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SPURIOUS SYMPTOM REDUCTION IN FAULT MONITORING

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EXECUTIVE SUMMARY

Work completed in 1991 (Ref 1) suggested NASA's Faultfinder concept for in-flight diagnosis of engine behavior was jeopardized by spurious symptoms generated in the monitoring phase. The purpose of the present research was to investigate methods of reducing generation of spurious symptoms for in-flight engine monitoring. The monitoring approach used in NASA's Faultfinder (Ref 2) is to utilize a computer simulation of the engine (henceforth called the "engine model") to generate expectation values for common engine sensors. These expectation values are then compared with actual sensor readings in real time to monitor current engine behavior. If sufficient variation is found between expectation values predicted by the engine model and actual engine sensor readings, a symptom is annunciated by the monitoring module. The original design of the monitoring module (MONITAUR) provided for the use of a rule base to filter potentially spurious symptoms.

Two approaches for reducing the number of spurious symptoms were investigated in this research. The first approach was to examine a large sampling of spurious symptoms generated from monitoring healthy engine data to extract generic sources of spurious symptoms. A knowledge base of rules used to filter known spurious symptoms was then constructed and tested, again using healthy engine data. The final step was to insure actual symptoms for real faults were not filtered by this rule base.

A second approach was to seek an alternative method of generating expectation values. A neural network was designed to predict an expectation value for each of the sensors monitored. The neural net was trained for a specific (serial number) engine during normal operation. After capturing patterns for normal operating engine behavior in the neural net, an expectation value for the sensor was predicted upon request. The success of this approach relies on generating better expectation values which in turn

produce smaller variations from actual operating behavior and hence generate fewer spurious symptoms.

The results demonstrate that both approaches are effective in reducing spurious symptoms. Using a baseline of spurious symptoms from the 1991 study, a reduction of at least 40 percent of the spurious symptoms was realized using the neural network. A reduction of at least 70 percent was achieved with the knowledge base filter. The best result was obtained using a hybrid system of a neural network to generate better expectation values and the knowledge base for filtering the spurious symptoms still generated. A reduction of at least 90 percent was achieved using the hybrid approach. It would appear that a trained neural network can generate expectation values which better represent the actual sensor values than those generated by the engine model. Thus, when spurious symptoms are generated, they can be more readily identified by rules in the knowledge base, resulting in superior spurious symptom reduction.

1.0 INTRODUCTION

The current project is part of a larger fault management research project funded by NASA Langley. This project was recommended as a follow-on study to Flight Deck Engine Advisor - Task 19, Contract NAS1-18027 completed in 1992 (Ref 1). In the Flight Deck Engine Advisor project, Boeing was tasked with modifying NASA's Faultfinder in-flight engine monitoring and diagnostic software to accept real flight data and evaluating its performance. Faultfinder consists of three modules, an engine monitoring component called MONITAUR, and two diagnostic components called DRAPhyS Stage 1 and 2. Stage 1 is a rule based diagnostic system, while Stage 2 is a model based reasoning system. The modified Engine Advisor is shown in Figure 1. The results of that study included a recognition that both spurious and real symptoms were generated by the MONITAUR module. As the spurious symptoms were passed on to DRAPhyS Stage 1 and 2, the potential for erroneous diagnosis was increased. Since the original design of MONITAUR included a procedure to access a filtering rule base, a preliminary study of the feasibility of filtering these spurious symptoms was completed and a small rule base was created to demonstrate the feasibility of using rules to delay the generation of spurious symptoms. This rule base was constructed in the Physical System File for Faultfinder, and input to MONITAUR.

The Final Report on Task 19 concluded with a recommendation to systematically categorize the sources of spurious symptoms by examining a large sampling of healthy engine data and identifying the types of spurious symptoms created as MONITAUR processed the healthy engine data. Once identified, the sources of spurious symptoms could be used to guide creation of a spurious symptom filter. By examining additional healthy engine data, the filter could be used to estimate the percentage of the spurious symptoms which might be eliminated.

The focus for the current project was to implement the recommendations from Task 19, namely identify and reduce spurious symptoms generated in MONITAUR. The original Statement of Work, included in the Appendix A, called for two approaches for spurious symptom reduction. The first was to identify sources of spurious symptoms from results of healthy engine

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monitoring, and create a knowledge base to filter identified spurious symptoms. The current software design of Faultfinder provides for a knowledge base, and a preliminary evaluation of filtering rules created in the previous contract demonstrated the feasibility of using this approach as a spurious symptom filter. The goal of this approach was to create new rules for filtering spurious symptoms from the identified sources, and populate MONITAUR's existing rule base structure with sufficient rules to maximize the percentage of spurious symptoms suppressed.

It should be noted that the rule base constructed in this approach consists of rules which are generic with respect to a selected manufacturer's engine type. Such a rule base is useable across serial numbers for all engines of the same type. Top level data flow diagrams and a data dictionary for the existing version of MONITAUR and for the enhanced version with the filtering rule base are included in Appendix B.

The second approach was to examine the feasibility of using an adaptive filter as a front end to MONITAUR to generate better expectation values than those generated by the engine simulation. If better expectation values could be generated, there would be a reduction in the deviation between the actual sensor reading and the expectation value. As deviations between actual and expected values are reduced, fewer spurious symptoms should be produced.

Six specific tasks were defined in the Statement of Work to achieve the objective of spurious symptom reduction. They are 1) Establish Baseline Value for Spurious Symptom Reduction, 2) Identify Sources of Spurious Symptoms, 3) Create Rule Base to Filter Spurious Symptoms, 4) Create Adaptive Filter to Enhance Generic Engine Model Data, 5) Determine Relative Improvement with Adaptive Filter and Rule Base, and 6) Generate Final Report.

The structure of this report will be to discuss the results of accomplishing each of the tasks in the order listed.
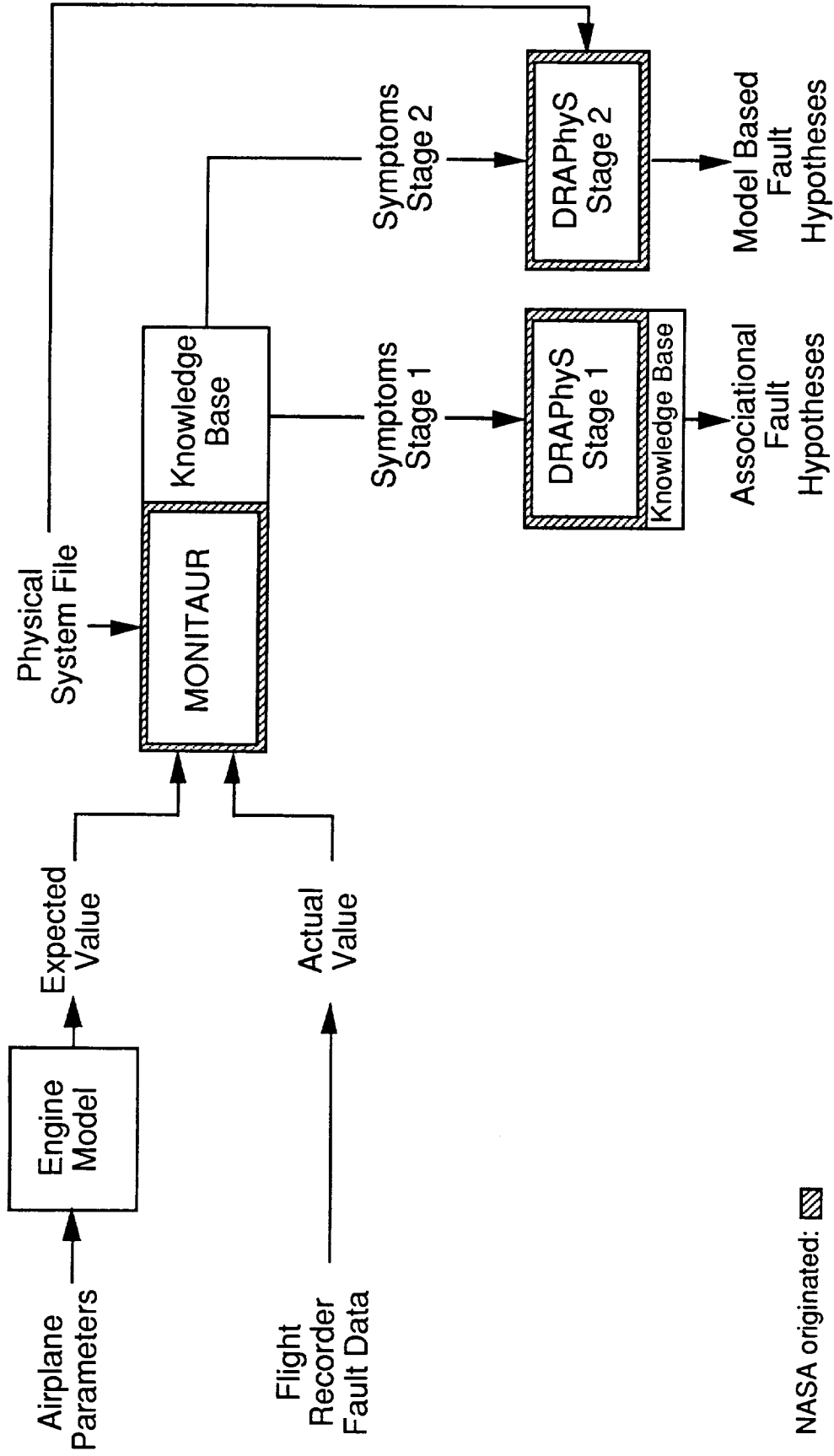
Figure 1. Flight Deck Engine Advisor Modules

NASA originated: ▨

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2.0 PROJECT TASK ACTIVITY

2.1 Establish Baseline Value for Spurious Symptom Generation

Before an evaluation of techniques to reduce spurious symptoms could be attempted, a baseline of spurious symptoms had to be established. The approach used was to first examine healthy engine data. Ideally, monitoring a healthy engine should produce no symptoms. Data collection was confined to a single engine type, but different serial number engines were utilized. Our previous study indicated that different manufacturer's engines manifested differing spurious symptoms. Therefore the objective of this study was to create reduction techniques for specific engine types. For the selected engine model, nine data files of healthy engine data were used which had a total of 6900 data slices containing 35,000 data points. A representative data subset was extracted for use as a baseline. This file was one of the nine healthy engine files (a single engine, with a unique serial number, covering one recorded run). The file contained 115 data slices with two thrust lever advances followed by thrust lever retards.

The data was processed in batch mode by Faultfinder's MONITAUR module. In this procedure MONITAUR calls a Boeing supplied engine simulation for generation of expectation values relevant to the current in-flight conditions. These values are compared by MONITAUR to the actual sensor data which was collected from the healthy engine during a flight. The baseline values obtained for spurious symptom generation are shown in Table 1.

Table 1. Baseline Values

Total number of spurious symptoms	256
No. of (115 possible) time slices w/o symptoms	0
Number of Fuel-Flow symptoms	97
Number of N1 symptoms	25
Number of N2 symptoms	31
Number of EPR symptoms	11
Number of EGT symptoms	92

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In the MONITAUR module, each of the sensors listed are monitored for deviations in three attributes - absolute value, first derivative, and long term trend. Definitions for symptoms for each of these attributes are found in the data dictionary in Appendix C. It should be noted that MONITAUR's design allows definition of acceptable deviation (effective noise level) between actual and expectation values for each of the three attributes for each sensor monitored. These deviation values are coded in the Physical System File, and are input to MONITAUR as shown in Figure 2. The level of spurious symptoms can readily be reduced by raising the acceptable level of deviation. The problem with this approach is that a large acceptable deviation not only ignores spurious symptoms, but also can ignore real symptoms as well. The result of increasing the acceptable deviation value is to delay the recognition of real symptoms (at best) or to ignore the symptom altogether! Part of the original research completed in 1991 was to set deviation levels for each of the sensors which would retain recognition of known symptoms for a given set of engine faults. These levels were used in the current study.
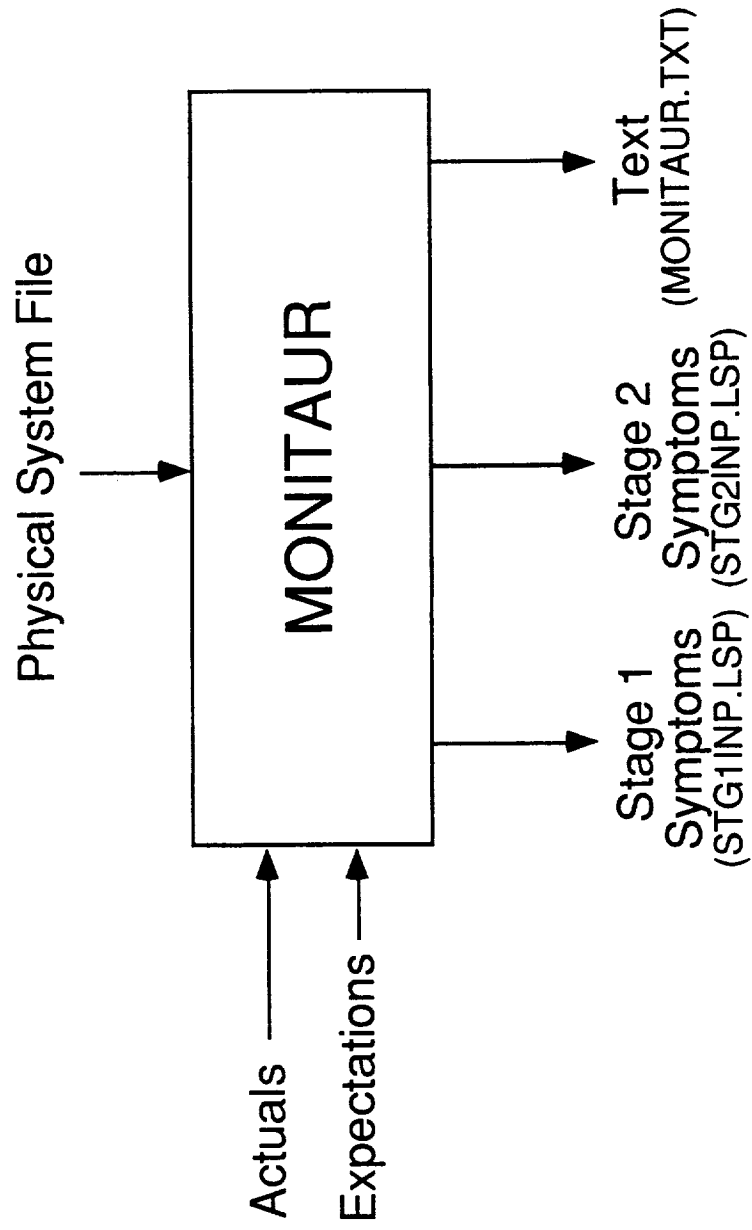
Figure 2. MONITAUR I/O

2.2. Identify Sources of Spurious Symptoms

Before a rule base could be constructed, it was necessary to determine the sources of spurious symptoms. This was accomplished by examining data files for healthy engines for each sensor which were known to produce spurious symptoms. A total of nine data files were processed in batch mode by MONITAUR. Figure 2 shows the output from MONITAUR consists of two files of symptoms, one for Stage 1 and the other for Stage 2. A third output is a text file which is displayed on the screen as MONITAUR processes data. This file was also captured as a disk file for this study, since it is a source of information about which rules have fired.

Analytical tools developed for this project were used to identify symptoms in specific time slices, along with the sensor affected and the sensor's qualitative assessment. The most complete file of symptoms output from MONITAUR is STG2INP.LSP, the file which becomes input to Stage 2. A LISP based tool for analyzing these symptoms was developed as a part of this study. Output from this tool consisted of a summary of symptoms discovered, and a detailed breakout for each sensor showing each symptom found, in time slice sequence. A sample output from this tool is shown in Figure 3.

```
* (TESTRULE)
(ENTER THE NAME OF THE FILE TO READ) stg2inp.lsp

"The number of time slices without symptoms is " 87
"The total number of symptoms is          " 35
"The number of fuel-flow symptoms is       " 4
"The number of n1 symptoms is              " 4
"The number of n2 symptoms is              " 9
"The number of epr symptoms is             " 3
"The number of egt symptoms is             " 15
(N1 NIL (LOWER-CAUTION) NIL NIL 234.0 (STEADY))
(N1 NIL (NORMAL) NIL NIL 238.0 (INCREASING))
(N1 NIL (LOWER-CAUTION) NIL NIL 294.0 (STEADY))
(N1 NIL (LOWER-CAUTION) NIL NIL 295.0 (STEADY))
"The number of N1 symptoms is       " 4
(N2 NIL (NORMAL) NIL NIL 233.0 (STEADY))
(N2 NIL (NORMAL) NIL NIL 237.0 (INCREASING))
(N2 NIL (NORMAL) NIL NIL 261.0 (STEADY))
(N2 NIL (NORMAL) NIL NIL 268.0 (DECREASING))
(N2 NIL (NORMAL) NIL NIL 293.0 (STEADY))
(N2 NIL (NORMAL) NIL NIL 294.0 (STEADY))
(N2 NIL (NORMAL) NIL NIL 300.0 (INCREASING))
(N2 NIL (NORMAL) NIL NIL 303.0 (STEADY))
(N2 NIL (NORMAL) NIL NIL 304.0 (STEADY))
"The number of N2 symptoms is       " 9
(FUEL-FLOW NIL (NORMAL) NIL NIL 237.0 (INCREASING))
(FUEL-FLOW NIL (UPPER-CAUTION) NIL NIL 258.0 (STEADY))
(FUEL-FLOW NIL (UPPER-CAUTION) NIL NIL 259.0 (STEADY))
(FUEL-FLOW NIL (NORMAL) NIL NIL 293.0 (STEADY))
"The number of fuel-flow symptoms is        " 4
(EGT NIL (NORMAL) NIL NIL 235.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 240.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 241.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 242.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 245.0 (INCREASING))
(EGT NIL (NORMAL) NIL NIL 246.0 (INCREASING))
(EGT NIL (NORMAL) NIL NIL 247.0 (INCREASING))
(EGT NIL (NORMAL) NIL NIL 248.0 (INCREASING))
(EGT NIL (NORMAL) NIL NIL 264.0 (DECREASING))
(EGT NIL (NORMAL) NIL NIL 265.0 (DECREASING))
(EGT NIL (NORMAL) NIL NIL 272.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 273.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 296.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 301.0 (STEADY))
(EGT NIL (NORMAL) NIL NIL 302.0 (STEADY))
"The number of EGT symptoms is       " 15
(EPR NIL (NORMAL) NIL NIL 235.0 (STEADY))
(EPR NIL (NORMAL) NIL NIL 237.0 (INCREASING))
(EPR NIL (NORMAL) NIL NIL 298.0 (INCREASING))
"The number of EPR symptoms is       " 3
* (DRIBBLE)
```

Figure 3

From this analysis six categories of spurious symptoms were identified:

Model Deficiencies
Nearly Parallel Expectation and Actual Curves
Qualitative Boundary Discrepancies
Catch-up Increasing and Decreasing
Data Spikes and Holes
Sensor Failures

Each category is discussed and illustrated below.

2.2.1 Spurious Symptoms Resulting from Model Deficiencies.

When expectation data is generated by an engine model simulation, two types of deficiencies have been observed. First, there are model deficiencies which are regular in nature, and are therefore predictable. An example is shown in Figure 4. Fuel flow expectation values generated by the engine model have a deviation from the actual value which increases as the throttle is advanced. Low throttle settings produce low deviations such as found in the region of time slices between 200 and 230, and again at 270 to 290 (labelled Region A). When the throttle is advanced, the deviation from the actual value increases, such as found in time slices 245 to 260 and at 300 to 330 (labelled Region B). Actual and simulated curves can typically be distinguished in this and similar figures by virtue of the fact that actual data curves have more irregularities in them.

When a single value for acceptable deviation (or noise) was used, either valid symptoms were ignored when the noise values were set to the maximum value, or spurious symptoms were generated, when the noise values were set to the minimum value. In the previous study, an average value was chosen for noise. This reduced the number of spurious symptoms generated for low throttle settings, but also delayed identification for real symptoms at low throttle settings. The problem of spurious symptoms persisted for higher throttle settings. A solution derived in this study was to find a polynomial function to return an acceptable noise value for any throttle setting. Such a function was created and is included in Appendix D.
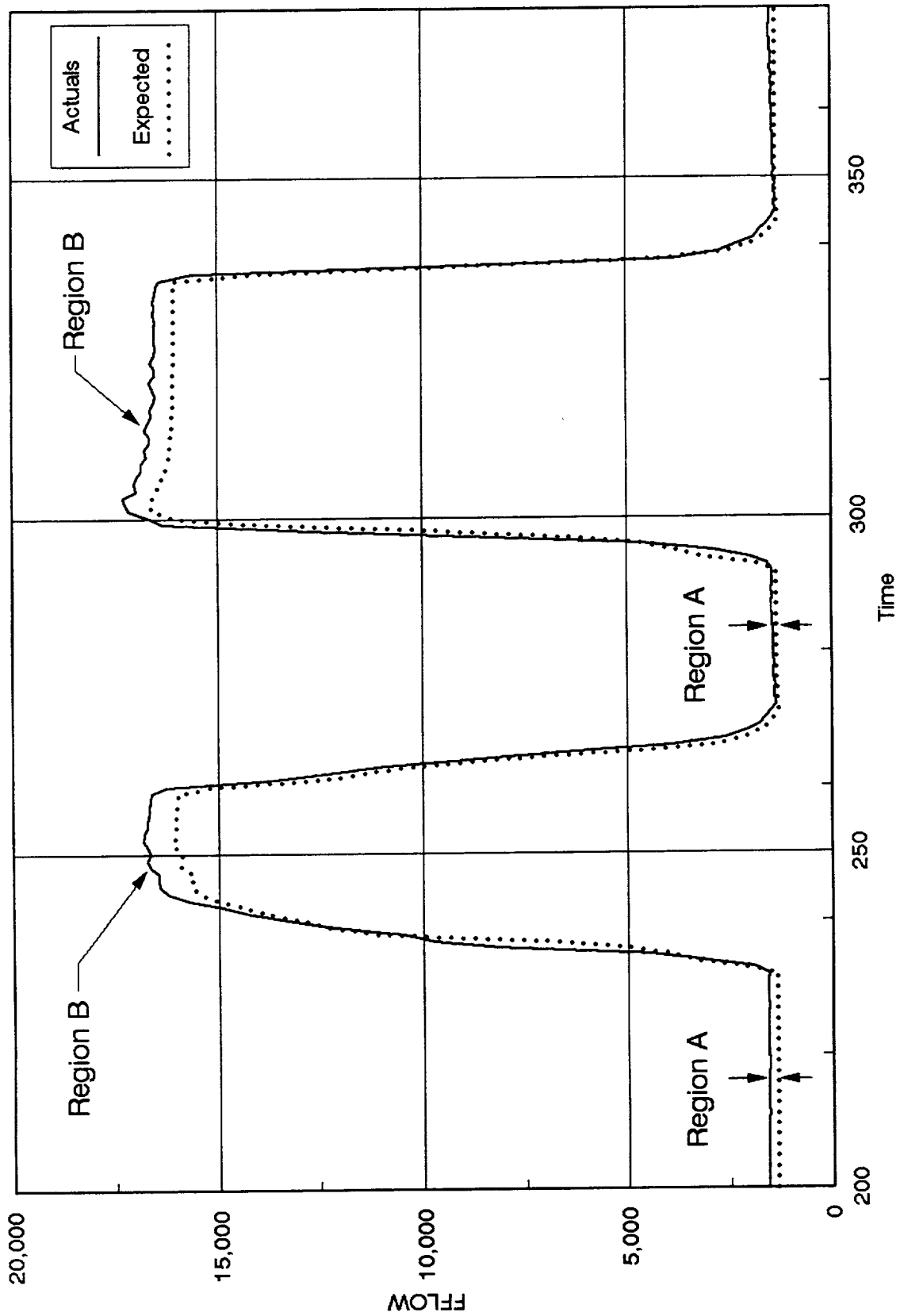
Figure 4. Model Deficiency - Predictable

The second type of model deficiency was the irregular variation such as that shown in Figure 5. EGT is more difficult to model than most other sensors. No observable pattern for deviation between expectation and actual has been determined. It was therefore necessary to eliminate this type of spurious symptom using other techniques for spurious symptom identification.
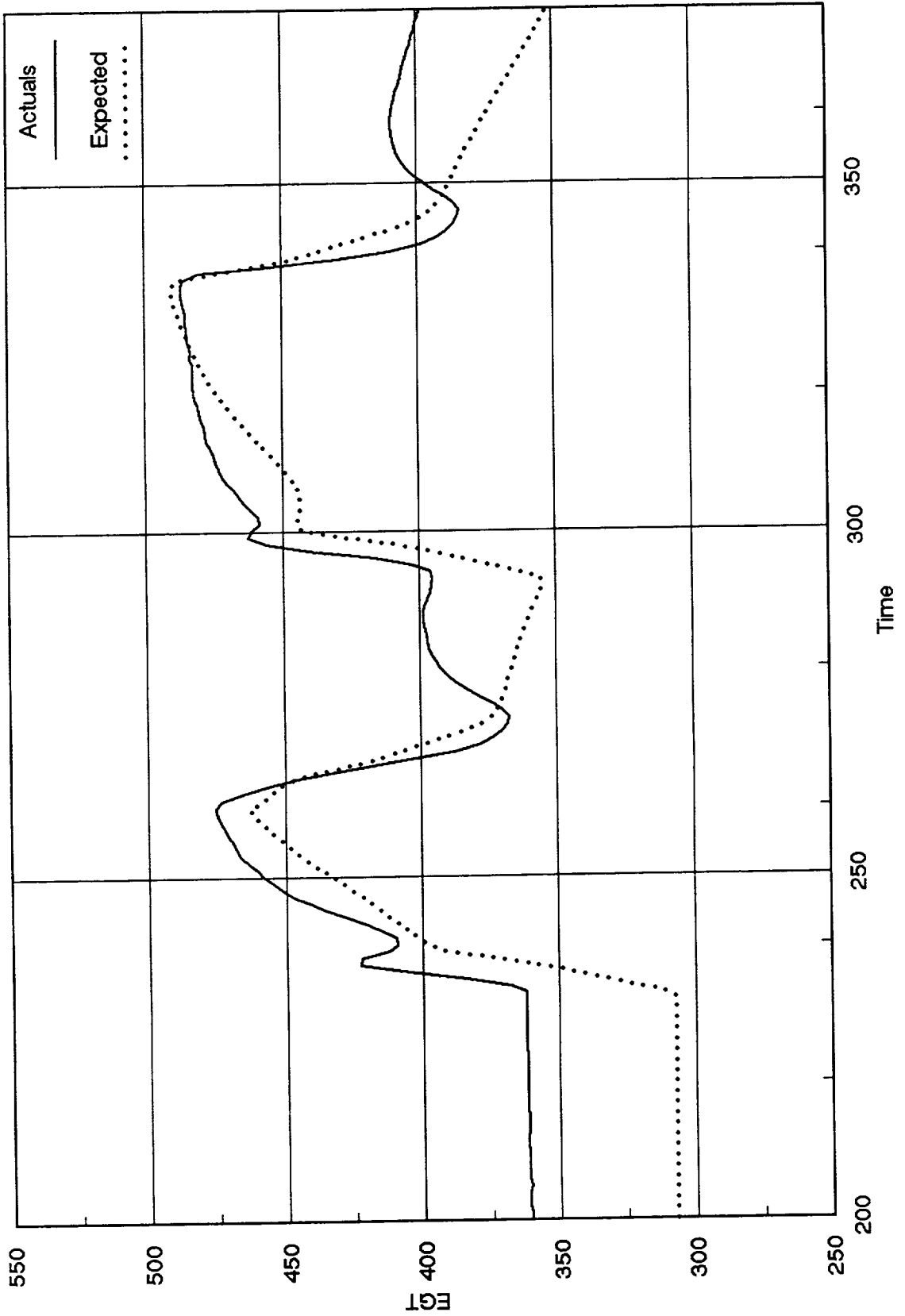
Figure 5. Model Deficiency - Random

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2.2.2 Spurious Symptoms Resulting from Nearly Parallel Expectation and Actual Curves

Because the expectation value generated by the engine model is close, but rarely identical to, the actual value, the time plots for these data are usually very nearly parallel giving large deviations in regions just prior to when the curves intersect. Most occurrences of this category are triggered with a throttle movement, and may be caused by a lag in the engine model. The region of the curves in which the slope is large, either positive or negative is most susceptible. An example of this condition is shown in Figure 6. Large deviations between expectation and actual values are produced at time slices 235 (Region A), 270 (Region B), 295 (Region C), and 345 (Region D). These large deviations will result in HIGHER THAN EXPECTED or LOWER THAN EXPECTED spurious symptoms, because, at the given time, the actual value is far above (or far below) the expectation value. Spurious symptoms produced by these conditions are of short duration, usually lasting only a few time slices.

2.2.3 Spurious Symptoms Resulting from Qualitative Boundary Discrepancies

The qualitative assessment for each sensor produced by MONITAUR requires qualitative boundary conditions be defined in Faultfinder's Physical System File. These qualitative descriptions are specific for a selected engine type. The collection of all qualitative descriptions for all sensors on an engine make that Physical System File unique for the selected engine type. Spurious symptoms can be generated when the actual and expectation values lie on the qualitative boundary with one value slightly above and the other slightly below the boundary. When this condition occurs, the value above the boundary is evaluated, or assessed higher than the value below the boundary. The fact that the actual and expectation values have different qualitative assessments suggests a potential symptom.
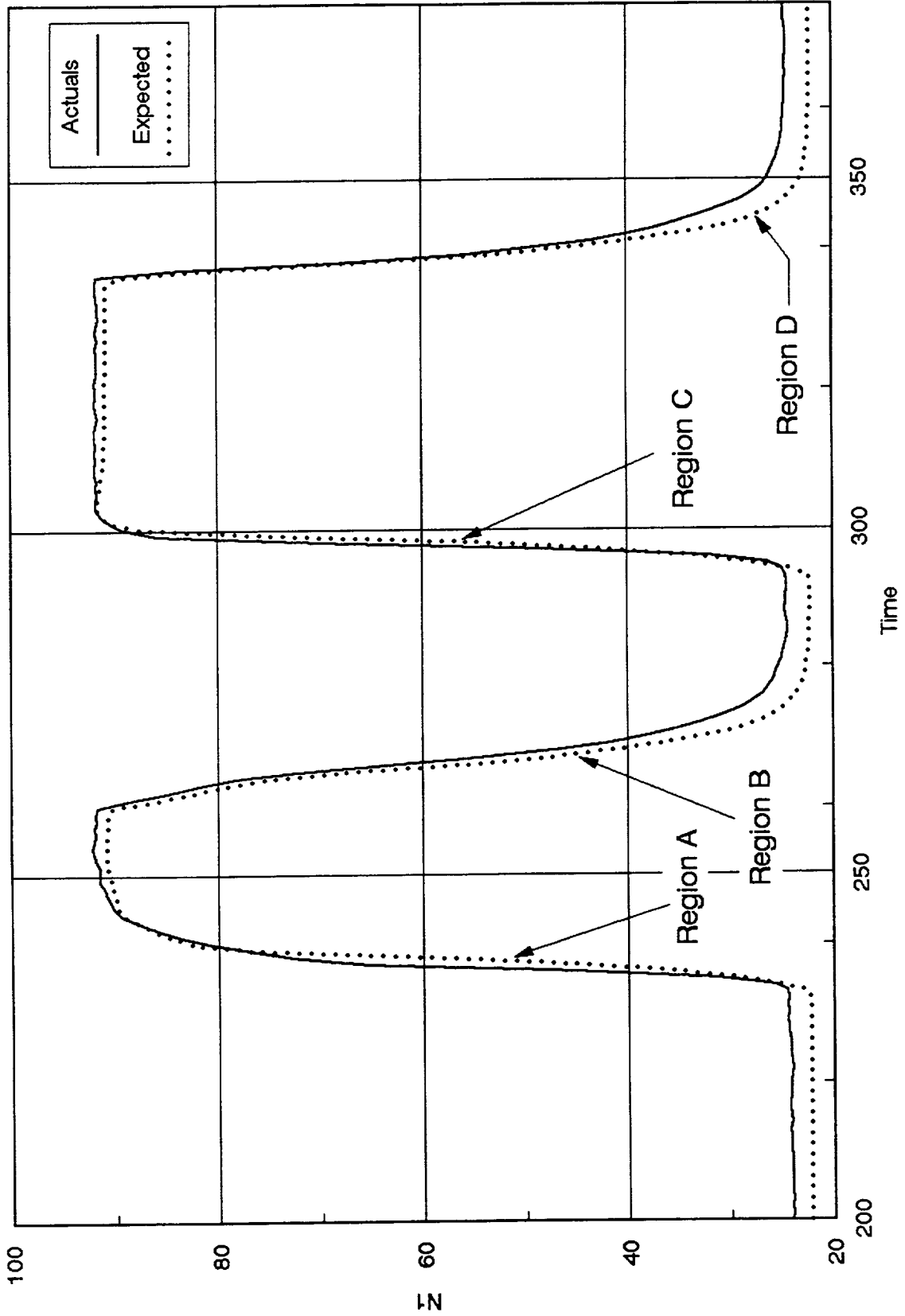
Figure 6. Nearly Parallel Curves

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An example of this condition is shown in Figure 7. The Physical System File classifies the normal N2 range with an upper boundary at 95 percent. Below 95 is assessed qualitatively as NORMAL and values of 95 to 100.1 are qualitatively assessed as UPPER CAUTION. Time slices between 300 and 305 (labelled Region A) show the condition in which the expectation value is assessed as UPPER CAUTION while the actual value is assessed as NORMAL. The fact that the real deviation between actual and expectation is lower than the acceptable noise range suggests there is no real symptom.

2.2.4 Spurious Symptoms Resulting from Catch-up Increasing and Decreasing

A condition similar (but not identical) to the nearly parallel category exists when either the expectation value or the actual value is lower than the other but is in the process of "catching up" within the next few time slices. This could be characterized by a qualitative assessment of LOWER THAN EXPECTED for the actual value and a trend assessed as NOT DECREASING AS FAST AS EXPECTED, or INCREASING FASTER THAN EXPECTED, or INCREASING ABNORMALLY. Another situation may be a HIGHER THAN EXPECTED actual value along with a trend assessment of NOT INCREASING AS FAST AS EXPECTED, or DECREASING FASTER THAN EXPECTED, or DECREASING ABNORMALLY.

An example of this condition is shown in Figure 8. There are two regions of catch-up for EPR, one at 235 (labelled Region A) and another at 345 (labelled Region B). The clearer example is at Region B. The expectation value us higher than the actual, but the slope of the actual is smaller than the expectation. Eventually the curves do intersect (at time slice 350), allowing the expectation and actual values to "catch up" with each other.
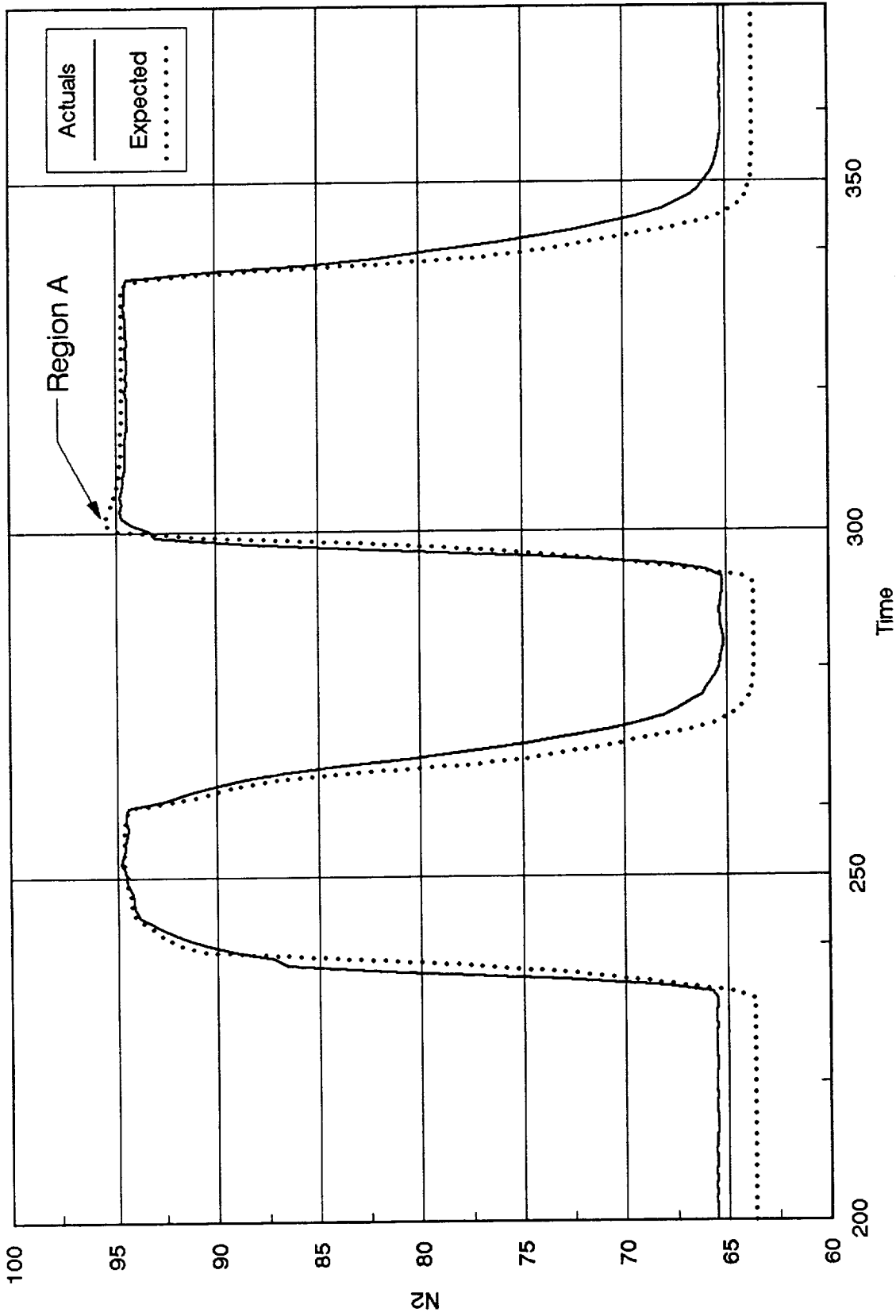
Figure 7. Qualitative Boundary
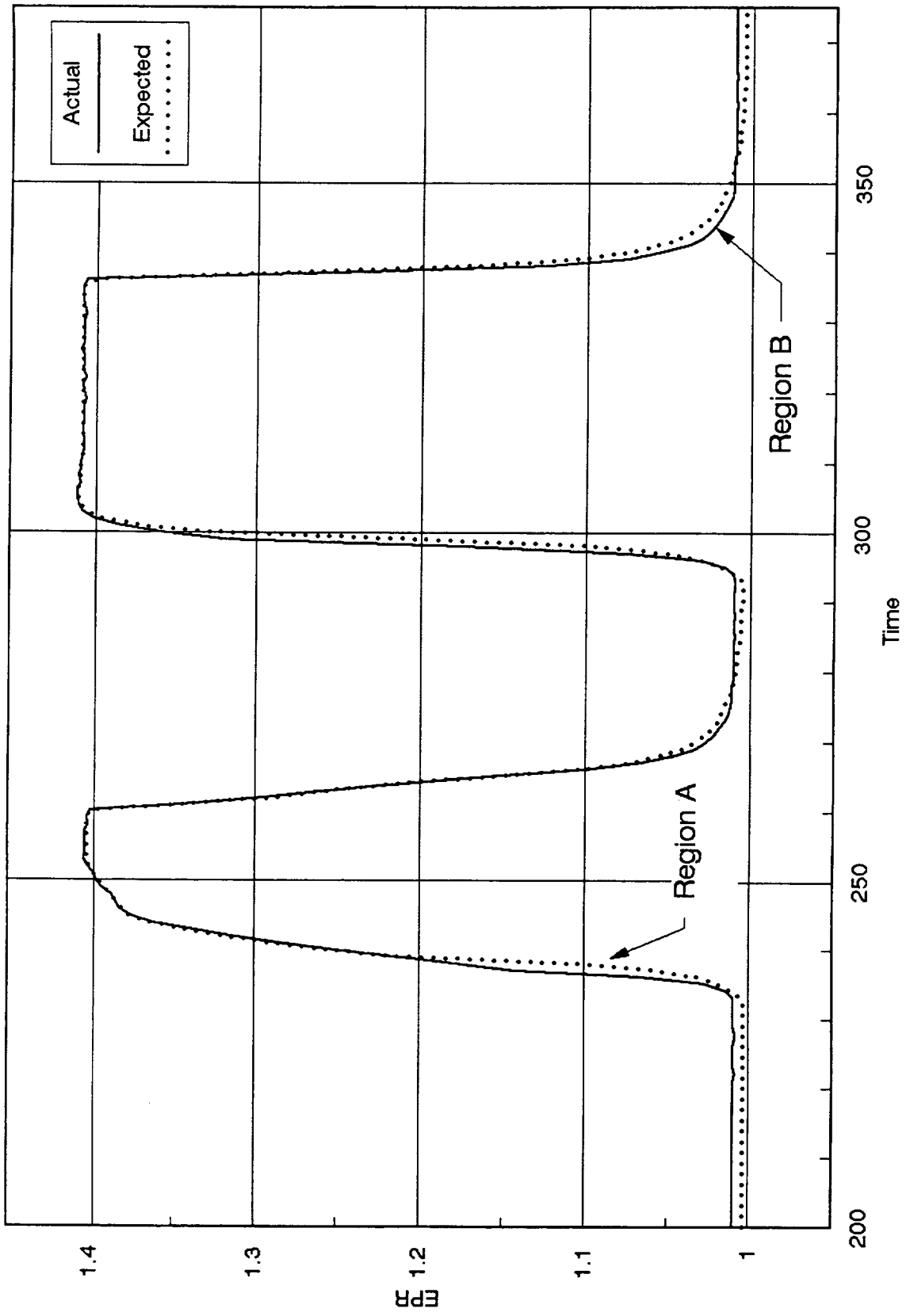
Figure 8. Catch - up

2.2.5 Spurious Symptoms Resulting from Data Spikes and Holes

Another type of spurious symptom results from a data spike or a hole in the data stream. These are manifested as short term (usually one time slice) variations in the data coming from a specific sensor, usually with large variation in absolute value. Data spikes are abnormalities in which a sensor produces an abnormally high reading for one or two time slices, then returns to reporting acceptable values. Data holes are short periods of time in which no signal is received from the sensor, followed by a series of normal readings.

An example of a data hole and a data spike is shown in Figure 9. There is a data spike at time slice 59 (labelled Region A) and a data hole at time slice 78 (labelled Region B) in the EGT data.

2.2.6 Spurious Symptoms Resulting from Sensor Failures

The last category of spurious symptoms is generated when the sensor fails. Diagnosis of sensor failure is a non-trivial problem which should be considered for a follow-on study. In this study we identified instances of sensor failure in which the sensor put out very large values and others in which the values simply became zero. Once the system has reached a condition in which the sensor is producing values which are obviously incorrect, steps can be taken to discount the readings. It is in the interim period, when values are not correct and yet not sufficiently poor, that detection is difficult. Several documented cases exist in which engine controllers took inappropriate actions as a result of this type of sensor failure. An attempt to assess sensor failure in a qualitative sense is included in the Physical System File for our known instances, but this is by no means a real solution to this category of spurious symptoms.

2.3 Create Rule Base to Filter Spurious Symptoms

This is the first of three approaches used to reduce the number of spurious symptoms generated from MONITAUR using healthy engine data. The strategy was to populate the rule base previously designed in MONITAUR (Ref 3) with rules which would classify the symptom as spurious. The feasibility of
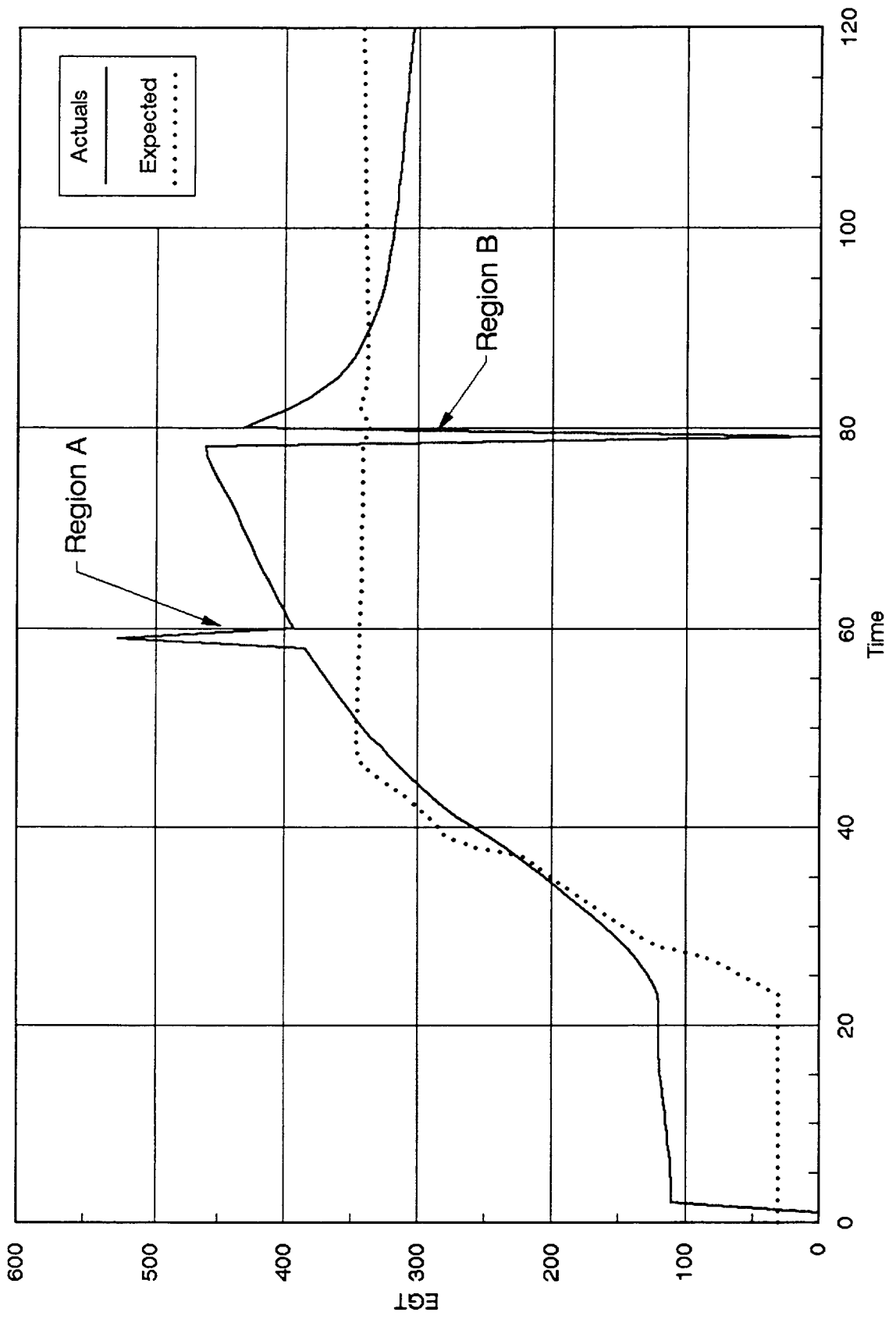
Figure 9. Data Spikes and Holes

this approach was demonstrated in the 1991 study (Ref 1), but the rules created for that study were only representative, and did not provide for all categories defined in the present study. A schematic which summarizes this approach is shown in Figure 10.

Analysis of the six categories of spurious symptoms indicated that only four of the six categories could be considered for rule base filtering. The two exceptions were addressed by 1) Modification of the noise levels for specific sensors from the engine model to reduce model discrepancies by substituting polynomial functions describing noise into the Physical System File replacing the static value for acceptable noise level, and 2) Adding qualitative assessment for sensor failure for known cases to the Physical System File. Rules were then generated for the other four categories.

The rules written were grouped according to specific sensor. This grouping was performed to allow analysis of which spurious symptoms were being filtered by which rules. Since the MONITAUR system already had a rule base design, the rules were grouped by rule number to designate filtering for a specific sensor. The rule base consists of 55 rules distributed as shown in Table 2.

Table 2. Rule Base Structure

Rule Number	Sensor	Total
100-199	Fuel Flow	12 rules
200-299	N1	14 rules
300-399	N2	13 rules
400-499	EPR	7 rules
500-599	EGT	9 rules
Total		55 rules

Analytical tools were developed to quantify filtering results. The text file output from MONITAUR (MONITAUR.TXT shown on Figure 2) was analyzed with a tool which recorded the rule number(s) fired during each time slice. Using output from this tool (shown in Figure 11) and the analytical output from the symptom analysis discussed in section 2.2, symptoms which disappeared from the symptom list could be cross-referenced by time slice
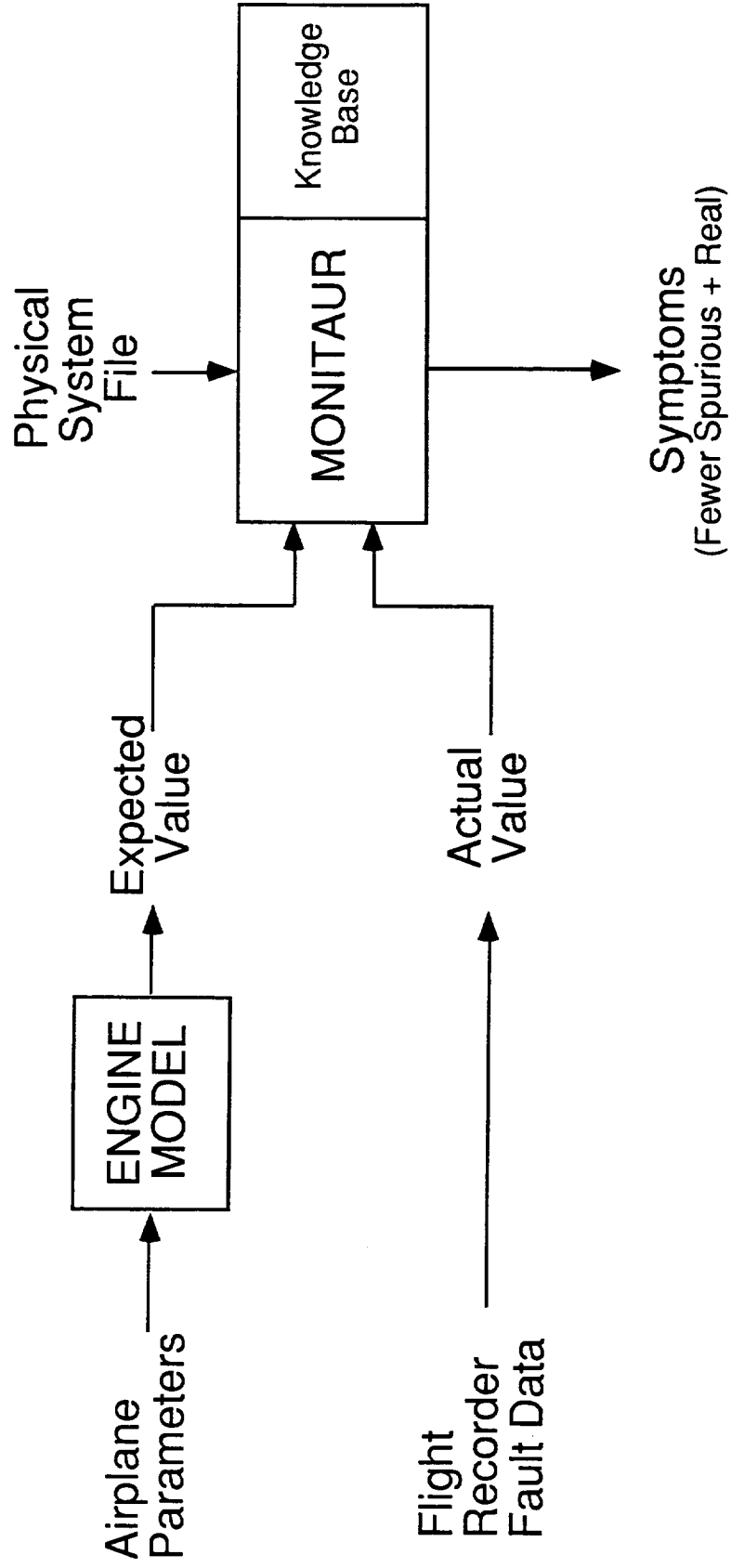
Figure 10. Fault Monitoring Using Knowlegde Base to Filter Spurious Symptoms

number to see which rule was responsible for filtering. For example, if an EPR symptom was present on the baseline data set, and was not present after the rule base was added, the conclusion could be made that some rule filtered the symptom. By finding the time slice number for the EPR symptom on the baseline analysis output and looking at that time slice on the rule analysis output, the specific rule number (between 400-499 for EPR rules) which filtered that symptom could be identified.

It should be noted that the contract does not call for any tool construction. The tools described in this report were created to facilitate the search for evidence of rule firing and spurious symptom elimination in rather large volumes of output data. It would no doubt be useful to extend the functionality of this minimal tool set to automate an analysis process which is still somewhat labor intensive. To cite one example, a tool could be designed to identify the categories of remaining spurious symptoms. However, such an extension of the basic analytic capabilities was beyond the scope of this investigation.

To minimize run time, an effort was made to keep the total number of rules small. Thus, if no instance of a specific category of symptom was discovered for a given sensor, no rule was generated. However, for purposes of generalizing, the rule base can be expanded to include all categories for all sensors. This should nearly double the number of current rules to about 100. To identify the symptom category, the rule name (provided for by MONITAUR) was coded with a phrase unique to that category. A sample rule is shown in Figure 12. It begins with a rule number (206 suggests an N1 rule). The rule name suggests it addresses the category of Catch-Up. The Antecedents follow in LISP clauses that are ANDED. The Consequent clauses show two types of N1 symptoms are being delayed - STATIC and TREND.

The complete rule base used to filter spurious symptoms is included in Appendix C. In addition to the rules added to MONITAUR from the Physical System File, additional functions were added to support these rules. Five functions were added to the MONITAUR code. Most of these are used in the premise of the rules which were added. A listing of the functions is found in Appendix D.

The following FUEL-FLOW Symptoms were removed

Rule Number	Time
101 106	in Time Slice 20.0:
101	in Time Slice 21.0:
101	n Time Slice 32.0:
101	in Time Slice 34.0:
107	in Time Slice 44.0:
107	in Time Slice 47.0:

The following N1 Symptoms were removed

Rule Number	Time
207	in Time Slice 34.0:
207	in Time Slice 35.0:
204	in Time Slice 37.0:
208	in Time Slice 42.0:
208	in Time Slice 46.0:
209	in Time Slice 79.0:
211	in Time Slice 87.0:

The following N2 Symptoms were removed

Rule Number	Time
306	in Time Slice 17.0:
300	in Time Slice 36.0:
302	in Time Slice 40.0:
303	in Time Slice 91.0:
303 305	in Time Slice 92.0:
305	in Time Slice 93.0:

The following EPR Symptoms were removed

Rule Number	Time
401 406	in Time Slice 15.0:
401	in Time Slice 16.0:
403	in Time Slice 17.0:
401	in Time Slice 20.0:
401	in Time Slice 21.0:
401	in Time Slice 22.0:
400	in Time Slice 25.0:
401	in Time Slice 36.0:
401 403	in Time Slice 37.0:
401 403	in Time Slice 38.0:
401 403 405	in Time Slice 39.0:

Figure 11

```
((RULE-NUMBER 206)
      (RULE-NAME "N1 Catch-up 4")

      (ANTECEDENT
            (
            (OR
            (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))
                  (MINUSP (- (RETRIEVE_DATA 'N1 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'N1 'EXPECTATIONS 'NEW-
STATIC)))
            )
            (OR
            (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N1 'DEVIATIONS 'QUALITATIVE-TREND))
                  (MEMBER 'INCREASING-ABNORMALLY (RETRIEVE_DATA
'N1 'DEVIATIONS 'QUALITATIVE-TREND))
            )

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'N1 'TREND)
            (SETQ RULE206_FIRED 'YES)
(print "                              rule 206 fired")

      ))
)
```

Figure 12

As the airplane sensor data is processed by MONITAUR, a set of symptoms are generated for each time slice. Before the symptoms are output from MONITAUR, the rule base is invoked to see if any symptoms are to be classified as spurious and need to be delayed. Then a filtering rule is fired, the message "Rule xxx fired" is output to the MONITAUR text file for rule use analysis. The effect of firing a symptom filtering rule is to delay for one time slice the output for the specific symptom.

When the representative baseline data set was processed with MONITAUR enhanced with the rule base filter, a reduction in spurious symptoms was achieved. A representative comparison of the results with the baseline by sensor is shown in Table 3.

Table 3. Reduction of Spurious Symptoms by Rules

	Rule Base	Baseline
Total number of spurious symptoms	35	256
No. of (115 possible) time slices w/o symptoms	87	0
Number of Fuel-Flow symptoms	4	97
Number of N1 symptoms	4	25
Number of N2 symptoms	9	31
Number of EPR symptoms	3	11
Number of EGT symptoms	15	92

Several other healthy engine files were processed through MONITAUR with the rule based filter. These additional files served to cross validate the rule base. Since the eight other healthy engine files were all from the same engine type, the generic rules should identify spurious symptoms in these data as well. The rule base achieved at least 70% reduction of spurious symptoms in the worst case tested.

The final question addressed in the rule base study pertains to potential for delaying enunciation of real symptoms. Since healthy engine data should contain no real symptoms, two files of engine data containing known fault conditions were processed using the filtering rule base. Analysis of the data revealed that a few real symptoms were filtered and delayed, but not missed, by the spurious symptom filtering process. However, the resulting delay was only for the initial few time slices as the fault developed. The net effect of using

only for the initial few time slices as the fault developed. The net effect of using the spurious symptom rule base filter was to delay identification of known fault symptoms no more than two seconds. This would appear to be a small price to pay for elimination of a significant portion of the spurious symptoms.

2.4 Create Adaptive Filter to Enhance Generic Engine Model Data

A second approach to reducing the number of spurious symptoms in healthy engine data is to create an adaptive filter whose purpose is to produce better expectation values. The strategy employed in this approach was the use of a back-propagation neural net to capture patterns of healthy engine behavior and generate an expected value for a given sensor within a given time slice matched to the current air and engine data. The architecture for this approach is a separate neural net for each engine sensor. A modification to MONITAUR substituted calls to these neural nets for expectation value generation replacing calls to the engine model.

An in-depth discussion of back-propagation neural nets is beyond the scope of this report, but the topic is covered well in other references (Ref 4,5). The development of this approach is actually a two step process (shown in Figure 13), consisting of a training cycle and a production cycle. The data patterns for healthy engine behavior are captured during the training cycle. The training is performed off-line and is very time consuming. The data used for training must be from the same serial number engine as the production data set. In this study, four of the nine data sets were from the same serial number engine. These four data sets were used for training and for the testing of the production cycle. Care was taken to train the neural net with data not used in testing. The output from the training cycle is a weight set which is used by the production net to evaluate each time slice. The production run is a one-time pass through the net, which is executed very quickly when called by MONITAUR.
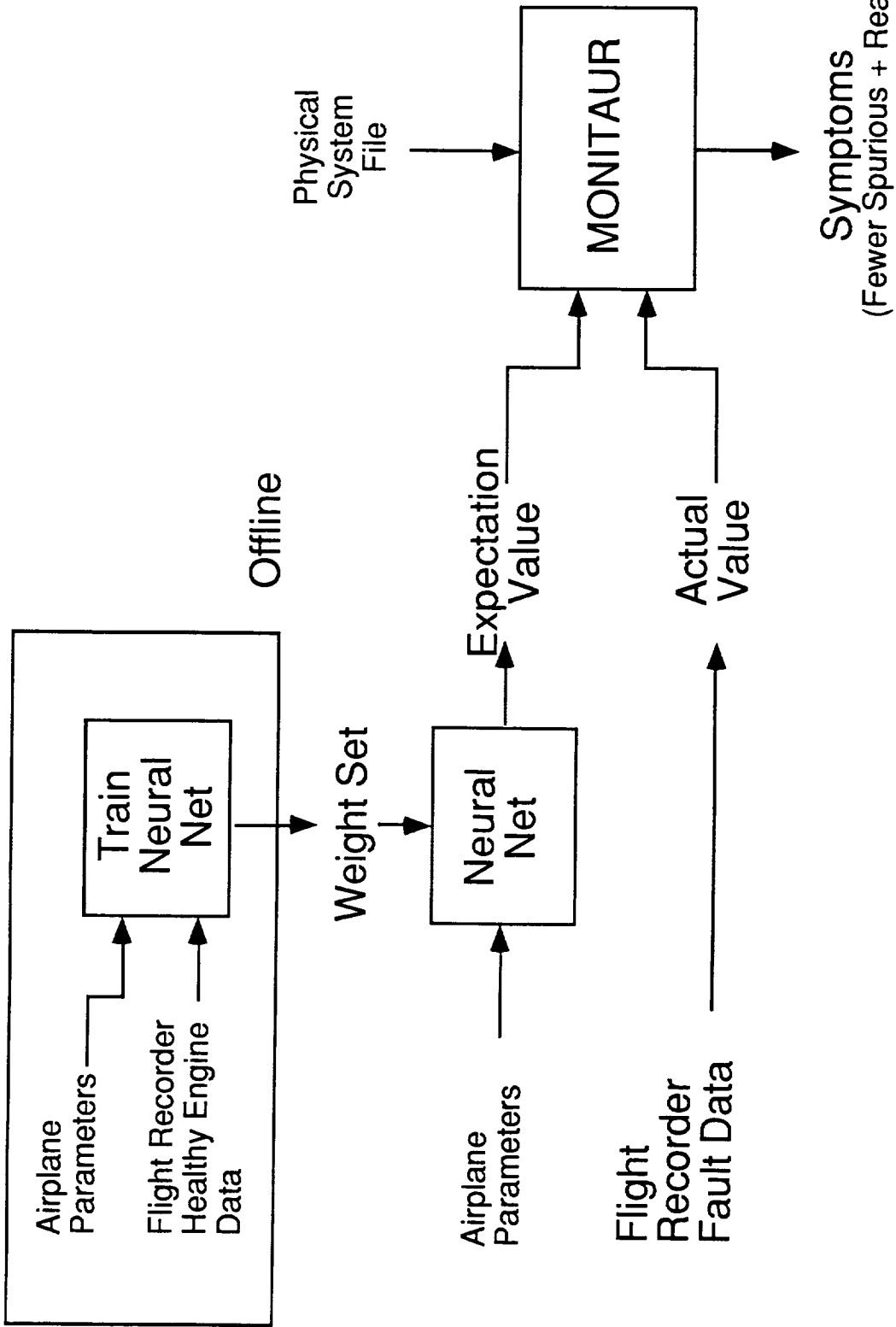
Figure 13. Fault Monitoring Using Neural Net to Enhance Expection Value

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The back-propagation neural net used in this project has a 5-10-5-1 architecture with five inputs, two hidden layers of ten and five neurons each, and one output value. Inputs considered in this study were throttle angle, air speed, altitude, and engine parameters N1, N2, EGT, EPR, and Fuel Flow. Since some of the healthy engine data was taken from engines on aircraft on the ground, air speed and altitude were eliminated, but would be important for in-flight operation. Prior to training the neural net, all input data was preprocessed to normalize sensor values. A series of preprocessing tools were constructed to compute mean, variation, minimum, maximum and normalized data for each sensor's data set. These normalized data were used in the training cycle. Several other configurations of back-propagation neural net were investigated, but results were not optimal.

When the training is completed, the modified MONITAUR system is used to process the baseline data set. It is important to repeat that all the training sets and the baseline data must be generated from the same serial number engine. It is this engine's unique behavior, not a generic engine's behavior that has been captured in the weight set during training. The results of processing the baseline test set of healthy engine data with expectation values generated by the neural net instead of the engine model is shown in Table 4.

Table 4. Reduction of Spurious Symptoms by Neural Net

	Neural Net	Baseline
Total number of spurious symptoms	96	256
No. of (115 possible) time slices w/o symptoms	42	0
Number of Fuel-Flow symptoms	51	97
Number of N1 symptoms	2	25
Number of N2 symptoms	8	31
Number of EPR symptoms	2	11
Number of EGT symptoms	33	92

Four healthy engine files from the same serial number engine were processed through MONITAUR with the neural net filter to cross validate the effect of the neural net. The neural net achieved at least a 40% reduction of spurious symptoms in the worst case. It should be noted that while a considerable reduction in spurious symptoms was achieved using the neural net, there were several instances in which the neural net did not perform as well as the

engine model in predicting expectation value. In those instances spurious symptoms were generated by the neural net where none had been generated by the engine model. It is hypothesized that this condition was the result of incomplete training of the neural net and not necessarily a failure of the adaptive filter concept.

2.5 Examine the Potential for Spurious Symptom Reduction with a Hybrid System

The third and final approach to reducing the number of spurious symptoms was to combine the rule base and the neural net to create a hybrid system. While this approach was not required in the original statement of work, it appeared to show promise when the results of the neural net study was completed. An analysis of spurious symptoms remaining after applying the neural net as a "front end" to the MONITAUR module revealed characteristics that were similar to the symptom categories previously identified. This led to the hypothesis that the rule base might offer additional filtering as a "back end" to the process. The hybrid approach was then attempted. A schematic for this configuration is shown in Figure 14. Using the hybrid, the neural net replaced the engine model as a source of expectation values. This served to reduce the number of spurious symptoms by generating better expectation values. Those spurious symptoms still generated were then better filtered by the rule base. The ability to better filter the surviving spurious symptoms results from generation of better expectation values which makes the expectation curve more nearly parallel to the actual curve. The rules in the "nearly-parallel" category are then more readily fired. The results of processing the baseline test set of healthy engine data with this hybrid system is shown in Table 5.
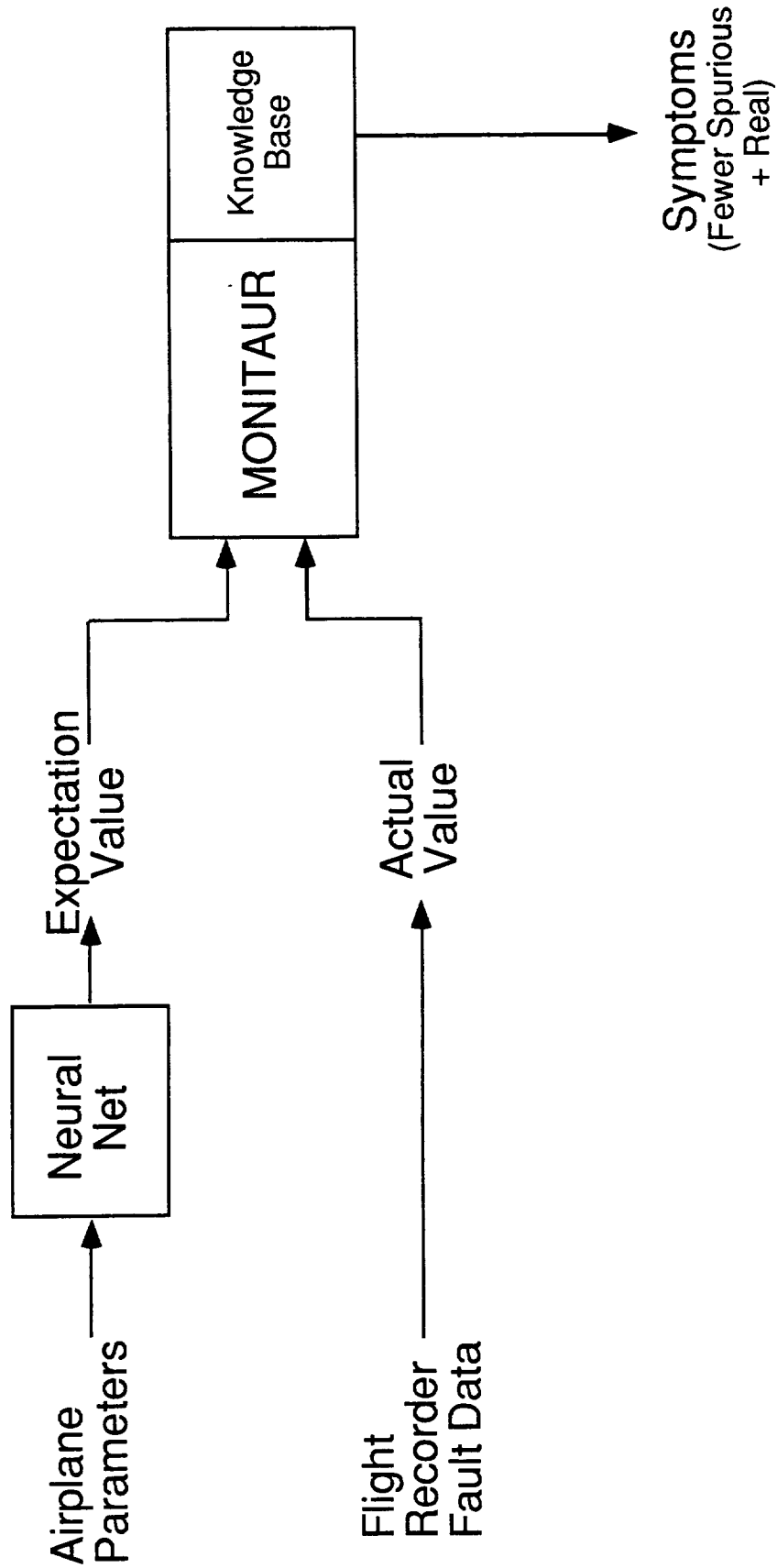
Figure 14. Fault Monitoring Using Hybrid System

Table 5. Reduction of Spurious Symptoms by the Hybrid System

	Hybrid System	Baseline
Total number of spurious symptoms	23	256
No. of (115 possible) time slices w/o symptoms	96	0
Number of Fuel-Flow symptoms	4	97
Number of N1 symptoms	0	25
Number of N2 symptoms	5	31
Number of EPR symptoms	0	11
Number of EGT symptoms	14	92

Only the four healthy engine files with identical serial number engines were processed through MONITAUR with the hybrid system filter for cross validation. The hybrid system achieved at least a 90% reduction of spurious symptoms in the worst case.

2.6 Determine Relative Improvement with Adaptive Filter and Rule Base

In summarizing the results of attempts to reduce spurious symptoms, it should be noted that the percentages cited represent the worst case runs in the cross validation process. A 40% reduction in spurious symptoms was achieved with the neural net alone. A 70% reduction was achieved with the rule base filter alone. The hybrid system of both neural net and rule base produced a 90% reduction in spurious symptoms for healthy engine data. The matrix of spurious symptom reduction by sensor and technique is shown in Table 6.

<u>Table 6. Comparison of Approaches</u>

	Basln	RulBas	Nrl Net	Hybrd Syst
Total No. spurious symptoms	256	35	96	23
No. time slices w/o symptoms	0	87	42	96
No. of Fuel-Flow symptoms	97	4	51	4
Number of N1 symptoms	25	4	2	0
Number of N2 symptoms	31	9	8	5
Number of EPR symptoms	11	3	2	0
Number of EGT symptoms	92	15	33	14
Percent Reduction	--	70	40	90

3.0 CONCLUSIONS AND RECOMMENDATIONS

This evaluation of strategies to reduce spurious symptoms should be discussed with the limitations of each approach in mind. First, there is no methodology which can be used for all high bypass engines. This is to say that both approaches considered in this study are engine type dependent. The rule base constructed works for a specific manufacturer on a specific engine type (e.g. a GE CF6, but not a CFM56 or a P&W 4000, but not a 2000). However the rule base filter is more generic than the neural net. The neural net must be trained for a specific serial number engine.

An issue not addressed in this study is the behavior of a neural net with an engine in a fault condition. No data containing known faults were available for the serial number engine used in this study. Until data for a serial number engine for both healthy and fault behavior are found, it remains a hypothesis that the neural net will not interfere with real symptom detection.

It is obvious that a reduction in spurious symptoms can be made with either approach. The question remains, can <u>enough</u> spurious symptoms be eliminated? The answer is not obvious. If we are looking for a technique that can be applied across a specific type of engine, without regard to individual (serial number) engine differences, the 70% reduction in spurious symptoms seems feasible. Can an in-flight fault monitoring system deal with the 30% remaining spurious symptoms? This question remains to be answered. It should be noted that spurious symptoms are <u>not</u> identical to false alarms. The fault monitoring module might be designed to ignore patterns of spurious

fault monitoring module might be designed to ignore patterns of spurious symptoms which survive the monitoring filter. Such a system then would not produce false alarms. Our goal was to reduce the number of spurious symptoms to as few as possible so as to effectively reduce the number of false alarms potentially annunciated.

On the other hand, if the fault monitoring technique is to be applied to engines at the serial number level by making use of the neural net, several related issues must be addressed. First, a suitable data collection and training procedure must be created. Obtaining multiple data files for the same serial number engine in varying operating environments is essential for continued research and almost certainly requires cooperation by the airlines. Second, procedures must be defined for retraining the neural net as the engine ages, or possibly even when the engine gets too dirty. These implementation concerns should be addressed in parallel with performance research. Results of the present study suggest that the neural net hybrid offers a potential increase to 90% reduction of spurious symptoms. The 10% spurious symptoms remaining may still result in too many false alarms, an issue which still requires more research. It can be concluded from this study that the hybrid system offers better potential for accurate in-flight fault monitoring than either the rule base or neural net approaches by themselves.

There are several options for continued research. Of the six categories of spurious symptom sources, sensor failure is the area in greatest need for further study. The current investigation suggests a rule base alone is not the paradigm of choice for additional research. A constrained model based filter could be designed using an enhanced version of Faultfinder's Stage 2 of DRAPhyS. The purpose of this filter would be to eliminate spurious symptoms resulting from failed sensors. This model based filter could be called immediately following the use of the rule base filter, before spurious symptoms related to sensor failure are output from MONITAUR.

Other related areas in need of additional research include determining a threshold number of tolerable spurious symptoms. It has already been stated that spurious symptoms are not equivalent to false alarms. On a flight deck with well managed information, the crew should not be required to interpret

symptoms, spurious or real. Those who are close to the problem of nuisance alarms on the flight deck will no doubt say "no false alarms". Determining how many and what kind of spurious symptoms can be tolerated without producing false alarms is worthy of additional research.

4.0 REFERENCE LIST

1.   "Flight Deck Engine Advisor Final Report", Shontz, W.D., Records, R.M., Antonelli, D.R., NASA Contractor Report 189562, NASA Langley Research Center. February 1992

2.   "Faultfinder: A Diagnostic Expert System with Graceful Degradation for Onboard Aircraft Applications", Abbot, K.H., Schutte, P.C., Palmer, M.T., Ricks, W.R., Paper presented at 14th International Symposium on Aircraft Integrated Monitoring Systems, Friedrichshafen, FRG, September 1987.

3.   "Real Time Fault Monitoring for Aircraft Applications Using Quantitative Simulation and Expert Systems", Schutte, P.C., Paper presented at AIAA Computers in Aerospace VII Conference, Monterey, CA, October 1989.

4.   "An Introduction to Computing with Neural Nets,", R. Lippmann, IEEE ASSP Magazine, pp.4-22, 1987.

5.   "Learning Representations by Error Propagation", D.E. Rumelhart, G.E. Hinton, and R.J. Williams, in Parallel Distributed Processing: Explorations in the Microstructure of Cognition, D.E. Rumelhart and J.L. McClelland, eds., MIT Press, Cambridge, Mass., 1986.

5.0 Appendix A

Statement of Work

Spurious Symptom Reduction in Fault Monitoring
Statement of Work

Problem:

Work completed in 1991 on monitoring engine health in Faultfinder suggests a high level of spurious symptoms are generated when real engine sensor data is compared to expectation values derived from a generic engine model. These spurious symptoms create a high probability of false alarm generation in the diagnostic phase of Faultfinder.

Preliminary Analysis:

Individual (serial number) engines may vary in behavior as much as 30%. If acceptable sensor deviation levels between expectation value and actual value are set this high, recognition of valid symptoms is delayed or totally inhibited. Setting deviation values lower than 30% introduces spurious symptoms.

Goal:

Determine methods for reducing spurious symptom generation for monitoring engine health in Faultfinder.

Approach:

Two approaches will be investigated.

1. Analysis and identification of generic conditions which result in spurious symptom generation will be performed. Rules will be added to MONITAUR's rule to filter spurious symptom reporting.

2. Create an improved expectation value from the engine model by constructing an adaptive filter which is engine specific. This will allow a lower deviation level, resulting in fewer spurious symptoms for a given sensor.

Deliverables:

A final report which includes:
*   Description of project activities
*   The amount of spurious symptom reduction achieved with each method.
*   A set of rules added to MONITAUR from approach #1.
*   Description of adaptive filtering techniques utilized from approach #2.
*   Results and recommendations.

Spurious Symptom Reduction in Fault Monitoring
List of Tasks

Task 1 Establish Baseline Value for Spurious Symptom Generation.

Using healthy engine sensor data, determine the level of spurious symptom generation using MONITAUR without filtering rules.

Task 2 Identify Sources of Spurious Symptoms.

Analysis of sensor output from healthy engine data compared with sensor output from a generic engine model will yield generic conditions resulting in spurious symptoms.

Task 3 Create Rule Base to Filter Spurious Symptoms.

From sources of spurious symptoms identified in Task 2 a set of filtering rules shall be created tested and documented. These rules will be added to MONITAUR's rule base.

Task 4 Create an Adaptive Filter for Specific (serial number) Engine to Enhance Generic Engine Model Data.

Design, condition and test an adaptive filter to model specific healthy engine behavior. Apply this filter to a generic engine model to generate enhanced expectation values.

Task 5 Determine Relative Improvement with Adaptive Filter and Rule Base.

Apply the adaptive filter and the rule base to a new set of healthy engine data to compare frequency of spurious symptom generation.

Task 6 Generate Final Report.

6.0 Appendix B

Data Flow Diagrams and Data Dictionary

Engine Monitor

Actual Engine
Sensor Data

Engine Model
Sensor Data

Sensor
Symptoms
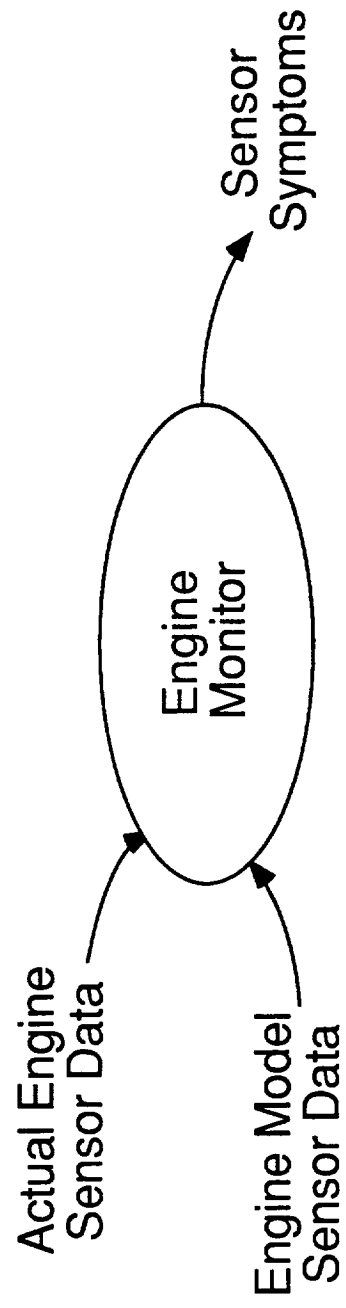
**Context Diagram
Old System**

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Make Qualitative
Assessment
Actuals
1

Actual Engine
Sensor Data

Actual

Compare
Actuals &
Expectations
3

Sensor
Symptoms

Expectations

Make Qualitative
Assessment
Expectations
2

Engine Model
Sensor Data
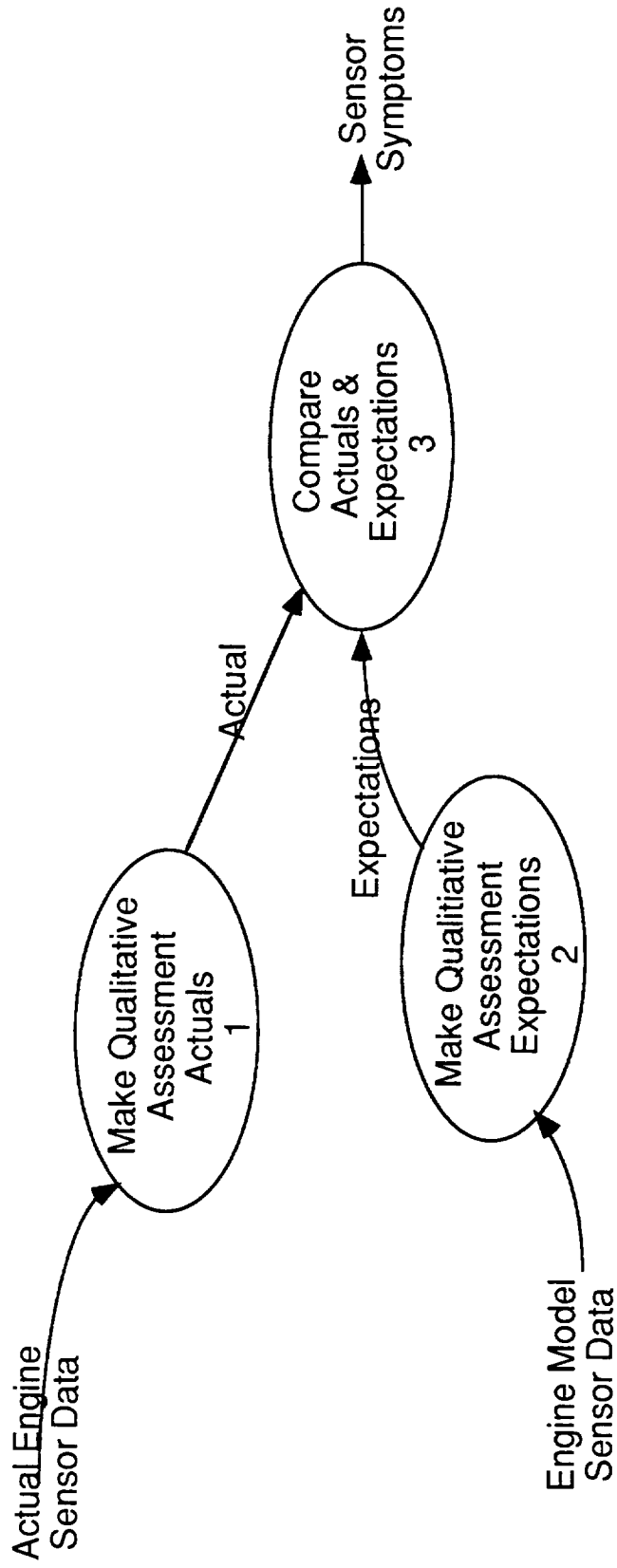
Level O
Engine Monitor
Old System

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Symptom Filtering Rule-Base

Actual Engine Sensor Data

Monitor Engine Performance

Engine Model Sensor Data

Non-Spurious Sensor Symptoms
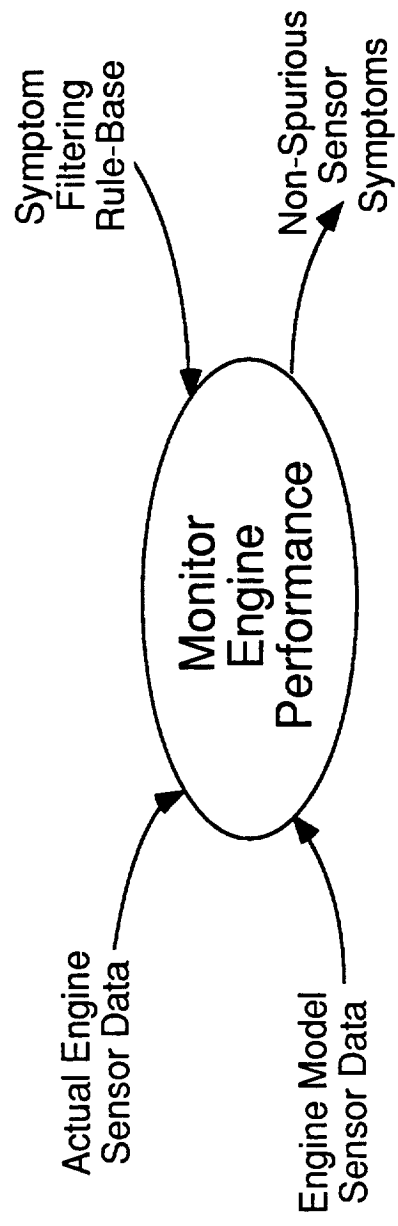
Context Diagram Enhanced System
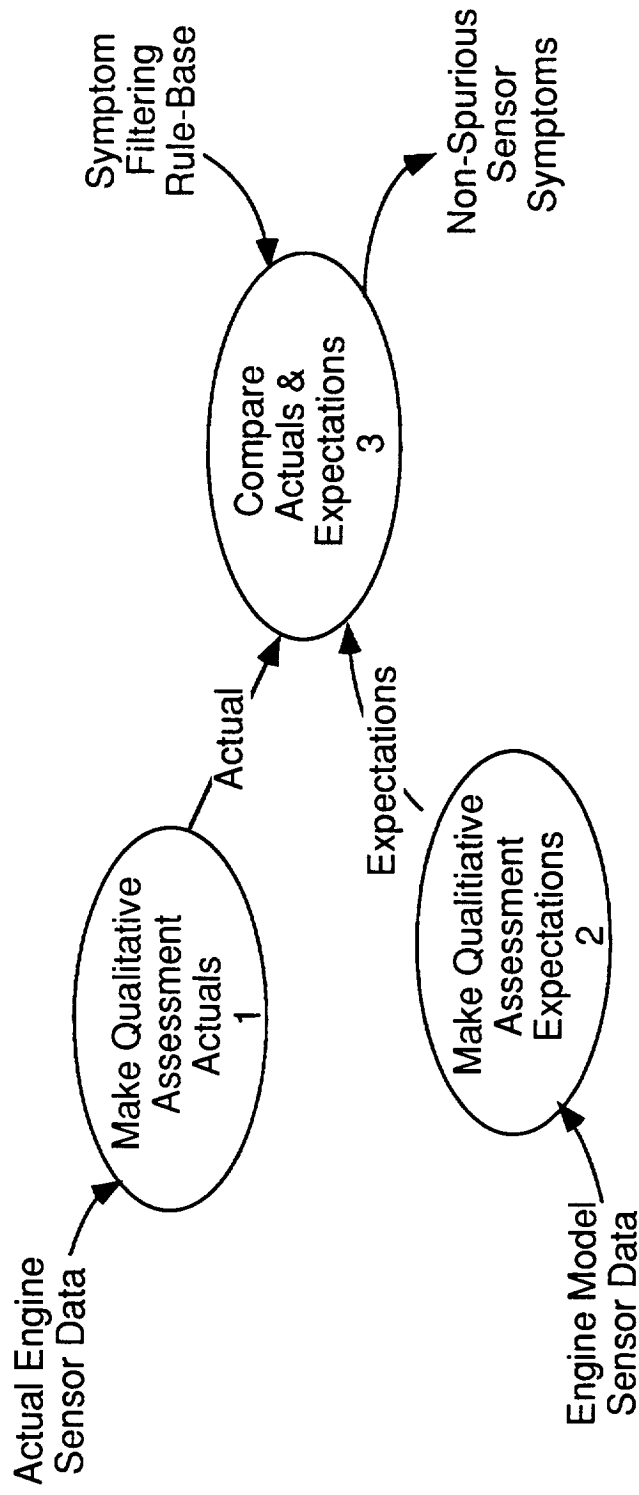
Level 0
Monitor Engine Performance
Enhanced System

Data Dictionary

Reducing Spurious Symptoms in Engine Monitoring

Context Diagram:

Actual Engine Sensor Data. Data obtained from in-flight recording of engine sensor output. Input for MONITAUR in a file called DATAFIL.DAT. Contains the following:

> Time stamp (in seconds)
> N1 (in percent)
> N2 (in percent)
> EGT (in degrees C)
> EPR (no dimension)
> Fuel_Flow (in pounds per hour)
> Altitude (in feet)
> Mach (no dimension)
> Throttle (in percent)
> Oil-Pressure (in PSI)
> Oil-Temperature (in degrees C)

Engine Model Sensor Data. Data generated by Boeing Propulsion's engine model for identical throttle settings to the actual. Used as expected value in the monitoring process. Contains the same information as described in Actual Engine Sensor Data. May also contain vibration data, but this data is not used in this study. This data is input to MONITAUR in a data file called MODEL.FIL.

Sensor Symptoms. Two files of symptoms are output from MONITAUR. STG1INP.LSP is a complete set of sensor states for each time slice and is input to Stage 1 of DRAPhyS (the rule-based module). This file is not used in this study. STG2INP.LSP is a set of abnormal symptoms identified by MONITAUR in one of three categories:

Static Value Symptoms -   generated when deviations between actual value
                          and expected is greater than a pre-defined limit.

Derivative Symptoms -   generated when deviations between actual
                          derivative and expected is greater than a pre-
                          defined limit.

Trend Symptoms   -   generated when deviations between actual trend
                          and expected is greater than a pre-defined limit.

Symptom Filtering Rule Base. A set of if-then rules located in the Physical System File. The rules are sensor specific, that is, there is a set for N1 and another set for Fuel-Flow, etc. The consequence of each rule is to inhibit the generation of a symptom in the STG2INP.LSP file. These rules are designed to filter spurious symptoms.

Monitor Engine Performance. A process which consists of comparing the actual sensor value generated in real time by the sensor with the expected sensor value generated in real time by the engine model. When the actual and expected values vary by more than a pre-defined limit, a symptom for that sensor is generated. This process is currently coded in MONITAUR.

Level 0 Diagram:

Make Qualitative Assessment Actuals. Quantitative data for actual sensor readings are assessed by sensor in three categories - static values, derivatives, and trends. Assessment criteria are coded in the Physical Systems File, (ENGINE.LSP). The resulting assessments are stored in data structures, not in an external file. These assessment slots are used in determining abnormal behavior for the sensor by comparison with expected values in process #3.

Make Qualitative Assessment Expectations. Quantitative data for expected sensor values are assessed by sensor in three categories - static values, derivatives, and trends. Assessment criteria are coded in the Physical Systems File, (ENGINE.LSP). The resulting assessments are stored in data structures, not in an external file. These assessment slots are used in determining abnormal behavior for the sensor by comparison with actual values in process #3.

Compare Actuals & Expectations. Both quantitative and qualitative data are compared for actual and expected values in three categories - static values, derivatives, and trends. Deviations are calculated and compared with pre-defined limits (coded in the Physical System File). If the quantitative limits are exceeded, or if the qualitative assessments do not match, a symptom is generated. There is a possibility of multiple symptoms for any sensor in each time slice. (For example, N1 could exhibit both static and trend symptoms.) Each symptom is filtered by the appropriate rules in the rule base. If the conditions in the antecedent portion of the rule are evaluated TRUE, the rule fires and the symptom is suppressed as spurious.

Non-Spurious Sensor Symptoms. File of symptoms generated and stored in STG2INP.LSP. Since these symptoms have been filtered by the rule base, they are actual symptoms not spurious.

Types of symptoms possible are:

Static Symptoms:

HIGHER-THAN-EXPECTED - generated when actual quantitative static value exceed expected quantitative static limit.

LOWER-THAN-EXPECTED - generated when expected quantitative static value exceed actual quantitative static limit.

Derivative Symptoms:

DECREASING-FASTER-THAN-EXPECTED - generated when the expected qualitative derivative value exceeds expected qualitative derivative (e.g. one is DECREASING the other is STEADY).

INCREASING-FASTER-THAN-EXPECTED - generated when actual qualitative derivative value exceed expected qualitative derivative (e.g. one is INCREASING the other is STEADY).

NOT-DECREASING-AS-FAST-AS-EXPECTED generated when expected qualitative derivative value exceed actual qualitative derivative (e.g. one is DECREASING while the other is STEADY).

NOT-INCREASING-AS-FAST-AS-EXPECTED - generated when expected qualitative derivative value exceed actual qualitative derivative (e.g. one is INCREASING while the other is STEADY).

DECREASING ABNORMALLY - generated when the qualitative assessment for actual and the expected derivative are opposite (e.g. actual is DECREASING and expected is INCREASING).

INCREASING ABNORMALLY - generated when the qualitative assessment for actual and the expected derivativeare opposite (e.g. actual is INCREASING and expected is DECREASING).

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Trend Symptoms:

DECREASING-FASTER-THAN-EXPECTED - generated when expected qualitative trend value exceeds expected qualitative trend (e.g. one is DECREASING the other is STEADY).

INCREASING-FASTER-THAN-EXPECTED - generated when actual qualitative trend value exceed expected qualitative trend (e.g. one is INCREASING the other is STEADY).

NOT-DECREASING-AS-FAST-AS-EXPECTED or expected qualitative trend value exceed actual qualitative trend (e.g. one is DECREASING while the other is STEADY).

NOT-INCREASING-AS-FAST-AS-EXPECTED - generated when expected qualitative trend value exceed actual qualitative trend (e.g. one is INCREASING while the other is STEADY).

DECREASING ABNORMALLY - generated when the qualitative assessment for actual and the expected trend are opposite (e.g. actual is DECREASING and expected is INCREASING).

INCREASING ABNORMALLY - generated when the qualitative assessment for actual and the expected trend are opposite (e.g. actual is INCREASING and expected is DECREASING).

Expectations. The results of performing qualitative assessment on the expected values is a set of expectation slots filled with both quantitative and qualitative data. The data, originally generated by the engine model, will be used in comparison with actual sensor data to identify sensor symptoms.

Actuals. The results of performing qualitative assessment on the actual sensor values is a set of actual slots filled with both quantitative and qualitative data. The data, originally collected from engine sensors, will be used in comparison with expected sensor data to identify sensor symptoms.

7.0 Appendix C

Physical System File

```
((RULES   ((INTERFACE) (RECOVERY) (STAGE2) (STAGE1)    (MONITAUR

(


      ((RULE-NUMBER 101)
            (RULE-NAME "FUEL-FLOW Derivative Delete")
            (ANTECEDENT
                  (
                  (OR
                        (NOT (NULL (RETRIEVE_DATA 'FUEL-FLOW
'DEVIATIONS 'QUALITATIVE-DERIVATIVE) ))
                        (NOT (EQUAL (RETRIEVE_DATA 'FUEL-FLOW
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE) (RETRIEVE_DATA 'FUEL-FLOW
'ACTUALS 'QUALITATIVE-DERIVATIVE)))
                        )
                  )
                  )
            (CONSEQUENT         (
            (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'DERIVATIVE)
            (SETQ RULE101_FIRED 'YES)
(print "                                            rule 101
fired")
            ))
)

((RULE-NUMBER 102)
      (RULE-NAME "Fuel-Flow Upper Caution Boundary")

      (ANTECEDENT
            (
            (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'FUEL-FLOW
'ACTUALS 'QUALITATIVE-STATIC))
            (MEMBER 'NORMAL (RETRIEVE_DATA 'FUEL-FLOW
'EXPECTATIONS 'QUALITATIVE-STATIC))
            (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA
'FUEL-FLOW 'DEVIATIONS 'QUALITATIVE-STATIC)))
            (MEMBER 'INCREASING (RETRIEVE_DATA 'FUEL-FLOW
'EXPECTATIONS 'QUALITATIVE-TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
            (SETQ RULE102_FIRED 'YES)
(print "                                            rule 102
fired")
      ))
)

      ((RULE-NUMBER 103)
            (RULE-NAME "FUEL-FLOW nearly parallel")
```

```
          (ANTECEDENT        (
          (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'FUEL-
FLOW 'DEVIATIONS 'QUALITATIVE-STATIC))
          (IS_NEARLY_PARALLEL_P1 'FUEL-FLOW)
          )
          )
          (CONSEQUENT        (
          (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
          (SETQ RULE103_FIRED 'YES)
(print "                                              rule 103
fired")
          ))
)


     ((RULE-NUMBER 104)
          (RULE-NAME "FUEL-FLOW nearly parallel")
          (ANTECEDENT        (
          (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'FUEL-FLOW
'DEVIATIONS 'QUALITATIVE-STATIC))
          (IS_NEARLY_PARALLEL_P2 'FUEL-FLOW)
          )
          )
          (CONSEQUENT        (
          (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
          (SETQ RULE104_FIRED 'YES)
(print "                                              rule 104
fired")
          ))
)



((RULE-NUMBER 105)
     (RULE-NAME "FUEL-FLOW Catch-up 1")

     (ANTECEDENT
          (
          (OR
          (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'FUEL-
FLOW 'DEVIATIONS 'QUALITATIVE-STATIC))
          (PLUSP (- (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'NEW-
STATIC)
                    (RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS
'NEW-STATIC)))
          )
          (OR
          (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
          )

     ))

     (CONSEQUENT
          (
          (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
```

```
                    (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'DERIVATIVE)
                    (SETQ RULE105_FIRED 'YES)
(print "                                                    rule 105
fired")


        ))
)
((RULE-NUMBER 106)
      (RULE-NAME "FUEL-FLOW Catch-up 2")

        (ANTECEDENT
                (
                (OR
                (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'FUEL-FLOW
'DEVIATIONS 'QUALITATIVE-STATIC))
                        (MINUSP (- (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'NEW-
STATIC)
                                (RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS
'NEW-STATIC)))
                )
                (OR
                (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
                )

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
                (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'DERIVATIVE)
                (SETQ RULE106_FIRED 'YES)
(print "                                                    rule 106
fired")


        ))
)


((RULE-NUMBER 107)
      (RULE-NAME "FUEL-FLOW Catch-up 3")

        (ANTECEDENT
                (
                (OR
                (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'FUEL-
FLOW 'DEVIATIONS 'QUALITATIVE-STATIC))
                        (PLUSP (- (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'NEW-
STATIC)
                                (RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS
'NEW-STATIC)))
                )
                (OR
```

```
              (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS 'QUALITATIVE-TREND))
              (MEMBER 'DECREASING-ABNORMALLY (RETRIEVE_DATA 'FUEL-
FLOW 'DEVIATIONS 'QUALITATIVE-TREND))
              )

     ))

     (CONSEQUENT
          (
          (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
          (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'TREND)
          (SETQ RULE107_FIRED 'YES)
(print "                                             rule 107
fired")

     ))
)

((RULE-NUMBER 108)
     (RULE-NAME "FUEL-FLOW Catch-up 4")

     (ANTECEDENT
          (
          (OR
          (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'FUEL-FLOW
'DEVIATIONS 'QUALITATIVE-STATIC))
          (MINUSP (- (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'NEW-
STATIC)
                     (RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS
'NEW-STATIC)))
          )
          (OR
          (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS 'QUALITATIVE-TREND))
              (MEMBER 'INCREASING-ABNORMALLY (RETRIEVE_DATA 'FUEL-
FLOW 'DEVIATIONS 'QUALITATIVE-TREND))
          )

     ))

     (CONSEQUENT
          (
          (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
          (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'TREND)
          (SETQ RULE108_FIRED 'YES)
(print "                                             rule 108
fired")

     ))
)


     ((RULE-NUMBER 109)
```

```
                    (RULE-NAME "FUEL-FLOW Spikes and Holes")
                    (ANTECEDENT
                            (
                            (CHECK_SPIKE 'FUEL-FLOW)
                            )

                    )
                    (CONSEQUENT        (
                    (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'DERIVATIVE)
                    (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'TREND)
                    (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'STATIC)
                    (SETQ RULE109_FIRED 'YES)
(print "                                              rule 109
fired")
                    ))
)

((RULE-NUMBER 110)
      (RULE-NAME "Fuel-Flow Trend Boundary")

      (ANTECEDENT
            (
            (MEMBER 'NOT-INCREASING-AS-FAST-AS-EXPECTED
(RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS 'QUALITATIVE-TREND))
            (< -30.00 (RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS
'TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'TREND)
            (SETQ RULE110_FIRED 'YES)
(print "                                              rule 110
fired")
      ))
)

((RULE-NUMBER 111)
      (RULE-NAME "Fuel-Flow Trend Boundary")

      (ANTECEDENT
            (
            (MEMBER 'INCREASING-ABNORMALLY (RETRIEVE_DATA 'FUEL-
FLOW 'DEVIATIONS 'QUALITATIVE-TREND))
            (> 30.00 (RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS
'TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'TREND)
            (SETQ RULE111_FIRED 'YES)
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(print "                                              rule 111
fired")
      ))
)

((RULE-NUMBER 112)
      (RULE-NAME "Fuel-Flow Trend Boundary")

      (ANTECEDENT
            (
            (MEMBER 'NOT-DECREASING-AS-FAST-AS-EXPECTED
(RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS 'QUALITATIVE-TREND))
            (> 30.00 (RETRIEVE_DATA 'FUEL-FLOW 'DEVIATIONS
'TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'FUEL-FLOW 'TREND)
            (SETQ RULE112_FIRED 'YES)
(print "                                              rule 112
fired")
      ))
)


((RULE-NUMBER 200)
      (RULE-NAME "N1 Upper Caution Boundary")

      (ANTECEDENT
            (
            (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-STATIC))
            (MEMBER 'NORMAL (RETRIEVE_DATA 'N1 'EXPECTATIONS
'QUALITATIVE-STATIC))
            (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC)))
            (MEMBER 'INCREASING (RETRIEVE_DATA 'N1 'EXPECTATIONS
'QUALITATIVE-TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
            (SETQ RULE200_FIRED 'YES)
(print "                                              rule 200
fired")

      ))
)

      ((RULE-NUMBER 201)
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                    (RULE-NAME "N1 nearly parallel")
                    (ANTECEDENT        (
                    (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))
                    (IS_NEARLY_PARALLEL_P2 'N1)
                    )
                    )
                    (CONSEQUENT        (
                    (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                    (SETQ RULE201_FIRED 'YES)
(print "                                           rule 201
fired")
                    ))
)


        ((RULE-NUMBER 202)
                    (RULE-NAME "N1 nearly parallel")
                    (ANTECEDENT        (
                    (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))
                    (IS_NEARLY_PARALLEL_P1 'N1)
                    )
                    )
                    (CONSEQUENT        (
                    (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                    (SETQ RULE202_FIRED 'YES)
(print "                                           rule 202
fired")
                    ))
)

((RULE-NUMBER 203)
        (RULE-NAME "N1 Catch-up 1")

        (ANTECEDENT
                (
                (OR
                (PLUSP (- (RETRIEVE_DATA 'N1 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'N1 'EXPECTATIONS 'NEW-
STATIC)))
                (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))
                )
                (OR
                (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N1 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
                )

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
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                    (DELAY-STAGE2-SYMPTOM 'N1 'DERIVATIVE)
                    (SETQ RULE203_FIRED 'YES)
(print "                                              rule 203
fired")

          ))
)
((RULE-NUMBER 204)
     (RULE-NAME "N1 Catch-up 2")

     (ANTECEDENT
            (
            (OR
            (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))
                    (MINUSP (- (RETRIEVE_DATA 'N1 'ACTUALS 'NEW-STATIC)
                         (RETRIEVE_DATA 'N1 'EXPECTATIONS 'NEW-
STATIC)))
            )
            (OR
            (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N1 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
            )

      ))

     (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'N1 'DERIVATIVE)
            (SETQ RULE204_FIRED 'YES)
(print "                                              rule 204
fired")

          ))
)

((RULE-NUMBER 205)
     (RULE-NAME "N1 Catch-up 3")

     (ANTECEDENT
            (
            (OR
            (PLUSP (- (RETRIEVE_DATA 'N1 'ACTUALS 'NEW-STATIC)
                    (RETRIEVE_DATA 'N1 'EXPECTATIONS 'NEW-
STATIC)))
            (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))
            )
            (OR
            (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N1 'DEVIATIONS 'QUALITATIVE-TREND))
            (MEMBER 'DECREASING-ABNORMALLY (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-TREND))
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                )

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                (DELAY-STAGE2-SYMPTOM 'N1 'TREND)
                (SETQ RULE205_FIRED 'YES)
(print "                                                    rule 205
fired")

        ))
)

((RULE-NUMBER 206)
        (RULE-NAME "N1 Catch-up 4")

        (ANTECEDENT
                (
                (OR
                (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))
                (MINUSP (- (RETRIEVE_DATA 'N1 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'N1 'EXPECTATIONS 'NEW-
STATIC)))
                )
                (OR
                (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N1 'DEVIATIONS 'QUALITATIVE-TREND))
                (MEMBER 'INCREASING-ABNORMALLY (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-TREND))
                )

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                (DELAY-STAGE2-SYMPTOM 'N1 'TREND)
                (SETQ RULE206_FIRED 'YES)
(print "                                                    rule 206
fired")

        ))
)

((RULE-NUMBER 207)
        (RULE-NAME "N1 Upper Caution Boundary 2")

        (ANTECEDENT
                (
                (MEMBER 'NORMAL (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-STATIC))
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                (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-STATIC))
                (NOT (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC)))
                (MEMBER 'INCREASING (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-TREND))

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                (SETQ RULE207_FIRED 'YES)
(print "                                          rule 207
fired")

        ))
)

((RULE-NUMBER 208)
        (RULE-NAME "N1 Upper Warning Boundary ")

        (ANTECEDENT
                (
                (MEMBER 'UPPER-WARNING (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-STATIC))
                (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-STATIC))
                (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC)))

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                (SETQ RULE208_FIRED 'YES)
(print "                                          rule 208
fired")

        ))
)

((RULE-NUMBER 209)
        (RULE-NAME "N1 Upper Caution Boundary 3")

        (ANTECEDENT
                (
                (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-STATIC))
                (MEMBER 'NORMAL (RETRIEVE_DATA 'N1 'EXPECTATIONS
'QUALITATIVE-STATIC))
                (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC)))
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                (MEMBER 'DECREASING (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-TREND))

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                (SETQ RULE209_FIRED 'YES)
(print "                                        rule 209
fired")

        ))
)

((RULE-NUMBER 210)
        (RULE-NAME "N1 Lower Caution Boundary ")

        (ANTECEDENT
                (
                (MEMBER 'NORMAL (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-STATIC))
                (MEMBER 'LOWER-CAUTION (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-STATIC))
                (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC)))
                (MEMBER 'DECREASING (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-TREND))

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                (SETQ RULE210_FIRED 'YES)
(print "                                        rule 210
fired")

        ))
)

((RULE-NUMBER 211)
        (RULE-NAME "N1 Lower Caution Boundary 2")

        (ANTECEDENT
                (
                (MEMBER 'LOWER-CAUTION (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-STATIC))
                (MEMBER 'NORMAL (RETRIEVE_DATA 'N1 'EXPECTATIONS
'QUALITATIVE-STATIC))
                (NOT (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC)))
                (MEMBER 'DECREASING (RETRIEVE_DATA 'N1 'EXPECTATIONS
'QUALITATIVE-TREND))
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      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
            (SETQ RULE211_FIRED 'YES)
(print "                                              rule 211
fired")

      ))
)

((RULE-NUMBER 212)
      (RULE-NAME "N1 Catch-up 5")

      (ANTECEDENT
            (
            (OR
            (MEMBER 'DECREASING (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-TREND))
            (MEMBER 'DECREASING (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-DERIVATIVE))
            )

            (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N1
'DEVIATIONS 'QUALITATIVE-STATIC))

            (OR
            (NOT (MEMBER 'NOT-DECREASING-AS-FAST-AS-EXPECTED
(RETRIEVE_DATA 'N1 'DEVIATIONS 'QUALITATIVE-DERIVATIVE)))
            (NOT (MEMBER 'NOT-DECREASING-AS-FAST-AS-EXPECTED
(RETRIEVE_DATA 'N1 'DEVIATIONS 'QUALITATIVE-TREND)))
            )

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
            (SETQ RULE212_FIRED 'YES)
(print "                                              rule 212
fired")

      ))
)

      ((RULE-NUMBER 213)
            (RULE-NAME "N1 Spikes and Holes")
            (ANTECEDENT
                  (
                  (CHECK_SPIKE 'N1)
                  )
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                       )
                       (CONSEQUENT          (
                       (DELAY-STAGE2-SYMPTOM 'N1 'DERIVATIVE)
                       (DELAY-STAGE2-SYMPTOM 'N1 'TREND)
                       (DELAY-STAGE2-SYMPTOM 'N1 'STATIC)
                       (SETQ RULE213_FIRED 'YES)
(print "                                              rule 213
fired")
                       ))
)




((RULE-NUMBER 300)
      (RULE-NAME "N2 Upper Caution Boundary")

      (ANTECEDENT
            (
            (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-STATIC))
            (MEMBER 'NORMAL (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-STATIC))
            (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC)))
            (MEMBER 'INCREASING (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (SETQ RULE300_FIRED 'YES)
(print "                                              rule 300
fired")

      ))
)

      ((RULE-NUMBER 301)
            (RULE-NAME "N2 nearly parallel")
            (ANTECEDENT          (
            (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC))
            (IS_NEARLY_PARALLEL_P2 'N2)
            )
            )
            (CONSEQUENT          (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (SETQ RULE301_FIRED 'YES)
(print "                                              rule 301
fired")
```

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                    ))
)


        ((RULE-NUMBER 302)
              (RULE-NAME "N2 nearly parallel")
              (ANTECEDENT        (
              (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC))
              (IS_NEARLY_PARALLEL_P1 'N2)
              )
              )
              (CONSEQUENT        (
              (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
              (SETQ RULE302_FIRED 'YES)
(print "                                              rule 302
fired")
              ))
)

((RULE-NUMBER 303)
      (RULE-NAME "N2 Catch-up 1")

      (ANTECEDENT
              (
              (OR
              (PLUSP (- (RETRIEVE_DATA 'N2 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'N2 'EXPECTATIONS 'NEW-
STATIC)))
              (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC))
              )
              (OR
              (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N2 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
              )

      ))

      (CONSEQUENT
              (
              (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
              (DELAY-STAGE2-SYMPTOM 'N2 'DERIVATIVE)
              (SETQ RULE303_FIRED 'YES)
(print "                                              rule 303
fired")

      ))
)
((RULE-NUMBER 304)
      (RULE-NAME "N2 Catch-up 2")

      (ANTECEDENT
              (
```

```
                (OR
                (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC))
                    (MINUSP (- (RETRIEVE_DATA 'N2 'ACTUALS 'NEW-STATIC)
                            (RETRIEVE_DATA 'N2 'EXPECTATIONS 'NEW-
STATIC)))
                )
                (OR
                (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N2 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
                )

        ))

        (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'N2 'DERIVATIVE)
            (SETQ RULE304_FIRED 'YES)
(print "                                              rule 304
fired")

        ))
)


((RULE-NUMBER 305)
        (RULE-NAME "N2 Catch-up 3")

        (ANTECEDENT
            (
            (OR
            (PLUSP (- (RETRIEVE_DATA 'N2 'ACTUALS 'NEW-STATIC)
                    (RETRIEVE_DATA 'N2 'EXPECTATIONS 'NEW-
STATIC)))
            (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC))
            )
            (OR
            (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N2 'DEVIATIONS 'QUALITATIVE-TREND))
                (MEMBER 'DECREASING-ABNORMALLY (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-TREND))
            )

        ))

        (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'N2 'TREND)
            (SETQ RULE305_FIRED 'YES)
(print "                                              rule 305
fired")
```

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        ))
)

((RULE-NUMBER 306)
     (RULE-NAME "N2 Catch-up 4")

     (ANTECEDENT
          (
          (OR
          (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC))
              (MINUSP (- (RETRIEVE_DATA 'N2 'ACTUALS 'NEW-STATIC)
                         (RETRIEVE_DATA 'N2 'EXPECTATIONS 'NEW-
STATIC)))
          )
          (OR
          (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'N2 'DEVIATIONS 'QUALITATIVE-TREND))
              (MEMBER 'INCREASING-ABNORMALLY (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-TREND))
          )

      ))

     (CONSEQUENT
          (
          (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
          (DELAY-STAGE2-SYMPTOM 'N2 'TREND)
          (SETQ RULE306_FIRED 'YES)
(print "                                              rule 306
fired")

      ))
)

((RULE-NUMBER 307)
     (RULE-NAME "N2 Upper Caution Boundary 2")

     (ANTECEDENT
          (
          (MEMBER 'NORMAL (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-STATIC))
              (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-STATIC))
              (NOT (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC)))
              (MEMBER 'INCREASING (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-TREND))

      ))

     (CONSEQUENT
          (
          (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
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                    (SETQ RULE307_FIRED 'YES)
(print "                                                    rule 307
fired")

        ))
)


((RULE-NUMBER 308)
      (RULE-NAME "N2 Upper Warning Boundary ")

      (ANTECEDENT
            (
            (MEMBER 'UPPER-WARNING (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-STATIC))
            (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-STATIC))
            (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC)))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (SETQ RULE308_FIRED 'YES)
(print "                                                    rule 308
fired")

        ))
)

((RULE-NUMBER 309)
      (RULE-NAME "N2 Upper Caution Boundary 3")

      (ANTECEDENT
            (
            (MEMBER 'UPPER-CAUTION (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-STATIC))
            (MEMBER 'NORMAL (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-STATIC))
            (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC)))
            (MEMBER 'DECREASING (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (SETQ RULE309_FIRED 'YES)
(print "                                                    rule 309
fired")
```

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        ))
)

((RULE-NUMBER 310)
      (RULE-NAME "N2 Lower Caution Boundary ")

      (ANTECEDENT
            (
            (MEMBER 'NORMAL (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-STATIC))
            (MEMBER 'LOWER-CAUTION (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-STATIC))
            (NOT (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC)))
            (MEMBER 'DECREASING (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (SETQ RULE310_FIRED 'YES)
(print "                                              rule 310
fired")

      ))
)

((RULE-NUMBER 311)
      (RULE-NAME "N2 Lower Caution Boundary 2")

      (ANTECEDENT
            (
            (MEMBER 'LOWER-CAUTION (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-STATIC))
            (MEMBER 'NORMAL (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-STATIC))
            (NOT (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'N2
'DEVIATIONS 'QUALITATIVE-STATIC)))
            (MEMBER 'DECREASING (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-TREND))

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
            (SETQ RULE311_FIRED 'YES)
(print "                                              rule 311
fired")

      ))
)
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((RULE-NUMBER 312)
      (RULE-NAME "N2 Spikes and Holes")
      (ANTECEDENT
            (
            (CHECK_SPIKE 'N2)
            )

      )
      (CONSEQUENT        (
      (DELAY-STAGE2-SYMPTOM 'N2 'DERIVATIVE)
      (DELAY-STAGE2-SYMPTOM 'N2 'TREND)
      (DELAY-STAGE2-SYMPTOM 'N2 'STATIC)
      (SETQ RULE312_FIRED 'YES)
(print "                                                  rule 312
fired")
      ))
)



((RULE-NUMBER 400)
      (RULE-NAME "EPR nearly parallel")
      (ANTECEDENT        (
      (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-STATIC))
      (IS_NEARLY_PARALLEL_P1 'EPR)
      )
      )
      (CONSEQUENT        (
      (DELAY-STAGE2-SYMPTOM 'EPR 'STATIC)
      (SETQ RULE400_FIRED 'YES)
(print "                                                  rule 400
fired")
      ))
)

((RULE-NUMBER 401)
      (RULE-NAME "EPR nearly parallel")
      (ANTECEDENT        (
      (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-STATIC))
      (IS_NEARLY_PARALLEL_P2 'EPR)
      )
      )
      (CONSEQUENT        (
      (DELAY-STAGE2-SYMPTOM 'EPR 'STATIC)
      (SETQ RULE401_FIRED 'YES)
(print "                                                  rule 401
fired")
      ))
)
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((RULE-NUMBER 402)
      (RULE-NAME "EPR Catch-up 1")

      (ANTECEDENT
            (
            (OR
            (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-STATIC))
                 (PLUSP (- (RETRIEVE_DATA 'EPR 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'EPR 'EXPECTATIONS 'NEW-
STATIC)))
            )
            (OR
            (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EPR 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
            )

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'EPR 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'EPR 'DERIVATIVE)
            (SETQ RULE402_FIRED 'YES)
(print "                                          rule 402
fired")

      ))
)
((RULE-NUMBER 403)
      (RULE-NAME "EPR Catch-up 2")

      (ANTECEDENT
            (
            (OR
            (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-STATIC))
                 (MINUSP (- (RETRIEVE_DATA 'EPR 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'EPR 'EXPECTATIONS 'NEW-
STATIC)))
            )
            (OR
            (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EPR 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
            )

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'EPR 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'EPR 'DERIVATIVE)
            (SETQ RULE403_FIRED 'YES)
```

```
(print "                                                    rule 403
fired")

       ))
)


((RULE-NUMBER 404)
      (RULE-NAME "EPR Catch-up 3")

      (ANTECEDENT
             (
             (OR
             (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-STATIC))
             (PLUSP (- (RETRIEVE_DATA 'EPR 'ACTUALS 'NEW-STATIC)
                       (RETRIEVE_DATA 'EPR 'EXPECTATIONS 'NEW-
STATIC)))
             )
             (OR
             (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EPR 'DEVIATIONS 'QUALITATIVE-TREND))
             (MEMBER 'DECREASING-ABNORMALLY (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-TREND))
             )

       ))

      (CONSEQUENT
             (
             (DELAY-STAGE2-SYMPTOM 'EPR 'STATIC)
             (DELAY-STAGE2-SYMPTOM 'EPR 'TREND)
             (SETQ RULE404_FIRED 'YES)
(print "                                                    rule 404
fired")

       ))
)

((RULE-NUMBER 405)
      (RULE-NAME "EPR Catch-up 4")

      (ANTECEDENT
             (
             (OR
             (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-STATIC))
             (MINUSP (- (RETRIEVE_DATA 'EPR 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'EPR 'EXPECTATIONS 'NEW-
STATIC)))
             )
             (OR
             (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EPR 'DEVIATIONS 'QUALITATIVE-TREND))
```

```
                        (MEMBER 'INCREASING-ABNORMALLY (RETRIEVE_DATA 'EPR
'DEVIATIONS 'QUALITATIVE-TREND))
                    )

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'EPR 'STATIC)
                (DELAY-STAGE2-SYMPTOM 'EPR 'TREND)
                (SETQ RULE405_FIRED 'YES)
(print "                                              rule 405
fired")

        ))
)


        ((RULE-NUMBER 406)
                (RULE-NAME "EPR Spikes and Holes")
                (ANTECEDENT
                    (
                    (CHECK_SPIKE 'EPR)
                    )

                )
                (CONSEQUENT           (
                (DELAY-STAGE2-SYMPTOM 'EPR 'DERIVATIVE)
                (DELAY-STAGE2-SYMPTOM 'EPR 'TREND)
                (DELAY-STAGE2-SYMPTOM 'EPR 'STATIC)
                (SETQ RULE406_FIRED 'YES)
(print "                                              rule 406
fired")
                ))
)


        ((RULE-NUMBER 500)
                (RULE-NAME "EGT nearly parallel")
                (ANTECEDENT         (
                (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
                (IS_NEARLY_PARALLEL_P1 'EGT)
                )
                )
                (CONSEQUENT          (
                (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
                (SETQ RULE500_FIRED 'YES)
(print "                                              rule 500
fired")
                ))
)
```

```
((RULE-NUMBER 501)
        (RULE-NAME "EGT nearly parallel")
        (ANTECEDENT        (
        (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
        (IS_NEARLY_PARALLEL_P2 'EGT)
        )
        )
        (CONSEQUENT        (
        (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
        (SETQ RULE501_FIRED 'YES)
(print "                                        rule 501
fired")
        ))
)


((RULE-NUMBER 502)
     (RULE-NAME "EGT Catch-up 1")

     (ANTECEDENT
            (
            (OR
            (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
            (PLUSP (- (RETRIEVE_DATA 'EGT 'ACTUALS 'NEW-STATIC)
                     (RETRIEVE_DATA 'EGT 'EXPECTATIONS 'NEW-
STATIC)))
            )
            (OR
            (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EGT 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
            )

     ))

     (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'EGT 'DERIVATIVE)
            (SETQ RULE502_FIRED 'YES)
(print "                                        rule 502
fired")

     ))
)
((RULE-NUMBER 503)
     (RULE-NAME "EGT Catch-up 2")

     (ANTECEDENT
            (
            (OR
```

```
                (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
                (MINUSP (- (RETRIEVE_DATA 'EGT 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'EGT 'EXPECTATIONS 'NEW-
STATIC)))
                )
                (OR
                (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EGT 'DEVIATIONS 'QUALITATIVE-DERIVATIVE))
                )

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
                (DELAY-STAGE2-SYMPTOM 'EGT 'DERIVATIVE)
                (SETQ RULE503_FIRED 'YES)
(print "                                              rule 503
fired")

        ))
)


((RULE-NUMBER 504)
        (RULE-NAME "EGT Catch-up 3")

        (ANTECEDENT
                (
                (OR
                (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
                (PLUSP (- (RETRIEVE_DATA 'EGT 'ACTUALS 'NEW-STATIC)
                        (RETRIEVE_DATA 'EGT 'EXPECTATIONS 'NEW-
STATIC)))
                )
                (OR
                (MEMBER 'DECREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EGT 'DEVIATIONS 'QUALITATIVE-TREND))
                (MEMBER 'DECREASING-ABNORMALLY (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-TREND))
                )

        ))

        (CONSEQUENT
                (
                (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
                (DELAY-STAGE2-SYMPTOM 'EGT 'TREND)
                (SETQ RULE504_FIRED 'YES)
(print "                                              rule 504
fired")
```

```
        ))
)

((RULE-NUMBER 505)
      (RULE-NAME "EGT Catch-up 4")

      (ANTECEDENT
            (
            (OR
            (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
            (MINUSP (- (RETRIEVE_DATA 'EGT 'ACTUALS 'NEW-STATIC)
                       (RETRIEVE_DATA 'EGT 'EXPECTATIONS 'NEW-
STATIC)))
            )
            (OR
            (MEMBER 'INCREASING-FASTER-THAN-EXPECTED
(RETRIEVE_DATA 'EGT 'DEVIATIONS 'QUALITATIVE-TREND))
            (MEMBER 'INCREASING-ABNORMALLY (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-TREND))
            )

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
            (DELAY-STAGE2-SYMPTOM 'EGT 'TREND)
            (SETQ RULE505_FIRED 'YES)
(print "                                        rule 505
fired")

      ))
)

      ((RULE-NUMBER 506)
            (RULE-NAME "EGT Derivative Delete")
            (ANTECEDENT
                  (
                  (OR
                        (NOT (NULL (RETRIEVE_DATA 'EGT 'DEVIATIONS
'QUALITATIVE-DERIVATIVE) ))
                        (NOT (EQUAL (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE) (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-DERIVATIVE)))
                  )
            )
            )
            (CONSEQUENT      (
            (DELAY-STAGE2-SYMPTOM 'EGT 'DERIVATIVE)
            (SETQ RULE506_FIRED 'YES)
(print "                                        rule 506
fired")
            ))
```

```
)

((RULE-NUMBER 507)
      (RULE-NAME "EGT Throttle-move")

      (ANTECEDENT
            (
            (OR
            (MEMBER 'HIGHER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
            (MEMBER 'LOWER-THAN-EXPECTED (RETRIEVE_DATA 'EGT
'DEVIATIONS 'QUALITATIVE-STATIC))
            )
            (OR
            (MEMBER 'INCREASING (RETRIEVE_DATA 'THROTTLE
'DEVIATIONS 'QUALITATIVE-TREND))
            (MEMBER 'DECREASING (RETRIEVE_DATA 'THROTTLE
'DEVIATIONS 'QUALITATIVE-TREND))
            )

      ))

      (CONSEQUENT
            (
            (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
            (SETQ RULE507_FIRED 'YES)
(print "                                         rule 507
fired")

      ))
)

      ((RULE-NUMBER 508)
            (RULE-NAME "EGT Spikes and Holes")
            (ANTECEDENT
                  (
                  (CHECK_SPIKE 'EGT)
                  )

            )
            (CONSEQUENT          (
            (DELAY-STAGE2-SYMPTOM 'EGT 'DERIVATIVE)
            (DELAY-STAGE2-SYMPTOM 'EGT 'TREND)
            (DELAY-STAGE2-SYMPTOM 'EGT 'STATIC)
            (SETQ RULE508_FIRED 'YES)
(print "                                         rule 508
fired")
            ))
)

))))
```

(COMPONENTS ((ENGINE COMPOSITE ((FUNCTIONALLY-PART-OF NIL)
(PHYSICALLY-PART-OF NIL) (FUNCTIONALLY-AFFECTS NIL)
(PHYSICALLY-AFFECTS NIL) (FUNCTIONALLY-AFFECTED-BY NIL)
(PHYSICALLY-AFFECTED-BY NIL)   (PHYSICAL-PARTS   (FAN
COMPRESSOR COMBUSTOR AFT-TURBINE FORWARD-TURBINE N1 N2 EGT EPR
FUEL-FLOW ALTITUDE   MACH THROTTLE TIME))   (FUNCTIONAL-
PARTS   (FAN COMPRESSOR COMBUSTOR AFT-TURBINE FORWARD-TURBINE
N1 N2 EGT EPR FUEL-FLOW ALTITUDE   MACH THROTTLE TIME))
(QUANTITY-SPACES NIL) (QUEUE-LENGTH NIL)))

(FAN PRIMITIVE   ((FUNCTIONALLY-PART-OF (ENGINE)) (PHYSICALLY-
PART-OF (ENGINE))   (FUNCTIONALLY-AFFECTS (N1 COMPRESSOR))
(PHYSICALLY-AFFECTS (N1 EPR COMPRESSOR))   (FUNCTIONALLY-
AFFECTED-BY (AFT-TURBINE)) (PHYSICALLY-AFFECTED-BY NIL)
(ASSOCIATED-SENSORS (N1 EPR))))

(COMPRESSOR PRIMITIVE   ((FUNCTIONALLY-PART-OF (ENGINE))
(PHYSICALLY-PART-OF (ENGINE))   (FUNCTIONALLY-AFFECTS
(COMBUSTOR N2 COMPRESSOR))   (PHYSICALLY-AFFECTS (COMBUSTOR N2
COMPRESSOR))   (FUNCTIONALLY-AFFECTED-BY (FORWARD-TURBINE
COMPRESSOR FAN))   (PHYSICALLY-AFFECTED-BY (COMPRESSOR FAN))
(ASSOCIATED-SENSORS (N2))))

(COMBUSTOR PRIMITIVE   ((FUNCTIONALLY-PART-OF (ENGINE))
(PHYSICALLY-PART-OF (ENGINE))   (FUNCTIONALLY-AFFECTS
(FORWARD-TURBINE)) (PHYSICALLY-AFFECTS (FORWARD-TURBINE))
(FUNCTIONALLY-AFFECTED-BY (COMPRESSOR)) (PHYSICALLY-AFFECTED-BY
(COMPRESSOR))   (ASSOCIATED-SENSORS NIL)))

(AFT-TURBINE PRIMITIVE   ((FUNCTIONALLY-PART-OF (ENGINE))
(PHYSICALLY-PART-OF (ENGINE))   (FUNCTIONALLY-AFFECTS (EGT EPR
FAN)) (PHYSICALLY-AFFECTS (EGT EPR))   (FUNCTIONALLY-AFFECTED-
BY (FORWARD-TURBINE)) (PHYSICALLY-AFFECTED-BY (FORWARD-TURBINE))
(ASSOCIATED-SENSORS (EGT EPR))))

(FORWARD-TURBINE PRIMITIVE   ((FUNCTIONALLY-PART-OF (ENGINE))
(PHYSICALLY-PART-OF (ENGINE))   (FUNCTIONALLY-AFFECTS
(COMPRESSOR AFT-TURBINE)) (PHYSICALLY-AFFECTS (AFT-TURBINE))
(FUNCTIONALLY-AFFECTED-BY (COMBUSTOR)) (PHYSICALLY-AFFECTED-BY
(COMBUSTOR))   (ASSOCIATED-SENSORS NIL)))

(TIME SENSOR   ((FUNCTIONALLY-PART-OF (ENGINE))
(PHYSICALLY-PART-OF (ENGINE))   (FUNCTIONALLY-AFFECTS
NIL) (PHYSICALLY-AFFECTS NIL) (FUNCTIONALLY-AFFECTED-BY NIL)
(PHYSICALLY-AFFECTED-BY NIL) (ASSOCIATED-COMPONENTS NIL)
(ASSOCIATION-TYPE NIL)   (INPUT (GET-DATA 'TIME))
(ACTUALS   ((NOISE-LEVELS ((STATIC 0.0) (DERIVATIVE 0.0)
(TREND 0.0)))   (QUANTITY-SPACES ((STATIC NIL)
(DERIVATIVE NIL) (TREND NIL)))   (QUEUE-LENGTHS
((QUALITATIVE 2) (QUANTITATIVE 2)))))   (EXPECTATIONS
((NOISE-LEVELS ((STATIC 0.0) (DERIVATIVE 0.0) (TREND 0.0)))
(QUANTITY-SPACES ((STATIC NIL) (DERIVATIVE NIL) (TREND NIL)))
(QUEUE-LENGTHS ((QUALITATIVE 2) (QUANTITATIVE 2)))))
(DEVIATIONS   ((NOISE-LEVELS ((STATIC 0.0) (DERIVATIVE

0.0) (TREND 0.0)))   (QUANTITY-SPACES ((STATIC NIL)
(DERIVATIVE NIL) (TREND NIL)))   (QUEUE-LENGTHS
((QUALITATIVE 2) (QUANTITATIVE 2)))))))))

(N1 SENSOR
        ((FUNCTIONALLY-PART-OF (ENGINE))
         (PHYSICALLY-PART-OF (ENGINE))
         (FUNCTIONALLY-AFFECTS NIL)
         (PHYSICALLY-AFFECTS NIL)
         (FUNCTIONALLY-AFFECTED-BY (FAN))
         (PHYSICALLY-AFFECTED-BY (FAN))
         (ASSOCIATED-COMPONENTS (FAN))
         (ASSOCIATION-TYPE ((FAN PARAMETER)))
         (INPUT (GET-DATA 'N1))

        (ACTUALS
            ((NOISE-LEVELS ((STATIC 1.0) (DERIVATIVE 0.0) (TREND
0.0)))
                  (QUANTITY-SPACES
                     ((STATIC   ((NORMAL (< 55.0 (:SELF)
95.0)) (UPPER-CAUTION (<= 95.0 (:SELF) 100.1))   (UPPER-
WARNING (< 100.1 (:SELF))) (LOWER-CAUTION (<= 0.0 (:SELF) 55.0))
(LOWER-WARNING (< (:SELF) 0.0)) (:OFF-SCALE-HIGH (< 110.0
(:SELF)))   (:OFF-SCALE-LOW (< (:SELF) 0.0))
                    (SENSOR-INOPERABLE (< 220 (:SELF))))   )
                     (DERIVATIVE   ((DECREASING (< (:SELF) -
0.5)) (STEADY (< -0.5 (:SELF) 0.5))   (INCREASING (< 0.5
(:SELF)))))
                     (TREND   ((DECREASING (< (:SELF) -.50))
(STEADY (< -.50 (:SELF) .50))   (INCREASING (< .50
(:SELF))))))))   (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

        (EXPECTATIONS
            ((NOISE-LEVELS ((STATIC 1.0) (DERIVATIVE 0.0) (TREND
0.0)))
                     (QUANTITY-SPACES   ((STATIC   ((NORMAL
(< 55.0 (:SELF) 95.0)) (UPPER-CAUTION (<= 95.0 (:SELF) 100.1))
(UPPER-WARNING (< 100.1 (:SELF))) (LOWER-CAUTION (<= 0.0 (:SELF)
55.0))   (LOWER-WARNING (< (:SELF) 0.0))))
                     (DERIVATIVE   ((DECREASING (< (:SELF) -0.5))
(STEADY (< -0.5 (:SELF) 0.5))   (INCREASING (< 0.5
(:SELF)))))
                     (TREND   ((DECREASING (< (:SELF) -.50))
(STEADY (< -.50 (:SELF) .50))   (INCREASING (< .50
(:SELF))))))))   (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

        (DEVIATIONS
            ((NOISE-LEVELS ((STATIC 3.0) (DERIVATIVE 0.0) (TREND
0.0)))
                     (QUANTITY-SPACES   ((STATIC (
                        (SENSOR-FAILURE
                        (MEMBER 'SENSOR-INOPERABLE

```
                          (RETRIEVE_DATA 'N1 'ACTUALS
                              'QUALITATIVE-STATIC)))
(HIGHER-THAN-EXPECTED (> (:SELF) 3.0)) (LOWER-THAN-EXPECTED (> -
3.0 (:SELF))))          )
              (DERIVATIVE
                (
                      (SENSOR-FAILURE
                      (MEMBER 'SENSOR-INOPERABLE
                      (RETRIEVE_DATA 'N1 'ACTUALS
                              'QUALITATIVE-STATIC)))

(INCREASING-FASTER-THAN-EXPECTED
                      (AND
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                          (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                      (INCREASING-ABNORMALLY
                      (AND
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING (RETRIEVE_DATA 'N1 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                      (NOT-DECREASING-AS-FAST-AS-EXPECTED
                      (AND
(MEMBER 'STEADY                          (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING                          (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                      (DECREASING-FASTER-THAN-EXPECTED
                      (AND
(MEMBER 'DECREASING                          (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                          (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                      (DECREASING-ABNORMALLY
                      (AND
(MEMBER 'DECREASING                          (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING (RETRIEVE_DATA 'N1 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                      (NOT-INCREASING-AS-FAST-AS-EXPECTED
                      (AND
(MEMBER 'STEADY                          (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))))

    (TREND              (
              (SENSOR-FAILURE
                      (MEMBER 'SENSOR-INOPERABLE
                      (RETRIEVE_DATA 'N1 'ACTUALS
                              'QUALITATIVE-STATIC)))
          (INCREASING-INSTEAD-OF-DECREASING
```

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```
            (AND
                    (MEMBER 'DECREASING (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'INCREASING (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-TREND))))

          (NOT-DECREASING-AS-FAST-AS-EXPECTED
            (AND
                    (MEMBER 'DECREASING (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'STEADY (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-TREND))))

          (NOT-INCREASING-AS-FAST-AS-EXPECTED
            (AND
                    (MEMBER 'INCREASING (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'STEADY (RETRIEVE_DATA 'N1 'ACTUALS
'QUALITATIVE-TREND))))

          (INCREASING-ABNORMALLY
            (AND
                    (MEMBER 'STEADY (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'INCREASING (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-TREND))))

          (DECREASING-INSTEAD-OF-INCREASING
            (AND
                    (MEMBER 'INCREASING (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'DECREASING (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-TREND))))

          (DECREASING-ABNORMALLY
            (AND
                    (MEMBER 'STEADY (RETRIEVE_DATA 'N1
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'DECREASING (RETRIEVE_DATA 'N1
'ACTUALS 'QUALITATIVE-TREND)))))))))

      (QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE 5)))))))))

(N2 SENSOR
    ((FUNCTIONALLY-PART-OF (ENGINE))
    (PHYSICALLY-PART-OF (ENGINE))
    (FUNCTIONALLY-AFFECTS NIL)
    (PHYSICALLY-AFFECTS NIL)
    (FUNCTIONALLY-AFFECTED-BY (COMPRESSOR))
    (PHYSICALLY-AFFECTED-BY (COMPRESSOR))
    (ASSOCIATED-COMPONENTS (COMPRESSOR))
    (ASSOCIATION-TYPE ((COMPRESSOR PARAMETER)))
    (INPUT (GET-DATA 'N2))
```

```
        (ACTUALS
                ((NOISE-LEVELS ((STATIC 1.0) (DERIVATIVE 0.0) (TREND
0.0)))
                (QUANTITY-SPACES
                        ((STATIC              ((NORMAL (< 33.0 (:SELF)
95.0)) (UPPER-CAUTION (<= 95.0 (:SELF) 100.0))              (UPPER-
WARNING (< 100.0 (:SELF))) (LOWER-CAUTION (<= 0.0 (:SELF) 33.0))
(LOWER-WARNING (< (:SELF) 0.0)) (:OFF-SCALE-HIGH (< 110.0
(:SELF)))            (:OFF-SCALE-LOW (< (:SELF) 0.0))
                (SENSOR-INOPERABLE (< 220   (:SELF)))))
                        (DERIVATIVE            ((DECREASING (< (:SELF) -
0.5)) (STEADY (< -0.5 (:SELF) 0.5))            (INCREASING (< 0.5
(:SELF)))))
                        (TREND             ((DECREASING (< (:SELF) -.50))
(STEADY (< -.50 (:SELF) .50))            (INCREASING (< .50
(:SELF))))))))    (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

        (EXPECTATIONS
                ((NOISE-LEVELS ((STATIC 1.0) (DERIVATIVE 0.0) (TREND
0.0)))
                (QUANTITY-SPACES         ((STATIC            ((NORMAL (<
33.0 (:SELF) 95.0)) (UPPER-CAUTION (<= 95.0 (:SELF) 100.0))
(UPPER-WARNING (< 100.0 (:SELF))) (LOWER-CAUTION (<= 0.0 (:SELF)
33.0))          (LOWER-WARNING (< (:SELF) 0.0))))
                        (DERIVATIVE            ((DECREASING (< (:SELF) -0.5))
(STEADY (< -0.5 (:SELF) 0.5))            (INCREASING (< 0.5
(:SELF)))))
                        (TREND            ((DECREASING (< (:SELF) -.50)) (STEADY
(< -.50 (:SELF) .50))            (INCREASING (< .50 (:SELF))))))))
(QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE 5)))))

        (DEVIATIONS
                ((NOISE-LEVELS ((STATIC 3.0) (DERIVATIVE 0.0) (TREND
0.0)))
                (QUANTITY-SPACES           ((STATIC (
                (SENSOR-FAILURE
                        (MEMBER 'SENSOR-INOPERABLE
                        (RETRIEVE_DATA 'N2 'ACTUALS
                        'QUALITATIVE-STATIC)))

(HIGHER-THAN-EXPECTED (> (:SELF) 3.0)) (LOWER-THAN-EXPECTED (> -
3.0 (:SELF))))            )
                (DERIVATIVE
                (
                (SENSOR-FAILURE
                        (MEMBER 'SENSOR-INOPERABLE
                        (RETRIEVE_DATA 'N2 'ACTUALS
                        'QUALITATIVE-STATIC)))


(INCREASING-FASTER-THAN-EXPECTED
                        (AND
```

```
(MEMBER 'INCREASING                              (RETRIEVE_DATA 'N2
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                       (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                    (INCREASING-ABNORMALLY
                         (AND
(MEMBER 'INCREASING                              (RETRIEVE_DATA 'N2
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                    (NOT-DECREASING-AS-FAST-AS-EXPECTED
                         (AND
(MEMBER 'STEADY                       (RETRIEVE_DATA 'N2
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING                              (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                    (DECREASING-FASTER-THAN-EXPECTED
                         (AND
(MEMBER 'DECREASING                              (RETRIEVE_DATA 'N2
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                       (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                    (DECREASING-ABNORMALLY
                         (AND
(MEMBER 'DECREASING                              (RETRIEVE_DATA 'N2
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                    (NOT-INCREASING-AS-FAST-AS-EXPECTED
                         (AND
(MEMBER 'STEADY                       (RETRIEVE_DATA 'N2
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING                              (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))))

        (TREND          (
            (SENSOR-FAILURE
                 (MEMBER 'SENSOR-INOPERABLE
                 (RETRIEVE_DATA 'N2 'ACTUALS
                      'QUALITATIVE-STATIC)))

        (INCREASING-INSTEAD-OF-DECREASING
             (AND
                  (MEMBER 'DECREASING (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-TREND))
                  (MEMBER 'INCREASING (RETRIEVE_DATA 'N2
'ACTUALS 'QUALITATIVE-TREND))))


        (NOT-DECREASING-AS-FAST-AS-EXPECTED
             (AND
                  (MEMBER 'DECREASING (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-TREND))
```

```
                                  (MEMBER 'STEADY (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-TREND)))))

            (NOT-INCREASING-AS-FAST-AS-EXPECTED
                    (AND
                            (MEMBER 'INCREASING (RETRIEVE_DATA 'N2
'EXPECTATIONS 'QUALITATIVE-TREND))
                            (MEMBER 'STEADY (RETRIEVE_DATA 'N2 'ACTUALS
'QUALITATIVE-TREND)))))


(INCREASING-ABNORMALLY                  (AND (MEMBER 'STEADY
(RETRIEVE_DATA 'N2 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'INCREASING (RETRIEVE_DATA 'N2 'ACTUALS 'QUALITATIVE-
TREND))))          (DECREASING-INSTEAD-OF-INCREASING
(AND (MEMBER 'INCREASING (RETRIEVE_DATA 'N2 'EXPECTATIONS
'QUALITATIVE-TREND))                    (MEMBER 'DECREASING
(RETRIEVE_DATA 'N2 'ACTUALS 'QUALITATIVE-TREND))))
(DECREASING-ABNORMALLY                  (AND (MEMBER 'STEADY
(RETRIEVE_DATA 'N2 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'DECREASING (RETRIEVE_DATA 'N2 'ACTUALS 'QUALITATIVE-
TREND)))))))))          (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))))

(EGT SENSOR
     ((FUNCTIONALLY-PART-OF (ENGINE))
     (PHYSICALLY-PART-OF (ENGINE))
     (FUNCTIONALLY-AFFECTS NIL)
     (PHYSICALLY-AFFECTS NIL)
     (FUNCTIONALLY-AFFECTED-BY (AFT-TURBINE))
     (PHYSICALLY-AFFECTED-BY (AFT-TURBINE))
     (ASSOCIATED-COMPONENTS (AFT-TURBINE))
     (ASSOCIATION-TYPE ((AFT-TURBINE OUTPUT)))
     (INPUT (GET-DATA 'EGT))

     (ACTUALS
          ((NOISE-LEVELS ((STATIC 5.0)  (DERIVATIVE 0.0)  (TREND
0.0)))
            (QUANTITY-SPACES
                    ((STATIC                 ((NORMAL (< 250.0 (:SELF)
500.0)) (UPPER-CAUTION (<= 500.0 (:SELF) 525.0))
(UPPER-WARNING (< 525.0 (:SELF))) (LOWER-CAUTION (<= 0.0 (:SELF)
250.0))          (LOWER-WARNING (< (:SELF) 0.0)) (:OFF-SCALE-
HIGH (< 550.0 (:SELF)))          (:OFF-SCALE-LOW (< (:SELF)
0.0))
                    (SENSOR-INOPERABLE (< 1100  (:SELF)))))
                    (DERIVATIVE              ((DECREASING (< (:SELF) -
10.)) (STEADY (< -10. (:SELF) 10.))          (INCREASING (< 10.
(:SELF)))))
                    (TREND                ((DECREASING (< (:SELF) -5.0))
(STEADY (<= -5.0 (:SELF) 5.0))          (INCREASING (< 5.0
(:SELF))))))          (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))
```

```
        (EXPECTATIONS
              ((NOISE-LEVELS ((STATIC 5.0) (DERIVATIVE 0.0) (TREND
0.0)))
              (QUANTITY-SPACES
                    ((STATIC          ((NORMAL (< 250.0 (:SELF)
500.0)) (UPPER-CAUTION (<= 500.0 (:SELF) 525.0))
(UPPER-WARNING (< 525.0 (:SELF))) (LOWER-CAUTION (<= 0.0 (:SELF)
250.0))          (LOWER-WARNING (< (:SELF) 0.0))))
                    (DERIVATIVE          ((DECREASING (< (:SELF) -
10.)) (STEADY (< -10. (:SELF) 10.))          (INCREASING (< 10.
(:SELF)))))
                    (TREND          ((DECREASING (< (:SELF) -5.0))
(STEADY (< -5.0 (:SELF) 5.0))          (INCREASING (< 5.0
(:SELF))))))          (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))


        (DEVIATIONS
              ((NOISE-LEVELS ((STATIC 60.0) (DERIVATIVE 0.0) (TREND
0.0)))
              (QUANTITY-SPACES
                    ((STATIC (
                    (SENSOR-FAILURE
                          (MEMBER 'SENSOR-INOPERABLE
                          (RETRIEVE_DATA 'EGT 'ACTUALS
                                'QUALITATIVE-STATIC)))

(HIGHER-THAN-EXPECTED (> (:SELF) 20.0)) (LOWER-THAN-EXPECTED (>
-20.0 (:SELF))))          )
                    (DERIVATIVE
                          (
                    (SENSOR-FAILURE
                          (MEMBER 'SENSOR-INOPERABLE
                          (RETRIEVE_DATA 'EGT 'ACTUALS
                                'QUALITATIVE-STATIC)))

(INCREASING-FASTER-THAN-EXPECTED
                          (AND
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                          (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                    (INCREASING-ABNORMALLY
                          (AND
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING (RETRIEVE_DATA 'EGT 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                    (NOT-DECREASING-AS-FAST-AS-EXPECTED
                          (AND
(MEMBER 'STEADY                          (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING                          (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                    (DECREASING-FASTER-THAN-EXPECTED
```

```
                              (AND
(MEMBER 'DECREASING                          (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                          (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                (DECREASING-ABNORMALLY
                      (AND
(MEMBER 'DECREASING                          (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING (RETRIEVE_DATA 'EGT 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                (NOT-INCREASING-AS-FAST-AS-EXPECTED
                      (AND
(MEMBER 'STEADY                          (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))))

(TREND           (
                (SENSOR-FAILURE
                      (MEMBER 'SENSOR-INOPERABLE
                      (RETRIEVE_DATA 'EGT 'ACTUALS
                            'QUALITATIVE-STATIC)))

    (INCREASING-INSTEAD-OF-DECREASING
          (AND
                (MEMBER 'DECREASING (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-TREND))
                (MEMBER 'INCREASING (RETRIEVE_DATA 'EGT 'ACTUALS
'QUALITATIVE-TREND))))

          (NOT-DECREASING-AS-FAST-AS-EXPECTED
                (AND
                      (MEMBER 'DECREASING (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-TREND))
                      (MEMBER 'STEADY (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-TREND))))

          (NOT-INCREASING-AS-FAST-AS-EXPECTED
                (AND
                      (MEMBER 'INCREASING (RETRIEVE_DATA 'EGT
'EXPECTATIONS 'QUALITATIVE-TREND))
                      (MEMBER 'STEADY (RETRIEVE_DATA 'EGT
'ACTUALS 'QUALITATIVE-TREND))))


(INCREASING-ABNORMALLY           (AND (MEMBER 'STEADY
(RETRIEVE_DATA 'EGT 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'INCREASING (RETRIEVE_DATA 'EGT 'ACTUALS 'QUALITATIVE-
TREND))))           (DECREASING-INSTEAD-OF-INCREASING
(AND (MEMBER 'INCREASING (RETRIEVE_DATA 'EGT 'EXPECTATIONS
'QUALITATIVE-TREND))           (MEMBER 'DECREASING
(RETRIEVE_DATA 'EGT 'ACTUALS 'QUALITATIVE-TREND))))
(DECREASING-ABNORMALLY           (AND (MEMBER 'STEADY
```

```
(RETRIEVE_DATA 'EGT 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'DECREASING (RETRIEVE_DATA 'EGT 'ACTUALS 'QUALITATIVE-
TREND)))))))))            (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))))))

(EPR SENSOR
     ((FUNCTIONALLY-PART-OF (ENGINE))
      (PHYSICALLY-PART-OF (ENGINE))
      (FUNCTIONALLY-AFFECTS NIL)
      (PHYSICALLY-AFFECTS NIL)
      (FUNCTIONALLY-AFFECTED-BY (AFT-TURBINE))
      (PHYSICALLY-AFFECTED-BY (AFT-TURBINE FAN))
      (ASSOCIATED-COMPONENTS (AFT-TURBINE FAN))
      (ASSOCIATION-TYPE ((AFT-TURBINE OUTPUT) (FAN INPUT)))
      (INPUT (GET-DATA 'EPR))

      (ACTUALS
           ((NOISE-LEVELS ((STATIC 0.05) (DERIVATIVE 0.0) (TREND
0.0)))
           (QUANTITY-SPACES          ((STATIC             ((NORMAL
(< 0.95                (:SELF)                 (EPR-UPPER-CAUTION
(RETRIEVE_DATA 'ALTITUDE 'ACTUALS 'NEW-STATIC)
(RETRIEVE_DATA 'MACH 'ACTUALS 'NEW-STATIC))))          (UPPER-
CAUTION            (<= (EPR-UPPER-CAUTION (RETRIEVE_DATA
'ALTITUDE 'ACTUALS 'NEW-STATIC)              (RETRIEVE_DATA
'MACH 'ACTUALS 'NEW-STATIC))            (:SELF)
(EPR-UPPER-WARNING (RETRIEVE_DATA 'ALTITUDE 'ACTUALS 'NEW-
STATIC)              (RETRIEVE_DATA 'MACH 'ACTUALS 'NEW-
STATIC))))          (UPPER-WARNING              (< (EPR-UPPER-
WARNING (RETRIEVE_DATA 'ALTITUDE 'ACTUALS 'NEW-STATIC)
(RETRIEVE_DATA 'MACH 'ACTUALS 'NEW-STATIC))
(:SELF)))          (LOWER-CAUTION (<= 0.7 (:SELF) 0.95))
(LOWER-WARNING (< (:SELF) 0.7))           (:OFF-SCALE-HIGH (<
2.6 (:SELF))) (:OFF-SCALE-LOW (< (:SELF) 0.7))
(SENSOR-INOPERABLE (< 5.2   (:SELF)))))
           (DERIVATIVE            ((DECREASING (< (:SELF) -0.010))
(STEADY (< -0.010 (:SELF) 0.010))           (INCREASING (< 0.010
(:SELF)))))
           (TREND            ((DECREASING (< (:SELF) -0.02))
(STEADY (< -0.02 (:SELF) 0.02))           (INCREASING (< 0.02
(:SELF)))))))          (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

      (EXPECTATIONS
           ((NOISE-LEVELS ((STATIC 0.05) (DERIVATIVE 0.0) (TREND
0.0)))
           (QUANTITY-SPACES           ((STATIC            ((NORMAL
(< 0.95                (:SELF)                 (EPR-UPPER-CAUTION
(RETRIEVE_DATA 'ALTITUDE 'ACTUALS 'NEW-STATIC)
(RETRIEVE_DATA 'MACH 'ACTUALS 'NEW-STATIC))))          (UPPER-
CAUTION            (<= (EPR-UPPER-CAUTION (RETRIEVE_DATA
'ALTITUDE 'ACTUALS 'NEW-STATIC)              (RETRIEVE_DATA
'MACH 'ACTUALS 'NEW-STATIC))            (:SELF)
(EPR-UPPER-WARNING (RETRIEVE_DATA 'ALTITUDE 'ACTUALS 'NEW-
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```
STATIC)                          (RETRIEVE_DATA 'MACH 'ACTUALS 'NEW-
STATIC))))          (UPPER-WARNING          (< (EPR-UPPER-
WARNING (RETRIEVE_DATA 'ALTITUDE 'ACTUALS 'NEW-STATIC)
(RETRIEVE_DATA 'MACH 'ACTUALS 'NEW-STATIC))
(:SELF)))          (LOWER-CAUTION (<= 0.7 (:SELF) 0.95))
(LOWER-WARNING (< (:SELF) 0.7))))
          (DERIVATIVE          ((DECREASING (< (:SELF) -0.010))
(STEADY (< -0.010 (:SELF) 0.010))          (INCREASING (< 0.010
(:SELF)))))
          (TREND          ((DECREASING (< (:SELF) -0.02))
(STEADY (< -0.02 (:SELF) 0.02))          (INCREASING (< 0.02
(:SELF)))))))          (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

     (DEVIATIONS
          ((NOISE-LEVELS ((STATIC 0.10) (DERIVATIVE 0.0) (TREND
0.0)))
          (QUANTITY-SPACES
               ((STATIC (
               (SENSOR-FAILURE
                    (MEMBER 'SENSOR-INOPERABLE
                    (RETRIEVE_DATA 'EPR 'ACTUALS
                         'QUALITATIVE-STATIC)))

(HIGHER-THAN-EXPECTED (> (:SELF) .02)) (LOWER-THAN-EXPECTED (> -
.02 (:SELF))))          )
          (DERIVATIVE
               (
               (SENSOR-FAILURE
                    (MEMBER 'SENSOR-INOPERABLE
                    (RETRIEVE_DATA 'EPR 'ACTUALS
                         'QUALITATIVE-STATIC))

(INCREASING-FASTER-THAN-EXPECTED
                    (AND
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                     (RETRIEVE_DATA 'EPR
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                    (INCREASING-ABNORMALLY
                    (AND
(MEMBER 'INCREASING                          (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING (RETRIEVE_DATA 'EPR 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                    (NOT-DECREASING-AS-FAST-AS-EXPECTED
                    (AND
(MEMBER 'STEADY                          (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'DECREASING                          (RETRIEVE_DATA 'EPR
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))
                    (DECREASING-FASTER-THAN-EXPECTED
                    (AND
```

```
(MEMBER 'DECREASING                              (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'STEADY                         (RETRIEVE_DATA 'EPR
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE)))))
                        (DECREASING-ABNORMALLY
                        (AND
(MEMBER 'DECREASING                              (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING (RETRIEVE_DATA 'EPR 'EXPECTATIONS
'QUALITATIVE-DERIVATIVE))))
                        (NOT-INCREASING-AS-FAST-AS-EXPECTED
                        (AND
(MEMBER 'STEADY                          (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-DERIVATIVE))
(MEMBER 'INCREASING                              (RETRIEVE_DATA 'EPR
'EXPECTATIONS 'QUALITATIVE-DERIVATIVE))))))

(TREND              (
                    (SENSOR-FAILURE
                        (MEMBER 'SENSOR-INOPERABLE
                        (RETRIEVE_DATA 'EPR 'ACTUALS
                            'QUALITATIVE-STATIC)))

    (INCREASING-INSTEAD-OF-DECREASING
            (AND
                (MEMBER 'DECREASING (RETRIEVE_DATA 'EPR
'EXPECTATIONS 'QUALITATIVE-TREND))
                (MEMBER 'INCREASING (RETRIEVE_DATA 'EPR 'ACTUALS
'QUALITATIVE-TREND))))


            (NOT-DECREASING-AS-FAST-AS-EXPECTED
                (AND
                    (MEMBER 'DECREASING (RETRIEVE_DATA 'EPR
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'STEADY (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-TREND))))

            (NOT-INCREASING-AS-FAST-AS-EXPECTED
                (AND
                    (MEMBER 'INCREASING (RETRIEVE_DATA 'EPR
'EXPECTATIONS 'QUALITATIVE-TREND))
                    (MEMBER 'STEADY (RETRIEVE_DATA 'EPR
'ACTUALS 'QUALITATIVE-TREND))))


(INCREASING-ABNORMALLY               (AND (MEMBER 'STEADY
(RETRIEVE_DATA 'EPR 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'INCREASING (RETRIEVE_DATA 'EPR 'ACTUALS 'QUALITATIVE-
TREND))))              (DECREASING-INSTEAD-OF-INCREASING
(AND (MEMBER 'INCREASING (RETRIEVE_DATA 'EPR 'EXPECTATIONS
'QUALITATIVE-TREND))              (MEMBER 'DECREASING
(RETRIEVE_DATA 'EPR 'ACTUALS 'QUALITATIVE-TREND))))
(DECREASING-ABNORMALLY              (AND (MEMBER 'STEADY
```

```
(RETRIEVE_DATA 'EPR 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'DECREASING (RETRIEVE_DATA 'EPR 'ACTUALS 'QUALITATIVE-
TREND))))))))        (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))))


(FUEL-FLOW SENSOR
    ((FUNCTIONALLY-PART-OF (ENGINE))
     (PHYSICALLY-PART-OF (ENGINE))
     (FUNCTIONALLY-AFFECTS NIL)
     (PHYSICALLY-AFFECTS NIL)
     (FUNCTIONALLY-AFFECTED-BY NIL)
     (PHYSICALLY-AFFECTED-BY NIL)
     (ASSOCIATED-COMPONENTS NIL)
     (ASSOCIATION-TYPE NIL)
     (INPUT (GET-DATA 'FUEL-FLOW))

    (ACTUALS
        ((NOISE-LEVELS ((STATIC 100.0) (DERIVATIVE 0.0) (TREND
0.0)))
            (QUANTITY-SPACES
                ((STATIC           ((NORMAL (< 1000.0 (:SELF)
16000.0)) (UPPER-CAUTION (<= 16000.0 (:SELF) 18000.0))
(UPPER-WARNING (< 18000.0 (:SELF))) (LOWER-CAUTION (<= 0.0
(:SELF) 1000.0))           (LOWER-WARNING (< (:SELF) 0.0))
(:OFF-SCALE-HIGH (< 18000.0 (:SELF)))           (:OFF-SCALE-LOW
(< (:SELF) 0.0))
                    (SENSOR-INOPERABLE (< 36000  (:SELF)))))
                (DERIVATIVE        ((DECREASING (< (:SELF) -400.))
(STEADY (< -400. (:SELF) 400.))           (INCREASING (< 400.
(:SELF)))))
                (TREND            ((DECREASING (< (:SELF) -30.0))
(STEADY (< -30.0 (:SELF) 30.0))           (INCREASING (< 30.0
(:SELF))))))))        (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

    (EXPECTATIONS
        ((NOISE-LEVELS ((STATIC 100.0) (DERIVATIVE 0.0) (TREND
0.0)))
            (QUANTITY-SPACES
                ((STATIC           ((NORMAL (< 1000.0 (:SELF)
16000.0)) (UPPER-CAUTION (<= 16000.0 (:SELF) 18000.0))
(UPPER-WARNING (< 18000.0 (:SELF))) (LOWER-CAUTION (<= 0.0
(:SELF) 1000.0))        (LOWER-WARNING (< (:SELF) 0.0))))
                (DERIVATIVE        ((DECREASING (< (:SELF) -400.))
(STEADY (< -400. (:SELF) 400.))           (INCREASING (< 400.
(:SELF)))))
                (TREND            ((DECREASING (< (:SELF) -30.0))
(STEADY (< -30.0 (:SELF) 30.0))           (INCREASING (< 30.0
(:SELF))))))))        (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

    (DEVIATIONS
```

```
        ((NOISE-LEVELS  ((STATIC 1000.0) (DERIVATIVE 0.0) (TREND
0.0)))
          (QUANTITY-SPACES
            ((STATIC (
                (SENSOR-FAILURE
                    (MEMBER 'SENSOR-INOPERABLE
                    (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS
                        'QUALITATIVE-STATIC)))

(HIGHER-THAN-EXPECTED (> (:SELF) (FF_GET (RETRIEVE_DATA
'THROTTLE 'ACTUALS'NEW-STATIC))))
            (LOWER-THAN-EXPECTED (>  (- 0.0 (FF_GET
(RETRIEVE_DATA 'THROTTLE 'ACTUALS'NEW-STATIC))) (:SELF))))
)
          (DERIVATIVE
            (
                (SENSOR-FAILURE
                    (MEMBER 'SENSOR-INOPERABLE
                    (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS
                        'QUALITATIVE-STATIC)))

(INCREASING-FASTER-THAN-EXPECTED
                (AND
                    (MEMBER 'INCREASING
(RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'QUALITATIVE-DERIVATIVE))
                    (MEMBER 'STEADY
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-
DERIVATIVE))))
            (INCREASING-ABNORMALLY
                (AND
                    (MEMBER 'INCREASING
(RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'QUALITATIVE-DERIVATIVE))
                    (MEMBER 'DECREASING
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-
DERIVATIVE))))
            (NOT-DECREASING-AS-FAST-AS-EXPECTED
                (AND
                    (MEMBER 'STEADY
(RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'QUALITATIVE-DERIVATIVE))
                    (MEMBER 'DECREASING
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-
DERIVATIVE))))
            (DECREASING-FASTER-THAN-EXPECTED
                (AND
                    (MEMBER 'DECREASING
(RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'QUALITATIVE-DERIVATIVE))
                    (MEMBER 'STEADY
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-
DERIVATIVE))))
            (DECREASING-ABNORMALLY
                (AND
                    (MEMBER 'DECREASING
(RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'QUALITATIVE-DERIVATIVE))
```

```
                              (MEMBER 'INCREASING
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-
DERIVATIVE)))))
                    (NOT-INCREASING-AS-FAST-AS-EXPECTED
                      (AND
                        (MEMBER 'STEADY
(RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'QUALITATIVE-DERIVATIVE))
                        (MEMBER 'INCREASING
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-
DERIVATIVE))))))

    (TREND            (
                (SENSOR-FAILURE
                    (MEMBER 'SENSOR-INOPERABLE
                    (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS
                        'QUALITATIVE-STATIC)))

        (INCREASING-INSTEAD-OF-DECREASING
            (AND
                (MEMBER 'DECREASING
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-TREND))
            (MEMBER 'INCREASING (RETRIEVE_DATA 'FUEL-FLOW
'ACTUALS 'QUALITATIVE-TREND))))


        (NOT-DECREASING-AS-FAST-AS-EXPECTED
            (AND
                (MEMBER 'DECREASING (RETRIEVE_DATA 'FUEL-
FLOW 'EXPECTATIONS 'QUALITATIVE-TREND))
                (MEMBER 'STEADY (RETRIEVE_DATA 'FUEL-FLOW
'ACTUALS 'QUALITATIVE-TREND))))

        (NOT-INCREASING-AS-FAST-AS-EXPECTED
            (AND
                (MEMBER 'INCREASING (RETRIEVE_DATA 'FUEL-
FLOW 'EXPECTATIONS 'QUALITATIVE-TREND))
                (MEMBER 'STEADY (RETRIEVE_DATA 'FUEL-FLOW
'ACTUALS 'QUALITATIVE-TREND))))

(INCREASING-ABNORMALLY            (AND (MEMBER 'STEADY
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'INCREASING (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS
'QUALITATIVE-TREND))))      (DECREASING-INSTEAD-OF-
INCREASING        (AND (MEMBER 'INCREASING
(RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS 'QUALITATIVE-TREND))
(MEMBER 'DECREASING (RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS
'QUALITATIVE-TREND))))        (DECREASING-ABNORMALLY
(AND (MEMBER 'STEADY (RETRIEVE_DATA 'FUEL-FLOW 'EXPECTATIONS
'QUALITATIVE-TREND))            (MEMBER 'DECREASING
(RETRIEVE_DATA 'FUEL-FLOW 'ACTUALS 'QUALITATIVE-TREND)))))
)))      (QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE 5))))))))

(ALTITUDE SENSOR
```

```
((FUNCTIONALLY-PART-OF (ENGINE))
(PHYSICALLY-PART-OF (ENGINE))
(FUNCTIONALLY-AFFECTS NIL)
(PHYSICALLY-AFFECTS NIL)
(FUNCTIONALLY-AFFECTED-BY NIL)
(PHYSICALLY-AFFECTED-BY NIL)
(ASSOCIATED-COMPONENTS NIL)
(ASSOCIATION-TYPE NIL)
(INPUT (GET-DATA 'ALTITUDE))

(ACTUALS
        ((NOISE-LEVELS ((STATIC 100.0) (DERIVATIVE 0.0)
(TREND 0.0)))
        (QUANTITY-SPACES
                ((STATIC            ((NORMAL (<= 50.0 (:SELF)
40000.0)) (UPPER-CAUTION (< 40000.0 (:SELF) 45000.0))
(UPPER-WARNING (<= 45000.0 (:SELF))) (LOWER-CAUTION (< 0.0
(:SELF) 50.0))       (LOWER-WARNING (< (:SELF) 0.0)) (:OFF-
SCALE-HIGH (< 50000.0 (:SELF)))        (:OFF-SCALE-LOW (<
(:SELF) 0.0))
                (SENSOR-INOPERABLE (< 100000   (:SELF)))))
                (DERIVATIVE           ((DECREASING (<
(:SELF) -10.)) (STEADY (< -10. (:SELF) 10.))
(INCREASING (< 10 (:SELF)))))
                (TREND              ((DECREASING (< (:SELF) -
50.0)) (STEADY (< -50.0 (:SELF) 50.0))         (INCREASING (<
50.0 (:SELF)))))))       (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

        (EXPECTATIONS
        ((NOISE-LEVELS ((STATIC 100.0) (DERIVATIVE 0.0)
(TREND 0.0)))
        (QUANTITY-SPACES
                ((STATIC            ((NORMAL (<= 50.0 (:SELF)
40000.0)) (UPPER-CAUTION (< 40000.0 (:SELF) 45000.0))
(UPPER-WARNING (<= 45000.0 (:SELF))) (LOWER-CAUTION (< 0.0
(:SELF) 50.0))        (LOWER-WARNING (< (:SELF) 0.0))))
                (DERIVATIVE           ((DECREASING (<
(:SELF) -10.)) (STEADY (< -10. (:SELF) 10.))
(INCREASING (< 10. (:SELF)))))
                (TREND              ((DECREASING (< (:SELF) -
50.0)) (STEADY (< -50.0 (:SELF) 50.0))         (INCREASING (<
50.0 (:SELF)))))))       (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5)))))

        (DEVIATIONS
        ((NOISE-LEVELS ((STATIC 100.0) (DERIVATIVE 0.0)
(TREND 0.0)))
        (QUANTITY-SPACES (
        (STATIC (
        (SENSOR-FAILURE
                (MEMBER 'SENSOR-INOPERABLE
                (RETRIEVE_DATA 'ALTITUDE 'ACTUALS
                        'QUALITATIVE-STATIC)))
```

```
            ))
            (DERIVATIVE (
            (SENSOR-FAILURE
                 (MEMBER 'SENSOR-INOPERABLE
                 (RETRIEVE_DATA 'ALTITUDE 'ACTUALS
                      'QUALITATIVE-STATIC)))
            ))
            (TREND (
            (SENSOR-FAILURE
                 (MEMBER 'SENSOR-INOPERABLE
                 (RETRIEVE_DATA 'ALTITUDE 'ACTUALS
                      'QUALITATIVE-STATIC)))
            ))
))        (QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE 5))))))))
```

(MACH SENSOR   ((FUNCTIONALLY-PART-OF (ENGINE)) (PHYSICALLY-
PART-OF (ENGINE)) (FUNCTIONALLY-AFFECTS NIL)   (PHYSICALLY-
AFFECTS NIL) (FUNCTIONALLY-AFFECTED-BY NIL) (PHYSICALLY-
AFFECTED-BY NIL)   (ASSOCIATED-COMPONENTS NIL) (ASSOCIATION-
TYPE NIL) (INPUT (GET-DATA 'MACH))   (ACTUALS   ((NOISE-
LEVELS ((STATIC 0.01) (DERIVATIVE 0.0) (TREND 0.0)))
(QUANTITY-SPACES   ((STATIC   ((NORMAL (<= 0.0
(:SELF) 0.85)) (UPPER-CAUTION (< 0.85 (:SELF) 0.92))
(UPPER-WARNING (<= 0.92 (:SELF))) (:OFF-SCALE-HIGH (< 1.0
(:SELF)))   (:OFF-SCALE-LOW (< (:SELF) 0.0))
            (SENSOR-INOPERABLE (< 2.0 (:SELF)))))
(DERIVATIVE   ((DECREASING (< (:SELF) -0.005)) (STEADY (<
-0.005 (:SELF) 0.005))   (INCREASING (< 0.005
(:SELF)))))   (TREND   ((DECREASING (< (:SELF) -
0.1)) (STEADY (< -0.1 (:SELF) 0.1))   (INCREASING (< 0.1
(:SELF))))))   (QUEUE-LENGTHS ((QUANTITATIVE 5)
(QUALITATIVE 5))))   (EXPECTATIONS   ((NOISE-LEVELS
((STATIC 0.01) (DERIVATIVE 0.0) (TREND 0.0)))   (QUANTITY-
SPACES   ((STATIC   (

```
            (SENSOR-FAILURE
                 (MEMBER 'SENSOR-INOPERABLE
                 (RETRIEVE_DATA 'MACH 'ACTUALS
                      'QUALITATIVE-STATIC))))
```

(NORMAL (<= 0.0 (:SELF) 0.85)) (UPPER-CAUTION (< 0.85 (:SELF)
0.92))   (UPPER-WARNING (<= 0.92 (:SELF)))))
(DERIVATIVE   (

```
            (SENSOR-FAILURE
                 (MEMBER 'SENSOR-INOPERABLE
                 (RETRIEVE_DATA 'MACH 'ACTUALS
                      'QUALITATIVE-STATIC))))
```

(DECREASING (< (:SELF) -0.005)) (STEADY (< -0.005 (:SELF)
0.005))   (INCREASING (< 0.005 (:SELF)))))
(TREND   (
            (SENSOR-FAILURE

C-2

```
                (MEMBER 'SENSOR-INOPERABLE
                (RETRIEVE_DATA 'MACH 'ACTUALS
                    'QUALITATIVE-STATIC)))


(DECREASING (< (:SELF) -0.1)) (STEADY (< -0.1 (:SELF) 0.1))
(INCREASING (< 0.1 (:SELF))))))))        (QUEUE-LENGTHS
((QUANTITATIVE 5) (QUALITATIVE 5)))))        (DEVIATIONS
((NOISE-LEVELS ((STATIC 0.02) (DERIVATIVE 0.0) (TREND 0.0)))
(QUANTITY-SPACES ((STATIC NIL) (DERIVATIVE NIL) (TREND NIL)))
(QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE 5))))))))

(THROTTLE SENSOR

 ((FUNCTIONALLY-PART-OF (ENGINE)) (PHYSICALLY-PART-OF (ENGINE))
(FUNCTIONALLY-AFFECTS NIL)        (PHYSICALLY-AFFECTS NIL)
(FUNCTIONALLY-AFFECTED-BY NIL) (PHYSICALLY-AFFECTED-BY NIL)
(ASSOCIATED-COMPONENTS NIL) (ASSOCIATION-TYPE NIL) (INPUT (GET-
DATA 'THROTTLE))

      (ACTUALS        ((NOISE-LEVELS ((STATIC 1.0) (DERIVATIVE 0.0)
(TREND 0.0)))        (QUANTITY-SPACES        ((STATIC
((IDLE (<= 0.0 (:SELF) 5.0)) (FULL (<= 55.0 (:SELF)))
(:OFF-SCALE-HIGH (< 85.0 (:SELF))) (:OFF-SCALE-LOW (< (:SELF) -
10.0))
                (SENSOR-INOPERABLE (< 170.0  (:SELF)))))
(DERIVATIVE        ((DECREASING (< (:SELF) -0.05)) (STEADY (<
-0.05 (:SELF) 0.05))        (INCREASING (< 0.05 (:SELF)))))
(TREND        ((DECREASING (< (:SELF) -.10)) (STEADY (< -.10
(:SELF) .10))        (INCREASING (< .10 (:SELF))))))))
(QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE 5)))))

      (EXPECTATIONS        ((NOISE-LEVELS ((STATIC 1.0) (DERIVATIVE
0.0) (TREND 0.0)))        (QUANTITY-SPACES        ((STATIC ((IDLE
(<= 0.0 (:SELF) 5.0)) (FULL (<= 55.0 (:SELF))))))
(DERIVATIVE        ((DECREASING (< (:SELF) -0.05)) (STEADY (<
-0.05 (:SELF) 0.05))        (INCREASING (< 0.05 (:SELF)))))
(TREND        ((DECREASING (< (:SELF) -.10)) (STEADY (< -.10
(:SELF) .10))        (INCREASING (< .10 (:SELF))))))))
(QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE 5)))))

      (DEVIATIONS        ((NOISE-LEVELS ((STATIC 2.0) (DERIVATIVE
0.0) (TREND 0.0)))        (QUANTITY-SPACES ((STATIC
(
                (SENSOR-FAILURE
                (MEMBER 'SENSOR-INOPERABLE
                (RETRIEVE_DATA 'THROTTLE 'ACTUALS
                    'QUALITATIVE-STATIC)))

))
(DERIVATIVE
(
                (SENSOR-FAILURE
                (MEMBER 'SENSOR-INOPERABLE
                (RETRIEVE_DATA 'THROTTLE 'ACTUALS
```

```
                         'QUALITATIVE-STATIC)))
))
(TREND (

             (SENSOR-FAILURE
                  (MEMBER 'SENSOR-INOPERABLE
                  (RETRIEVE_DATA 'THROTTLE 'ACTUALS
                         'QUALITATIVE-STATIC)))
))
))          (QUEUE-LENGTHS ((QUANTITATIVE 5) (QUALITATIVE
5)))))))))


(FUNCTIONS   ((INTERFACE) (RECOVERY) (STAGE2) (STAGE1)
(MONITAUR

(
(DEFUN FF_GET (THR)
     (LET (FUEL_F)
     (SETQ FUEL_F (+ (* .16327 (* THR  THR))
                 100.0
                 ))
     )
)


(DEFUN GET-DATA (SENSOR-NAME)         (SECOND (ASSOC SENSOR-NAME
*REAL-DATA-LIST*)))

(DEFUN GET-FLIGHT-PHASE NIL          'CRUIZE)        (DEFUN EPR-UPPER-
WARNING (ALT MACH)        (LET ((FPHASE (GET-FLIGHT-PHASE)))
(COND ((EQUAL FPHASE 'TAKEOFF) (EPR-TAKEOFF-LIMIT ALT MACH))
((EQUAL FPHASE 'CLIMB) (EPR-CLIMB-LIMIT ALT MACH))
((EQUAL FPHASE 'CRUIZE) (EPR-CRUIZE-LIMIT ALT MACH)))))

(DEFUN EPR-UPPER-CAUTION (ALT MACH)          (LET ((PHASELIM (EPR-
UPPER-WARNING ALT MACH))           (CONTLIM (EPR-CONTINUOUS-
LIMIT ALT MACH)))        (- (MIN PHASELIM CONTLIM) 0.05)))

(DEFUN COMPUTE-TT2C (ALT MACH)        (LET (CFACT TEMPK THETA)
(SETQ CFACT (+ 1.0 (* 0.2 MACH MACH)))          (SETQ THETA (-
1.0 (* 6.87535e-6 ALT)))        (SETQ TEMPK (* 288.15 THETA))
(- (* TEMPK CFACT) 273.15)))        (DEFUN EPR-STRUCTURAL-LIMIT
(NEWEPR ALTITUDE)        (COND ((>= 6000.0 ALTITUDE 4000.0) (MIN
2.282 NEWEPR))            ((> 4000.0 ALTITUDE 2000.0) (MIN 2.16
NEWEPR))         ((>= 2000.0 ALTITUDE 1000.0) (MIN 2.06
NEWEPR))          ((> 1000.0 ALTITUDE 0.0) (MIN 2.01 NEWEPR))
((>= 0.0 ALTITUDE -1000.0) (MIN 1.96 NEWEPR))          ((> -
1000.0 ALTITUDE) (MIN 1.92 NEWEPR))        (T (MIN 2.282
NEWEPR))))

(DEFUN EPR-TAKEOFF-LIMIT (ALTITUDE MACHNUM)        (LET (TT2C
NEWEPR)          (SETQ TT2C (COMPUTE-TT2C ALTITUDE MACHNUM))
(SETQ NEWEPR            (COND ((> ALT 8000.0)
(COND ((> TT2C 32.0) (- 1.96 (* 0.009644 (- TT2C 32.0)))))
```

```lisp
((> TT2C 26.5) (- 1.98 (* 0.00363636 (- TT2C 26.5))))
((> TT2C 15.0) 1.98)                                    ((> TT2C -15.0)
(- 2.155 (* 0.0058333 (+ TT2C 15.0))))
(T (- 2.35 (* 0.004875 (+ TT2C 55.0))))))))
((> ALT 6000.0)                          (COND ((> TT2C 32.0) (-
1.96 (* 0.009644 (- TT2C 32.0))))
((> TT2C 29.0) (- 1.97 (* 0.0033333 (- TT2C 29.0))))
((> TT2C 16.0) 1.97)                                    ((> TT2C 15.0)
(- 1.98 (* 0.01 (- TT2C 15.0))))                                    ((>
TT2C -15.0) (- 2.155 (* 0.0058333 (+ TT2C 15.0))))
(T (- 2.35 (* 0.004875 (+ TT2C 55.0))))))))
(T (COND ((> TT2C 32.0) (- 1.96 (* 0.009644 (- TT2C 32.0))))
((> TT2C 17.5) 1.96)                                    ((> TT2C
15.0) (- 1.98 (* 0.008 (- TT2C 15.0))))
((> TT2C -15.0) (- 2.155 (* 0.0058333 (+ TT2C 15.0))))
(T (- 2.35 (* 0.004875 (+ TT2C 55.0))))))))))        (EPR-
STRUCTURAL-LIMIT NEWEPR ALTITUDE)))


(DEFUN EPR-CLIMB-LIMIT (ALTITUDE MACHNUM)        (LET (TT2C
NEWEPR)        (SETQ TT2C (COMPUTE-TT2C ALTITUDE MACHNUM))
(SETQ NEWEPR                   (COND ((> TT2C 20.0) (- 1.8375 (*
0.0059286 (- TT2C 20.0))))                          ((> TT2C 5.0) (-
1.94 (* 0.0068333 (- TT2C 5.0))))                          ((> TT2C
-15.0) (- 2.08 (* 0.007 (+ TT2C 15.0))))                          (T
(- 2.325 (* 0.006125 (+ TT2C 55.0))))))))        (EPR-STRUCTURAL-
LIMIT NEWEPR ALTITUDE)))


(DEFUN EPR-CRUIZE-LIMIT (ALTITUDE MACHNUM)        (LET (TT2C
NEWEPR)        (SETQ TT2C (COMPUTE-TT2C ALTITUDE MACHNUM))
(SETQ NEWEPR                   (COND ((> TT2C 35.0) (- 1.595 (*
0.006500593 (- TT2C 35.0))))                          ((> TT2C 25.0)
(- 1.665 (* 0.007 (- TT2C 25.0))))                          ((> TT2C
12.5) (- 1.765 (* 0.008 (- TT2C 12.5))))
((> TT2C 0.0) (- 1.875 (* 0.0088 TT2C)))
((> TT2C -15.0) (- 1.98 (* 0.007 (+ TT2C 15.0))))
((> TT2C -30.0) (- 2.075 (* 0.0063333 (+ TT2C 30.0))))
(T (- 2.225 (* 0.006 (+ TT2C 55))))))))        (EPR-STRUCTURAL-
LIMIT NEWEPR ALTITUDE)))


(DEFUN EPR-CONTINUOUS-LIMIT (ALTITUDE MACHNUM)        (LET (TT2C
NEWEPR)        (SETQ TT2C (COMPUTE-TT2C ALTITUDE MACHNUM))
(SETQ NEWEPR                   (COND ((OR (> ALTITUDE 20000.0)
(< ALTITUDE 2500.0))                   (EPR-CLIMB-LIMIT
ALTITUDE MACHNUM))                   ((> TT2C 22.5) (- 1.92
(* 0.008615 (- TT2C 22.5))))                          ((> TT2C 15.0)
(- 1.98 (* 0.008 (- TT2C 15.0))))                          ((> TT2C
-15.0) (- 2.155 (* 0.0058333 (+ TT2C 15.0))))
(T (- 2.35 (* 0.004875 (+ TT2C 55.0))))))        (EPR-
STRUCTURAL-LIMIT NEWEPR ALTITUDE)))))))))
```

8.0 Appendix D

New LISP Functions

```
;*******************************************************************
;
;              Function IS-NEARLY-PARALLEL-P1 Preamble
;
;     PURPOSE:    This function is used to see if the actual
;                 and expectation curves are nearly parallel
;                 by comparing values from the previous time
;                 slice.  It is a predicate returning T or F.
;
;     PARAMETERS: NAME - Sensor name
;
;     LAST MODIFIED:    None - this is original Boeing code
;                       created 3/91
;
;                       5/92 - Modified noise for fuel flow
;                              adding the algorithm here
;
;                       5/92 - Removed processing for time
;                              slice 2, not it only has one
;                              time slice comparison.
;
;                       5/92 - Divided higher-thn-expected
;                              processing from lower-than-
;                              expected
;
;*******************************************************************

(defun is_nearly_parallel_p1(sensor)
     (let (actual_minus_one
              actual_minus_two
              expected_minus_one
              expected_minus_two
              actual
              expected
              difference1
              difference2
              difference5
              difference6
              noise)

        (setq actual_minus_one (cadr (retrieve_data sensor 'actuals
'quantitative-history-queue)))
        (setq expected_minus_one (cadr (retrieve_data sensor
'expectations 'quantitative-history-queue)))
        (setq expected (car (retrieve_data sensor 'expectations
'quantitative-history-queue)))
        (setq actual (car (retrieve_data sensor 'actuals
'quantitative-history-queue)))
        (setq difference1 (- actual_minus_one expected))
        (setq difference2 (- expected_minus_one actual))
        (setq difference5 (-  actual actual_minus_one))
        (setq difference6 (-  actual expected_minus_one))
        (if (equal sensor 'fuel-flow)
```

```
            (setq noise (ff_calc))
            (setq noise (eval(retrieve_data sensor 'deviations
'noise-level)))
       )
;      (print "actual ")(princ actual)
;      (print "actual -1 ")(princ actual_minus_one)
;      (print "expected ")(princ expected)
;      (print "expected -1 ")(princ expected_minus_one)
;      (print "difference1 ")(princ difference1)
;      (print "difference2 ")(princ difference2)
;      (print "difference5 ")(princ difference5)
;      (print "difference6 ")(princ difference6)
;      (print "noise ")(princ noise)(terpri)
       (cond ((and
                 (> noise (abs difference1)))                'T)
              ((and
                 (< 0 difference5 )
                 (> 0 difference1 ))                         'T)
              ((and
                 (> 0 difference5 )
                 (> 0 difference6 ))                         'T)
              ((and
                 (> 0 difference5 )
                 (> noise (abs difference6)))
        'T)
              (T                                             'NIL)
       )
))
;*****************************************************************
;
;            Function IS-NEARLY-PARALLEL-P2 Preamble
;
;     PURPOSE:    This function is used to see if the actual
;                 and expectation curves are nearly parallel
;                 by comparing values from the previous time
;                 slice.  It is a predicate returning T or F.
;
;     PARAMETERS: NAME - Sensor name
;
;     LAST MODIFIED:   None - this is original Boeing code
;                           created 3/91
;
;                      5/92 - Modified noise for fuel flow
;                             adding the algorithm here
;
;                      5/92 - Removed processing for time
;                             slice 2, not it only has one
;                             time slice comparison.
;
;                      5/92 - Divided higher-thn-expected
;                             processing from lower-than-
;                             expected
;
;
```

```
;*****************************************************

(defun is_nearly_parallel_p2 (sensor)
      (let (actual_minus_one
              actual_minus_two
              expected_minus_one
              expected_minus_two
              actual
              expected
              difference1
              difference2
              difference5
              difference6
              noise)

      (setq actual_minus_one (cadr (retrieve_data sensor 'actuals
'quantitative-history-queue)))
      (setq expected_minus_one (cadr (retrieve_data sensor
'expectations 'quantitative-history-queue)))
      (setq expected (car (retrieve_data sensor 'expectations
'quantitative-history-queue)))
      (setq actual (car (retrieve_data sensor 'actuals
'quantitative-history-queue)))
      (setq difference1 (- actual_minus_one expected))
      (setq difference2 (- expected_minus_one actual))
      (setq difference5 (-  actual actual_minus_one))
      (setq difference6 (-  actual expected_minus_one))
      (if (equal sensor 'fuel-flow)
            (setq noise (ff_calc))
            (setq noise (eval(retrieve_data sensor 'deviations
'noise-level)))
      )
;     (print "actual ")(princ actual)
;     (print "actual -1 ")(princ actual_minus_one)
;     (print "expected ")(princ expected)
;     (print "expected -1 ")(princ expected_minus_one)
;     (print "difference1 ")(princ difference1)
;     (print "difference2 ")(princ difference2)
;     (print "difference5 ")(princ difference5)
;     (print "difference6 ")(princ difference6)
;     (print "noise ")(princ noise)(terpri)
      (cond
            ((and
                (> noise (abs difference2)))                    'T)
            ((and
                (> 0 difference2))                  'T)
            (T                                      'NIL)
      )
))

;*****************************************************
;
;                    Function FF_CALC Preamble
;
;
```

```
;      PURPOSE:    This function is used to calculate an
;                  accepatble noise value for fuel flow as
;                  a function of throttle setting.
;
;      PARAMETERS: NONE
;
;      LAST MODIFIED:   None - this is original Boeing code
;                       created 6/92
;
;                       7/92 - Modified coefficients from a new
;                              least squares analysis
;
;*********************************************************

(DEFUN FF_CALC ()
      (LET (FUEL_F
            THR )
            (setq thr (retrieve_data 'throttle 'actuals 'new-
static))
;      (SETQ FUEL_F (+ (* .076012 (* THR  THR))
;                      (* 3.0539  THR)
      (SETQ FUEL_F (+ (* .16327 (* THR  THR))
                      100.0
                    ))
      )
)

;*********************************************************
;
;
;                  Function CHECK_SPIKE Preamble
;
;      PURPOSE:    This function is used to determine if
;                  a data spike has occurred.  It is a predicate
;                  returning T or F.
;
;
;      PARAMETERS: SENSOR - The specific sensor name
;
;      LAST MODIFIED:   None - this is original Boeing code
;                       created 7/92
;
;*********************************************************


(defun check_spike (sensor)
      (let ((act_hist  (retrieve_data sensor 'actuals
'quantitative-history-queue))
            (exp_hist  (retrieve_data sensor 'expectations
'quantitative-history-queue))
            )
            (cond ((equal (length act_hist) 5) (calc_spike_vars
act_hist exp_hist sensor))
```

```
                     (T    NIL)
             )
      ))

;************************************************************
;
;           Function CALC_SPIKE_VARS Preamble
;
;     PURPOSE:    This function is used to determine if
;                 a data spike has occurred.  It looks for
;                 very large changes in the history queue
;                 which are not expected.
;                 It is a predicate returning T or F.
;
;     PARAMETERS: ACT_HIST - Queue of historical data for
;actuals.
;                 EXP_HIST - Queue of historical data for
;                           expectations.
;                 SENSOR - The specific sensor name
;
;     LAST MODIFIED:   None - this is original Boeing code
;                      created 7/92
;
;************************************************************


(defun calc_spike_vars (act_hist exp_hist sensor)
      (let ( (a1)
             (a2)
             (a3)
             (a4)
             (a5)
             (e1)
             (e2)
             (e3)
             (e4)
             (e5)
           )


             (setq a1 (car act_hist))
             (setq a2 (cadr act_hist))
             (setq a3 (caddr act_hist))
             (setq a4 (cadddr act_hist))
             (setq a5 (car(last act_hist)))
             (setq e1 (car exp_hist))
             (setq e2 (cadr exp_hist))
             (setq e3 (caddr exp_hist))
             (setq e4 (cadddr exp_hist))
             (setq e5 (car(last exp_hist)))

      (cond ((and
                (or
```

```
                    (member 'higher-than-expected (retrieve_data
sensor 'deviations 'qualitative-static))
                    (member 'lower-than-expected (retrieve_data
sensor 'deviations 'qualitative-static))
                    )
                (> (abs(- a1 a2)) (* 10 (/
                                    (+ (abs(- a2 a3))
                                       (abs(- a3 a4))
                                       (abs(- a4 a5))
                                    ) 3.
                                )
                            )
            )
            (not(> (abs(- e1 e2)) (* 10 (/
                                    (+ (abs(- e2 e3))
                                       (abs(- e3 e4))
                                       (abs(- e4 e5))
                                    ) 3.
                                )
                            )
            )))
                T)
            (T  NIL)
        )
))
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13. ABSTRACT *(Maximum 200 words)*

Previous work accomplished on NASA's Faultfinder concept suggested that the concept was jeopardized by spurious symptoms generated in the monitoring phase. The purpose of the present research was to investigate methods of reducing the generation of spurious symptoms during in-flight engine monitoring. Two approaches for reducing spurious symptoms were investigated. A knowledge base of rules was constructed to filter known spurious symptoms and a neural net was developed to improve the expectation values used in the monitoring process. Both approaches were effective in reducing spurious symptoms individually. However, the best results were obtained using a hybrid system combining the neural net capability to improve expectation values with the rule-based logic filter.

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