecting a PC instead of an APOLLO, is the need to create an interface between engine model data generated on an APOLLO and the PC. If an APOLLO had been chosen as the development hardware, this would be an internal link which should be more easily developed.

2.3.2 DRAPhyS STAGE1 Development

The development of enhancements to MONITAUR was performed on a 386 PC also using GCLISP Developer software. This development was completed using the 3.1 version of the GCLISP Developer. There are several advantages to both NASA and Boeing which are summarized below.

NASA advantages include the following:

1. Since the selection is identical to that for MONITAUR, all six of the advantages cited in the MONITAUR evaluation apply to STAGE1 as well.

2. In addition, the compatibility between MONITAUR and STAGE1 resulted in efficient linkage between the modules. NASA's current blackboard was replaced with a PC compatible implementation.

Boeing advantages include:

1. Since the selection is identical to that for MONITAUR, all five of the advantages cited in he MONITAUR evaluation apply to STAGE1 as well.

2. In addition, the compatibility between MONITAUR and STAGE1 resulted in efficient linkage between the modules. NASA's current blackboard was replaced with a PC compatible implementation.

The performance disadvantages of a 386 PC platform with GCLISP are similar to those cited for MONITAUR. When the two modules run sequentially, the performance is degraded. No additional penalty exists for interfacing to APOLLO, since the STAGE1 module does not have engine model input.

In addition to a PC 386 GCLISP implementation, a second option was investigated as an alternative for STAGE1 processing. A demonstration of STAGE1 processing using NEXPERT OBJECT was produced for alternatives analysis. A separate set of potential advantages was evaluated including:

For NASA:

1. Develop experience with a commercial shell, one that is emerging as a front runner in the AI community.

2. Create a viable alternative to allow tractable rule base processing.

3. Other potential NASA customers will have this shell so dissemination will be more efficient.

4. Boeing has considerable experience with this development environment, so productivity will be increased.

5. The knowledge bases developed in a shell are highly portable within NEXPERT OBJECT applications.

For Boeing:

1. Boeing owns NEXPERT OBJECT, so no additional software costs will be incurred.

2. Other AI applications have been developed in Flight Deck Research, so this version will be highly compatible.

3. Reasoning is traceable in NEXPERT OBJECT, which is important for Verification and Validation required for FAA certification.

The disadvantages in NEXPERT OBJECT use is the additional cost to NASA to obtain NEXPERT OBJECT, and NASA's lack of familiarity with this development tool.

2.3.3 DRAPhyS STAGE2 Development

The development of enhancements to DRAPhyS STAGE2 was performed on the McIvory workstation using Genera Common LISP. To allow for PC compatibility, Boeing investigated the feasibility of porting the product to a PC 386 using the CLOE implementation of LISP produced by Symbolics.

NASA advantages include the following:

1. NASA has all hardware and software in place, therefore no additional cost will be incurred.

2. This is NASA's original development environment, so they have a broad experience base.

3. The symbolics will give better run-time performance than a PC.

4. The PC porting under CLOE was demonstrated, and the product is usable by a wide variety of NASA customers.

Boeing advantages include:

1. The PC porting under CLOE was demonstrated, and the product is compatible with other Flight Deck Research applications in the MicroCab.

The disadvantages of this selection include a productivity penalty for working on the McIvory due to lack of familiarity for Boeing personnel. Boeing has incurred additional cost in securing a McIvory for production use. Finally, the product is not portable from McIvory to the PC by any means but CLOE LISP translation. No graphics can be translated under the current version of CLOE. The functional portion of STAGE2 was ported, but the interface had to be redeveloped for the PC version.

2.4 TASK 4 - Fault Scenario Selection

2.4.1 Engine Model Selection

Criteria for the selection of an engine model for use in this project were developed as a part of preparation of the Detailed Program Plan. These criteria were applied to several engine models which have been developed by Boeing for implementation on flight simulators. This section of the report deals with a discussion of proprietary issues and their resolution plus the details of the engine and fault selection processes.

2.4.1.1 Proprietary Issues

At the present time, no written proprietary agreement exists between Boeing and NASA which adequately protects the proprietary rights of engine manufacturers and other parties with vested interests in the engine model and/or real engine data which are being used to carry out some of the tasks of this project should an engine model and the quantitative fault data be delivered to NASA. Further, no permission has been granted by parties with vested interest in the real data to release such data to a third party. Neither an engine model nor real engine data are deliverables under the contract Statement of Work as written. This situation does not in any way preclude Boeing from performing on the contract. The Technical Monitor had indicated early in the process of developing the Detailed Program Plan for this project that having an engine model and real engine data included in the Final Report would be a plus for their related in-house work. However, the nature of the engine data and the number of parties with vested interest involved are such that no attempt was made on the current contract to secure proprietary agreements or permission to release data covering engine parameters on the faults analyzed or any quantitative output from the engine model which reflects this data. Qualitative representations of engine parameter characteristics during fault propagation will be described in the Final Report. In light of the above, it is Boeing's intention to deliver qualitative representations of engine parameter characteristics during fault propagation as a part of the Final Report, but no quantitative data will be included.

Attempts to resolve proprietary issues on the engine model and engine data are continuing with respect to follow on work on the Flight Deck Engine Advisor program.

2.4.1.2 Model Selection Process

Engine models considered in this selection process represent classes of engines used on Boeing airplanes. The search for a suitable engine model was restricted to models of engines currently implemented in Boeing flight simulators for three reasons. First, this restriction is required because of the necessity to run the model in order to process inputs and provide outputs necessary to develop and implement fault scenarios. Engine models which come from the engine manufacturers are not implemented in this sense. The programming effort required to implement engine models for simulation is far beyond the resources of the present project. Hence, no consideration was given to using new engine models not already implemented. Second, the expertise needed to utilize the simulation models to provide the fault propagation information on the engine faults is available in house. Third, real engine data are available in-house on the sample of engines considered. Any engine model which did not have the aforementioned characteristics could not be given serious consideration within the scope of the project.

In order to avoid proprietary issues and constraints while documenting project activities or results, no identification will be made of specific engines or classes of engines by engine manufacturer at any time during the discussion of the selection process or in any subsequent discussions relating to engine models. Engine models will henceforth be referred to as Models A, B, C, and D. Since each model is a different engine type and possibly a different engine manufacturer, separate Physical Systems Files (PSF) were created for each model. The only PSFs included in this report are those for which real engine data was obtained. In the process of developing fault scenarios, no attempt was made to restrict the fault selection to a specific (serial number) engine. The associated PSF has not been customized for a specific (serial number) engine, but instead is intended to represent any serial number engine of that type, and hence is generic for that engine type.

The criteria used in the engine selection process are described below as a prelude to the description of the selection process and results. The criterion labels are those used in Figure 2 to facilitate interpretation of the data.

<u>Model Availability</u>: This refers to the availability within Boeing of an implemented model for a particular class of engines which can be utilized with little or no modification.

Model Validation[1]: Refers to the fact that the engine model is known to run without problems and has been demonstrated to match the engine it represents.

Proprietary Protection: Proprietary protection for all parties can be assured and permission to transfer data to a third party can be obtained.

Real Engine Data: The extent of inflight and test data available on faults which might be selected for scenario development. This criterion also refers to the ease with which fault data from other engines can be modified to work in concert with the model. (This criterion and that of "availability of failure mode data" listed in the Detailed Program Plan are redundant.)

Accuracy, etc.: This refers to whether the accuracy, consistency, stability, and tolerances of the engine model are within acceptable ranges.

Propagation Information: This refers to the availability of expertise on fault propagation within and beyond the engine. High ratings were given when the needed expertise was available within Boeing.

Change Information Available: This refers to the availability of information on changes made to the engine manufacturer's model to adapt it for simulation.

Computing Requirements: This refers to the type and amount of hardware/software support needed to run the model. Specifically, can the model be run on the types of hardware/software combinations being considered for the project, and if not, how much effort would be required to translate the model. A low rating indicates the required hardware platform is not readily available to the project and/or a large effort would be required to translate the model to a more accessible platform.

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[1] This criterion label has been used in place of "Simulator Ready" which appeared in the Detailed Program Plan because it better reflects the basis for judgements on this dimension. Simulator Ready was deemed to overlap too greatly with "Model Availability" as defined above.

Propulsion experts thoroughly familiar with the characteristics of all engine models under consideration evaluated the models in terms of the criteria described above. Additional factors to be mentioned later were also taken into consideration in making the final determination as to which model to use. The results of this evaluation represent a consensus of expert opinion.

Figure 2 represents a Criteria by Engine Model matrix with the weights used for each criterion shown in the second column. The first three criteria were considered critical. Thus, a weight of 0 or 1 was used in a cutoff mode. This meant that if an engine model received a weight of 0 on any one of there three criteria it was dropped from any further consideration. The remaining criteria could receive weights ranging from 1 to 5. The values shown in the matrix cells represent a rating arrived at by consensus among the propulsion simulation experts. These weights were simply added up across criteria within engine models. The model with the highest total was chosen for use on the project. This choice was further substantiated by additional factors.

As can be seen, Engine Model A has the best showing across the criteria used. In addition, this model is implemented as a FORTRAN callable subroutine on the Apollo computer using the Boeing Parallel Simulation System (PSIM). The PSIM is software which facilitates integration of other analysis tools or simulations. The other models do not use the PSIM software, and some run on other computers such as the Harris. The model for Engine A also runs as a multi-engine model. None of the other models have this capability. This feature will have little impact on the current project work, but will make the simulation of differential engine performance much easier in the future.

Candidate Engines

Criteria	Weight	A	B	C	D
Model Availability	0-1	1	1	1	1
Model Validation	0-1	1	0	0	0
Proprietary Protection[2]	0-1				
Real Engine Data	1-5	5	2	5	4
Accuracy, etc.	1-5	4	4.5	1	2
Propagation Information	1-5	5	3	2	1
Change Information available	1-5	5	5	5	5
Computing Requirements	1-5		2	2	2
Evaluation Score		**25**	**17.5**	**16**	**15**

Figure 2. Engine By Criteria Evaluation Matrix

2.4.2 Fault Selection

A set of candidate faults has been identified for use in developing fault scenarios. The strong points of the subset identified to date are: a) real engine data exist for them, and b) the expertise for specifying fault propagation sequences is available in-house. The characteristics (referred to as criteria in the Detailed Program Plan) which the faults should have in order to be maximally useful are listed below with brief descriptions.

Credibility: Real engine fault propagation data are available on the fault.

Within Engine: The fault propagation sequence is constrained to components within the engine subsystem.

Between Subsystems: The fault propagates functionally or physically to related or proximate subsystems.

Data Availability: Quantitative data are readily available on the fault in a useable format.

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2 This criterion could not be met by any of the engine model candidates so it was given no weight in the selection process. (See also Section 2.4.1.1)

Propagation Expertise: The expertise needed to develop the fault propagation sequence is readily available and accessible.

Doable: Scenario development is doable within project resource and schedule constraints if the fault is selected.

Action Required: Dealing with the fault must call for action on the part of the crew, be it subsystem reconfiguration or control, or crew awareness for inflight replanning.

Trend, Inconsistency: The fault propagation occurs over considerable time so as to generate negative trends in engine parameters which may not break a threshold for some time. The fault produces inconsistencies in expected engine parameter values.

Accurate Time Data: Accurate time line data are available to support fault propagation scenario development. The minimum requirement here is for accurate sequence data.

Figure 3 represents a Characteristic by Fault Candidate matrix which illustrates the coverage of characteristics achieved across the fault scenario developed.

Characteristics	Candidate Faults							
	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
Credibility	X	X	X	X	X	X	X	X
Within engine	X		X	X	X	X	X	X
Between subsystems		X						
Data availability	X	X	X	X	X	X	X	X
Propagation expertise	X	X	X	X	X	X	X	X
Doable	X	X	X	X	X	X	X	X
Action required	X	X	X	X	X	X	X	X
Trend, inconsistency			X*	X	X			
Accurate time data	X	X	X	X	X	X	X	X
Evaluation Score	7	7	8	8	8	7	7	7

Figure 3. Characteristic By Fault Candidate Matrix

*Trend occurs across scenarios F3, F4, F5

2.4.2.1 Fault Candidates

The following candidates were identified. As can be seen in Figure 3, when taken together, they contain all of the characteristics outlined above.

F1 - Malfunctioning fuel metering unit - Hung Start, ground ✓

F2 - Fuel boost pump failure - Flame out ✓

F3 - Ice damaged fan blades, light - Thrust Shortfall

F4 - Ice damaged fan blades, moderate - Thrust Shortfall

F5 - Ice damaged fan blades, heavy - Thrust Shortfall

F6 - Foreign Object Damage (FOD): volcanic ash - Flame out

F7 - Fuel nozzle coking - Hung Start, air ✓

F8 - Stability margin problem - Stall/Surge

All of the above fault candidates were eventually developed as fault scenarios. The resulting scenarios are contained in Appendix A.

2.5 TASK 5 - Fault Scenario Development

Early in the course of the project, it was determined that an iterative approach to the tasks of fault selection, scenario development, and information requirements identification would be most effective. Thus as real engine data became available on a fault, the process of developing the contents of the fault scenario began. As this process proceeded, the concepts and definitions structuring the scenario contents were fleshed out and modified. It was also at this time that it became obvious that the identification of information requirements needed to carry out fault detection and diagnosis was an integral part of fault scenario development. Therefore, the information requirements task was folded into scenario development and scheduling of the project tasks was modified to reflect the iterative nature of the overall scenario development process.

Eight (8) fault scenarios were developed during the course of the study. All eight are included in their entirety as Appendix A of this report.

2.5.1 Concepts and Definitions for Structuring Fault Scenarios and the Information Requirements Analysis

The framework for diagnosing faults is the fault propagation sequence expressed in terms of system components involved and the functional and/or physical relationships affected. The framework for analyzing pilot information requirements is the event-fault-context-action alternative relationship which exists in a specific fault scenario. Depending on the fault and context variables relevant to the scenario, context may be used in two ways; as an aid in diagnosing faults, and in terms of its impact on action alternative selection. Before discussing the nature of these relationships and the format and content of a fault scenario, we should define the terms and components to be used.

2.5.1.1 Definitions

Events - Events are those conditions which the crew must deal with. They are the end result of a propagation of malfunctioning components. The propagation may be functional, physical, or both. Examples of events are: flameout; hung start; thrust shortfall; excessive vibration.

Fault - The fault is the failure of an engine component which propagates through the engine subsystem and via this propagation results in an event. Examples of faults are: sensor failures, valve open/close failures, software logic failures or inadequacies; any mechanical, electrical, or software component failure; procedural failures (both maintenance and operational). Faults in the new engines may be mechanical, electrical, or software related, or may be flight crew or maintenance induced. For any given event, it is assumed that there can be multiple potential faults. Faults may be grouped in terms of the crew action alternatives; i.e., several faults may map onto a single crew action such as "Shut down engine for remainder of flight". It is also assumed that different faults will have at least slight differences (either temporal or sequential) in the way they propagate. Thus, if the propagation sequence and temporal relationships are known, the nature of the fault can be inferred with some degree of accuracy. The degree of accuracy in differentiating among faults will be a function of the number and degree of differences in their propagation sequences. However, if faults have essentially the same propagation sequence and/or the same action alternative is appropriate, no attempt is made to differentiate among them. These are said to belong to the same Fault/Action Class.

Context - This refers to external variables which may: a) affect the way a fault propagates, b) affect the criticality of the fault and hence the crew action alternatives, or c) alter the appropriateness of crew actions. These variables include: phase of flight, weather, airplane systems status, engine fault history, engine commanded status, airline policy, FARs, pilot error, workload. As mentioned earlier, context variables may play two roles. Variable status may be used to aid the diagnostic process as well as influence the relevance of action alternatives. Context variable status can eliminate potential fault alternatives as well as make others more viable.

The relationship of context variables to action alternatives is an IF-THEN relationship. If certain variables are operative, then a particular action alternative is appropriate. If the variable(s) is(are) not operative, then there is no impact on action alternatives. In other cases, the context variable(s) may have no affect on the action alternatives whether operative or not. In any event, the relevant context variables must be considered in the diagnostic process in order to produce relevant recommendations on action alternatives.

The event-fault-context-action alternative relationship is illustrated in Figure 4. Within this framework, context variables may be thought of as filters which may or may not be in place for a given fault.

Crew Action Alternatives - These define, at least to a category level, the actions the flight crew might take when confronted with an event precipitated by the occurrence of a particular fault within a Fault/Action class. It is assumed that action alternatives can be related to faults or Fault/Action classes via context variables. Examples of action alternatives might be: shut down engine for duration of flight; engine shutdown with possibility of restart later in flight (delay unspecified at present); execute engine shutdown/restart procedures; reduce throttle setting but continue to operate engine; restart engine immediately and continue to operate normally; no action required (a pseudo problem). The set of potential alternative actions will vary somewhat from event to event.

Symptoms - The manifestation of the fault in system parameters against a time base represents the symptoms of the fault. These symptoms are defined, for the most part, in terms of engine parameters such as low rotor speed, high rotor speed, EGT, fuel flow (FF). However, other symptoms which are not sensed or are not displayed in the cockpit, or both may be relevant to the diagnosis of faults. An attempt will be made to identify such symptoms or infer their existence if possible.

Impact on Other Subsystems - Faults within the engines may eventually affect other subsystems such as generators and hydraulic systems. These impacts are noted in the fault scenario but unless they are important to the diagnosis of the fault, they will not be included in the propagation sequence per se.

Time Base - All fault candidates being analyzed have flight recorder data on engine parameters plotted against a time base; usually at .1 second intervals. This time base is taken as relative for purposes of analysis since it would differ in detail across engines and within engines across time or fault occurrences.

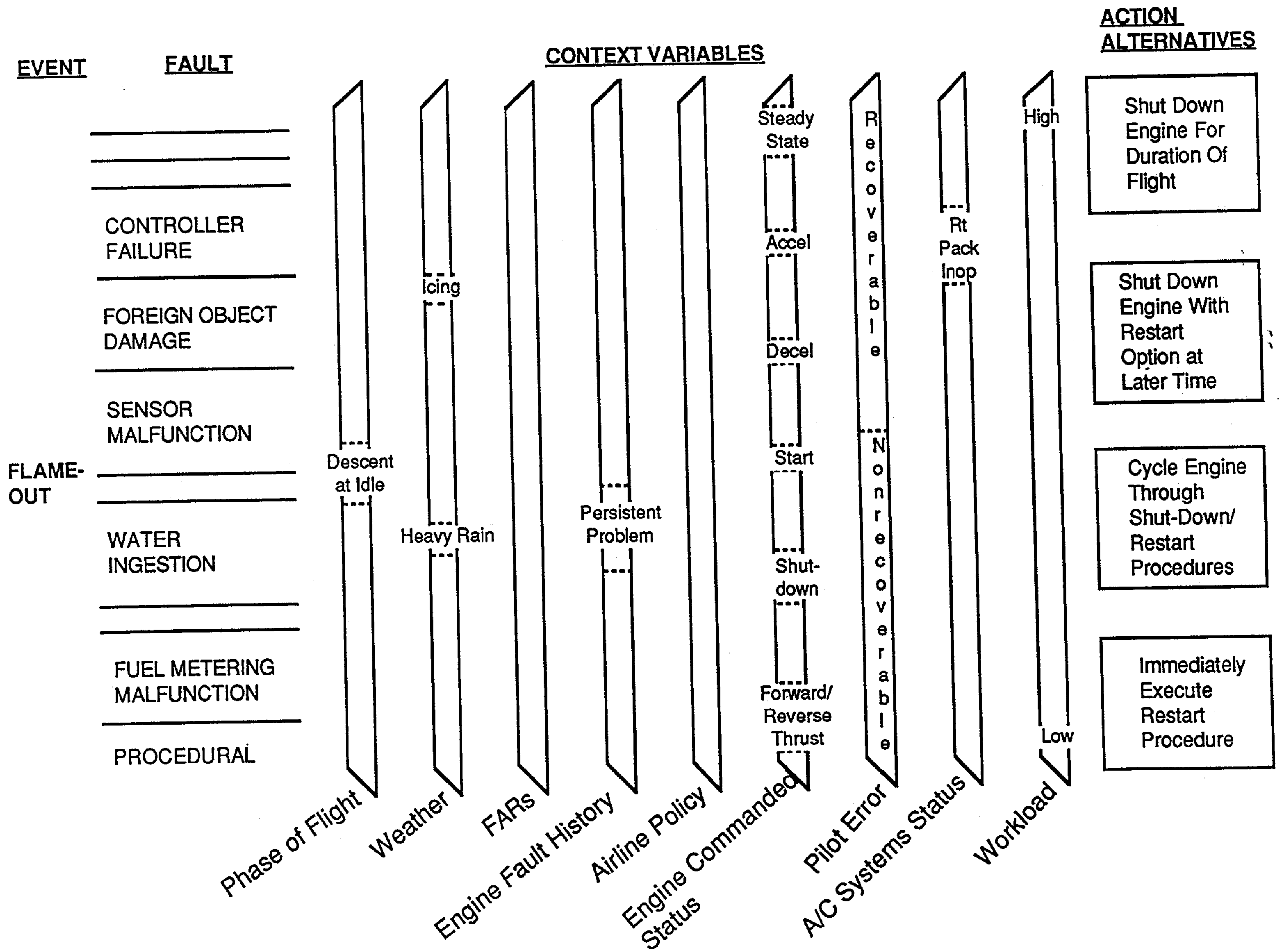

Figure 4. Context Variables As Filters Affecting The Fault/Action Relationship

2.5.1.2 Fault Scenario Sections

Each section of the fault scenario is identified below along with a description of its contents. Because the fault scenario development process is iterative, the only sections in which the information is not subject to change are Event and Fault. All others can be revised during review and knowledge base development. Revisions in the fault scenario data base were made as long as the need for more and better data continued during knowledge base development.

Event - contains only the name of the event.

Fault - contains a descriptive label of the specific fault being analyzed plus any qualifying or modifying information.

Potential Fault Alternatives - contains a list of other faults which could lead to the same event. This list was expanded as additional alternatives became known, but is not exhaustive.

Relevant Context Variables/Status - contains a list of the relevant context variables and their particular status or "value" for the scenario. Initially, the relevancy of particular context variables per se or their relevance as a function of particular values they might assume may not be known. Thus, the listing for a particular fault scenario may change as knowledge base development progresses. Context variables identified to date are listed below along with examples to illustrate the status or value these variables might assume.

Phase of Flight - Take Off; Initial Climb; Cruise; Descent; Approach; Landing; Go-Around.

Weather - Clear and dry; Heavy rain; Icing; Turbulence; etc.

FOD Potential - Several scenarios involve foreign object damage of one sort or another as the fault. Examples include; ice damage, volcanic ash damage, bird strikes, blown tire piece ingestion.

Federal Aviation Regulations (FARs) - relative to constraints or options pilots have in specific situations.

Engine Fault History - Information on whether the particular engine or engine type has a history of the fault/event occurrence and how it has been resolved in the past.

Airline Policy - Specific actions may be dictated for specific events. Other context variables may or may not interact to affect prescribed actions.

Engine Commanded Status - Steady State; Acceleration; Deceleration; Start; Shutdown; Forward/Reverse Thrust.

Pilot Error - Procedural errors can be made which are in themselves faults in that they will produce events; e.g., improper start procedures can produce a hung start. However, pilot error can also exacerbate a fault and alter the appropriateness of particular action alternatives. For example, at one time certain engines would flame out when significant amounts of water in the form of rainfall were ingested. If the pilots reacted immediately, the correct action was to immediately execute the restart procedure. If the pilots did not react immediately or they moved the throttles, the only action alternative left was to shut down the engine for the duration of the flight. It is in this latter sense that pilot error is a context variable.

Airplane System Status - Basically, this refers to what is working on the airplane and what is not. Airplanes may be dispatched with certain components or subsystems inoperative if they are not critical to flight safety. An air conditioning pack might be an example.

Workload - This refers to the aggregate demands on the flight crew in addition to those imposed by the event. It can be assumed that workload will be high during certain phases of flight (e.g., take off and initial climb; approach and landing) and lower at others (e.g., cruise). However, the correlation is not perfect. Workload can be expected to influence the relevancy of action alternatives; particularly when it is high.

Crew Action Alternatives - contains a listing of all action alternatives appropriate for the event under any circumstance. Options are determined in consultation with engineering and/or training pilots and propulsion experts. An objective is to have this section and that on potential fault alternatives mesh well in that all action alternatives are identified for the fault alternatives listed.

Subsystems Affected - contains a list of the subsystems involved in the propagation sequence. Subsystems which may be affected by the event but are not crucial to the diagnostic process are also identified and effects noted. These latter subsystems will not be mentioned in the fault propagation sequence.

Propagation Sequence with Rank Order Time Base - The propagation sequence is described in qualitative terms against a rank-ordered time base. Components and engine parameters are identified in the sequence in which they are affected by the fault. Qualitative values are given for the parameters. Each point on the time base when components become involved or parameter values change is labelled consecutively so that the order in which involvement and/or change occurs is apparent.

Data Pilots Have Available - This section represents an attempt to identify and evaluate the sources and sequence of data acquisition pilots currently use in diagnosing the fault under analysis. It provides the basis for an evaluation of what could or should be expected of pilots when compared with the data from the next section. Subsections include:

Source(s) of Data
Explanation of Relationships
Quality of Data
Heuristics or Rules of Thumb Used
Time Constraints

Information Required to Make Diagnosis - This represents a generic description of the information required to make a diagnosis in that it does not distinguish between what information the diagnostic module would use versus what pilots might use. It will, however, contain comments relevant to whether pilots currently have an adequate source, if any, of information needed to make the diagnosis. This section, the propagation sequence, and the context variables/status provide the data base for knowledge base development on a fault. Subsections include:

Key Parameters
Symptoms
Interpretation

Information Required for Decision Aiding - This section contains an analysis of the relationship between fault and action alternatives given the relevant context variables and their status. Subsections include:

Nature of the Fault
Relevant Context Variable Set
Relationship Between Fault and Context Variables
    Diagnostic Application
    Action Recommendation Application
Consequences of Inappropriate Alternative Actions

Information is included in the subsections of these last three sections if and when it is available. A comment section may also be included when the analyst feels it is appropriate to provide additional information.

2.5.2 Lessons Learned in Fault Scenario Development

2.5.2.1 Data Availability

With two exceptions, fault scenarios were based on flight test data. In all but two of the scenarios based on flight test data , the fault was induced in order to study the effects. This is typical of flight test data. The fact that we have data of such granularity on two uninduced faults is fortuitous. For the staged faults such as flame out due to fuel pump failure, the fault itself is not necessarily low probability but very special circumstances have to obtain in order for it to propagate to the event which occurred.

The faults represented are not complex (particularly in terms of the propagation sequence), they are never multiple, and they are certainly not novel. If novel faults are defined as those which have not occurred, then of course we will never have them in our data base. This does not mean that we cannot eventually devise a system which would recognize them as faults, at least at some level of specificity relative to actions required by the pilots.

A number of faults were known to have occurred, but for various reasons the detailed engine parameter data was not available. These included:

Flame Out in Idle Descent - electronic engine controller fault;
Hung Start, Ground - bleed valve out of position;
Engine Overspeed - electronic engine controller fault.

The first would have been an excellent example of a subtle fault. The second, would have allowed us to compare hung starts produced by fuel management vs. pneumatic problems. The third is an example of unalerted automation failure requiring crew intervention.

Clearly, we need an expanded fault data base for feasibility testing and for longer range development efforts. Some additional fault data will be available through further efforts to mine the flight test data files. Also needed however is additional operational data on both faults and normal operating engines. An expansion of the rationale for these needs is provided in the next subsection and in the section on Knowledge Base Development. An effort to identify sources, extent, and accessibility of a greatly expanded operational data base is proposed for follow on to the present study. Preliminary inquiries in this area indicate that the airlines probably would be the major source for such a data base; more so, surprisingly, than engine manufacturers.

2.5.2.2 Nature of the Data

Six of the fault scenarios developed are based on flight test data. The remaining two are based on data taken on a flight deck recorder. There are major differences between flight test data and operational data in terms of parameters recorded and granularity of the data. It is instructive to note the differences between these two data sources and the implications for system development.

Flight tests are typically very heavily instrumented in order to: a) get the most data for the money, and b) obtain the clearest picture possible of the way various engine parameters behave during the event observed. Further, the data recordings are quite brief (at least in terms of data retained for storage), typically lasting no more than 100 seconds. Thus, the only trend data available is of very short duration. Operational data, on the other hand, has the potential of covering a much longer time span but fewer parameters are measured and the data is much courser.

Parameters pertaining to internal engine pressures and temperatures are very useful in anticipating the onset of an event such as a surge, but the high fidelity sensors which provide the data during flight test are also very fragile and thus are unacceptable on operational engines. Another type of problem encountered was having data available on a parameter, but not having the parameter modelled in the engine model. Vibration is a case in point. Until engine manufacturers can provide a reliable and meaningful measure of vibration, this valuable diagnostic parameter will not be available. This is particularly frustrating in the case of the ice damage scenarios. Here a step increase in vibration level is the only reliable symptom indicating foreign object damage has occurred at low levels of damage.

There is also the situation where engine parameters are measured and are among the inputs the electronic engine controller uses but the parameter values are not available outside the controller. These parameter values could be made available to a data bus if a system like the Flight Deck Engine Advisor were available to use them. Therefore, it is appropriate to use data from flight test engine measurements to anticipate parameter values which may be available to the diagnostic process on future operational engines.

There is some pressure from engine manufacturers to reduce the number of engine sensors. This is understandable in that sensors do fail and can produce false alarms which can be costly under engine warranties. However, a reduction in sensors would be counterproductive from a diagnostic standpoint. Through sophisticated conditional processing with a reliable engine advisor system, the additional sensor data could be acquired and used while at the same time lowering the false alarm rate below current levels.

The data base survey task included in proposed follow on efforts would address the problems identified here.

2.5.2.3 Analysis of Information Requirements

There are three levels or types of analyses of information requirements related to the development of fault management systems. There is a top level analysis of fault management functions as they relate to other functional categories covering all air crew functions. NASA is supporting research in this area on other contracts. At the most detailed and specific level, there is the analysis of information required to diagnose faults. The results of this level of analysis could apply to either pilot information requirements or system information requirements. System information requirements represent the inputs needed in knowledge base development for engine monitoring and diagnosis activities carried out by an engine advisor system. Most of the effort in analyzing information requirements on the current project was focused at this level. A third type of information requirements analysis focuses on the type of information pilots need to make decisions about appropriate action to take given a particular fault/event combination. A conceptual framework for the analysis of this third type of information requirement was developed as a part of the present project. A description of the framework and results to date are contained in the next section.

The information requirements analysis for the present study was data base driven. This meant that the analysis had to focus on specific faults for which real engine data was available. There was little opportunity to expand the analysis to other faults beyond listing potential alternative faults which might lead to the same event. The number of such alternatives varied considerably across fault/event combinations. Being data driven also meant that we were forced to exclude several faults we would have liked to analyze for their contribution to the study of fault management but could not for lack of data. Examples of such faults were given earlier in the discussion of fault selection.

The propagation sequence contained in the fault scenarios provided the basic inputs to the information requirements analysis. From this, an evaluation was made of the data that pilots have available without the aid of a Flight Deck Engine Advisor system. The quality of the data, pilot heuristics relevant to the fault, and any time constraints were also addressed. Information required to make a diagnosis was then analyzed. This served two purposes. It provided the core data required in knowledge base development and provided a basis for determining how much of a gap exists between information needs and information available. Little time was spent addressing this gap. To do so would have required an analysis involving the systematic consideration of context variables and level of automation. This was clearly beyond the scope of the present study.

Because context variables can be useful in the diagnostic process as well as in decision making regarding alternative courses of action, subsections were included to address the application of context information to both diagnosis and action selection. The conceptual framework for application to action selection is discussed in detail in the next section.

The complete text of each fault scenario developed is contained in Appendix A. It will be noted that the amount of information varies considerably across scenarios. This variation occurs for two reasons; the nature of the fault, and the availability of background data. Some faults such as "Hung Start-Ground" have a wealth of potential fault alternatives, a relatively slow propagation of the fault's effects, a clear key parameter in diagnosis, and straightforward relationships between context variables and action alternatives. Others such as "All Engine Flame out" which are based on flight data recorder output have a much more limited data base on which to draw for analysis.

The major limitation of the total fault scenario data base at present is the lack of comparable fault/event combinations for reliability checking and the lack of different fault/same event combinations to assess ability to distinguish among faults. The need for distinctions among faults must be determined in an analysis of the relationship between fault/event combinations, relevant context variables, and the resulting action alternative options. Such an analysis is proposed for a follow on effort.

2.5.3 Event/Fault/Context/Action Relationships

Understanding the event/fault/context/action relationships in fault detection and diagnosis is critical to designing the knowledge base to deal with them. This section provides a generic outline of the concepts being implemented in the Flight Deck Engine Advisor development effort. Most of the terms to be used have been defined in preceding sections. This section deals with the relationships. When specific examples are needed to illustrate points in this discussion, reference will be made to the Hung Start-Ground scenario in Appendix A.

Figure 5 will provide a generic framework for the discussion of concepts and relationships. It also represents an attempt to illustrate what is meant by the "mapping of faults onto action alternatives". Events are used as the organizing concept in describing the relationship between faults, context variables, and action alternatives within a fault scenario. The event is shown on the left as in Figure 4 even though, in a propagation sense, faults precede events.

Two additional terms are introduced in Figure 5 which need to be defined. Fault category is introduced at this point as an organizing concept. It may or may not play a role in rule-base development. Examples of these categories can be found in the Hung Start-Ground scenario under "Potential Fault Alternatives". For the hung start, they include pneumatic system failures, fuel system failures, procedure failures, etc. Context variable set refers to the context variables relevant to a fault and the status or value of each variable. With this definition, if one value for one variable in the set were to change, a new set would be defined. This implies that the mapping of faults to action alternatives could change with the change of one value for one variable. Probably the best example of this are changes in phase of flight.

The reader may refer to the contents of the Hung Start-Ground scenario for examples of everything shown in Figure 5. However, it should be noted that there is no correspondence intended between fault category letters, fault numbers, or action alternative labels and the actual material in the scenario.

As can be seen, there are many faults which can produce the same event. The fault categories are used as an organizing concept in scenario development. It may be that most if not all faults within a category would map to a single action alternative thus forming a Fault/Action class.

The concept of <u>Fault/Action Classes</u> is one introduced to reduce complexity in defining the relationship between faults and action alternatives. For example, the line connections in Figure 5 show faults 1, 2, 3, 4, 5, 6, and 8 mapping onto action alternative Able. These faults would then constitute a Fault/Action class. This means that if any one of these faults occurred within the framework of a specific context variable set, the appropriate action alternative would be the same. Thus, diagnosis need only proceed to the point where the appropriate Fault/Action class has been identified. Other connections are shown between faults and action alternatives to illustrate that faults in a particular category may also map to very different action alternatives. The relationships depicted between faults in Category D and the action alternatives illustrate this situation.

The wavy line descending from Context Variable Set through the fault/action connections is used to indicate that the pattern of connections may change considerably with different context variable sets. For example, changing phase of flight might have considerable effect on the mapping. It may become more complex, or in very high workload conditions may become highly simplified with only one or at most two alternatives being appropriate.

So far, the picture suggests the potential for overwhelming complexity. It also suggests the myriad of factors which may or may not, should or should not influence the pilots' decision making process. As more real data are collected, the actual level of complexity to be dealt with will become clearer.

Testing of the overall concept was not possible during the present contract due to a lack of appropriate data. We would like to exercise the MONITAUR and DRAPhyS modules with two different faults which result in a hung start (one

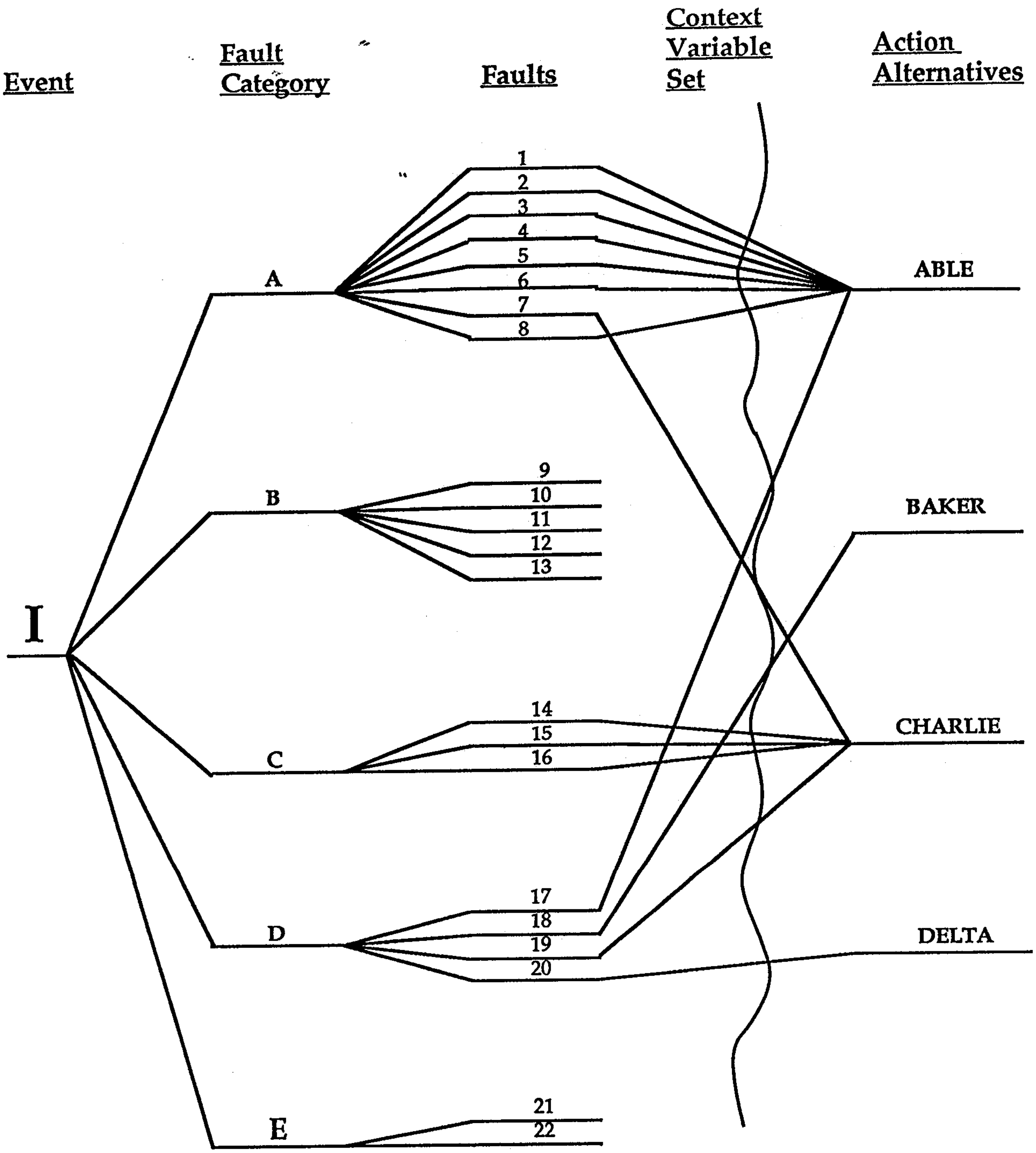

Figure 5.
Generic Illustration Of The Event-Fault-Context-Action Relationship

involving the fuel system and one the pneumatic system) during follow on work. If the monitoring and diagnostic modules can distinguish between the two (should such distinction be appropriate), we will have taken an important step in demonstrating the feasibility of the overall concept.

Eventually we hope to be able to demonstrate the role of context variables in diagnosis by using rules based on context variable sets to prune fault hypotheses in the STAGE1 diagnostic phase. As we gain knowledge about fault-fault and fault-action relationships, it may be possible to identify Fault/Action classes which are stable across most if not all context variable sets. It may also be possible to reduce the complexity of the knowledge base development process by pruning very low probability faults from consideration. These complexity reducing activities will remain as future research possibilities.

To date, the beginnings of a data base on the relationship between fault/event combinations, context variables, and appropriate action alternatives has been included at the end of each fault scenario. Pilot information requirements for fault category management and flight planning would be an output of the context analysis proposed for a follow on effort. Specific requirements will be a function of the event/fault/context/action relationships <u>and</u> level of automation in systems affected by the fault.

2.6 TASK 6 - Identification of Pilot Information Requirements

The task of analyzing information requirements was fully integrated into the fault scenario development process. A distinction between types of information requirements analysis was made in Section 2.5.2.3 to clarify the activities accomplished under the present contract and to relate these activities to other types of information requirements. Rationale for the type of information requirements analysis conducted was also included. The various categories of information developed and lessons learned in its compilation were also covered in that section. A further discussion of pilot information requirements was included in Section 2.5.3.

2.7 TASK 7 - Knowledge Base Development

The Detailed Program Plan called for a minimum of effort expended on MONITAUR with a bulk of the development assigned to enhancement of DRAPhyS. Following the conversion of MONITAUR to GCLISP, several problems were encountered while modifying MONITAUR to accept the Boeing data and engine model. Initial efforts to generate symptoms consistent with those identified by propulsion experts using real fault data have emphasized to Boeing developers the importance of MONITAUR's output to the entire diagnostic process. For this reason more emphasis has been placed on MONITAUR development than was originally anticipated. The goal was to identify and solve all issues required to produce accurate symptoms of Boeing supplied faults. The result of more effort expended on MONITAUR is less development completed for DRAPhyS. This reprioritization of effort was coordinated with and approved by the Technical Monitor. The details will be discussed by module below.

2.7.1 Work in MONITAUR

2.7.1.1 Conversion

The first task was to convert MONITAUR code from Genera LISP on a MacIvory to GCLISP on a PC. All formatting was lost in porting from Macintosh to a PC since carriage returns are not recognized. Several software tools were created to pretty print each LISP function and the data structure found in LITTLE_ENGINE.

In addition to formatting problems there were several syntax incompatibilities as well. LOOP structures and SEND functions were unsupported in GCLISP, so recoding was required. Some changes were also made to eliminate warning messages in the LISP interpreter. Chief among these were function names beginning with semicolon.

To enhance our understanding of MONITAUR processing, high level data flow diagrams for Faultfinder were constructed along with control flow charts for MONITAUR to capture the relationships between functions.

We also experienced some difficulty with GCLISP Developer Version 3.1 as a development environment. Incompatibilities between GCLISP version 3.1 and DOS 4.01 were difficult to identify. This problem occurred when Gold Hill was reorganizing as a corporation, thus technical support was a commodity difficult to find for a time. A beta copy of the enhanced MONITAUR was given to NASA during their Boeing review in September 1990. This software runs using GCLISP Developer version 3.1 under DOS 3.31.

2.7.1.2 Using Real Fault Data

After conversion, real fault data was obtained for a hung start and several degrees of engine icing. This data was supplied from a FORTRAN/APOLLO environment and had to be conditioned to conform to input currently used with MONITAUR. Utility programs were created to perform the data conditioning. These utilities allow the user to specify a selected time interval which contains the specific features which will generate symptoms. In addition, the size of the time slice can be set by the user within the limits of the granularity of the data supplied. Since each fault supplied by Boeing propulsion may come from a different flight source, all will have unique formats, so the conditioning utilities must be adapted for each fault.

After conditioning was completed several trial runs were made with MONITAUR using the internal NASA engine model and Boeing fault data. A Boeing propulsion expert had identified specific symptoms for the faults supplied. A poor match was found with symptoms generated by these first experimental runs. MONITAUR generated extraneous symptoms and missed critical symptoms. No attempt was made to alter the internal NASA engine model. Instead modification of MONITAUR to accept a Boeing engine model data was initiated. The modified MONITAUR system includes a new function which reads fault data from a file collected from sensors during flight (DATAFIL.DAT). This file is parsed to yield an actual value.

2.7.1.3 Using a Boeing Engine Model

The original plan was to network a Boeing (APOLLO based) engine model with the PC version of MONITAUR to accept engine model data on a time slice basis. When it was discovered that this strategy violated Boeing propulsion's engine model distribution policy, an alternate plan was devised which used data generated by propulsion in a batch mode matching the fault data file. New LISP functions to parse the engine model data file were created and substituted for calls to the internal engine model. The modified MONITAUR system consists of a program which reads this model data from a file (MODEL.FIL) which yields an expectation value. Experimental runs were made using Boeing fault data and Boeing engine model data. The results were improved, but not perfect when compared with symptoms identified by experts.

2.7.1.4 Additional Modifications

Modifications to the MONITAUR code were made to reduce differences between expected symptoms and generated symptoms. An algorithm change in trend calculation yielded more consistent trend symptoms.

An additional concern about noise levels for each sensor for each parameter (actual value, deviation, and trend) was identified. The design of MONITAUR is excellent in that it allows individual noise levels to be set for each sensor for each parameter. A task was defined to utilize healthy engine data to compare with a Boeing engine model to yield initial noise levels. The issue was to be able to set values high enough to eliminate spurious symptoms yet low enough to not miss significant symptoms. The comparison of engine model data with data collected from healthy engines yielded values for noise. These were coded into the Physical System File (PSF) for the engine model selected. A comparison of healthy engine data with expectation data produced about 30% fewer spurious symptoms when the custom PSF was used.

A third area of concern was the MONITAUR knowledge base which is used to filter symptoms generated solely due to engine model behavior, and are not real performance symptoms. The original plan was to not address modifications in the MONITAUR knowledge base, but our work with diagnostics has shown the tremendous importance of being able to generate symptoms with very high reliability. The bottom line is that without extremely accurate symptoms, the diagnostic phase development is worth very little.

This reasoning prompted the Boeing developers to elevate the priority of spurious symptom analysis to a much higher status. A second engine (from a different manufacturer) was examined to insure the problem was generic. A second PSF was customized for the new engine and heathy data was analyzed. Consistent spurious symptoms were detected for both engines. Analysis of both engine's spurious symptoms was completed. Several sources of spurious symptoms were identified. These were documented and forwarded to NASA in November 1990.

For each source of spurious symptom documented, an analysis of potential solutions was also provided. From December 1990 to present the major developmental effort for MONITAUR has been to investigate a subset of the alternatives suggested to determine effectiveness of the selected alternative. Several new LISP functions were written and tested to support new symptom filtering rules for the PSF. A significant reduction in spurious symptoms has been achieved, but we have not addressed each alternative, nor even each source. A large part of our follow-on recommendation will be to find an optimal solution to spurious symptoms generation. The work accomplished to-date can be considered proof-of-concept for spurious symptom reduction.

2.7.1.5 Output from MONITAUR

There are three levels of output from MONITAUR. The first, and most voluminous, is the "encyclopedia run" for each fault and healthy engine file. This file shows the state of each sensor for each time slice along with every symptom generated. It also contains the numbers of filtering rules fired as the symptom was analyzed.

A sample set of "encyclopedia" output is shown in Figure 6. It shows a time slice identified by its time value, in this case "237". Prior to evaluating the actual and expectation data, five filtering rules from the MONITAUR knowledge base fired, #7, #9, #10, #11, and #12. These rules resulted in five potential symptoms not being passed to DRAPhyS STAGE2. The state of each sensor is then printed, first the actual, then the expectation states. Following the states of the actual and expectation data, the symptoms discovered by MONITAUR are printed. In the case of N1, the difference between the actual static (NORMAL) and the expectation static (LOWER-CAUTION) yield a static symptom of HIGHER-THAN-EXPECTED. Each sensor can potentially have three symptoms (Static symptom, Derivative symptom, and Trend Symptom) generated. When all three actual states agree with all three expectation states, no symptoms are generated, as shown in the ALTITUDE sensor. We will use this same time slice in the discussion of output files in the following paragraphs.

"   rule 7 fired"
"   rule 9 fired"
"   rule 10 fired"
"   rule 11 fired"
"   rule 12 fired"

For Time 237.0:

SENSOR: N1

The following symptoms reflect the actual data.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect the expected values.
Static Symptoms: (LOWER-CAUTION)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect differences between the actual data and the expected values.
Static Symptoms: (HIGHER-THAN-EXPECTED)

SENSOR: N2

The following symptoms reflect the actual data.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect the expected values.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect differences between the actual data and the expected values.
Static Symptoms: (HIGHER-THAN-EXPECTED)

SENSOR: EGT

The following symptoms reflect the actual data.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect the expected values.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect differences between the actual data and the expected values.
Static Symptoms: (HIGHER-THAN-EXPECTED)

SENSOR: EPR

The following symptoms reflect the actual data.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect the expected values.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (STEADY)
The following symptoms reflect differences between the actual data and the expected values.
Trend Symptoms: (INCREASING-ABNORMALLY)

SENSOR: FUEL-FLOW
The following symptoms reflect the actual data.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect the expected values.
Static Symptoms: (NORMAL)
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)

The following symptoms reflect differences between the actual data and the expected values.
Static Symptoms: (HIGHER-THAN-EXPECTED)

SENSOR: ALTITUDE
The following symptoms reflect the actual data.
Static Symptoms: (NORMAL)
Derivative Symptoms: (STEADY)
Trend Symptoms: (STEADY)
The following symptoms reflect the expected values.
Static Symptoms: (NORMAL)
Derivative Symptoms: (STEADY)
Trend Symptoms: (STEADY)

SENSOR: MACH
The following symptoms reflect the actual data.
Static Symptoms: (NORMAL)
Derivative Symptoms: (STEADY)
Trend Symptoms: (STEADY)
The following symptoms reflect the expected values.
Static Symptoms: (NORMAL)
Derivative Symptoms: (STEADY)
Trend Symptoms: (STEADY)

SENSOR: THROTTLE
The following symptoms reflect the actual data.
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)
The following symptoms reflect the expected values.
Derivative Symptoms: (INCREASING)
Trend Symptoms: (INCREASING)

Figure 6. "Encyclopedia" Output from MONITAUR

In addition, an output file is created for STAGE1 of DRAPhyS and for STAGE2 of DRAPhyS. The STAGE1 output consists of all sensor states and symptoms generated from MONITAUR.

A sample of the STAGE1 input file is shown in Figure 7. It is a file with the format

```
(
(time (sensor1) (sensor2)...)
(time (sensor1) (sensor2)...)
 •
 •
 •
)
```

The first time slice shown is identified with the time value "237.0". Following the time is a list of sensor states and symptoms for each sensor in the Physical System File. This file can be passed as a list of time slices for batch processing by STAGE1, or as individual time slices and processed sequentially in unison with MONITAUR.

```
(237.0
 (THROTTLE
  ((STABILITY-EQT (INCREASING)) (STATUS-OF-DERIVATIVE-EQD (INCREASING))
   (STABILITY-AQT (INCREASING)) (STATUS-OF-DERIVATIVE-AQD (INCREASING))))
 (MACH
  ((STABILITY-EQT (STEADY)) (STATUS-OF-DERIVATIVE-EQD (STEADY))
   (STATUS-OF-VALUE-EQS (NORMAL)) (STABILITY-AQT (STEADY))
   (STATUS-OF-DERIVATIVE-AQD (STEADY)) (STATUS-OF-VALUE-AQS (NORMAL))))
 (ALTITUDE
  ((STABILITY-EQT (STEADY)) (STATUS-OF-DERIVATIVE-EQD (STEADY))
   (STATUS-OF-VALUE-EQS (NORMAL)) (STABILITY-AQT (STEADY))
   (STATUS-OF-DERIVATIVE-AQD (STEADY)) (STATUS-OF-VALUE-AQS (NORMAL))))
 (FUEL-FLOW
  ((STATUS-OF-VALUE-DQS (HIGHER-THAN-EXPECTED)) (STABILITY-EQT
(INCREASING))
   (STATUS-OF-DERIVATIVE-EQD (INCREASING)) (STATUS-OF-VALUE-EQS (NORMAL))
   (STABILITY-AQT (INCREASING)) (STATUS-OF-DERIVATIVE-AQD (INCREASING))
   (STATUS-OF-VALUE-AQS (NORMAL))))
 (EPR
  ((STABILITY-DQT (INCREASING-ABNORMALLY)) (STABILITY-EQT (STEADY))
   (STATUS-OF-DERIVATIVE-EQD (INCREASING)) (STATUS-OF-VALUE-EQS (NORMAL))
   (STABILITY-AQT (INCREASING)) (STATUS-OF-DERIVATIVE-AQD (INCREASING))
   (STATUS-OF-VALUE-AQS (NORMAL))))
 (EGT
  ((STATUS-OF-VALUE-DQS (HIGHER-THAN-EXPECTED)) (STABILITY-EQT
(INCREASING))
   (STATUS-OF-DERIVATIVE-EQD (INCREASING)) (STATUS-OF-VALUE-EQS (NORMAL))
   (STABILITY-AQT (INCREASING)) (STATUS-OF-DERIVATIVE-AQD (INCREASING))
   (STATUS-OF-VALUE-AQS (NORMAL))))
 (N2
  ((STATUS-OF-VALUE-DQS (HIGHER-THAN-EXPECTED)) (STABILITY-EQT
(INCREASING))
   (STATUS-OF-DERIVATIVE-EQD (INCREASING)) (STATUS-OF-VALUE-EQS (NORMAL))
   (STABILITY-AQT (INCREASING)) (STATUS-OF-DERIVATIVE-AQD (INCREASING))
   (STATUS-OF-VALUE-AQS (NORMAL))))
 (N1
  ((STATUS-OF-VALUE-DQS (HIGHER-THAN-EXPECTED)) (STABILITY-EQT
(INCREASING))
   (STATUS-OF-DERIVATIVE-EQD (INCREASING))
   (STATUS-OF-VALUE-EQS (LOWER-CAUTION)) (STABILITY-AQT (INCREASING))
   (STATUS-OF-DERIVATIVE-AQD (INCREASING)) (STATUS-OF-VALUE-AQS
(NORMAL)))))
```

Figure 7. STAGE1 Input Sample - (continued on next page)

```
(238.0
 (THROTTLE
  ((STABILITY-EQT (INCREASING)) (STATUS-OF-DERIVATIVE-EQD (INCREASING))
   (STATUS-OF-VALUE-EQS (FULL)) (STABILITY-AQT (INCREASING))
     (STATUS-OF-DERIVATIVE-AQD (INCREASING)) (STATUS-OF-VALUE-AQS (FULL))))
 (MACH
  ((STABILITY-EQT (STEADY)) (STATUS-OF-DERIVATIVE-EQD (STEADY))
   (STATUS-OF-VALUE-EQS (NORMAL)) (STABILITY-AQT (STEADY))
   (STATUS-OF-DERIVATIVE-AQD (STEADY)) (STATUS-OF-VALUE-AQS (NORMAL))))
 (ALTITUDE
  ((STABILITY-EQT (STEADY)) (STATUS-OF-DERIVATIVE-EQD (STEADY))
   (STATUS-OF-VALUE-EQS (NORMAL)) (STABILITY-AQT (STEADY))
   (STATUS-OF-DERIVATIVE-AQD (STEADY)) (STATUS-OF-VALUE-AQS (NORMAL))))
 (FUEL-FLOW
  ((STABILITY-EQT (INCREASING)) (STATUS-OF-DERIVATIVE-EQD (INCREASING))
   (STATUS-OF-VALUE-EQS (NORMAL)) (STABILITY-AQT (INCREASING))
   (STATUS-OF-DERIVATIVE-AQD (INCREASING)) (STATUS-OF-VALUE-AQS (NORMAL))))
 (EPR
  ((STABILITY-EQT (INCREASING)) (STATUS-OF-DERIVATIVE-EQD (INCREASING))
   (STATUS-OF-VALUE-EQS (NORMAL)) (STABILITY-AQT (INCREASING))
   (STATUS-OF-DERIVATIVE-AQD (INCREASING)) (STATUS-OF-VALUE-AQS (NORMAL))))
 (EGT
  ((STATUS-OF-DERIVATIVE-DQD (NOT-INCREASING-AS-FAST-AS-EXPECTED))
   (STABILITY-EQT (INCREASING)) (STATUS-OF-DERIVATIVE-EQD (INCREASING))
   (STATUS-OF-VALUE-EQS (NORMAL)) (STABILITY-AQT (INCREASING))
   (STATUS-OF-DERIVATIVE-AQD (STEADY)) (STATUS-OF-VALUE-AQS (NORMAL))))
 (N2
  ((STATUS-OF-VALUE-DQS (HIGHER-THAN-EXPECTED)) (STABILITY-EQT
(INCREASING))
```

Figure 7. STAGE1 Input Sample

The STAGE2 output consists of filtered symptoms from MONITAUR. A sample of the STAGE2 input file is shown in Figure 8. It is a file with the format

```
(
((sensor1) (sensor2) (sensor3) ...)
)
```

Each of the elements of the file is a list of sensor symptoms for one time slice. Each sensor entry is a list in a format expected by the function ADD_SYMPTOM from STAGE2. The first time slice shown is time 200. There are no STAGE2 symptoms for this time slice, so the entry is NIL. Examination of time slice 233 shows it is reporting sensor symptoms for N2. Examination of time slice 237 will show it is reporting sensor symptoms for EGT, but the other sensor symptoms shown in the "encyclopedia" run were filtered out as spurious symptoms.

```
(
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
NIL
((N2 NIL (NORMAL) NIL NIL 233.0 (STEADY)))
((EPR NIL (NORMAL) NIL NIL 234.0 (STEADY)) (EGT NIL (NORMAL) NIL
NIL 234.0 (STEADY)) (N1 NIL (LOWER-CAUTION) NIL NIL 234.0 (STEADY)))
((EGT NIL (NORMAL) NIL NIL 235.0 (STEADY)))
NIL
((EPR NIL (NORMAL) NIL NIL 237.0 (INCREASING)))
((EGT NIL (NORMAL) NIL NIL 238.0 (INCREASING)))
((EGT NIL (NORMAL) NIL NIL 239.0 (INCREASING)))
((EGT NIL (NORMAL) NIL NIL 240.0 (STEADY)))
((EGT NIL (NORMAL) NIL NIL 241.0 (STEADY)))
((EGT NIL (NORMAL) NIL NIL 242.0 (STEADY)))
((N2 NIL (NORMAL) NIL NIL 243.0 (INCREASING)))
((N2 NIL (NORMAL) NIL NIL 244.0 (INCREASING)))
((EGT NIL (NORMAL) NIL NIL 245.0 (INCREASING)) (N2 NIL (NORMAL) NIL
NIL 245.0 (INCREASING)))
((EPR NIL (NORMAL) NIL NIL 246.0 (STEADY)) (EGT NIL (NORMAL) NIL
NIL 246.0 (INCREASING)))
((EGT NIL (NORMAL) NIL NIL 247.0 (INCREASING)))
```

Figure 8. STAGE2 Input Sample

2.7.1.6 Lessons Learned on MONITAUR

As reflected in the previous section, the most important lesson learned is to recognize how vital an accurate set of symptoms is to the remainder of the system. At this point in the development it seems like an obvious fact, but the result is that we felt it was important to expend more than anticipated effort on MONITAUR to insure a valid set of symptoms are identified.

It is also obvious that more effort must be expended to minimize the number of spurious symptoms. Identification of spurious symptoms is readily achieved by processing healthy engine data through MONITAUR and looking for <u>any</u> symptom output. To date seven different files of healthy engine data have been examined representing about 900 seconds of engine run time. This represents about 900 time slices under normal query frequency. The analysis of these symptoms for source is more complex. About 70% of the time expended in our spurious symptom investigation was used for analysis. Several categories of symptoms were identified. Another 30% of effort was expended in coding and testing a subset of potential solutions for these symptom categories. At this point in the study, we believe the list of categories is incomplete and only a limited success in spurious symptom elimination has been achieved. It is estimated that four man months of total effort has been devoted to spurious symptom investigation. The goal of spurious symptom reduction will be a major portion of a follow-on contract. It is estimated that five to ten times as much data will be required for closure on this topic.

What is not so apparent, is how many spurious symptoms are generated by differences in individual (serial number) engines. Boeing propulsion estimates these differences may approach 30% for some sensors. Elimination of spurious symptoms with known causes will help to identify a reasonable value for those whose source is individual engine differences.

There is a potential to greatly enhance the quality of valid symptoms. Preliminary work on valid symptom analysis suggests that some valid symptoms may be temporally conditioned. For example, if the expectation value is much lower than the actual value so as to generate a static symptom, but the derivative and trend of the expectation value is much higher than the actual, the expectation value may be trying to "catch up" with the actual value. In this case it may be better to delay a static symptom generation for a few time slices. Exactly how to inhibit this symptom is a topic of investigation. Rules can be written for the MONITAUR filter to inhibit symptom generation, but another alternative is to consider differing classes of symptom - perhaps a warning class for stable symptoms and a caution class for a "catch up" situation as described above. The topic of symptom enhancement should definitely be studied further.

There is also evidence that the duration of time slice taken may affect symptoms and that heuristics might be developed to dynamically select time slice duration for each sensor as a function of developing conditions. The cost of redesigning the data structures required to provide unique time slices for each sensor would have to be evaluated and compared with the value of higher fidelity sensor behavior.

2.7.2 Work in DRAPhyS STAGE1

2.7.2.1 Conversion

The work done on DRAPhyS STAGE1 began with conversion from Genera LISP To GCLISP with problems similar to those discussed in 2.7.1.1. Following conversion, the system was tested using the rule base supplied with the NASA version. The interactive function was utilized to enter symptoms and basic functionality of STAGE1 was verified. A decision was made not to attempt to extend the STAGE1 knowledge base until real symptoms from MONITAUR could be input to DRAPhyS STAGE1.

2.7.2.1.1 Analysis of STAGE1

Before extending the knowledge base or accepting any output from MONITAUR, a better knowledge of how STAGE1 functioned was needed. An analysis of what each function did and its relationship to the other functions in STAGE1 was performed. To further clarify STAGE1, a detailed flow chart was constructed for all of the functions that were used in STAGE1.

Examining the results of the analysis program and the detailed flow chart revealed that three functions, INIT-STAGE1, INTERACT and START form the core of STAGE1. To pull these three functions together, a shell that accommodated the three core functions and the user was written for batch file processing (discussed below in section 2.7.2.2). The shell, RUN-STAGE1, is called by the LOAD function. RUN-STAGE1 calls INIT-STAGE1 and informs the user that STAGE1 is initialized. It then allows the user to choose between the interactive mode (call INTERACT) or the automatic mode (call START2). After STAGE1 has completed its run, the shell allows the user to rerun STAGE1, remain in LISP, return to the operating system or terminate the session.

Next, the analysis showed that there were six functions that were neither called by other functions or called other functions. These functions are used in temporal reasoning and are listed below.

STARTS
FINISHES
BEFORE
OVERLAP
MEETS
DURING

There are two other temporal reasoning functions in STAGE1, TMPRL and TMPRL-AUX. These two functions make use of the six temporal function listed previously, but the function TMPRL requires that it be called by the user. This means that temporal reasoning is not presently used in STAGE1 diagnostics unless it is called by the user. The nature of the gas turbine engine and the way events occur during its operation triggered further examination of the MONITAUR output data. The results of this examination indicate that temporal reasoning could be an important part of the analysis and diagnostic process

In using STAGE1 in the interactive mode, it was discovered that the WHY and SHOW functions did not work. This problem was not pursued because building a rule base for STAGE1 had a higher priority and these functions appear to have no use in an integrated system.

2.7.2.2 Integration of DRAPhyS STAGE1 with MONITAUR

Two approaches for integration were evaluated. The first was to generate a file of symptoms for multiple time slices from MONITAUR and use these as a batch input to DRAPhyS STAGE1. This offers advantages of being able to test changes in STAGE1 without running MONITAUR. Most of the analysis described in this report was performed using the batch method. A second alternative was to load both MONITAUR and DRAPhyS STAGE1 and sequentially call STAGE1 for evaluation after each symptom set is generated for each time slice. Both approaches have been developed. The latter approach was developed since it more closely represents the processing required for a real time system and offers a greater technical challenge in terms of allocating PC resources.

MONITAUR was modified to produce a data structure which will eventually be passed to STAGE1 for parsing into symptoms. Initially, however, this structure was written as an output from MONITAUR for each time slice. The file is then read into STAGE1 for parsing and analysis. The main reason for the interim file is to allow an audit trail for system debugging.

To accommodate running the output from MONITAUR, changes to STAGE1 were required. Specifically, the function START was modified twice. The first modification, START1, is used for the integrated version. The second modification, START2, is used for batch processing. START2 allows the user to name the file to be processed. While it is analyzing each time slice the results of the analysis are printed to the screen. The results of each session is saved in a file named by the user.

2.7.2.2.1 Using MONITAUR Output Data In STAGE1

MONITAUR's output consists of a data structure for each time slice generated by the Boeing engine model. Each time slice contains data for up to eight sensors. The sensors are N1, N2, EGT, EPR, FUEL-FLOW, ALTITUDE, MACH and THROTTLE. For each sensor there can be up to nine pieces of more detailed data. They are Actual - static, derivative and trend; Expectation - static, derivative and trend and Deviation - static, derivative and trend.

For batch processing MONITAUR output data is input to STAGE1 via a floppy disk file. Hard copies of the files were available in the form of an encyclopedia and a print out of the disk file. The number of time slices for each file ranged from forty five to one hundred eighty. Given the number of time slices and the preponderance of data for each time slice, interpretation of the data was difficult. To solve this problem, a program was written that displays the data in an abbreviated format. This is a matrix type form with a row for each time slice and a column for each sensor name. Presently, only five sensors are displayed; N1, N2, EGT, EPR and FUEL-FLOW. To further simplify the analysis, only the three Deviations are shown for each time slice/sensor combination. Using the abbreviated format has greatly simplified analysis of this data and building rules for STAGE1.

2.7.2.3 Adding New Rules to DRAPhyS STAGE1

Rules for Boeing identified faults were developed as a part of the fault scenario development activity. Four rules have been added to STAGE1 during the second half of the project. These rules are based on the work of knowledge engineers working with experts using actual flight data from Boeing files.

<u>Analysis of Symptom Data</u>

To date six files have been output from MONITAUR. They are Healthy-EngineA, Healthy-EngineB, Ground-Hung-Start, Light-Ice, Moderate-Ice and Heavy-Ice. Each of these files was passed through the program that produced the abbreviated symptom report.

Analysis of MONITAUR Output

Healthy-Engine

It would be expected that both Healthy-Engine outputs from MONITAUR would contain little if any symptom data, but this is not so. Both reports showed about 10% of the spaces contained symptom data. This is quite high considering that an engine with known faults i.e. Light-Ice, had a symptom population of about 6%. These spurious symptoms were discussed in detail in section 2.7.1.4.

Ground-Hung-Start

Hung starts can occur both on the ground and in the air, and can result from a number of different causes. The experts provided us with data for a ground hung start. The hung start was caused by a fuel metering unit malfunction, providing too little fuel to the fuel nozzles. It was found that the fuel valve either moved to a partially open position and stuck or failed to move from the minimum open position. This resulted in insufficient combustion to support normal spool-up to idle.

The experts' report stated that at time t3, fuel flow began to drop below the flow rate for normal start. In addition N2 rotor speed began to lag below normal rate. N1 and EGT remained normal at this time. At time t4, N2 and EGT did not reach normal values and N1 leveled at 53% of normal. EGT was increasing at the normal rate. At t5 N2 should have been at idle speed, but was at only 67% of idle RPM. EGT was still normal. At t6 N1 and N2 were still at below normal speeds, and EGT continued to increase to 13% above normal, instead of leveling off.

A rule set was constructed for ground hung start using the data supplied by the experts. The rule set was tested against the output data from MONITAUR and fired successfully when the data indicated a hung start.

Light-Ice

Any ingestion of foreign matter such as birds, volcanic ash, or ice is classified as foreign object damage (FOD). In the case of light-ice damage, FOD results in an step-function change in the level of vibration produced by the engine, while all other parameters remain relatively normal. The effect of damage and the resulting thrust shortfall may be so subtle that it would not be detected by the crew until the throttle is advanced for take-off or go-around (TOGA) power (advancing the throttle).

The output from MONITAUR for light-ice damage comes close to verifying this. The only real deviation from this is the Higher-Than-Expected EGT. This may be due to a number of factors, from the age of the engine to problems with the model. Because vibration data is not normally collected, and the lack of other symptom data produced by MONITAUR, no rules were constructed for light-ice.

Moderate-Ice

The symptoms for moderate ice damage differ depending on the commanded power setting. The two power settings observed were climb and cruise.

In the climb setting, N1 speed was on target while N2 showed a decrease of 5%. Both EGT and Fuel-Flow fell slightly below expected value. As in low ice damage, these shortfalls could be difficult for the crew to observe. Also, the vibration level on N1 exceeded the expected value by 25%. A spike appeared in N2 vibration reading, then it dropped to the expected value.

In the cruise setting, thrust shortfall increased slightly from climb setting. N2 was at the expected level. EGT and Fuel-Flow remained slightly lower than expected. N1 vibration remained at 25% above expected value, but N2 vibration reading was averaging 200% higher than expected value. Acceleration to the commanded thrust level was slightly slower than expected.

The output from MONITAUR for moderate-ice damage is difficult to interpret for three reasons. First, sensor data for any given series of time slices is not consistent. Second, symptoms differ between modes of operation, i.e., climb and cruise. Third, vibration data is not available from MONITAUR, and vibration, as with low ice damage seems to be the only clear indication of damage in an FOD situation. The other indications (EGT, N2 speed and Fuel-Flow) are subtle and may not be noticed in the cockpit. In addition, these differences could fall within the noise bands of MONITAUR deviation detection and not appear in the symptom file. Due to these reasons, no rules were constructed for moderate ice damage.

Heavy Ice

While changes in vibration levels on low (N1) and high (N2) speed rotors are evident with light and moderate ice damage, they do not show up with heavy damage. Instead, the vibration symptom evident for heavy damage is a marked increase in broad band vibration. In addition, the shortfall with light ice damage is only evident under TOGA power settings. Moderate ice damage results in a slight shortfall at climb power. But, with heavy ice damage, the shortfall is very evident even at cruise power (i.e., approximately 80% of normal). N2 was lower than expected, and both EGT and Fuel-Flow were lower than expected.

The output from MONITAUR for heavy ice damage is heavily populated with symptom data and compares closely with the expert's statement. The only disagreement is in EPR and Fuel-Flow. MONITAUR shows EPR lower than expected and no Deviation for Fuel-Flow for the first eighteen time slices. It then shows Fuel-Flow increasing until time slice 60.5. At time 61.0, it begins to decrease till time 69.0, after that it remains normal. The experts statement shows lower than expected for both EPR and Fuel-Flow. The reasons for this discrepancy are still being investigated.

Based on the expert's information a set of rules was built for Heavy Ice damage. However, the data concerning Fuel-Flow was left out of the rule set pending further investigation into the problem. The rule set was tested against the MONITAUR output and was successful in firing when Heavy Ice damage was indicated.

2.7.2.4 Alternate DRAPhyS STAGE1 Development

An alternate to DRAPhyS STAGE1 was also examined. In an attempt to allow STAGE1 processing on incomplete symptom information, a fault pruning paradigm was created using NEXPERT OBJECT. A knowledge base consisting of an object architecture and a rule base were designed to allow incremental knowledge to be accumulated with a corresponding incremental reasoning about the associated fault(s). The paradigm consists of an object architecture with a set of faults modeled with associated properties. The rule base examines the current set of symptoms and dynamically prunes potential faults from the object architecture using negative evidence. Thus as the set of symptoms is developed, the list of possible faults is diminished. The advantage of this approach is the development of partial knowledge with incomplete evidence (as opposed to conventional approach which only fires rules when complete knowledge is available).

The status of this alternative is a current working demo with information modeled from a NASA supplied rule base. This demo lacks fidelity, and is not a proof of concept. It was demonstrated to NASA in September 1990 as a potentially more robust approach to conventional STAGE1 processing. No further development on this alternative is anticipated unless specifically requested by NASA.

2.7.2.5 Lessons Learned on DRAPhyS STAGE1

1. More data is needed to ensure the fidelity of rules generated in STAGE1. Multiple incidences of the same fault and an expanded range of faults are both required. Each individual engine is different from the next. In addition, as engines age, their operational characteristics change. And finally, any repair or adjustment made to an engine, during routine maintenance or unscheduled maintenance, can change its operational characteristics. Thus, more comparisons are needed to establish the reliability and validity of the diagnostic process.

   A solution to the above problem is to collect data and create separate data files for different engines and measure differences between engines.

The analysis should take into consideration the fact that as the engine accumulates operation time, its operation characteristics will change, therefore, operating time of the engine should by collected by the system.

2. Diagnosing with symptoms from only one time slice at a time is not effective. Engine failures and problems are progressive in nature. A complete set of symptoms do not occur all at once. They may occur one or two at a time, or a new symptom may take the place of the previous symptom. Symptoms may also by intermittent and/or transient and go away.

   Building a history of sensor symptoms for each time slice and analyzing them with temporal reasoning to see if they match a rule, would be a more realistic type of diagnosis. Both data collection and accumulation, and diagnosis would occur in the same time slice.

3. Data could be collected by MONITAUR and analyzed in a three dimensional matrix. Each plane of the matrix would be a fault file in the matrix format described in section 2.7.2.3. Each file produced by MONITAUR could be analyzed for the number of symptoms it holds. Symptoms may occur in clusters or groups; certain symptoms within time slice by sensor cells of the matrix may form patterns that could be built into rules. The data could be analyzed for symptom trends which could be used for early detection of problems. The data for one operational period could be compared with data from other operational periods to establish trends in symptom occurrence. And finally, the data used to build possible rules could be compared with the data that was used to build existing rules. This would prevent building identical rules for different failures.

   If a failure occurs during operation, and the collected data did not match a rule, it may be possible that the data could be analyzed to determine an alternate or additional symptom for the failure. This may be another way to use collected data to build rules.

4. Include altitude, Mach and throttle sense data in the data analyzed by STAGE1. Analysis of present symptom data shows that symptoms change during different phases of flight and engine operation. The symptoms for FOD in climb are different from the FOD symptoms in cruise. In fact, the total engine operational characteristics could change during different phases of flight and engine operation.

   These different phases of flight and engine operation could be detected by monitoring actual altitude, Mach and throttle settings. This data would also be included in the rules.

There are some factors, not previously considered within the scope of this study, which may have a significant bearing on the Boeing perspective. One of these is the response required for the fault. If there are a limited number of valid responses to all engine faults, perhaps diagnosis does not have to be accomplished to the granularity previously defined. It may be that STAGE1 only needs to associate symptoms with classes of faults in order to generate the correct response to the problem. These issues will not be addressed in the current contract, but should be noted for further study. They also suggest that STAGE1 (associational) processing may not be as dependent on fault specificity as originally thought.

2.7.3 Work in DRAPhyS STAGE2

Work completed on DRAPhyS STAGE2 began with a Boeing analysis of the model based paradigm utilized in this NASA- developed module. As an initial effort to gain understanding of the software, high level data flow diagrams and control flow charts have been constructed to document the system functionality. The demonstration system supplied by NASA was installed and made functional on Boeing hardware. This demonstration program is a stand-alone interactive system with symptoms input through mouse selection from a GUI or by using text based LISP functions. Boeing's first objective was to create a connection from the output from MONITAUR, which is a list of symptoms, to the DRAPhyS STAGE2 program.

2.7.3.1 Development Strategy for DRAPhyS STAGE2

Since DRAPhyS STAGE2 contains extensive use of Flavors, which is not supported in GCLISP, conversion to GCLISP was not an option. To make STAGE2 compatible with the PC versions of MONITAUR and DRAPhyS STAGE1, two alternatives were considered. The first was to develop a stand alone version of STAGE2 on the MacIvory under Genera LISP which is CLOE compatible. When the desired functionality could be demonstrated on the MacIvory, the code would be ported to a PC using CLOE. A run time version would then be completely PC based. A second alternative (not implemented) was to leave the development on the MacIvory workstation and network the PC with MONITAUR output to the MacIvory for STAGE2 processing.

2.7.3.2 STAGE2 Development

DRAPhyS STAGE2 was redeveloped to a PC-connectable module capable of accepting symptom input from MONITAUR using CLOE. Minor modifications were made to DRAPhyS STAGE2 for the CLOE version. Most were syntax incompatibilities between CLOE LISP and Genera LISP. Just as the development of PC versions of MONITAUR and DRAPhyS STAGE1 with real fault and Boeing engine model input led to discovery of issues of concern and strategies for further development, STAGE2 yielded similar concerns and strategies. The CLOE version of STAGE2 was modified to accept input from the MONITAUR program. The data can be passed to STAGE2 in a time slice format or in a batch mode consisting of multiple time slices.

A major concern was the effect of spurious symptoms in the DRAPhyS STAGE2 system. Current STAGE2 processing allows no symptom evaluation. Each symptom is processed as valid and appropriate fault hypotheses are generated and tested. For this reason, extensive symptom evaluation must be completed in MONITAUR. Most of the rules added to the current version of MONITAUR have the function of filtering spurious symptoms from STAGE2 input. As was discussed in section 2.7.1.4, this task remains incomplete and would be a major effort in a follow-on project.

Once the problem of spurious symptoms is solved, the next question to consider is enhancement of STAGE2 analysis. The current model based reasoning paradigm utilizes only functional and physical connectivity for fault analysis and hypothesis generation and testing. The symptom input mechanism currently defined in ADD_SYMPTOM contains sensor behavior information, but knowledge of this information is not exploited within DRAPhyS STAGE2. An enhancement strategy would be to expand the current paradigm to include exploitation of behavioral information to increase the fidelity of the valid hypotheses produced.

One method would be to add behavior to the appropriate data structure for each component modeled in each subsystem. Instead of propagating the binary condition "abnormal sensor" through the model, agreement between actual sensor behavior and modeled behavior would be required for fault propagation. We could still retain the binary condition as a default if other search strategies fail. A second method would be to incorporate rules from DRAPhyS STAGE1 directly into STAGE2. One architecture would have sensor behavior feeding inputs into component objects, and part of the component's behavior would derive an output of the condition of that component. An alternative architecture would have the component control an output for related sensor behavior such that if the component is in a specific state, it would assign values to the associated sensors. If we were to adopt this strategy, STAGE1 would become a testing vehicle for adding new rules. Yet a third method would be to model the fault mechanism (i.e., various known ways a device can break along with the safety net of "UNKNOWN", which we have now, where known modes carry alternate behaviors that can be tested against later data). These approaches should be subjected to an alternatives analysis in a follow-on project.

Finally, the anticipated use of context variables for enhanced fault identification and for response clarification may also impact STAGE2 development. Use might be made of context variables to prune the multiple fault hypotheses currently generated in STAGE2. This question should be addressed in a follow-on project.

2.7.3.3 Lessons learned on DRAPhyS STAGE2.

The most important lesson learned from processing real data in DRAPhyS STAGE2 is the unacceptability of spurious symptoms. When healthy engine data was processed by MONITAUR and spurious symptoms were passed to STAGE2, a host of hypotheses were generated with several being validated as faulty sensors. What remains to be investigated is whether sufficient symptom conditioning can be performed to render STAGE2 processing usable. At present, the current system does not represent a feasible approach to processing real engine data.

2.7.4 Prioritized Suggestions for Further Study

In view of the progress on all three modules outlined above, the following is the recommended development strategy for the follow-on Flight Deck Engine Advisor Project.

Priority 1.

A maximum effort should be made to eliminate as many spurious symptoms as possible from MONITAUR. Only when spurious symptoms have been absolutely minimized can we evaluate individual engine differences to determine feasibility of real symptom identification. A few of the alternatives suggested in the spurious symptom analysis previously sent to NASA have been explored with encouraging results, but this list needs to be exhausted.

Real symptom enhancement needs to be explored, both within MONITAUR and in the follow-on diagnosis. The example of actual versus expected "catch-up" cited in section 2.7.1.6 is only one of several potential enhancement strategies which may be promoted. Addition of temporal reasoning and ability to reason over multiple time slices to either MONITAUR or STAGE1 (more efficiently done in STAGE1) falls in this category. This will require the propagation of historical queue data from MONITAUR to STAGE1 or the reconstruction of this data within STAGE1.

More fault data must be collected to ensure the fidelity of rules generated in STAGE1. Multiple incidences of the same fault and an expanded range of faults are both required. To fully evaluate the symptom generation from MONITAUR, STAGE1 development must be maintained in the next iteration. Only with a STAGE1 in place can the identity of unique combinations of conditions (and related symptoms) be determined.

Priority 2.

The effect of individual engine differences needs to be investigated. This should be a follow-on activity to elimination of spurious symptoms, but a parallel effort could be undertaken to identify alternatives for dealing with individual differences.

Addition of behavior (in some form) to STAGE2 needs to be addressed as well. This could be a follow-on activity to spurious symptom identification, but could also be a parallel effort. In either case it would be better to utilize real fault data for this task.

3.0 COMMUNICATIONS

3.1 Contacts with NASA-Langley Personnel

3.1.1 Meetings

Coordination meetings to identify specific content for the Detailed Program Plan were held at NASA-Langley, Hampton VA - 4/10/90 to 4/13/90. Participants: NASA-Langley - K.H. Abbott, P.C. Schutte; Boeing - W.D. Shontz, R.M. Records.

Project definition presentation and discussions for ATOPS- TRCO held at Boeing Commercial Airplane Group, Renton facility - 8/7/90. Participants: NASA-Langley - Cary Spitzer; Boeing - Ralph Erwin, Bill Shontz, Mary Hornsby.

Presentation on project progress and discussion of potential follow-on topics held at Boeing, Renton facility - 9/26/90 and 9/27/90. Participants: NASA-Langley - K.H. Abbott, P.C. Schutte; Boeing - W.D. Shontz, R.M. Records, J.G. Lutch.

Presentation of Oral Interim Report followed by discussions with NASA, BB & N, and Boeing personnel held at NASA-Langley, Hampton, VA - 11/27/90 and 11/28/90. Participants: NASA-Langley - K.H. Abbott, P.C. Schutte; BB & N - W.H. Rogers; Boeing - W.D. Shontz, G.P. Boucek.

Coordination meetings to discuss issues affecting follow on to the current project and to clarify details of follow on activity which would be acceptable to NASA were held at NASA-Langley, Hampton, VA - 2/28/91 and 3/1/91. Participants: NASA-Langley - K.H. Abbott, P.C. Schutte; Boeing - W.D. Shontz. Also coordinated Flight Deck Engine Advisor activities on pilot information requirements with W.H. Rogers of BB & N.

Attended meeting and made presentation on the Flight Deck Engine Advisor project at the GE installation at Evensdale, OH - 3/20/91. Participants: NASA-Langley - K.H. Abbott; Boeing - W.D. Shontz; GE - Dave Doel, et al

3.1.2 Telephone Consultations

Clarification of specific project activities as described in the Detailed Program Plan - 5/6/90 and 5/9/90. Participants: NASA-Langley - Paul Schutte; Boeing - Roger Records, Bill Shontz.

Discussion of revision to the Detailed Program Plan suggested by Kathy Abbott - 6/1/90. Participants: NASA-Langley - Kathy Abbott; Boeing - Bill Shontz.

Further discussion of proprietary issues and current status with respect to being able to deliver an engine model and real engine data - 6/18/90. Participants: NASA-Langley - Kathy Abbott; Boeing - Bill Shontz.

Phone consultations with BB & N subcontractor to NASA-Langley to coordinate BB & N and Boeing efforts on pilot information requirements as they relate to work both companies are doing for NASA-Langley on the Faultfinder concept. Several phone calls over the course of the project. Participants: BB & N - W.H. Rogers; Boeing - W.D. Shontz.

Phone consultations on project progress, direction, and trip planning. Numerous phone calls over the course of the project on technical issues, status and content of follow on SOW, status of resolution of proprietary data issues, coordination of trips and meetings. Participants: NASA-Langley - Kathy Abbott, Paul Schutte; Boeing - Bill Shontz, Roger Records.

3.2 Contacts with Engine Manufacturers

3.2.1 Pratt & Whitney

Person Contacted:	Bill Stepule (203)565-9371
Contacted by:	Bill Shontz
Data of Contact:	8/9/90

Summary of Information Obtained:

Mr. Stepule is in a diagnostics group where they evaluate flight data, program ACMS, and have developed ground based software for monitoring engine performance at the module level. The PW engine condition monitoring program is called Turbine Engine Aids Monitoring (TEAM 3).

We discussed at some length the kind of monitoring and control activity that occurs in the engine controller on new engines. We also discussed PW's engine condition monitoring program with the airlines. I will have more comments on these areas in a general summary at the end of this section. In general, Stepule indicated PW was interested in the type of engine monitoring represented by the Engine Advisor project but that they lacked the time to investigate it more thoroughly at present.

3.2.2 Rolls Royce

Person contacted:	Mike Barwell (011)44-332-249505
Contacted by:	Bill Shontz
Date of Contact:	8/23/90

Summary of Information Obtained:

Each of the engine manufacturers contacted has a software program for monitoring engine condition. The Rolls Royce system is call COMPASS - Condition Monitoring and Performance Analysis Software System. COMPASS is said to have an engine model embedded in it. However, the nature of this model is not entirely clear from the written material Mr. Barwell referred me to (Ref 7) and he did not elaborate beyond the information contained in the paper. The frame of reference I gave in introducing myself was our interest in airborne engine model/monitoring systems to provide diagnostic and trend information on engine performance on the flight deck. Mike indicated that RR was not doing anything at the moment that would convert COMPASS to an airborne system. However, the COMPASS features of deviation detection and trend analysis are certainly capabilities which an airborne system should have.

3.2.3 General Electric

Persons Contacted:	Neal Walker - 8/23/90 - (513)774-6083
	Jim Elliot - 9/11/90 - (513)774-6143
	Kiyoung Chung - 9/11/90 - (513)583-5401
	Dave Doel - 9/11/90 - (513)583-5469
	Hal Brown - 9/13/90 - (513)583-5441
	George Converse - 9/17/90 - (513)583-5466
	Ron Plybon - 10/4/90 - (513)583-5472
Contacted by:	Bill Shontz
Dates of Contact:	Between 8/23/90 and 10/4/90

Summary of Information Obtained:

My contacts with Walker, Elliott, and Chung served to identify additional people within GE with whom I should talk. In fact, each person in the list above referred me to the next person as one I should really talk with. The conversations with Doel, Brown, Converse, and Plybon were all of a technical nature and with increasing level of specific technical details. Of these contacts, Dave Doel will probably be the primary focal point for further contacts with GE for two reasons. One, he is familiar with the Faultfinder concepts via having read paper presentations of Abbott, et al at NASA-Langley and will be the GE focal point for contact with NASA-Langley. Two, Ron Plybon referred me back to Dave at the end of our conversation on 10/4/90.

As with the other two engine manufacturers, GE is focusing primarily on ground based engine condition monitoring for maintenance (they call their system GEM). However, there appears to be a great deal of activity in engine monitoring and control which would be relevant to the development of a flight deck engine advisor system. Further, one of Dave Doel's charges appears to be to keep up with developments of flight deck engine advisor concepts. Hal Brown indicated GE has done some work towards fault detection on civilian engines; they have done much more on military contracts - particularly the Pilot's Associate program. He also indicated they will be doing more in the future.

Of particular interest was the concept of "hard and soft failures" discussed by both Brown and Plybon. Hard failures are those that occur over a relatively short time span and are relatively easy to detect and diagnose. Soft failures, on the other hand, are the result of slow degradation in part or component performance and are very difficult to detect and diagnose. It is in detecting and diagnosing these latter types of failures that the Faultfinder concept could have a major impact.

3.2.4 General Summary of First Half Contacts

All engine manufacturers surveyed have developed major software packages for engine condition monitoring to support maintenance planning activities.

However, interest in the Faultfinder concept of monitoring and diagnosis varied considerably. It is not known whether this represents genuine differences in levels of interest within companies or different levels of concern for proprietary issues among individuals I talked with.

It also became clear, that there is considerable monitoring going on in new electronic engine controllers that is of the type that would be directly applicable to the Engine Advisor concepts. Further, the continual addition of parameters that are sensed suggests the possibility of much more sophisticated trend monitoring and fault prediction than has been possible in the past. The weak links to date in developing engine monitoring and fault diagnosis systems which provide information to the flight deck is the availability of sophisticated and reliable real-time engine models. These models must have stable, narrowly defined bands for normal parameter performance yet be adaptable to the variations across engines of the same type. A second weakness is the lack of a well organized, structured data base readily available for engine model and monitoring and diagnosis module development. The engine performance data base being accrued by the major airlines along with Boeing flight test data and engine manufacturer data may serve as a starting point for data base development.

A second round of contacts with Key individuals at each company will be initiated during the second half of the contract.

3.3 Second Half Contacts with Engine Manufacturers

3.3.1 Pratt & Whitney

Persons Contacted:	Rick LaPrad - 1/29/91 - (203)565-6883 Bill Stepule - 2/11/91 Dick Meisner - 4/11/91 - (203)565-3842 Bill Gallops - 5/13/91 - (407)796-2172
Contacted by:	Bill Shontz
Dates of Contact:	Between 1/29/91 and 5/13/91

Summary of Information Obtained:

The contact with Rick LaPrad served only as reference back to Bill Stepule who was contacted early in the current project. The discussion with Stepule focused on his work in performance monitoring. It appears, based on discussions of performance monitoring work with the engine manufacturers, that the airlines may be the best source of fault data acquired in an operational environment. Stepule also referred me to Dick Meisner at Hartford. Meisner in turn referred me to Bill Gallops of PW's newly renamed Government Engines and Space Propulsion Division (formerly the Government Products Division) in West Palm Beach. It was with the Gallops contact that I was at last talking with the right person at Pratt & Whitney. As with GE, PW's work on engine modelling has been largely supported by military programs. Both PW and GE have approaches to adaptive engine modelling which are similar in some ways but quite different in others. It remains to be seen which approach would best support the monitoring function within the Flight Deck Engine Advisor system. The proprietary issues surrounding transfer of engine model code and engine data was raised with Gallops. He indicated he would try to contact people in the commercial group at Hartford regarding the issue. He also suggested that perhaps an industry group such as an SAE committee should be formed to coordinate efforts in engine modelling so that people retain an appropriate focus.

Contact will be maintained with PW through Bill Gallops. He knows Dave Doel of GE and they appear to be comparable contacts at the two engine manufacturers.

3.3.2 Rolls Royce

Person Contacted:	Dennis Burnell - (011) 44-332-247922
Contacted by:	Bill Shontz
Date Contacted:	1/29/91

Summary of Information Obtained:

Dennis Burnell is in the Advanced Controls group of RR Bristol. He was an appropriate person to be talking with but as in the earlier conversation with Mike Burwell very little information was gained about what RR may be doing that is related to the current contract. No further contact is planned with Rolls Royce.

3.3.3 General Electric

Persons Contacted:	Dave Doel, et al
Contacted by:	Bill Shontz
Date(s) Contacted:	Doel phone calls re meeting at Evensdale 3/20/91 - meeting at Evensdale, OH

Summary of Information Obtained:

The meeting at GE in Evensdale, OH consisted of a number of presentations by GE people describing work they have undertaken which they felt relevant to the fault management program efforts being sponsored by NASA-Langley. Speakers included:

Dave Doel - GEAE	
Kathy Abbott - NASA-Langley	
Bill Shontz - Boeing	
Hal Brown - GEAE	
Dick Dyson - GEAE	(phone number not available)
Bruce Pomeroy - GE CR & D	(phone number not available)
Pete McDonald - GEAE	(phone number not available)

Presentations were followed by a discussion of issues of common interest to the group. Included in this discussion was the potential for NASA obtaining an engine model from GE. There was no one present who could really address the issue.

3.3.4 General Summary of 2nd Half Contacts

It appears that both GE and PW have some activity under way directed at developing the kind(s) of engine model(s) needed to support a flight deck engine advisor system. The approaches appear to be similar in some ways and very different in others. The information available at this time is insufficient to permit any judgement on the feasibility of the approaches. Such a judgement should be made, however, before tying the development of the Flight Deck Engine Advisor system to a particular approach.

4.0 RESULTS AND CONCLUSIONS

4.1 Hardware and Software Selection

The selection of a PC environment using GCLISP and CLOE for enhancement of Faultfinder has provided additional flexibility for the research process. We were able to modify MONITAUR to accept real fault data in a batch mode and integrate the associated engine model data files. The GCLISP environment, while not as elegant as Genera LISP, still proved adequate to accommodate the revisions implemented to reduce spurious symptom generation in MONITAUR and fault-symptom association in STAGE1 of DRAPhyS. The CLOE implementation was, in like manner, adequate for testing the through put of real fault data in STAGE2 of DRAPhyS.

We recommend the continued use of both PC development environments for a follow on project. Should NASA choose to disseminate our enhanced versions of MONITAUR, STAGE1 and STAGE2, they will find the engineering community at large has a much larger PC base than LISP workstations.

4.2 Fault Scenario Selection and Development

4.2.1 Selection

The selection process involved selection of an engine model to be used in the enhancement process and candidate faults to be used in the information requirements analysis and knowledge base development. Engine model selection was quite straight forward once available models were identified. Propulsion simulation experts familiar with the strengths and weaknesses of the various models evaluated each model on the basis of criteria developed by Boeing and NASA. The model selected had clear advantages over competing models. The details of this process are described in Section 2.4.1. Proprietary issues have precluded inclusion of the modelled engine's identity and code in the Final Report. Efforts to permit inclusion of an engine model and engine data as a part of the deliverables in any future work on Flight Deck Engine Advisor are being carried out as a part of the follow on proposal process.

Fault candidate selection was driven by two factors; availability of real engine data, and the match between fault data characteristics and the criteria for selection developed by NASA and Boeing. Of these two, availability was the key factor. Eventually we were able to acquire data on eight faults which, taken together, provided coverage of all nine criteria established. The process of selecting faults continued over a much longer period during the contract than had originally been planned because of the nature of the process of identifying potential faults and locating and preparing the engine data for analysis. The identity of faults and location of the data resided in the memory of engineers who had worked with the data rather than being available through a readily accessible cataloging system. Rather than arbitrarily terminate the search for additional fault data early in the contract, we elected to leave the possibility of acquiring additional data open as long as possible. This did not delay work on knowledge base development and allowed us to devote more time to the details of fault scenario development than would have otherwise been possible. The result was an iterative approach to fault scenario and knowledge base development which allowed us to complete more fault scenarios than would have been possible under the original schedule.

4.2.2 Development

Fault scenarios were developed to serve as the data base for knowledge base development. They are the repository of data on the fault propagation sequence and symptoms. Because the pilot information requirements were in fact an integral part of data needed for knowledge base development, information requirements analysis was carried out as a part of scenario development. The information requirements analysis and related conceptual development are discussed separately below. A complete version of each fault scenario is contained in Appendix A. The overall concepts developed and definitions of the various entries in the scenarios are contained in Section 2.5.

The process of developing data on fault propagation, symptoms, and information requirements for fault diagnosis represented the knowledge engineering phase of knowledge base development. The experts involved in this process were propulsion simulation experts and research pilots. Fault candidates were identified and engine data acquired by the propulsion experts. Preliminary guidance on fault propagation sequence and symptoms was also provided. From this, the fault scenario contents were developed. Propulsion experts and pilots then reviewed the contents for accuracy, clarity, and completeness. Additional potential fault alternatives were typically identified at this stage. When a fault scenario had completed this process it was turned over to the knowledge base developers. Any modifications to the scenario data base required to enhance its use in knowledge base development were also made. The result is a well coordinated and integrated data base for knowledge base development and a starting point for future analyses of pilot information requirements.

While the fault data base used in the present study was adequate to support initial enhancement activities on the MONITAUR and DRAPhyS modules, additional data will be required for further development of the DRAPhyS modules and feasibility testing of MONITAUR. Some additional fault data will be available from flight test files but efforts to identify and expand the data base through engine manufacturers and airlines are proposed as a part of follow on work.

4.3 Pilot Information Requirements

The information requirements analysis conducted as a part of fault scenario development focused on information required to diagnose faults without concern for whether the diagnostic process was carried out by humans or computers. This approach was necessary to provide the data needed for knowledge base development. It may be contrasted with higher level analyses of pilot information requirements in fault management being supported by NASA through other contractors. As a part of the analysis conducted on the current project, information now available to pilots was identified as well as the information required for diagnosis. The criticality of any discrepancies defined is a function of the level of diagnosis the pilot must go to in order to select the optimal action alternative. This in turn will be affected by the level of automation present in the system(s) in which the fault propagates and the ability of the automation to control fault management. An issue which needs a good deal of further investigation is impact of state-of-the-art automation in airplane systems on fault management problems. This issue would be addressed in a Context Analysis task proposed for follow on work.

An important aspect of the information requirements work on the present contract was the development of a conceptual framework for addressing the event/fault/context/action relationships involved in fault management. The relationships are complex but analysis could also indicate ways to simplify the problems in fault management while allowing pilots to deal with faults more selectively than they now can. Allowing pilots to deal with more complexity while simplifying the decision process would, of course, require the support of a Flight Deck Engine Advisor system. Details of the conceptual framework are to be found in Section 2.5.3. The feasibility and efficacy of the concepts would be tested in the Context Analysis proposed for follow on work.

A number of issues related to information requirements are discussed within the context of specific fault scenarios. This is as it should be because the issues are context specific. However, the issues which generalize are:

- granularity of the data (which includes sensor resolution); and

- reliability and validity of parameter data for fault diagnosis and action recommendations.

Generally speaking, the engine parameter data available from flight tests is based on sensors which have much greater resolution (i.e., are much more sensitive) than sensors available on operational engines. Further, more sensors are installed for flight testing; hence more parameters are measured. These sensors also happen to be too fragile for the operational environment. Probes would break off and create their own faults. Thus it is possible, with the test flight data, to see the potential for detecting the adverse trends of fault propagation much earlier and with more precision than may be possible with data from operational sensors. The issue is not simply the presence or absence of sensors. In some cases, the parameters are sensed and the information used by the electronic engine controller but is not currently available to systems which communicate with the flight deck. In other cases, the availability of sensors is an option to the airline purchasing the engine. Therefore, it is appropriate to base our analyses on what may be available operationally as well as what is.

The reliability and validity issue relates to the fact that our current data base does not contain enough samples of same event caused by same fault or same event caused by different fault. These additional fault data samples are needed to test the effectiveness of the Flight Deck Engine Advisor modules in detecting and diagnosing faults across engines and event/fault combinations. These issues would be addressed as a part of the Engine Data Survey task proposed as a part of a follow on effort.

4.4 Knowledge Base Development

As real engine data for known faults were processed through MONITAUR for symptom identification, the problem of spurious symptoms became apparent. When healthy engine data was passed through the system, the extent of spurious symptom generation was found to be present in excess of 50% of the time slices. Analysis revealed several potential causes and initial efforts to reduce spurious symptoms have been quite successful. The current level for healthy engine data stands at between 20-30% of the time slices, a value still too high for operational integrity. We have identified several additional strategies for further reducing spurious symptoms which should be pursued in a follow on project.

As a result of our work on symptom generation, NASA agreed to a reduction in effort on knowledge base development. We have done significant development in associational fault identification in STAGE1 of DRAPhyS. Our investigation with real fault data has produced a strategy for knowledge acquisition that includes traditional expert interviews coupled with a data verifying technique using a matrix format for symptom analysis. As this process is refined, it can probably be automated. More fault data is needed for a follow on project - especially multiple occurrences of the same fault, as well as a broader spectrum of faults.

Our work with STAGE2, the model based reasoning component of DRAPhyS, has been primarily familiarization and conversion to a PC environment. We have analyzed the current model based implementation and have made recommendations for potential enhancement by identifying several alternatives for incorporating sensor behavior into the system. We are confident that any of the alternatives will improve the fidelity of the hypotheses generated by the model based system. One of the alternatives would allow a merger of STAGE1 and STAGE2 forming a hybrid capable of both robust behavior and fault association.

5.0 RECOMMENDATIONS

Based on lessons learned in conducting the current project, the following recommendations are made as reasonable and appropriate next steps in follow on work for the Flight Deck Engine Advisor program.

5.1 Stand Alone MONITAUR

There are three areas of improvement which should be developed for a demonstration of MONITAUR feasibility. First, spurious symptoms must be eliminated, or at least minimized to an acceptable level. Next, steps must be taken to insure that valid symptoms are retained in the process of eliminating spurious symptoms. Finally, valid symptoms must be enhanced to promote successful diagnosis.

5.1.1 Spurious Symptom Elimination

A primary goal of a follow on project must be to minimize the number of spurious symptoms generated from MONITAUR. During the present investigation we have identified multiple sources of spurious symptoms and have significantly reduced the initial volume. Additional alternatives have also been identified and must be developed. We anticipate that other sources of small numbers of spurious symptoms can yet be determined. This should be a priority in the next project.

To insure a true minimum of spurious symptoms, more fault data must be collected. To verify the generality of current symptom-fault association, multiple instances of the same fault should be used. To verify that a broad spectrum of spurious symptoms have been filtered, more individual faults need to be analyzed.

5.1.2 Valid Symptom Retention

A possible consequence of spurious symptom filtering is the loss of valid symptoms. Great care must be taken to avoid the loss of valid symptoms while eliminating spurious symptoms. A method of evaluating the quality of valid symptoms is needed. Validating the existence of all anticipated symptoms for known faults is one approach to safeguarding valid symptom generation. We recommend a minimal STAGE1 development as a MONITAUR evaluation tool. The secondary effect of constructing a STAGE1 knowledge base with enhanced fault identification will be of mutual benefit to both NASA and Boeing.

5.1.3 Valid Symptom Enhancement

The last category of work for MONITAUR is valid symptom enhancement. Boeing has identified two strategies for enhancing the fidelity of valid symptoms generated by MONITAUR - Use of context variables and use of symptom type.

The effect of context variables is discussed in section 5.3, but provision for incorporating knowledge about context variables needs to be made in MONITAUR. Symptom enhancement may take the form of symptom elimination, symptom addition, or symptom modification. An example is the phase of flight. During our current study, a pattern of symptoms for ground hung start was found similar to a pattern for heavy ice damage. A simple addition of phase of flight would have enhanced this symptom pattern enough to be unique.

The analysis of symptom development with real fault data has shown that not all symptoms have the same severity. The case of sensor "catch up" described in section 2.7.1.6, when the actual value of a sensor was approaching, but not quite close enough to, the expected value, is a good example. Categorization of symptom severity offers potential for valid symptom enhancement and should be developed in the follow on project.

5.2 Engine Fault Data Base Survey

The current data base on engine faults is inadequate to support feasibility testing of the expert system based modules for fault detection and diagnosis. The nature and extent of a relevant data base made up of real in-flight engine fault data is unknown at this time. Indications are that the necessary data base will need to be assembled from a number of sources - primarily airlines and engine manufacturers. It is recommended that a survey of potential data base sources be made to determine: a) the nature of the data available; b) problems in accessing the data; c) proprietary issues to be dealt with; and d) data format problems. Additional fault data is also available from the Boeing flight test data base although the extent of this data is limited. The fault scenario data base should be expanded using flight test data plus any fault data which may become available as a result of the data base survey activities. An expanded fault scenario data base would be used in the development and testing of a stand alone MONITAUR.

5.3 Context Impact Analysis

Context variables can have a major impact on action alternatives available to the crew for any given fault/event combination. A framework for conceptualizing the event/fault/context/action (E/F/C/A) relationship was developed during the present contract. A systematic understanding of these relationships across fault/event combinations when different context variables are present or absent could be used to evaluate the viability of crew action alternatives. This information could in turn be used to develop rules for the knowledge base which fine tune the diagnostic process within the Flight Deck Engine Advisor system. It is recommended that a systematic analysis be carried out to assess the impact of context variable status on specific fault/event combinations. Particular attention should be given to those circumstances where context variable status might turn a viable crew action alternative into a potentially unsafe action. The analysis should be conducted within the context of a state-of-the-art glass cockpit airplane so as to provide the greatest relevance to future flight deck systems.

5.4 Automation in Fault Management

If the Faultfinder concept is to be relevant to advanced technology airplanes, the impact of automation on current and anticipated engine fault management function allocation decisions must be fully understood. It is recommended that an effort be undertaken to inventory the allocation of fault management functions which has been implemented for state-of-the-art commercial transport airplanes and critique the impact of this allocation pattern on pilot situational awareness and crew fault management options.

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5. "Flight Deck Automation: Promises and Realities", Norman, S.D. and Orlady, H.W. (Eds) Final Report of a NASA/FAA/Industry Workshop, Carmel Valley, CA, Aug. 1988.

6. " A Performance Assessment of a Real-Time Diagnostic System for Aircraft Applications", Schutte, P.C., Abbott, K.H., Ricks, W.R., Working Draft paper, NASA Langley Research Center, Hampton, VA.

7. "COMPASS - Ground Based Engine Monitoring Program for General Application", Barwell, M.J., SAE Technical Paper Series, SAE 87-1734, paper presented at the Aerospace Technology Conference and Exposition, Long Beach, CA, October 5-8, 1987.

APPENDIX A

FAULT SCENARIOS

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F1

Event: Hung Start - Ground

Fault: Fuel metering unit malfunction - providing too little fuel to fuel nozzles

Potential Fault Alternatives

Pneumatic System Faults

- Pneumatic pressure too low
- Airplane pneumatic duct failure
- Starter air valve failure
- " " duct failure
- Starter failure (partial failure results in too little air flow/pressure

Fuel System Faults

- Fuel metering unit
- Fuel shutoff valve
- Engine fuel pump
- fuel boost pump (high altitude air starts)
- Engine fuel line
- Mismanaged fuel system configuration

Start Procedure Faults

- Attempt start with excessive tail wind

- Airplane pneumatic system improperly configured

- Too cold: failure to use RICH; improper selection of fuel; too cold even for RICH

- Outside of start envelope

- improper fuel

- Fuel pressurization when high rotor speed too low

Gas Generator Faults (Compressor/Turbine)

- Bleed valve failure

- Stator vanes off schedule (mechanical failure or misrigging

- Compressor damage

- Turbine damage

- Low speed rotor locked (stuck)

Engine Control Faults

- Sensor fault

- Software error

- Hardware failure

- Actuator failure

- Engine wiring (e.g., intermittent broken connection between engine controller and fuel metering unit)

<u>Relevant Context Variables - Status</u>

Phase of Flight - Ground start

Weather - Clear and dry; light crosswind; temp 50 deg F

FARs -

Engine Fault History - no persistent, related problems for engine or type

Airline Policy -

Engine Commanded Status - Start

Pilot Error - None

Airplane System Status - Right Pack Inoperative

Workload - Moderate

Action Alternatives

Shut down and secure engine

Execute shutdown/restart procedures

Shutdown engine, correct fault, and execute restart procedures

Subsystems Affected

Engine

Electrical, hydraulic and pneumatic power from affected engine would not be available, but this information plays no role in fault diagnosis.

Propagation Sequence with Rank Order Time Base

Time t - Fuel metering valve commanded to start position by electronic control.

Time t1 - Valve moves to a partially open position and sticks OR fails to move from minimum open position.

Time t2 - Fuel going into burner not sufficient to support normal spool up of engine to idle.

Time t3 - FF begins to drop below flow rate for normal start.
High rotor speed acceleration rate begins to lag behind normal rate.
Low rotor speed still appears normal at this point.

EGT increase rate normal.

Time t4 - High rotor speed still increasing but has only reached 75% of normal for time into start sequence.
FF increasing but has only reached 70% of normal.
Low rotor speed levelled off at 53% of normal.
EGT still appears to be increasing at approximate normal rate.

Time t5 - High rotor speed still increasing but rate of increase falling off. Should be at idle RPM at this point but only at 67% of idle RPM.
FF fluctuating (probably not visible on cockpit gauge) and still increasing slowly; should be stable at this point.
Low rotor speed very slow increase, 41% below normal.
EGT rate of increase right on normal for time into start sequence.

Time t6 - High rotor speed, FF, low rotor speed all 40-70% below normal.
EGT continuing to increase instead of levelling off; 13% above normal and rising.

Time t7 - High rotor speed, FF, and low rotor speed leveling off below normal. High rotor speed peaks at 49% and begins sharp decline following starter disengage. Low rotor speed begins to decline a few seconds later.
EGT continues to rise at same rate and is approaching start red line (hot start conditions developing).

Time t8 - Fuel cutoff switch closed.

<u>Data Pilots Have Available</u>

<u>Source of Data</u>:

EICAS Engine Instruments

Engine Start Panel

<u>Explanation of Relationships</u>:

Pilots use high rotor speed to indicate appropriate time to turn fuel ON then go by the "clock" (real time monitored or estimated) to determine if "light off" has occurred normally. Once light off has occurred, they monitor high rotor speed and EGT to determine if a start is progressing normally. Fuel Flow (FF), EGT, and low rotor speed also have appropriate rates of increase during a normal start; however, the rate of change for each parameter will be different. If a normal start is not achieved, high rotor speed will begin to decline if a 50% speed has been achieved and the starter disengages. When starters disengage, starter switches snap to the GRND or OFF position. This produces an audible click which is a cue for starter disengage in addition to a visual check of the switch position.

Quality of Data:

Fuel flow data is processed and smoothed before being presented on the EICAS display. Thus the fine grain data on this parameter which can be used for early detection of a hung start due to fuel metering problems is not available in the cockpit in a easily detectable form.

Heuristics or Rules of Thumb Used:

The typical high rotor speed/EGT relationship looked for is high rotor speed X 10 = EGT. Since the critical factor is avoiding a hot start, more attention is probably paid to EGT than anything else. In the type of fault leading to a hung start presented in this scenario, focusing attention on EGT can lead to delayed detection of the hung start condition. EGT continues to increase at a close to normal rate long after definite symptoms of a hung start are apparent in other parameters.

Time Constraints:

Light off normally occurs within 10 seconds after fuel ON. Stable parameter readings at idle should be achieved at approximately time t5. Hot start indications become apparent very rapidly once conditions are right. Pilots will have only a few seconds at most to recognize them and shut off fuel to the engine before an overtemp condition develops.

Comments:

If the data used in this fault scenario is typical, then hung starts are difficult for pilots to detect until either a) a long time has passed (well over a minute), or b) the hot start phase begins and EGT rapidly heads for the "start" red line.

Information Required to Make Diagnosis

Key Parameters:

Fuel Flow
High Rotor Speed
EGT
Low Rotor Speed

Symptoms:

At time t3:

- Marked departure of fuel flow from normal rate of increase.
- Small deviation in rate of change in High Rotor Speed.
- Low Rotor Speed rate of increase normal.
- EGT rate of increase normal.

At time t4:

- High Rotor Speed still increasing but with marked deviation from normal in rate.
- Fuel flow increasing but far below normal rate.
- Low rotor speed essentially levelled off, should be increasing rapidly.
- EGT increasing at normal rate.

Fuel flow and high and low rotor speed continue to increase at decreasing rates until starter cutout at t7. At that point, high rotor speed begins to decline sharply followed by declining low rotor speed. EGT continues to increase at a normal rate until t5. Beyond t5, EGT continues to increase at the same rate instead of leveling off as it should. This leads to the hot start phase of the hung start.

Interpretation:

In general, detecting a hung start in progress requires the detection of deviations from normal in the rates of change on the four parameters listed above; i.e., detecting changes in the rates of change[1]. The symptoms for detecting the onset of a hung start caused by a fault in the fuel metering system present a particular challenge to pilots because the parameter showing the earliest departure from normal is fuel flow (see time t3 above). The change in the rate of change in high rotor speed has also begun to take place by t3 but would be difficult to detect in the cockpit at this point. Adding to the detection problem is the fact that low rotor speed and EGT are progressing normally at this point. By t4, FF and High and Low Rotor Speeds clearly indicate a hung start in progress but EGT is progressing normally. The problem, from a pilot's perspective, is; a) determining that a hung start is in progress, while b) seeing that high rotor speed is still increasing at a rate which is not perceptibly different from normal but knowing that at that point it is in fact 15% low, and c) all the while seeing EGT progress normally. The data available from sensors is not available to the crew at the same grain on the EICAS as it shown on sensor data printouts. And even if it were, the complexity of the monitoring and deviation detection process required for early detection of a hung start is clearly beyond the capability of the crew. Hence the start scenario heuristic reported above which pilots use to monitor engine starts. This heuristic inevitably leads to much later recognition of the event in progress and much higher probability of an over temp condition occurring. This particular scenario is a case in point. EGT continued to progress normally long after the hung start condition was obvious in the pattern of the other three engine parameters. Engine shut down was not initiated until much later when a hot start was in progress.

There are two objectives of diagnosis in an event such as hung start. The first objective must be to provide an alert to the crew that the event is in progress;

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[1] MONITAUR does not now contain a parameter for processing changes in rates of change.

i.e., a normal start is not in progress. This requires evaluation of information about changes in rates of change on four parameters (high and low rotor speeds, FF, EGT). By comparing this information with the output from an engine model, it is possible to diagnose a developing hung start less than half way into the start sequence.

The second objective is to diagnose to the fault or Fault/Action Class. This may be taken to the subsystem (e.g., fuel pneumatic, procedural, etc.) or component level (fuel metering) within the propulsion system. Here the purpose is to provide part of the basis for determining relevant action alternatives. The Hung Start-Ground data plot on fuel flow shows a marked deviation from normal before mid point in the start sequence (t3). This may be sufficient to narrow the location of the fault to the fuel subsystem. While it may not be possible to differentiate among all potential fault alternatives within the fuel subsystem, it may be possible to distinguish between subclasses. The importance of such distinctions will depend on their impact on action alternatives.

Information Required for Decision Aiding

Nature of the Fault:

Selection of or recommendations on the appropriate action alternative requires knowledge of the nature of the fault or fault/action class. The components of that knowledge are: 1) a hung start is in progress; 2) the engine is not receiving the appropriate fuel/air mixture; and 3) whether electrical, mechanical, or procedural subsystems are involved. The actions required by pilots in dealing with the fault generally will differ only if the fault is procedural vs. electrical or mechanical.

The data for this fault scenario is based on a mechanical failure. It is a malfunctioning valve in the fuel metering system. It is not a transitory failure. The corrective action must be taken by Maintenance.

Relevant Context Variable Set:

- Phase of Flight
- Weather
- Engine Fault History
- Engine Commanded Status
- Pilot Error
- Airplane System Status
- Workload

Relationship Between Fault and Context Variables for:

Diagnostic Application - Because phase of flight is "ground start", all those potential fault alternatives peculiar to air starts can be eliminated from further consideration. The value of the weather variable would serve to eliminate the possibility of gusts up the tail pipe and temperature too cold as potential faults. Improper fuel, pneumatic system configuration, and premature fuel ON during start sequence cannot be eliminated. These procedural faults need crew and/or maintenance input to eliminate. For the particular context variable set chosen, no history values will aid in diagnosing the fault. The system status item is not relevant as a direct contributor but would have influenced pneumatic system configuration. The workload variable operates in conjunction with other variables to produce an effect. It can operate with other context variables or with certain fault categories, namely procedural faults. Beyond this point, diagnosis must rely on the propagation sequence and pattern of symptoms.

Action Alternatives Application - The application here is very straightforward. Given the context variable set plus the fact that diagnosis has been made to the component level (fuel metering unit), there is only one appropriate action. The "Shutdown, correct fault, and execute restart procedures" is not appropriate because the pilots can not carry out the corrective action.

Recommended Action Alternative - Shut down and secure engine.

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F2

<u>Event</u>: Engine Flameout

<u>Fault</u>: Fuel Boost Pump failure - due to A/C power loss

<u>Potential Fault Alternatives</u>

Loss of both boost pumps in same tank

Engine fuel pump failure

Mismanaged fuel configuration

Fuel line fracture

<u>Relevant Context Variables - Status</u>

Phase of Flight - Cruise: above fuel suction feed altitude

Weather -

FARs -

Engine Fault History -

Airline Policy -

Engine Commanded Status - Steady state

Airplane Systems Status - Crossfeed valves closed

Fuel Type -

Workload - Light

<u>Action Alternatives</u>

Recycle generator and bus tie switches

Reconfigure fuel system

Reduce altitude to suction feed level

Subsystems Affected

Fuel Delivery

Engine

AC electrical (a failure malfunction in this subsystem would produce the same event. Some or all of the action alternatives might be the same as those identified above.)

Propagation Sequence with Rank Order Time Base

(The same propagation sequence within the engine would occur if AC power were lost to the fuel boost pump.)

Time t -	All subsystem operation and parameter values normal for conditions of flight
Time t1 -	Fuel boost pump fails.
Time t2 -	A 25# (approx.) step drop occurs in fuel pressure. This is not enough to trip fuel pressure switch light or EICAS message circuits. No change occurs in fuel flow, High or Low Rotor Speeds.
Time t3 -	Fuel pressure shows only slight further decline over approx quarter of a minute. No change in other engine parameters.
Time t4 -	Fuel pressure drops precipitously to near zero. Fuel flow drops to near zero (this indication should be clearly visible in the cockpit). High and low rotor speeds begin to drop off gradually. Fuel pressure switch light and EICAS message circuits would be tripped by this drop.
Time t5 -	Fuel pressure has levelled off at approx 25#. Fuel flow is at zero. High rotor speed is slipping into sub-idle.

Data Pilots Have Available

Sources of Data:

A/C Electrical Control Panel
Fuel Control Panel
Altimeter
EICAS Messages
EICAS Engine Instruments

Explanation of Relationships:

The amber PRESS light within the fuel boost pump switch illuminates if pump output pressure drops below 5-7 lbs. for 10 seconds for any reason. Thus with an A/C power loss, lights on both the A/C Control Panel and the Fuel Control Panel would come on. EICAS messages would appear for both the A/C power loss and the boost pump pressure loss. If the airplane is above the suction feed altitude for the airplane/fuel type combination, an EICAS message on fuel system pressure loss will be displayed when cavitation occurs and the engine driven pump pressure drops below threshold. The difference between fuel boost pump failure indications and those for engine driven fuel pump failure would be that a sequence of indications would occur for the boost pump failure but only the fuel system pressure message would occur for engine driven pump failure. Action alternatives for the two failures would be quite different.

Fuel flow does not change until flame out occurs. As the engine spools down following flame out, an EICAS message indicating the generator on the affected engine is off. For subtle faults producing a flame out, this message is often the first indication of an event. This may be **the** event to the crew; however, it is not the event of interest.

The altimeter reading combined with fuel type information would provide information on whether the airplane was above suction feed altitude.

Quality of Data:

Switch lights and EICAS messages are triggered by parameters breaking thresholds. No analog data on fuel pressure changes is available in the cockpit. Thus, there is no information indicating a flame out is imminent and no indication that it has occurred until the fuel system pressure and A/C power loss messages appear.

Heuristics or Rules of Thumb Used:

None identified.

Time Constraints:

At high altitude cruise without fuel boost pump pressure, pilots have approximately 15-20 seconds to detect the failure and take appropriate action before flame out occurs.

Comments:

At altitudes where suction feed is only partially effective and cavitation is beginning, the indications of fuel boost pump failure (or failure to turn on boost pumps during climbout) will include fluctuations in fuel flow, and eventually, fluctuating rotor speeds. Because fuel flow data is heavily massaged before being displayed on EICAS, this source of information will not be indicative of a problem until well after pump failure.

If a single fuel boost pump fails, no change is required in configuring the fuel system because each tank has at least two boost pumps in it. Also, the airplane must be above the altitude at which fuel cavitation occurs for that particular plane/fuel combination. To have a flame out due to a fuel boost pump related problem, one must a) be above suction feed altitude, and b) have partial or total A/C power loss (depending on the airplane model), or c) have multiple pump failures in the same tank under special fuel system configuration conditions. EICAS messages will indicate low fuel pressure due to pump failures or A/C generator failures. However, generator failure messages will also appear when engines spool down below a certain RPM following flame out even though there is no problem with the generator per se. The yaw produced by loss of an engine would probably not be felt in the cockpit if the autopilot were engaged. Loss of airspeed, throttle lever movement, attitude change, and possible initiation of drift down would be other indications the crew might have that an engine had been lost.

Information Required to Make Diagnosis

Key Parameters:

Fuel Boost Pump Output Pressure

OR

Engine Driven Fuel Pump Pressure

AND

Fuel System Configuration
Altitude

Symptoms:

When at high altitude cruise:

Fuel boost pump output pressure drops to zero.

Fuel system pressure drops as a step function by approximately 25 lbs. and levels off for approximately 15-20 seconds then drops by another step function to about 25 lbs.

Flame out occurs in less than 5 seconds after the precipitous drop in fuel system pressure.

When at transitional altitude:

Fuel boost pump pressure drops to zero.

Suction feed is only partially effective in supplying fuel to engine driven pump. Fuel system pressure fluctuates below what it would be with boost pumps on.

Fuel flow begins to fluctuate below cruise level.

High rotor speed begins to fluctuate and gradually fall off.

Interpretation:

The 25 lb. step function drop in fuel system pressure is the event signalling fuel boost pump failure. If the airplane is above the suction feed altitude limit, pilots have 15-20 seconds to take action to prevent a flame out. If the airplane is in the transition zone, fuel system pressure, fuel flow, and high rotor speed will begin to fluctuate with ever increasing excursions and fuel flow and high rotor speed will begin to decrease.

Information Required for Decision Aiding

Nature of the Fault:

Selection of or recommendation of the appropriate action alternative requires knowledge of the nature of the fault or fault/action class. The components of that knowledge are: 1) a flameout is imminent; 2) the engine is not receiving adequate fuel; and 3) whether the fault is electrical, mechanical, or procedural in nature. The actions required to deal with the fault are different for the three types of fault. Each require the reconfiguration of systems but the specific actions are quite different.

Relevant Context Variable Set:

See earlier listing of context variables where relevant variables have status values provided.

Relationship Between Fault and Context Variables for:

Diagnostic Application - Loss of fuel boost pressure below the suction feed altitude limit will not result in a flame out. Loss of fuel boost pressure with the crossfeed valve open will not result in a flame out. The airplane/fuel type combination will determine the suction feed altitude limit. Knowledge of the altitude of the airplane is a factor in determining the cause of low fuel pressure.

<u>Action Recommendation Application</u> - Action options can be exercised in turn until the problem is solved.

<u>Consequences of Inappropriate Alternative Actions</u>:

Failure to properly configure the fuel system could lead to loss of up to four engines.

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F3

Event: Thrust Shortfall at TOGA

Fault: FOD - Ice Ingestion: light damage

Potential Fault Alternatives:

FOD - bird ingestion

Relevant Context Variables - Status

Phase of Flight - Climb out

Weather - Icing conditions

FARs -

Engine Fault History -

Airline Policy -

Engine Commanded Status - Climb power

Pilot Error - Engine anti-ice system not turned on before entering icing conditions

Airplane System Status - Engine anti-ice system activated after moderate ice build up on engine cowl and/or spinner

Workload - Moderate

Action Alternatives

Continue to operate damaged engine at current power setting

Continue to operate damaged engine at reduced power setting

Shut down and secure damaged engine with restart option later in flight

Shut down and secure damaged engine for duration of the flight

Subsystems Affected

Engine

Thrust Management System (Autothrottle)

Propagation Sequence with Rank Order Time Base

Time t -	Ice strikes fan blades
Time t1 -	Vibration in low speed rotor increases approx. .5 units as a step function. Vibration in high speed rotor increases as a step function by approximately the same magnitude. No change is discernible in any other parameters.
Time tn -	Ice-damaged engine does not produce commanded thrust level

Data Available to Pilots

Source of Data:

Lower EICAS display of vibration

Explanation of Relationships:

Foreign object damage (FOD), in this case caused by ice ingestion, produces an abrupt change in the level of vibration in the engine while all other parameters remain normal. This indicates some level of fan or compressor blade damage. The damage in turn reduces by some amount, directly related to the extent of the damage, the amount of thrust shortfall experienced for a given throttle setting. At low to moderate levels of FOD, pilots may not notice the relatively small step increase in vibration level. Therefore, they would have no reason to test thrust indication for shortfall. If the step increase were noticed, an indication of shortfall to be expected under TOGA conditions could be ascertained by advancing the throttles to maximum power and comparing expected with achieved thrust indications. It is possible at altitudes above FL170 for the engine controller to derate thrust and thus preclude detection of thrust shortfall.

Quality of Data:

The vibration display on EICAS is graduated in arbitrary units. The source of vibration may be the frequency band monitored for the high speed rotor, the band monitored for the low speed rotor, or what is referred to as broad band vibration which is vibration measured over a wider band of frequencies which includes the bands measured for the low and high speed rotors. Engines vary considerably in their inherent vibration characteristics. Therefore, a specific vibration reading has little generalizable meaning unless it is in the caution range. Most engines do not even have caution range designations. Thus, the pilots are left to judge the criticality of vibration level without guidance.

Vibration may appear to be an obvious cue, but cross-engine comparisons of readings on the vibration instrument may not be helpful. These instruments report the highest level of vibration present in one of three frequency bands being monitored. A scan of the vibration gauges will not necessarily allow the pilots to compare broad band vibration levels across engines. Each of the two or four engines could be displaying vibration level from a different source.

The effects of light ice damage on thrust shortfall may be so subtle that they would not be detected by the crew - until they needed TOGA power. As with any FOD fault, the projection of engine performance and integrity over time is a very important piece of information pilots need in their decision making but one that is very difficult to predict unless the exact nature and extent of damage is known.

Heuristics or Rules of Thumb Used:

None identified.

Time Constraints:

(See comments under this heading in the moderate and heavy ice damage fault scenarios.)

Information Required to Make Diagnosis:

Key Parameters:

Vibration

Primary Thrust Indicator

Symptoms:

The relatively small (.5 unit) step function change in vibration level is the only symptom across all engine parameters indicating the presence of ice damage until max power is applied. The relevance of going to max power to produce the thrust shortfall indication is tempered by comments made earlier that, depending on the altitude, the engine controller may thwart attempts to check for thrust shortfall in the damaged engine.

Interpretation:

As can be seen, the symptoms for diagnosing light ice damage are extremely subtle. Detection of the damage requires; a) that the step function increase in vibration be detected, and b) that the difference in vibration level before and after damage has occurred can be recognized as a reliable symptom. The confirming factor is the recognition of thrust shortfall. With light damage, the task may not be easy or even possible. What makes detection important is the potential for engine performance degradation to levels critical to flight safety **either** within the time frame of the current flight **or** on subsequent flights, if undetected. A worst case scenario would be loss of the engine near V1 on take off on a subsequent flight.

Information Required for Decision Aiding

Nature of the Fault:

Ice ingestion has caused light damage to fan blades.

Further deterioration, if any, which might occur in available thrust within the duration of the current flight.

Relevant Context Variable Set:

The relevant context variable set is composed of those variables listed earlier which have status information included.

Relationship Between Fault and Context Variables for:

Diagnostic Application - If different types of FOD result in different projections of engine performance and or integrity, then context variables may be useful in relevant differentiation among FOD faults. Phase of flight, weather, and airplane system status will aid in differentiating ice damage from other FOD faults if appropriate.

Action Recommendation Application - Pilots may have the widest range of action alternatives in this situation depending on the need for TOGA power from the affected engine and the projected effect of maintaining thrust setting(s) at the desired or required levels.

Consequences of Inappropriate Alternative Actions:

Acceleration and deceleration of the affected engine could lead to additional damage if ice is dislodged from the spinner.

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F4

Event: Thrust Shortfall at cruise power and above

Fault: FOD - Ice Ingestion: moderate damage

Potential Fault Alternatives:

FOD - Large bird ingestion

FOD - Multiple bird ingestion

Fan blade tip loss

Relevant Context Variables - Status:

Phase of Flight - Climb

Weather - Icing conditions

FOD Potential - Moderate

FARs -

Engine Fault History -

Airline Policy -

Engine Commanded Status - Climb power

Pilot Error - Engine anti-ice system not turned on before entering icing conditions

Airplane System Status - Engine anti-ice activated after moderate ice build up on engine cowl

Workload - light to moderate

Action Alternatives

Continue to operate damaged engine at current power setting

Continue to operate damaged engine at reduced power setting

Shut down and secure damaged engine with restart option later in flight

Shut down and secure engine for duration of the flight

Accelerate and decelerate engines. Check instruments for vibration levels, sluggish acceleration, thrust shortfall.

Subsystems Affected

Engine

Thrust Management System

Propagation Sequence with Time Base

Time t - Precise timing on occurrence of moderate ice damage unknown

Time t1 - Climb power commanded. Small thrust shortfall occurs at climb power. Low rotor speed on target. High rotor speed shows 5% shortfall. EGT and fuel flow slightly below expected values for thrust setting. Increase in vibration on low speed rotor precedes normal onset and exceeds expected value by 25%. Spike in high speed rotor vibration as climb power is commanded then drop to expected level.

Time t2 - Cruise power commanded. Thrust shortfall increased slightly from climb power shortfall. High rotor speed at expected level. EGT and fuel flow remain slightly lower than expected. Vibration in low speed rotor remains 25% above expected. Vibration in high speed rotor averaging 200% higher than expected level. Acceleration to commanded thrust level is slightly slower than expected.

Data Available to Pilots

Source of Data:

EICAS display: vibration and related thrust parameters

Explanation of Relationships:

No time marker is available to indicate the onset of ice ingestion which causes moderate damage. Therefore, differences in vibration level must be evaluated when power levels are changed rather than detecting a step function in vibration level as an indicator of damage having occurred as was the case with light ice damage. Interestingly enough, vibration levels and thrust shortfall appear greater when cruise power is commanded than when climb power is set and thrust shortfall, as indicated by the primary thrust parameter, is also greater at the cruise setting (albeit by a small amount). The differences between high rotor speeds and high speed rotor vibration at the two power settings will make it difficult to use these information sources in generating rules for diagnosing deviation patterns. Vibration, and particularly high speed rotor vibration again seems to be the only clear indication of damage. The problems pilots have in trying to interpret the vibration parameter have already been discussed in the scenarios on light and heavy ice damage. The other indications such as EGT and fuel flow shortfall as well as the high rotor speed shortfall at climb power are subtle and would not likely be noticed in the cockpit. These differences will likely fall within the noise band of MONITAUR deviation detection and will not provide symptoms for diagnosis.

Quality of Data:

Factors which relate to the quality of the data as presented to pilots have been discussed above. These are: small differences in parameter levels across engines; inconsistent differences in parameter levels at different power settings; and the problem of interpreting changes in vibration level without clear guidelines.

Heuristics or Rules of Thumb Used:

Time Constraints:

This issue of time constraints is the same as with light and heavy damage conditions. A great deal depends on phase of flight. The current data set was obtained in climb and cruise. Thus, time constraints in dealing with the problem are not serious.

Information Required to Make Diagnosis

Key Parameters:

Thrust parameter

High rotor speed

Vibration : High and Low speed rotors

Fuel Flow and EGT may be secondary

Symptoms:

Slight shortfall in thrust parameter at climb power

Slight shortfall in high rotor speed at climb power

Moderate elevation of expected level of vibration in low speed rotor at climb power

Marked increase in vibration level on high speed rotor at climb power

Interpretation:

In the final analysis, the only reliable symptoms indicating fan and/or compressor damage are the step function increases in vibration level regardless of the source of the vibration reading. Vibration measurement for low and high speed rotors and the broad band measure are described in the fault scenario on light ice damage.

Information Required for Decision Aiding

Nature of the Fault:

The pattern of symptoms found with moderate ice damage differs from those found with light and heavy damage. The consistent theme across all levels of damage is the increase in vibration level. In the long run, when vibration levels and patterns in modern jet engines are adequately understood, this parameter should be very useful in diagnosing the existence of FOD and predicting the time course and levels of deterioration in engine performance and integrity which results. In the meantime, step function increases in vibration levels remain the only reliable indication of compressor damage. If the damage is severe, other engine parameters will begin to deteriorate.

Relevant Context Variable Set:

The relevant context variable set is comprised of those variables listed earlier which have a status indicated.

Relationship Between Fault and Context Variables for:

Diagnostic Application - It is not clear at this point whether distinguishing between objects ingested is useful in terms of implications for crew actions. The utility of such a distinction probably lies in determining whether the time course of deterioration in engine performance and/or integrity is changed as a function of the object ingested. To the extent that it is, then it becomes important to make the diagnostic distinction in order to provide the crew with the information they need to properly determine their course of action.

Action Recommendation Application - Action alternatives very greatly in this situation depending on the need for power from the affected engine and the projected effect of maintaining throttle setting(s) at desired or required levels. If projected effects could be determined with enough accuracy and reliability, this information would be very valuable to the pilots in deciding among possible courses of action.

Consequences of Inappropriate Alternative Actions:

Acceleration and deceleration of engine could lead to additional damage if ice is dislodged from spinner.

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F5

Event: Thrust Shortfall at cruise power and above

Fault: FOD - Ice Ingestion: heavy damage

Potential Fault Alternatives:

FOD - Large bird(s) ingestion

Fan blade tip(s) loss

Relevant Context Variables - Status:

Phase of Flight - Cruise

Weather - Icing conditions

FOD Potential - high

FARs -

Engine Fault History -

Airline Policy -

Engine Commanded Status - Climb power

Pilot Error - Engine anti-ice system not turned on until major build up of ice occurs on cowling and/or spinner

Airplane System Status - Engine anti-ice OFF

Workload - light to moderate

Action Alternatives

Continue to operate damaged engine at current power setting

Continue to operate damaged engine at reduced power setting

Shut down and secure damaged engine with restart option later in flight

Shut down and secure engine for duration of the flight

Accelerate and decelerate engines. Check instruments for vibration levels, sluggish acceleration, thrust shortfall

Subsystems Affected

Engine

Propagation Sequence with Time Base

Time t -	Timing on occurrence of heavy ice damage unknown
Time t1 -	Cruise thrust commanded. Acceleration to commanded thrust level is slower than expected. Thrust shortfall occurs at climb power. Achieved thrust is approximately 80% of commanded. Low rotor speed acceleration normal; high rotor speed slower than expected. Fuel flow and EGT lower than expected. Broadband vibration level increases 3 units above expected level.
Time t2 -	At commanded thrust level, low and high speed rotor vibration at expected levels. Broadband vibration remains 3 units higher than expected on ice damaged engine.

Data Available to Pilots

Source of Data:

EICAS display: vibration, thrust parameters, cross engine comparisons

Explanation of Relationships:

No time marker on the occurrence of heavy ice ingestion was available in the data base. Therefore, the step increase in vibration apparent with initial light ice damage was not available. It is not known if such a step increase would have occurred. The vibration symptom only becomes apparent when the throttle on the ice damaged engine is advanced in concert with throttle advance on the normal engine. Changes in vibration levels in the ice damaged engine on low and high speed rotors are evident with light and moderate ice damage but do not show up with heavy damage. Instead, the vibration symptom evident for heavy damage is a marked increase in broad band vibration. The reliability of this difference in symptoms cannot be ascertained without comparable duplication of the incident and/or verification by expert opinion. The extent of damage is clearly evident in the amount of thrust shortfall which occurs at higher power settings. The shortfall with light ice damage is only evident under TOGA power settings. Moderate ice damage results in a slight shortfall at climb power. Whereas with heavy ice damage, the shortfall is very evident even at cruise power (i.e., approximately 80% of normal). Thus, heavy damage may be more easily detected than light or moderate damage. Although, the problem noted in regard to light damage (i.e., where in some cases above FL170 the engine controller may derate thrust) could mitigate the value of throttle movement as a source of information about the extent or possibly even the presence of thrust shortfall.

Changes in vibration level, while obvious when viewing the data printouts, may not be obvious or even detectable on vibration indicators in the cockpit.

Quality of Data:

Pilots must rely on memory and cross engine comparisons to detect the problem and assess severity. Neither source provides high quality comparative data. Pilots must detect the step increase in vibration as such as a major initial symptom of FOD. If the damage is light, this is a very difficult task. With heavy damage, the problem is more obvious and the action alternatives more limited. Thrust shortfall with light to moderate damage will only be detected at relatively high power settings (the lighter the damage, the higher the power setting must be to detect the shortfall). Cross engine comparisons **may** provide evidence of damage but normal engine differences in vibration and thrust can mask the effects of light to moderate damage. The same can be said of differences across engines in thrust and rotor speed acceleration.

Heuristics or Rules of Thumb Used:

None identified.

Time Constraints:

Whether time constraints exist will depend on phase of flight. The data which support this scenario were gathered during climb out and cruise. Thus time would be available to assess the problem and determine action options without serious constraint. If the icing and damage had occurred during descent, the time available for diagnosis and planning could be constrained. However, the need for maximum power under these conditions would only occur if a go around were required.

Information Required to Make Diagnosis

Key Parameters:

Vibration

Thrust

Low and high rotor speed

Symptoms:

Noticeable (e.g., 20%) thrust shortfall at cruise power settings; i.e., engine is producing only 80% of the thrust normally expected at the throttle setting used.

Thrust acceleration below expected when throttle advanced.

Both low and high speed rotor vibration normal

Broad band vibration 3 units higher than expected on ice damaged engine

Interpretation:

As can be seen, the symptoms for diagnosing even heavy ice-induced damage are quite subtle. Vibration may be an obvious cue, but cross-engine comparisons of readings on the vibration instrument may not be helpful. These instruments report the highest level of vibration present in one of three locations on the total bandwidth of frequencies monitored; i.e., frequency windows for low or high speed rotor and broad band. A scan of the vibration gauges will not necessarily allow the pilots to compare broad band vibration levels across engines. Each of the two or four engines could be displaying vibration level from a different source.

The ice damage fault is an example of the type of fault which may require pilot action to provide the type of information really needed to complete the diagnosis of a fault or **even to make the crew aware of the presence of an event**; i.e., that there is a definite thrust shortfall in the affected engine. This presents some interesting issues. Is it possible that a different fault may lead to the same event, but the pilot action required to fully diagnose the ice damage fault would have serious negative consequences such as loss of the engine for the duration of the flight? Addressing these issues fully is beyond the scope of the present analysis.

The three fault scenarios on ice damage are the closest thing we have to trend data. The change in symptoms which represent damage at different levels is interesting to note. We do not know at this point whether the pattern of changes in relevant symptoms will generalize across FOD faults. Nor do we know what further deterioration in engine performance and integrity will occur as a function of continuing to operate the engine at a particular power setting[2] . Although propulsion engineers may be able to provide general, qualitative projections, they are not willing to do so formally. In the real world, predictions on performance trends and integrity may range in importance from useful to critical depending on phase of flight.

Information Required for Decision Aiding

Nature of the Fault:

Clearly, the extent of the ice damage is an important factor in decisions which involve the availability of thrust. The detection of thrust shortfall and the prediction of additional deterioration in engine performance and integrity is important regardless of the specific nature of the FOD fault. Because of the

[2] The engine on which data were gathered was operated for several hours after the damage occurred. However, it would not have been had the pilot realized the extent of the damage incurred.

procedure used in inducing ice damage, we can not be sure that the symptom pattern would be the same with say the ingestion of small, medium, and large birds. That is, the sudden onset of FOD at different levels of damage may produce a different pattern of symptoms.

There should be additional contextual information available which would allow the diagnostic system to differentiate among at least some of the fault alternatives which could lead to the event in question - thrust shortfall.

Relevant Context Variable Set:

The relevant context variable set is comprised of those variables listed earlier which have a status indicated.

Relationship Between Fault and Context Variables for:

Diagnostic Application - If different types of FOD result in different projections of engine performance and or integrity, then context variables may useful in relevant differentiation among FOD faults. Several factors will aid in differentiating between ice damage and at least one other fault alternative, namely large bird ingestion. Phase of flight is cruise (although not high cruise) thus greatly reducing the odds of bird ingestion[3] . Icing conditions are present and the anti-ice system(s) are not on. Workload is such that requiring pilot action to generate additional symptoms is not out of the question.

Action Recommendation Application - Action alternatives very greatly in this situation depending on the need for power from the affected engine and the projected effect of maintaining throttle setting(s) at desired or required levels. If projected effects could be determined with enough accuracy and reliability, this information would be very valuable to the pilots in deciding among possible courses of action. The British Midlands crash is an example of depending on an engine with FOD (fan blade tip loss and ingestion) as, in that

[3] Although there has been at least one report of an eagle striking the windscreen on a commercial transport jet at cruise altitude.

case, the only source of power. The pilots need information as to what they can count on in the way of thrust under all relevant circumstances.

Consequences of Inappropriate Alternative Actions:

Acceleration and deceleration of engine could lead to additional damage if ice is dislodged from spinner. Depending on the engine and the nature of the FOD, throttle movement of any kind may be very inappropriate.

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F6

Event: All Engine Flameout

Fault: FOD - Volcanic ash ingestion producing fuel nozzle clogging

Potential Fault Alternatives:

Mismanaged fuel system configuration

Relevant Context Variables - Status:

Phase of Flight - Descent

Weather - Broken clouds below. Thin layer of "white clouds" at FL260

FOD Potential - High, volcanic eruption in area

FARs -

Engine Fault History -

Airline Policy - with regard to use of Autostart

Engine Commanded Status - Before encountering ash, Low rotor speed at idle. Subsequent commands were 60%, 80%, Max Power, 80%, Max Power. Engines were at commanded Max Power when power loss began.

Pilot Error - Throttle advances not advised under circumstances[4] .

Airplane Systems Status - All operating normally

Workload - Moderate, before flameout

Training/Procedures - Event/fault combination not anticipated

Action Alternatives:

Airspeed to middle of start envelope

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[4] It is unfair to label the crew action as pilot error for the particular incident on which data were available because the crew performed as trained and on the basis of information available in Ops Manuals at the time. Adjustments to training and Ops Manuals have since been changed to reflect appropriate action alternatives.

Attempt immediate restart (manual or auto)

Execute shutdown/restart procedures

Reduce throttles to idle while in vicinity of ash cloud(preventative measure)

Engines 1 & 4 (or left) to idle, use 2 & 3 (or right) as needed

Subsystems Affected:

Engines

Engine driven electrical and hydraulic subsystems drop off line as engine spool down below idle, but this information plays no role in fault identification.

Propagation Sequence with Time Base:

Time t - Proximity to volcanic ash cloud realized

Time t1 - Low rotor speed increases on all engines - commanded

Time t2 - Descent halted

Time t3 - Max power applied and airplane begins to climb

Time t4 - Climb stops at 28000 feet

Time t5 - High and low rotor speed on all engines drops sharply

Time t6 - Sharp rise in all EGT's accompanied by decreasing high rotor speed

Time t7 - All engines go sub-idle

Time t8 - All engine flameout has occurred, all generators drop off line

Data Available to Pilots

Source of Data:

Visual sighting of ash cloud

EICAS display of engine parameters

ATC relayed reports of location of ash cloud

Explanation of Relationships:

In this case, the information needed to select the appropriate action alternative is available only through hindsight and much testing. The actions taken in this case were exactly the opposite of those which should have been taken. Increasing power while ingesting volcanic ash accelerates the sooting or coking action on the turbine fuel nozzles which in turn starves the engine of fuel. Diagnosis of the fault requires information beyond the airplane; i.e., visual sighting of the ash cloud and/or communications from ATC or other aircraft. There is no pattern of engine parameter behavior which would alert the crew to impending FOD from volcanic ash. Neither is there a pattern in engine parameter behavior on which the monitoring and diagnostic modules could reason. Selecting the correct action alternative depends on recognition of external conditions and training as to the appropriate action(s) in the presence of these conditions.

Quality of Data:

No information is available to the pilots from flight deck instrumentation which would allow them to predict the potential for an all engine flameout. The "data" available for dealing with this situation would be training and experience.

Heuristics or Rules of Thumb Used:

To avoid trouble - climb

Time Constraints:

Time constraints for an all engine flameout are a function of altitude. However, any time all power is lost on all engines, time will be perceived as being very short indeed.

Information Required to Make Diagnosis

Key Parameters:

Fuel Flow

Low and High Rotor Speeds

EGT

Symptoms:

The initial symptom would be the deviation of actual fuel flow from fuel flow needed to achieve commanded thrust level. Propagation symptoms include a rapid loss of high and low rotor speed accompanied by rapidly increasing EGT. These latter symptoms are evident in the cockpit, but by the time they appear the flameout cannot be avoided.

Interpretation:

The time frame from onset of the coking action to flameout is not known but is dependent upon power settings. The DFDR data would indicate that the time frame may be very short indeed if inappropriate thrust commands are implemented.

An accurate measure of actual fuel flow compared to the engine controller "model" of fuel flow for commanded thrust level would show the inconsistency in fuel flow needed for commanded thrust vs. that being achieved. This a case where all the information MONITAUR would require to identify the deviation is available in the engine controller but is not available to the crew.

Information Required for Decision Aiding

Nature of the Fault:

This fault represents and interesting challenge because it involves the need for information external to the airplane for accurate diagnosis. It also represents an example of where context variable status is critical to accurate diagnosis. The requirement for accurate diagnosis to the specific fault level is still under study. The question is How does appropriate crew action differ for flameout from fuel nozzle clogging due to volcanic ash ingestion vs. say flameout due to water ingestion? In this particular comparison, the answer is interesting. When in the presence of or about to encounter volcanic ash, retard the throttles. When ingesting large amounts of water, advance throttles to full power. If use of the autostart system is the answer for all faults in this and related categories, then the mapping of Event/Fault combinations via context variables to appropriate action alternative will be a simple, straightforward relationship. If not, the Flight Deck Engine Advisor system may require pilot input to complete the diagnostic process. The example given just above suggests the relationship will not be simple or straightforward.

Relevant Context Variable Set:

Phase of Flight - Descent

Weather - Broken clouds below. Thin layer of "white clouds" at FL260

FOD Potential - High, volcanic eruption in area

Airline Policy - especially with regard to use of Autostart

Pilot Error - Throttle advances not advised under circumstances.

Airplane Systems Status - All operating normally

Workload - Moderate, before flameout

Relationship Between Fault and Context Variables for:

Diagnostic Application - Accurate diagnosis requires timely information on deviations in fuel flow from normal for commanded thrust level and external information about the potential for FOD from volcanic ash in the vicinity.

Action Recommendation Application - The relationship of this particular Event/Fault combination to action alternatives has not been determined as yet. The determination will hinge on the effectiveness of potential crew actions on correcting or mitigating the effects of volcanic ash ingestion.

Consequences of Inappropriate Alternative Actions: Advancing the throttles to max power when ingesting volcanic ash produces the conditions within the engine which result in a flameout; i.e., temperatures are increased and the coking or clogging of fuel nozzles results in reduced thrust and eventually flameout - the higher the power setting called for, the greater the coking action. Thus, advancing throttles in the presence of volcanic ash is an action alternative to be avoided. Without appropriate instructions on the appropriate action coupled with pilots' conditioned response to climb out of trouble, the stage is set in these circumstances for an all engine flameout.

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F7

Event: Hung Start - Air

Fault: Fuel nozzle coking (due to ingestion of volcanic ash)

Potential Fault Alternatives:

Pneumatic System Faults

- Pneumatic pressure too low
- Airplane pneumatic duct failure
- Starter air valve failure
- " " duct failure
- Starter failure (partial failure results in too little torque

Fuel System Faults

- Fuel metering unit
- Fuel shutoff valve
- Engine fuel pump
- fuel boost pump (high altitude air starts)
- Engine fuel line
- Mismanaged fuel system configuration
- Crossfeed valve failure

Start Procedure Faults

- Airplane pneumatic system improperly configured

- Too cold: failure to use RICH; improper selection of fuel; too cold even for RICH

- Outside of start envelopes

- Fuel pressurization when high rotor speed too low

Gas Generator Faults (Compressor/Turbine)

- Bleed valve failure

- Stator vanes off schedule (mechanical failure)

- Compressor damage

- Turbine damage

- Low speed rotor locked (stuck)

Engine Control Faults

- Sensor fault

- Software error

- Hardware failure

- Actuator failure

- Engine wiring (e.g., intermittent broken connection between engine controller and fuel metering unit)

<u>Relevant Context Variables - Status</u>:

Phase of Flight - Descent

Weather - High thin clouds

FOD Potential - High, volcanic eruption in area

FARs -

Engine Fault History -

Airline Policy - Autostart system use not mandatory

Engine Commanded Status - Start

Pilot Error - Autostart system OFF; Failure to distinguish between air and ground start characteristics

Airplane Systems Status - All engines flamed out; battery standby power only available. Windmilling start required.

Workload - High; Stress level extremely high

Action Alternatives:

Activate Autostart system (if available)

Execute shutdown and manual restart procedures - single engine

Execute shutdown and manual restart procedures - multi-engine

Subsystems Affected:

Engine(s)

All airplane systems are affected. Normally however, the PFD, ND, and upper EICAS will remain on being powered as they are by the standby bus.

Propagation Sequence With Time Base:

Start sequence data plots are truncated due to generators dropping off line and resulting loss of power in flight deck recorders. Several hung starts occurred in start attempts on three of four engines during the course of the event. The sequence reported below will be an amalgamation of data across engines and start attempts.

t(unknown) - Engine start initiated

Time t1 - Low rotor speed at approximately 24%; high rotor speed nearly level at 45%; EGT at 510 deg. C.; fuel flow nearly flat at 800#

Time t2 - low rotor speed flat at 24%; high rotor speed nearly flat at 46%; EGT rising rapidly at 540; fuel flow nearly flat at 850#

Time t3 - low rotor speed flat; high rotor speed nearly flat at 48%; EGT rising rapidly to 610; fuel flow nearly flat at 900#

Time t4 - Start attempt aborted

Data Available to Pilots

Pilots use high rotor speed to indicate appropriate time to turn fuel ON then go by the "clock" (real time monitored or estimated) to determine if "light off" has occurred normally. Light off can take 2 to 3 minutes in an air start. Once light off has occurred, they monitor high rotor speed and EGT to determine if a start is progressing normally. Fuel Flow (FF), EGT, and low rotor speed also have appropriate rates of increase during a normal air start. However, this rate of change for each parameter can differ somewhat from that achieved during a ground start. On the ground, if a normal start is not achieved, high rotor speed will begin to decline when a speed of 50% has been achieved and the starter disengages. In an air start with all engines flamed out, no bleed air is available to power the starter so a windmilling start must be accomplished. Rate of increase in engine parameters during such a start may be significantly slower than for a normal ground start.

Source of Data:

Upper EICAS is the only source of data on engine parameter behavior. The primary thrust parameter would be shown in full scale. All other engine parameters are shown in digital form only.

Explanation of Relationships:

Quality of Data:

The quality of the data available to the pilots on key parameters with only the upper EICAS available would not be degraded from normal. However, the "grain" of the data available normally is not fine enough to pick up trends in parameters until major departures from normal have occurred.

Heuristics or Rules of Thumb Used:

The typical high rotor speed/EGT relationship looked for is high rotor speed X 10 = EGT during the initial stages of spool-up following light off. On the ground, a normal start should be accomplished in 45 to 60 seconds. In an air start however, the time frame for a normal start may be doubled, tripled, or more.

The appropriateness of this rule of thumb varies across engines and is not applicable to an air start.

Time Constraints:

Light off normally occurs within 10 seconds after fuel ON for a ground start but may take 2-3 minutes in an air start. Stable parameter readings at idle should be achieved within one to two minutes for a ground start but can take much longer in an air start. Changes in the rates of change for high rotor speed and EGT are slower for an air start. Thus, hung and hot start indications will not be as obvious as they typically are in a ground start. Likewise, a normal start may be in progress, but if ground start criteria are used, a hung start may be assumed.

Information Required to Make Diagnosis

Key Parameters:

High rotor speed

EGT

Fuel Flow

Symptoms:

High rotor speed remains relatively flat for up to 60 seconds or more after light off. EGT rises relatively quickly and fails to stabilize with evidence of normal spool up. Under the event/fault condition defined for this scenario (i.e., all-engine flameout) EGT exceedences would probably be ignored in the interest of getting **an** engine started.

Interpretation:

In this incident, the engine parameters during start exhibited typical hung/hot start characteristics. With fuel input low and relatively constant, combustion processes were not sufficient to drive the turbines, and consequently the high speed rotor, to normal idle speed. With high rotor speed low relative to normal, insufficient air was flowing through the engine relative to the amount of fuel available resulting in rapidly rising EGT.

As many as twelve restart attempts were performed on some of the engines. For those restart attempts where data are available, the parameter values for high rotor speed and fuel flow improve slightly with each restart attempt until a normal start is achieved.

Information Required for Decision Aiding

Nature of the Fault:

The fault is in the fuel system; specifically clogged fuel nozzles. Typically, with faults other than procedural faults there is little pilots can do to correct the fault. However, speculation is that the numerous attempts to restart the engines may have aided in dislodging the coking on the fuel nozzles.

<u>Relevant Context Variable Set</u>:

Phase of Flight - Descent

Weather - High thin clouds in area make it difficult to identify volcanic ash clouds

FOD Potential - High, volcanic eruption in area

Airline Policy - Autostart system use not mandatory

Engine Commanded Status - Start

Pilot Error - Autostart system OFF; possible failure to distinguish between air and ground start characteristics; advancing throttle to climb power accelerated coking process

Airplane Systems Status - All engines flamed out; only systems powered by standby bus available

Workload - High; Stress level extremely high

<u>Relationship Between Fault and Context Variables for</u>:

<u>Diagnostic Application</u> - Phase of flight is a major factor in diagnosing the fault. The rates at which parameters change during an air start are different than the rates during a ground start. Rates which would indicate a hung start on the ground may be normal for an air start. All starter related items among the fault alternatives are eliminated if the starter is not available or not used.

<u>Action Recommendation Application</u> - When in the vicinity of volcanic ash, the recommended action is to reduce power setting; e.g., pilots could reduce power on half their engines and use the other half for maintaining altitude or climbing. In the event of an all engine flameout, engine start attempts should be monitored closely to avoid shutting down engines which have a normal start in progress vs. those that have hung or hot starts in progress.

Consequences of Inappropriate Alternative Actions:

Advancing throttles to climb power in the presence of volcanic ash accelerates the coking or clogging process on the fuel nozzles. Appropriate action is to retard the throttles. This is contrary to the natural tendency of pilots to climb out of trouble.

FLIGHT DECK ENGINE ADVISOR
FAULT SCENARIO - F8

Event: Stall/Surge

Fault: Stability margin problem

Potential Fault Alternatives:

FOD

Procedural error

Stator vane failure

Bleed valve control failure

Relevant Context Variables:

Phase of Flight - Take Off

Weather - Clear and 15

FOD Potential -

FARs -

Engine Fault History - prototype engine

Airline Policy -

Pilot Error - Throttle on affected engine should be retarded

Airplane System Status -

Workload - High

Action Alternatives:

Retard throttle on affected engine

Retard throttle on affected engine, command full power on other engine(s)

Subsystems Affected:

Engine

Propagation Sequence with Rank Order Time Base:

Time t1 - Beta stator vane angle showing high frequency, low amplitude fluctuations

Time t2 - Fluctuations in Beta SVA increase in amplitude and become quite regular in pattern

Time t3 - High response low pressure compressor (LPC) static pressure sensor[5] shows definite high frequency, moderate amplitude fluctuation

Time t4 - High response LPC static pressure shows very definite high frequency, high amplitude fluctuations

Time t5 - High response total LPC pressure beginning to show definite fluctuating pattern

Time t6 - Standard LPC static pressure sensor[6] showing definite low frequency fluctuating pattern

Time t7 - Fuel flow shows uncommanded[7] drop

Time t8 - Low and high rotor speeds decelerate sharply

Time t9 - EGT goes off scale several times at less than 1 sec intervals

---

5 Sensor unique to flight test.

6 Sensor is on some operational engines. Getting information on some of these parameters would be possible if the engine controller uses the information in it control laws.

7 Throttle not retarded but engine controller cut fuel flow.

Data Pilots Have Available

Source of Data:

EICAS display of engine parameters

The auditory indicators (pops and/or loud bangs) of surging

Explanation of Relationships:

The indications in the cockpit are after the fact. Engine controller commanded reduction in fuel flow occurs about 1.5 sec before the throttle is chopped. Low and high rotor speeds drop sharply when fuel flow is cut back. The EGT excursions **may** be displayed on the EICAS if the EICAS system does not damp high frequency oscillations. However, the excursions may not be seen by the pilots.

Quality of Data:

No information on the flight deck of impending stall and surging. This type of information (were it available) should be processed through an engine advisor system and presented to the crew as an alert.

Heuristics or Rules of Thumb Used:

None identified

Time Constraints:

The data from special flight test instrumentation provides a clear indication that stalls and surges are developing up to 15 seconds or more before the surge occurs. With operational sensors a 5 second warning may be possible. This is still adequate for crew action. However, the appropriate action depends on where the airplane is in terms of phase of flight. With the case in point, the actual stall occurred very early in initial climb. Here the appropriate action would be to retard the throttle on the affected engine and command full throttle on the remaining engine(s). With 15 seconds warning and assuming at that point the airplane was below V1, the appropriate action would be to abort the takeoff; if above V1 **and** at a safe altitude, retard throttle as required and command full throttle on other engine(s). During climb, TOC, TOD, or descent, time constraints are less critical and appropriate action is to retard the throttle.

Information Required to Make Diagnosis

Key Parameters:

Beta Stator Vane Angle - an operational sensor but data not available to the flight deck

High Response Discharge Static Pressure at Low Pressure Compressor - special flight test instrumentation

High Response LPC Discharge Total Pressure - special flight test instrumentation

Standard LPC Discharge Static Pressure - operational instrumentation but data not available to the flight deck

All engine parameter data available on EICAS display the results of the stall and surging; i.e., fuel flow, high and low rotor speeds, EGT.

Neither the stator vane angle sensor nor the discharge pressure sensors are represented in the engine model or MONITAUR.

Symptoms:

At time t1 - The earliest indication of a problem developing appears to be the high frequency oscillation of Beta stator vane angle. However, stator vane angle is on steady state schedule; i.e., the level of the parameter is alright. Since it is on schedule, stator vane failure can be eliminated as a potential fault alternative. The very high frequency oscillation does not appear in the stator vane angle data after recovery although oscillation is still present and amplitude is reduced.

At time t2 - Beta SVA oscillations increase in frequency and amplitude.

At time t3 - High response LPC static pressure has definite high frequency, moderate amplitude oscillations.

At time t4 - High response LPC static pressure has very definite high frequency, high amplitude oscillations.

At time t5 - High response total LPC pressure beginning to show definite oscillations

At time t6 - Standard LPC pressure showing definite oscillating pattern

Interpretation:

The problem here from the standpoint of Engine Advisor development is that we have sensor data that clearly indicates the onset of stalls and surges; BUT, the best indications come from delicate flight test sensors, AND we have no engine model parameter data for these sensors. Advanced engine controllers now have some capability to sense, interpret, and act to prevent stalls and surging. If this capability is reliable and appropriately activated throughout the flight regime, then the Engine Advisor role is one of advising after the fact in terms of action alternatives and implications for safety of flight and flight replanning. If this automation has not been implemented, then the Engine Advisor role is that of alerting the crew in a timely manner of the action required. In the first case, improvements focus on increased sensitivity of sensors and development of the crew interface capability of Engine Advisor. In the second case, improvements focus on adequate sensor development for the operational environment and development of the appropriate parameter models for an engine model.

Information Required for Decision Aiding

Nature of the Fault:

In discussing the nature of the fault, we have an interesting problem here. The fault, a stability margin problem is not supposed to occur on operational engines. Yet operational engines do stall and surge. The question is how well does the data we have to develop and test Engine Advisor represent stall and surging data from an operational setting? Further, there are a number of faults or flight conditions which can produce stall and surging. The problem is basically that of detecting the onset of symptoms which lead to stall and surging in a timely manner so that either the crew or engine controller can take action to prevent the full development of the condition. As outlined above, in the first case, the Engine Advisor system must provide an alerting function; in the second, an advisory function.

Relevant Context Variable Set:

Phase of Flight - Take Off (TOC, TOD ; i.e., significant changes in angle of attack)[8]

Weather - (especially heavy rain)

FOD Potential - (birds, blown tire parts, etc.)

Engine Fault History - propensity for stall and surging

Pilot Error - overreaction in reducing throttle setting(s)

Workload - high

Relationship Between Fault and Context Variables for:

Diagnostic Application - Stall and surging symptoms may be different in either degree or sequence or both as a function of phase of flight. The nature of FOD source may also affect symptom presence and/or degree.

Action Alternatives Application - Phase of flight is a key factor in determining the appropriateness of action alternatives. Engine fault history may be such

8 Status information in parentheses indicates status level of relevant alternative faults.

that crews have a good deal of actual experience in dealing with stall and surging conditions.

Consequences of Inappropriate Alternative Actions:

Stall and surge conditions developing at or near V1 can lead to inappropriate actions on the part of the pilots. A good deal of accident and incident data attest to this. Pilots should take no action at all under these conditions until reaching a safe altitude. The need for either timely alerting or appropriate advisory information is critical to the selection of the correct action alternative.

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W. D. Shontz, R. M. Records, and D. R. Antonelli

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13. ABSTRACT *(Maximum 200 words)*
The current project is part of a larger fault management research program funded by NASA Langley. The focus of this project is on alerting pilots to impending events in such a way as to provide the additional time required for the crew to make critical decisions concerning non-normal operations. The project addresses pilots' need for support in diagnosis and trend monitoring of faults as they affect decisions that must be made within the context of the current flight.

Monitoring and diagnostic modules developed under the NASA Faultfinder program were restructured and enhanced using as inputs data from an engine model and real engine fault data. Fault scenarios were prepared to support knowledge base development activities on the MONITAUR and DRAPhyS modules of Faultfinder. An analysis of the information requirements for fault management was included in each scenario. A conceptual framework was developed for systematic evaluation of the impact of context variables on pilot action alternatives as a function of event/fault combinations.

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