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PRELIMINARY DEVELOPMENT OF AN INTELLIGENT COMPUTER ASSISTANT FOR ENGINE MONITORING

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Abstract

This paper presents the preliminary development of a method for monitoring the propulsion system and identifying correct recovery procedures for the F404 engine in support of the F-18 high-angle-of-attack research vehicle program. By using artificial intelligence techniques and modern display technology, we have been able to design a system that aids in real-time monitoring of propulsion systems. This expert system is designed to operate as an "expert aid" to an engineer with little or no experience in propulsion system monitoring. The goals of this expert system development project are to provide enhanced safety of flight and to relieve the propulsion engineers of the time-consuming but necessary task of propulsion system monitoring on flight programs, particularly those with nonexperimental engines. As telemetry data is received, the results are continually being displayed to the engineer in a unique manner. The engineer has the choice of a number of different color graphical displays he may use. These include being able to monitor the engine state, monitor individual parameters and watch time histories or strip chart displays. When an anomaly is identified, that information is displayed to the engineer. Any additional information is also displayed, such as the procedures necessary to recover from the anomaly.

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Nomenclature

A8	nozzle area, ft^2
CLIPS	C Language Production System
CRT	cathode-ray tube
E_Lube_P	engine lubrication pressure
ICAEM	intelligent computer assistant for engine monitoring
LVDT	linear voltage differential transformer
N1	rotational fan speed, percent or RPM
N2	rotational compressor speed, percent or RPM
Nz	normal acceleration, g's
Ps0	ambient static pressure, $lb/in.^2$
Ps3	compressor discharge static pressure, $lb/in.^2$
Pt5	turbine discharge total pressure, $lb/in.^2$
PLA	power lever angle position, deg
tt1	inlet total temperature, C°
tt5	turbine discharge total temperature, C°

Introduction

Propulsion system monitoring is a flight safety function that is often performed for aircraft operating with experimental propulsion systems. Propulsion system monitoring may also be a safety-of-flight requirement for an aircraft performing extreme maneuvers or flying near the boundaries of the normal operating envelope.

At the Dryden Flight Research Facility of the NASA Ames Research Center, this monitoring function is performed in the mission control center of the Western Aeronautical Test Range. The task of propulsion system monitoring is normally performed by an experienced, senior-level propulsion system engineer familiar with the specific aircraft and engine being flown using strip chart recorders, computer-formatted displays,

and indicator lights providing data from instrumentation on board the aircraft (Fig. 1). Table 1 shows a list of representative propulsion system instrumentation for a research program not involving experimental propulsion system elements; those parameters designated "flight mandatory" indicate instrumentation that must be operational for flight testing. Formatted displays provide digital values of the main propulsion system instrumentation parameters.

Table 1. X-29A representative propulsion system instrumentation list.

Parameter	Flight mandatory
Inlet temperature	
Fan speed	×
Core speed	×
Compressor discharge pressure	×
Main fuel flow	
Main ignitor lead temperature	
Flame sensor temperature	
Turbine discharge pressure	
Turbine discharge temperature	×
Afterburner fuel flow	
Afterburner ignitor lead temperature	
Exhaust nozzle area	
Nozzle LVDT temperature	
Power lever angle position	×
Engine fuel pressure	×
Engine fuel temperature	×
Engine lubrication pressure	×
Fuel tank pressure	×
Fuel tank temperature	×

Each mission control center strip chart recorder provides eight channels of analog information. Typically, the propulsion engineer monitors two of these recorders for both trends and limits. A representative list of some of the parameters displayed on these strip chart recorder channels is provided in Table 2.

Indicator lights are used to monitor system status or to indicate parameters that are out of limits. The number of indicator lights used for propulsion system monitoring varies from program to program. A list of representative limits that might be monitored are included in Table 3.

Currently, engine monitoring is done by senior-level propulsion engineers and operations engineers in the control room and by pilots in the cockpit. Strip charts, CRT's with both digital and graphic data, warning lights, analog gauges, and color panels are all monitored in the control room or similar facility while the pilot monitors his engine gauges in the cockpit.

Table 2. Representative strip chart recorder parameter list.

Parameter	Parameter designation
Fan speed	N1
Core speed	N2
Compressor discharge pressure	Ps3
Main fuel flow	wf_e
Turbine discharge pressure	Pt5
Turbine discharge temperature	tt5
Afterburner fuel flow	wf_{ab}
Exhaust nozzle area	A8
Power lever angle position	PLA
Engine lubrication pressure	E_Lube_P

Table 3. Representative indicator light list.

Parameter	Indication
Fan speed	$> N1_{max}$
Core speed	$> N2_{max}$
Turbine discharge temperature	$> Tt5_{lim}$
Engine fuel temperature	$> T_{eng_{lim}}$
Fuel tank pressure	$< P_{tank_{min}}$
Engine lubrication pressure	$< P_{lube_{min}}$
Engine skin temperature	$> T_{skin_{max}}$

As can be seen in Tables 1 and 2, the total number of parameters and conditions that must be monitored is not overwhelming, but there is a sufficient number so that a novice would have difficulty providing adequate real-time monitoring. The task of monitoring individual parameters and conditions is only one part of the propulsion system engineer's responsibility. Additionally, the propulsion engineer must also recognize and correctly identify a number of systems-level anomalies that require understanding of a pattern in several parameters simultaneously. The recognition of a systems-level anomaly and the correct identification of that condition is essential for a corrective or preventative action and for communication with the pilot.

Another problem is that the control rooms are usually limited in the number and type of strip

charts, cathode-ray tube (CRT) displays, and warning lights. As aircraft and engines increase in complexity, changes need to be made to these displays.

In order to ease some of the burden on the propulsion engineer, the NASA Ames Research Center's Dryden Flight Research Facility has been investigating methods to aid in the monitoring process. Expert systems provide a means of increasing the propulsion engineer's productivity by taking over some of the monitoring functions. By using expert system's technology, the experience of several propulsion engineers can be used.

This work was based on knowledge gained from previous work done on an expert system flight status monitor[1–3] and is similar in function to the expert system for shuttle mission control. The program documented here was developed to support the F-18 high-angle-of-attack research vehicle program.

This paper describes a preliminary version of an expert system engine monitor that aids the propulsion engineer with many monitoring tasks. In order to evaluate the preliminary version, data from the F404 engine in the X-29A forward-swept wing was used.

System Description

Engine Description

The F404 engine is a low bypass axial-flow turbofan with afterburner. The three-stage fan (low pressure compressor) is driven by a single-stage turbine. Approximately one-third of the fan discharge air is bypassed to the afterburner for combustion and cooling. The seven-stage, high-pressure compressor is also driven by a single-stage turbine. The first- and second-stage compressor stators are variable. Fourth-stage compressor air is used by the engine's anti-ice system. A set of variable inlet guide vanes are mounted in front of both the fan and compressor to direct the inlet air at the best angle for the existing engine operation.

Atomized fuel and compressor discharge air is mixed and ignited in the combustion chamber. These ignited gases then pass through the compressor and fan turbines and out the engine exhaust. Afterburner operation uses added atomized fuel mixed with the compressor discharge gases and the bypass fan discharge air to produce additional thrust. The military (nonafterburning) thrust of each engine is approximately 10,700 lb with maximum afterburner thrust in the 16,000-lb class.

The electrical control assembly, variable exhaust nozzles, main fuel control, and afterburner control provide coordinated operation of the engine throughout the flight envelope. The engine accessory gearbox, driven by the compressor rotor, powers the lubrication and scavenge oil pumps, variable exhaust nozzle power unit, alternator, main fuel pump and control, and afterburner fuel pump and control.

During development there was no available F-18 data to test the intelligent computer assistant for engine monitoring (ICAEM). The only F-404 engine data available at the time was from the X-29. Since the X-29 has only one engine as opposed to two engines for an F-18, telemetry data was mapped to both engine displays (Figs. 5–6). In this way actual flight data could be used for testing ICAEM.

Current Monitoring System

Figure 2 shows how monitoring is currently being done at Ames-Dryden. Radar tracking and telemetry tracking devices pass information to the telemetry and radar acquisition processing system. Data is then transmitted to the control room to drive CRT displays, indicator lights, strip chart recorders, and color panels. There is much data, but little information. The propulsion engineer is required to process the data into useful information. Since the knowledge required to transform the data into information is in the engineer's mind, a senior-level propulsion engineer is required to perform this task.

ICAEM Description

Figure 3 shows how monitoring is done with ICAEM. Telemetry and radar information are received as before. However, rather than having data sent to different devices as before, real-time data are transmitted to a single workstation through a local area network using a standard protocol.

There are many advantages to the new system. The most important advantage is that the programmable workstation has the capability to put some of the engineers' knowledge into the system. This is done through the use of expert systems which use the declarative knowledge contained in rules that evaluate the system being monitored. In this way data, as well as useful information, is displayed to the user. Also, use of programmable workstations for graphic displays substantially reduces the workload, allows for sophisticated graphics without impacting the critical acquisition software, and provides greater flexibility in display design and reconfiguration.[4]

Description of Internal Structure of ICAEM

The overall internal structure of ICAEM is shown in Fig. 4. The main portion of ICAEM is a program that acts as an interface between the telemetry data being provided by way of Ethernet and the expert system. Once given data, the expert system decides if any condition exists that the engineer needs to know. If so, that information is sent to another program that displays the necessary information to the engineer.

When telemetry data is received, the main program asserts a fact into a fact base in the expert system. Once enough facts are generated to match the conditions of a rule, the rule is "fired." For example, consider a rule in the expert system such as one to monitor a potential hung start:

```
  If
    Starting engine and
    N2 is less than 60 percent and
    N2 is not increasing for 1 sec and
    PLA is greater than 14 and less than 24,
  then
    Engine state is Potential Hung Start.
or
  If
    Starting engine and
    N2 is less than 60 percent for 35 sec,
  then
    Engine state is Potential Hung Start.
```

This warns the engineer of the danger of a hung start before the hung start actually takes place. The main program receives telemetry data for many parameters including those needed for the above rules. It then asserts facts into the expert system fact base. The expert system looks at all the facts being asserted, and if every condition in the rule is satisfied, it "fires" that rule. The consequent of the rule is then passed to the display program so that the engineer will receive the necessary information. If any condition is not satisfied, the rule is not fired.

The expert system used in ICAEM is the C Language Production System (CLIPS) inference engine produced by the Mission Planning and Analysis Directorate of NASA's Johnson Space Center.[5] The primary representation methodology used in CLIPS is a forward-chaining rule language based on the Rete algorithm.[6] CLIPS was chosen because it was written in the "C" language and was designed to be embedded within an application. This is a very important feature for this project because of the need to interface the inference engine to a real-time application written in a procedural language. Other expert systems exist but provide no means of interfacing since they provide a "total environment."

Using the rule-based expert systems approach allows gathering and implementing the propulsion engineer's knowledge very quickly, which in turn allows quick feedback on the quality of the knowledge captured in the expert system and quickly raises the quality level with just a few iterations.

Overview of ICAEM's Capabilities

Determining Engine Operational State

The main functions to be performed by the propulsion system expert system are monitoring, anomaly classification, and both normal and recovery procedure aiding.

The monitoring task involves the following functions:

- Determination of engine operating state
- Detection of parameters whose value has exceeded limits
- Detection of the rates of change of parameters
- Prediction of trends
- Timing of duration of parameters outside of limits

This information is then used to identify any anomalous system behavior (see Identification of Anomalies) and, when this behavior corresponds to a predefined pattern of behavior, to identify the type of anomalous behavior being exhibited by the propulsion system. Two types of anomalous behavior must be identified by the system: single parameter and systematic. Single parameter anomalies are those in which a parameter exceeds a limit or exceeds a limit for too long a period. Systematic anomalies are those in which the propulsion system exhibits anomalous behavior in multiple parameters in some pattern.

The system is partitioned by engine states as follows:

- Ground start
- Normal ground operation
- Take-off

- Normal flight operation
- Airstart

Partitioning in this way allows partitioning the rules in a similar manner so that only the rules within each partition will fire at one time, thus significantly reducing the processing time for the expert system.

Within each of the above partitions, ICAEM monitors only those parameters and rules associated with that state. In the ground start state, for example, ICAEM monitors for engine start, power level angle (PLA) to ground idle, lite-off and normal start, hung start, or hot start.

Given any state, ICAEM monitors only those parameters necessary. Some parameters, however, are always monitored whether or not they are displayed. For instance, engine lubrication pressure (E_Lube_P) is a parameter that is always monitored, whereas Nz is only monitored when E_Lube_P is out of limits (that is, E_Lube_P is usually disregarded if Nz is less than 0.5 *g*'s).

Identification of Anomalies

The primary function of propulsion system monitoring is the detection of system anomalies. These anomalies fall into the categories of "system anomalies" and "engine anomalies." System anomalies are abnormal operation within the total propulsion system but external to the gas generator and afterburner. Engine anomalies are those that occur within the gas generator. Whenever any of these anomalies occur, they must be correctly identified and appropriate corrective action taken.

The anomalous system conditions that must be detected are:

- excessive engine fuel temperature
- high or low engine fuel pressure
- engine compartment overheating
- low or high oil pressure
- excessive oil temperature

The anomalous engine conditions that must be detected are:

- stagnation
- hot start
- hung start
- engine overtemp
- engine stall
- engine failure
- engine overspeed
- afterburner malfunction
- engine flameout

Some of these anomalies are not presently monitored. Methods to monitor them are still in the development stage. At present, monitoring is being done for hot start, hung start, engine stall, and engine overtemp for the engine anomalies, and low lubrication pressure for the system anomalies.

Procedural Aiding

As stated earlier, it was convenient to distinguish between five specific conditions: ground start, normal ground operation, take-off, normal flight operation, and airstart. Associated with each of these conditions or "modes" is a set of anomalous conditions to watch for and a corresponding procedure for each anomaly.

In the ground start mode, monitoring is being done for a hot start and a hung start. If there is a hot start or a hung start, a window will appear at the top of the display containing two sets of procedures. One is a ground station procedure for this particular condition and the other is a cockpit procedure. These procedures are taken directly from the flight manual. Figure 6 shows the procedures display for a stall. Besides having the ability to bring up the procedures automatically on an anomaly, the user also has the ability to bring up any procedure he wishes in order to review it at any time.

Information Displays

The display or user interface serves to enhance the propulsion engineer's processing of data. Typically, a propulsion engineer must process a textual data screen from which a mental model of the corresponding subsystems is built. ICAEM reduces the mental processing time and reduces the data monitoring load.

The ICAEM display is partitioned into three major sections (Fig. 5). The bottom portion of the display shows a cross-sectional view of two engines—left

shows a cross-sectional view of two engines—left and right. This section of the display shows parameters that are always monitored. Thermometer-like displays are at respective engine stations. The right vertical bar (blue) indicates the actual value of a given parameter while the left vertical bar (green) indicates a predicted value of the same parameter. This predicted value is based on a number of previous data samples and indicates a trend (for example, if the predicted value is consistently higher than the actual value, it indicates the value has been increasing). The box containing digital data at each station will change to yellow when the parameter is near a predetermined limit and will turn red when the parameter reaches that limit.

The center display is two colored horizontal bars containing text. These bars show the actual state of the engine. Any nominal condition is displayed with a green background, while a warning condition or a condition of potential concern is displayed with a yellow background. Any serious condition is displayed with a red background. The center display is used to monitor the status of the engine. As shown previously, in a normal ground start the following statuses would be shown as they occur:

- Starting engine
- PLA to ground idle
- Lite-off
- Normal start

The top portion of the display is used to show user-requested information. Using a mouse, the user may request strip charts on any parameter desired and/or pop up a display with a procedure on it, or turn off a parameter believed to be an erroneous sensor or faulty telemetry data.

The strip chart displays resemble conventional pen-and-ink recorders (Fig. 5). The engineer may call up as many parameters on this display as desired—not just predetermined parameters as before. Signal traces are displayed and tagged with limits. The strip charts demonstrate how a current capability need not be lost but can be provided in a better form while still making use of the propulsion engineer's training and experience.

The top portion of the display is also used for procedures (Fig. 6). At any time, the user may bring up a display that shows the procedures required of the engineer on the ground and the necessary procedures required of the pilot in any given anomalous situation. The procedural displays also pop-up automatically when an anomaly is encountered by the expert system.

There are conceivably times when a propulsion engineer is aware that some data must be disregarded. It may be obvious from the data displayed that a certain sensor is bad and the information received is erroneous. In that case, the engineer can, in effect, turn off the sensor. The expert system stops using that parameter's information, and data for that parameter is not displayed.

Conclusion

This document presents a preliminary version of a propulsion system expert system that was developed for monitoring and procedural aiding in support of the F-18 high-angle-of-attack research vehicle program. This expert system is designed to operate as an "expert aide" to an engineer with little or no experience in propulsion system monitoring. The goal of this expert system development project is to relieve the propulsion engineer of the time-consuming, but necessary, task of propulsion system monitoring on flight programs with nonexperimental engines. The intelligent computer assistant for engine monitoring provides a better monitoring environment because it uses the knowledge and experience of several propulsion engineers. It is always attentive and never distracted as a human may be. And the system displays information, not raw data, therefore enhancing safety of flight and improving the engineer's efficiency in propulsion system monitoring.

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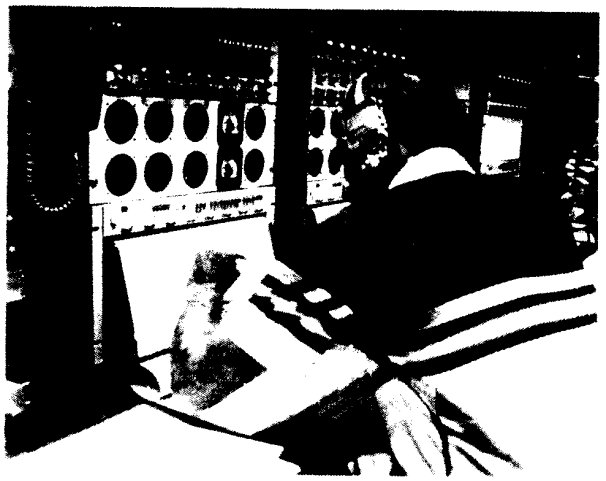

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Fig. 1 Control room.

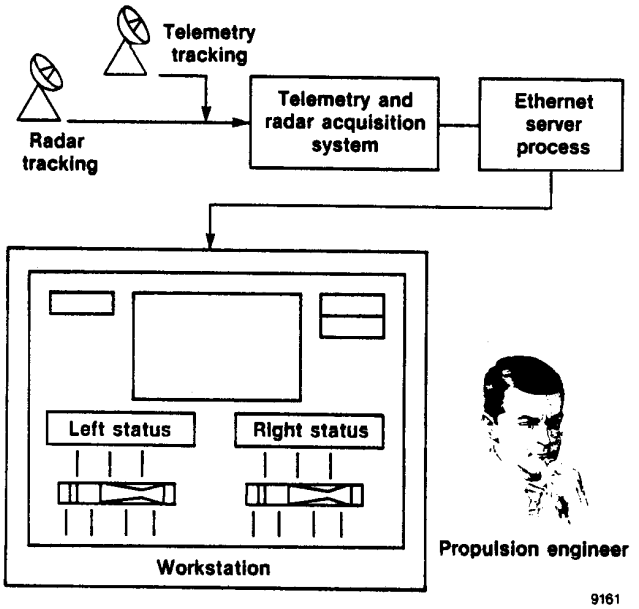

Fig. 3 ICAEM system.

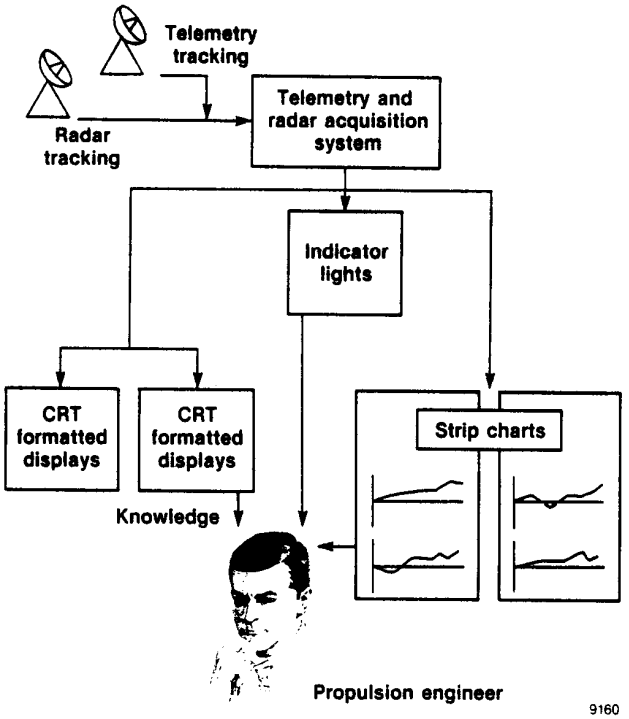

Fig. 2 Current system.

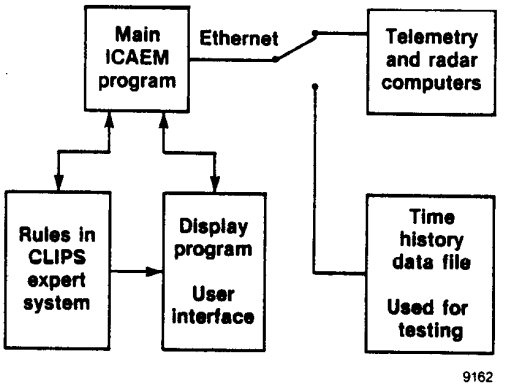

Fig. 4 Internal structure.

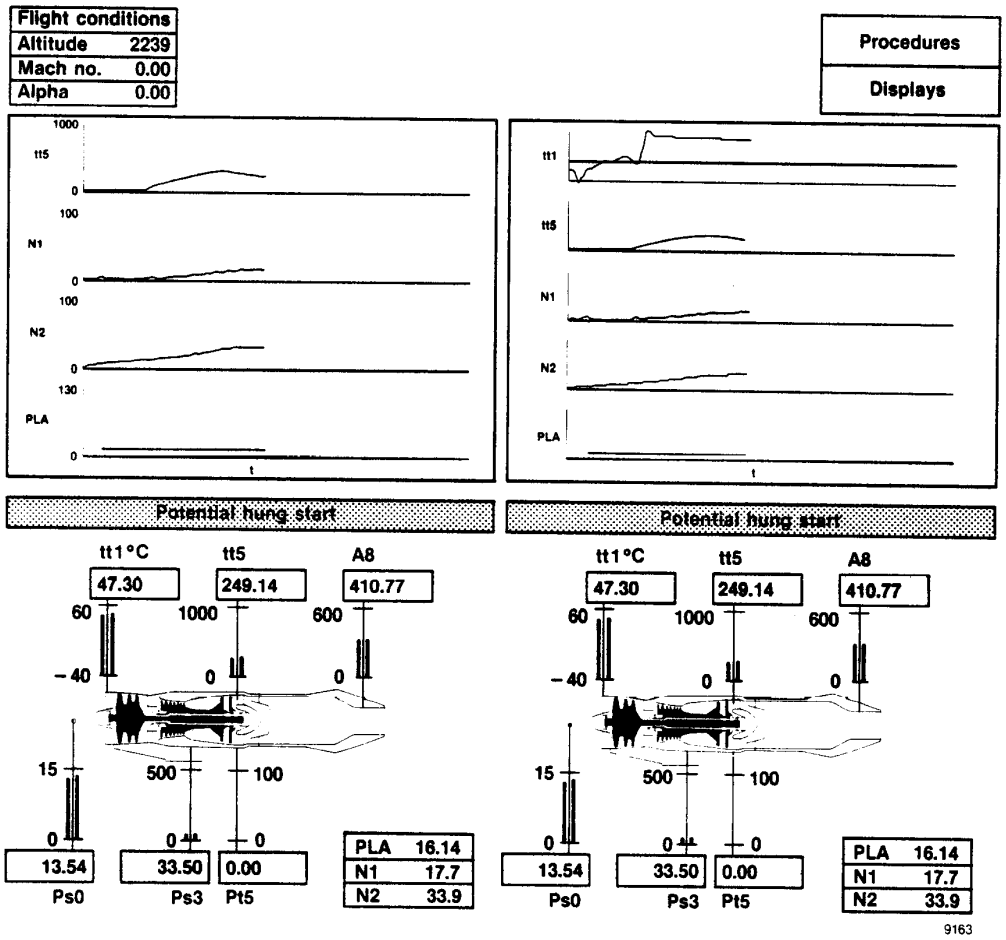

Fig. 5 Display with strip charts.

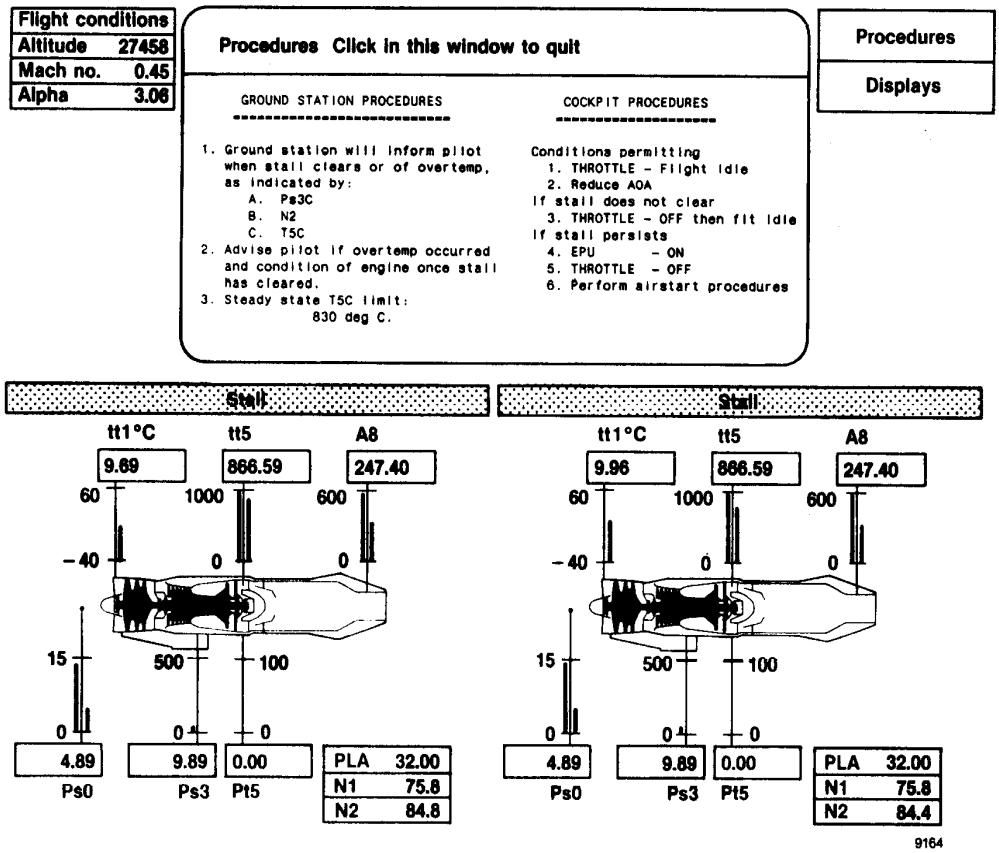

Fig. 6 Display with procedure.

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16. Abstract

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