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AERONAUTICAL RESEARCH LABORATORY

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Propulsion Technical Memorandum 471

ENSURING THE INTEGRITY AND VERACITY OF AN INTERACTIVE FAULT DIAGNOSIS AND ISOLATION SYSTEM FOR A GAS TURBINE ENGINE

by

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SUMMARY

The tasks involved in developing a fault diagnosis expert system for a gas turbine engine are examined. Particular attention is given to the options available to maximise the quality of the advice given by the expert system. All phases of system development from knowledge acquisition, through to system support are covered. A general example of diagnosis by engineering analysis is given to demonstrate the concepts involved. Using acquired knowledge, a limited qualitative fault model of the TF30-P3 gas turbine engine afterburner has been developed, and application to some fault case examples is described.

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ABBREVIATIONS

General

ARL	Aeronautical Research Laboratory.
IFDIS	Interactive Fault Diagnosis and Isolation System.
PWA	Pratt and Whitney Aircraft.
QFM	Qualitative Fault Model.

TF30-P3 Gas Turbine Related Terms.

AB	Afterburner.
ABFC	Afterburner fuel control.
Aj	Afterburner primary nozzle position (0-10).
ECS	Environmental control system.
EPR	Engine pressure ratio.
Mil Power	Military power throttle setting.
Pb	Static pressure at high pressure compressor outlet.
Pb/Pt7	Turbine pressure ratio.
Pt7	Total pressure at turbine exhaust.
Wf	Fuel flow.

Qualitative Fault Model Parameters

Actuator	Action taken by nozzle actuator.
Aj	Nozzle area change.
Aji	Nozzle area change indicated to the ENC.
ENC Trim	Afterburner suppression change request.
Noz sig	Signal from the ENC to the nozzle actuators.
Pb	Pressure signal from the burner to the ENC.
Pb/Pt7	Turbine pressure ratio error signal.
PLA	PLA request to the ENC pilot servo valve.
Pt7	Tailpipe pressure change.
Pt7I	Tailpipe pressure change indicated to the ENC.
Wf	Fuel flow change to the afterburner.

1. INTRODUCTION

The use of expert system technology to provide aircraft engine maintenance personnel with an expert advisor has the potential to raise overall fault diagnosis performance. The processes involved in creating an expert system to perform this role are now quite well developed. The success of the IFDIS concept demonstrator at proving the concept of providing an acceptable advisor for troubleshooting is an example of this fact.

The task at hand now is to ensure that,as these expert systems pass from prototype and concept demonstrator phases into systems that are implemented on line in the maintenance environment, the advice given becomes worthy of the "Expert Advisor" name.

This document examines the ways in which the knowledge behind the advice given can be of the highest attainable quality. Broadly the recommended approach is to aquire integrated experiential and engineering knowledge, and apply this knowledge to the causal justification of the expert system rules and the development of a qualitative fault model.

The three concepts given above of acquiring integrated experiential and engineering knowledge, causal justification of rules, and qualitative fault modeling are central to overcoming the problem of producing an expert system which performs with a high degree of integrity and veracity. These qualities are crucial to the success of a diagnostic expert system. As such, investigative effort into these fields is seen as a worthwhile exercise.

2. INTERACTIVE FAULT DIAGNOSIS AND ISOLATION SYSTEM.

The IFDIS project utilises expert system techniques in the field of jet engine diagnostics. A concept demonstrator has been developed which is an expert advisor for troubleshooting faults in the afterburner of the TF30 jet engine. The problem domain dealt with in the concept demonstrator was in the main restricted to the afterburner. The concept demonstrator allows in-depth troubleshooting to be performed. The degree of integrity and veracity with which IFDIS performed its diagnostic task was however an unknown quantity.

It is the goal of this document to examine the possible alternatives available to ensure that IFDIS performs with a high degree of integrity and veracity.

3. JUSTIFICATION FOR INVESTIGATIVE EFFORT INTO VERIFICATION AND VALIDATION OF IFDIS.

To facilitate the development of procedures for raising the diagnostic performance of IFDIS, methods which are integral to the development process will be examined. These methods are required to be such that they enhance the normal system development and produce a high quality final product .

The environment of aircraft fault diagnosis has several special considerations which demand that an effort in verification and validation of any diagnostic system be undertaken. These considerations are the high cost (both human and monetary) which is involved with incorrect diagnosis, the complexity of the engine, and the need for the expert system to be an expert advisor to maintenance personnel. To perform this latter role successfully the fundamental requirement is that the system provides advice which justifies the title of 'Expert Advisor'. If the users do not perceive this quality of advice to be present, then their confidence in the consultation sessions may be expected to be low.

The task is further complicated by the performance of current diagnostic techniques. The figure for successful diagnosis of an engine fault with current procedures is commonly placed at approximately 50%.The introduction of a system like IFDIS provides a chance to improve this situation if action is taken to raise the level of 'deep knowledge' behind the IFDIS diagnostic decisions. This possibility of improving the low success rate is a major incentive to expend the effort involved in verifying and validating the expert system to a level above current diagnostic procedures.

4. OVERALL STRATEGY.

If the requirement for ensuring that an expert system performs to a high level of quality is accepted, then the choice of the overall strategy which should be adopted is the first issue to be addressed.

Two overall strategies present themselves as the possible alternatives. The first method would be to develop the system to the point where it could perform the troubleshooting task, and to then focus energies upon correcting faults in the developed system. The second strategy would be to apportion a degree of the resources available at every phase to ensure that the end result of each phase was of the highest attainable quality, and hence that the end product was as complete as possible at that point in time.

The fundamental difference between these two approaches is in effectiveness of effort.

The first method of developing the system and then correcting it, has to contend with the inertia of an existing system. This requires effort and resources to ensure that corrections and changes are propagated throughout the entire system. Furthermore implementing these changes may prove to be impractical if the detected fault is fundamental to a large part of the troubleshooting, and hence the effort involved is comparable to a major rewrite of the knowledge base.

The second method of continuous assessment during the development of the system tends to use the minimum effort for the maximum effect. This occurs when mistakes are corrected as they occur and hence before they have a chance to propagate throughout the system.

So in terms of efficient use of resources the second method may be seen to be the ideal towards which the development methods of the system should aspire.

Therefore all of the phases which are involved in developing an expert system are examined below, and procedures are defined for each of the phases which are aimed at maximising the quality of knowledge in the final product, as well as maintaining the knowledge quality throughout the life of the system.

For the purposes of this description the development of a fault diagnosis expert system has been divided into the following phases:

- Knowledge Acquisition,
- Knowledge Manipulation,
- Knowledge Validation and Verification,
- Knowledge Support.

5. KNOWLEDGE ACQUISITION.

Knowledge acquisition is the first phase of the expert system creation. The quality of the knowledge which is acquired at this stage is the fundamental limiting factor for the performance of the expert system. The expert system is based upon this knowledge and without feedback the system can never perform above the quality of this knowledge. The job of the knowledge engineer is to strive to represent this knowledge as exactly as possible. As the knowledge engineer is not a domain expert, it should not be the knowledge engineer's task to raise the quality of the knowledge above that originally acquired for the system. Therefore it can be seen that the efforts of the knowledge engineer can only be justified when the knowledge acquired from domain experts is considered to be of a high standard.

5.1. Maximising the Quality of Acquired Knowledge.

If optimum performance is sought from the expert system then the task of acquiring the knowledge should be tailored to the nature of the problem, in this case the TF30-P3. A modern gas turbine engine such as the TF30-P3 is among the most complex mechanical systems in use today. The parameters involved in diagnosing a fault are numerous and often subtly inter-related. The knowledge involved in successfully diagnosing faults must be such that it recognises these interrelations and their implications. So the initial problem becomes one of how to acquire such knowledge.

The sources of knowledge which are available for the TF30-P3 are:

1. Maintenance documentation,
2. Maintenance personnel (technical & engineering).
3. Propulsion engineers (ARL & PWA).

In order to extract the maximum from these information sources it should be recognised that two fundamentally different forms of knowledge are present. These are heuristic or experiential knowledge, and engineering knowledge. It has been previously recognised [1] that the optimum path for many expert systems lies in developing their knowledge bases using the individual strengths of both types of knowledge. It is proposed here that it would be possible to utilise the information sources given above, to develop a system based upon both types of knowledge. This is seen as being advantageous given the complexity of the problem.

In order to optimise the acquired knowledge, the knowledge types should be implemented according to their strengths. Examination of the exclusive use of either type reveals the strengths and weaknesses of each knowledge source.

Engineering knowledge is that knowledge which is solely derived from an understanding of the system's design. This knowledge forms a description of the system and its possible behaviours.Such knowledge may be obtained from descriptive documentation including the maintenance documentation, and from personnelsuch as propulsion engineers who are familiar with design considerations. From these knowledge sources it is possible to systematically examine the entire engine, at a component level that is appropriate to the troubleshooting task. The aim of this examination is to enumerate component behaviour, relationships and effects with and upon other components, and any relevant observables.
The result of this process is that it effectively defines the scope, coverage, and completeness which may be attributed to the expert system. It also provides the system with a deeper level of knowledge than is possible with purely experiential reasoning .This high degree of completeness is the major strength of engineering analysis, however the implications of this completeness show the major weakness of engineering analysis. For although it provides the foreseeable range of fault possibilities for a given set of symptoms, it does not provide a basis for discriminating between the possibilities. In effect, engineering analysis provides the possibilities which should be considered, but it does not reveal the optimum troubleshooting paths to arrive at and eliminate possibilities.

Experiential knowledge, by comparison, is gained from experience in maintaining the engine. It is based upon, for the TF30-P3, well established troubleshooting techniques, the historical record of symptom to fault,relationships, and a hands-on knowledge of the engine's operation. The sources of experiential knowledge are the maintenance personnel and the troubleshooting documentation. This knowledge type is aimed at finding the most probable causes of any problem and addressing the order in which they should be investigated to find the actual cause in the minimum time. The strength of this knowledge type is this inherent focusing upon the most probable cause of the unserviceability. The accompanying drawback however is that this focused outlook does not provide an indication as to the coverage which has been achieved for the problem. Furthermore experiential knowledge has difficulty dealing with a fault that has not been experienced before. This means that extremely rare or first occurrences of a fault will not be correctly diagnosed or even considered.

From the preceding description it may be seen that exclusive use of either type of knowledge leads to a knowledge base which is deficient in some important performance aspect. It may also be seen that the two types of knowledge are complementary in that the deficiencies of one are covered by the characteristics of the other.

This leads to the conclusion that a system which acquires its scope, structure, and completeness from engineering analysis, and acquires its controlling and troubleshooting guidance from experiential sources, will be an expert system which has the capability of performing with a high degree of integrity and veracity.

5.2. Acquiring Engineering and Experiential Knowledge.

The task of acquiring the knowledge so that it conforms to the above ideal may be achieveable by several knowledge acquisition techniques.The basic requirement is that the knowledge engineer receives input from both experiential and engineering knowledge sources.

It is envisaged that this may be achieved by the knowledge engineer acquiring knowledge from a team of experts, being personnel who are considered as the most capable of examining and debating to a satisfactory conclusion the troubleshooting problems at hand.

It is envisaged that the team would be led by a senior engineer who is responsible for conflict resolution and communication of knowledge to the knowledge engineer. The team would be comprised of maintenance technicians and engineers who are familiar with the engine.The maintenance technicians would provide the main heuristic input to the knowledge, while the role of the engineers would be to provide engineering analysis of the fault situation. In this way the engineers on the panel set out in a particular problem field to enumerate the possible faults and system behaviours. An example of this is given in Appendix 1 where the problem of full afterburner power not being attainable is examined purely from a description of the engine design.

The maintenance technicians may then apply their knowledge to the matter of troubleshooting the faults listed as possible. Any conflict in opinion between the two knowledge sources would be resolved by the requirement to justify any conflicting beliefs to the senior engineer . This arrangement allows the strengths of both types of knowledge to be exploited. The scope of any investigation would be determined by the propulsion engineers and the troubleshooting procedure by the maintenance technicians.

6. KNOWLEDGE MANIPULATION.

Once the knowledge has been acquired the next phase of development which has a bearing upon the expert system's performance is the knowledge manipulation. Knowledge manipulation may be thought of as the processes involved in turning the acquired knowledge into verifiable rules and an associated inference engine. It is the knowledge engineer's task to interpret the acquired knowledge into a rule set. It is not the purpose of this document to delve into the knowledge engineer's task, and as such the interpretation process will not be detailed. However, knowledge manipulation may also involve the development of a method with which to check the developed rule set. The options which are available for providing the knowledge supervisor with a facility for checking the rule set are detailed below.

6.1. Application of Acquired Knowledge to Check Developed Rule Sets.

The knowledge which has been acquired in the first phase of operations may be applied by the knowledge supervisor and associated personnel to ensure the performance of the expert system. Two possible methods of applying the acquired knowledge to verify rules are outlined below. These involve causal justification of rules and the development of a qualitative fault model.

6.2. Causal Justification of Rules.

The knowledge engineer attempts to interpret the acquired knowledge into rules. This implies that the knowledge engineer forms the rule from his or her interpretation of the reasoning which was extracted from the experts. In this way the knowledge engineer arrives at a set of conditions, and a set of conclusions and actions which pertain to each individual hypothesis or rule. The main question at this stage is: how can it be ensured that the knowledge engineer has successfully translated the expert's reasoning and conclusion into a rule?

Causal justification of rules aims at providing a method to achieve this requirement. A rule may be said to be causally justified when the linkages between the conditions and the actions of the rule are enumerated in a causal fashion. This enumeration is required to be such that an independent engineer, with experience in the field of jet propulsion and access to TF30-P3 documentation, would be able to follow and judge the validity of the causal linkages. An example of this method is given below.

Example

In troubleshooting the unserviceability of "Full Afterburner power not available." the following rule may be employed. This rule is brought into consideration when the symptom set provided by the user agrees with the rule's conditions. This is not the sole conclusion which may be derived from these symptoms and as such it should be viewed as an isolated element of the complete set of conclusions and actions which would result from the symptoms provided.

IF full afterburner power not available,
AND fuel flow state at maximum is steady,
AND fuel flow maximum (on ground) < 32000pph,
AND nozzle position at maximum < 10,

THEN Afterburner Fuel Pump is possible fault.

Causal Justification.

A degraded afterburner pump will not be capable of producing the fuel flow rate and head required by maximum afterburner selection. The result of a fuel pump degradation, if the pump is still operating, will be either a reduced flow at the required head or a reduction in the head obtainable, both of which would normally result in reasonably steady conditions. Therefore if the afterburner pump is the fault then the fuel flow may well be steady and below 32000pph. If the exhaust nozzle control is operating correctly it will not allow the nozzle area to reach 10. This will be required as the reduced fuel flow would result in a low Pt7 if the nozzle attained 10. Hence the exhaust nozzle control will lower the nozzle area to maintain the desired turbine pressure ratio. Therefore the symptoms which may be noted with a faulty afterburner pump are:

(1). reduced but steady fuel flow, and
(2). reduced nozzle size.

These justifications not only allow the verification and validation of the expert system to be carried out but they also may be manipulated to facilitate the knowledge support as will be described in the knowledge support section.

6.3. Qualitative Fault Model.

Acquiring experiential and engineering knowledge of the TF30-P3 provides an opportunity to develop a qualitative fault model for the engine. This task is compatible with a desire to produce an expert system which performs with a high degree of integrity and veracity. As developing the qualitative model captures the acquired knowledge in a form which can be used to verify and validate the expert system.

A qualitative fault model is a computer simulation of the engine which utilises the qualitative relationships between engine and aircraft components to model engine behaviour. The type of model which may be constructed is dictated by the knowledge which is available and the relative value of the knowledge in constructing a fault model. These factors of applicability and availability of information resulted in the choice of a qualitative model as opposed to a quantitative model. The qualitative information available on the TF30-P3 is of sufficient detail to construct a qualitative model which would be useful for verifying a diagnosis system. In contrast the quantitative data are in general not as readily available and even if available they do not readily lend themselves to the task of fault modelling.

Therefore if the knowledge which has been acquired for the expert system is to be utilised in the construction of the qualitative model then the nature of the model is predetermined to a large extent. For the knowledge gained in the development of the expert system deals almost exclusively with line replaceable units and their observable behaviour. This dictates the fundamental model elements (typically aircraft or engine components) which the modelling process utilises and the interactions between these elements which the model will consider. Furthermore the purpose of using this model to check the performance of the expert system, provides most of the additional guide-lines required for the model's structure. This requirement specifies the behaviours which are to be considered in the model. The behaviours are those associated with each failure mode for any component of the model which has been considered in the expert system.
Hence the form which the model will take is reasonably defined by the considerations given above. For further description of the qualitative model concept and an example of a limited qualitative model, which deals with the operation of the TF30-P3 afterburner, refer to Appendix 2.

The method of using a qualitative fault model to check the expert system is further detailed in the verification and validation, and expert system support sections. Briefly, the QFM enhances these later stages of the development process by providing a systematic way of checking the entire expert system's performance, hence providing a check for the integration of all related causal justifications into a cohesive system.

7. VALIDATION AND VERIFICATION.

The process of validation and verification should be the natural culmination of the work done in the knowledge manipulation phase. The way in which this can be achieved is set out below.

7.1. Causal Justification.

Validation and verification using causal justification is an iterative process. The knowledge engineer provides the knowledge supervisor with subsets of the rules and their justifications as they are developed. The knowledge supervisor then instructs a propulsion engineer to review all justifications. This review compares the justifications to the knowledge as acquired and determines whether the rule is an accurate representation of the causal justification, and if the causal justification is in itself valid.

Feedback regarding any proposed changes which are required to correct detected errors is then provided to the knowledge engineer . The knowledge engineer may then address the identified errors. The final justification then occurs when the rules and justifications submitted by the knowledge engineer are deemed satisfactory by the knowledge supervisor.

7.2. Qualitative Fault Model.

If the knowledge acquired in the first phase of the system development was utilised to produce a qualitative fault model (QFM) then the verification of the system may proceed as follows. The fault model may be activated so that the symptom sets associated with each fault are generated. These symptom sets may now be used to answer the diagnostic queries of the expert system. The system may be considered to be performing satisfactorily when

1. the fault associated with the symptom set is identified as 'indicated'.

2. other faults which the system determines to be 'indicated' or ' possible' are not associated with contradictory symptom sets .

3. those faults with symptom sets which are not contradictory to the input symptom set are not rated as 'not indicated' by the system.

When the system can satisfy these three conditions for the entire fault set then it may be considered to be verified.

8. KNOWLEDGE SUPPORT.

Knowledge support is the mechanism by which the expert system's support authority responds to feedback from the users, and implements new knowledge as it becomes available. The feedback from the users identifies any errors which may have escaped detection during the development process, as well as allowing the users have an input into improving the system when they consider that an improvement in the diagnosis could be achieved. The implementation of new knowledge as it becomes available allows the system to respond to updates in the engine and to changing operating environment aspects, such as the ageing of the fleet, and any changes in usage of the fleet.

The approach to knowledge support is dependent upon the development method which was utilised. If causal justification was employed to verify the original system then this method can be extended to perform the knowledge support role.

In this case the response to feedback involves the initiator(s) of the feedback setting out the perceived error in the system.The support authority may then respond to the problem by reviewing the justifications used in the suspect area to determine any possible fault in belief or execution by the system. If such a fault is found then the proposed correction must be causally justified and the change propagated throughout the system.

New knowledge may be dealt with by determining the alterations and additions which this new information projects onto the knowledge which was used to construct the system. To achieve this the justifications used in the development and support of the system are reviewed to determine what changes are required. The changes may then be implemented to utilise this new knowledge. In this way the causal justifications associated with the expert system rules may be used to maintain the system.

If in addition a QFM was constructed during the system development then all possibilities for knowledge support mentioned above are possible. Additionally the QFM may be used to great advantage in the knowledge support role if any changes which are deemed to be worth implementing on the expert system are reproduced on the QFM. This having been done the QFM may then be run for the full fault set to observe any alterations in symptom sets associated with any faults. In this way the full implications of any change to the knowledge behind the expert system may be revealed. This provides the opportunity to note implications of the feedback or new knowledge which otherwise may not have been recognised.

In this way a QFM may be used to significantly enhance the knowledge support performance of the justification process given above.

9. CONCLUSIONS

The 'complete approach' is required to produce a diagnostic expert system which performs with the highest degree of integrity and veracity.

This 'complete approach' involves all phases of the system development as follows:

Knowledge acquisition acquires engineering knowledge to determine the scope of the knowledge required, and acquires experiential knowledge to focus the troubleshooting most appropriately.

Knowledge manipulation should transform the acquired knowledge into a representation that may readily be proven to be an accurate or inaccurate interpretation of the expert's knowledge(which represents the best knowledge available at the time of acquisition). This is achieved by supplying causal justification for all of the rules in the expert system to the knowledge supervisor who will only pass the rules when satisfied that they accurately represent the knowledge as acquired. If the resources are available the acquired knowledge may also be utilised to develop a qualitative fault model of the engine. This development is seen as being justified by the enhancement in the quality of the validation and verification, and the support phases of the expert system development.

Knowledge validation and verification is seen as a process which should have its basis in the knowledge manipulation phase. Initially during the manipulation phase and finally in the validation and verification phase the knowledge engineer should supply the knowledge supervisor with the proposed justifications for the rules in the expert system.This is an iterative process which is carried out until the knowledge supervisor is satisfied that the rules and their justifications accurately represent the knowledge as acquired. Further, if a qualitative fault model has been developed it may be used to examine the system's performance over the entire problem domain. In that way it is possible to ensure that the system as a whole performs to the potential of the justified component system elements.

Knowledge support is achieved by taking the feedback and new knowledge which becomes available and passing it through an extension of the same process which the originally acquired knowledge was subject to. In this way the system's performance can be increased above the level achievable with the original expert knowledge. Hence the system has the capability of providing expert advice which starts off as being the best available at the time of release, and improves with time.

This complete approach affects all aspects of the development and support of the expert system. It is the most effective way of producing an expert advisor which performs, and will continue to perform with the highest degree of integrity and veracity.

As such it is recommended that all phases in the development of IFDIS or a similar system should be carried out in such a way that the ability to verify and validate the system being generated is a primary goal of all personnel involved. Then systems may be produced which can successfully make the transition from prototypes to operational expert advisory systems.

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Appendix 1. Troubleshooting "Full Afterburner Power Not Available" by Engineering Analysis.

1.Unserviceability definition.

"Full afterburner power not available " describes several possible engine conditions. If maximum afterburner has been selected on the throttle and either the nozzle indication is below 10, or fuel flow is below expected (36000pph on the ground), or EPR is below day temperature limits then any occurrence or combination of these symptoms leads to the unserviceabilty "Full afterburner power not available ".

2.First level analysis of Primary symptoms.

In order to ascertain the relevant starting points for the physical investigations, the primary symptoms listed above were examined. These symptoms provide pointers to the influences of the fault. The naming of these influence occurrences, in turn generates the directions which the next level of investigation should follow.

This first level analysis leads to the following influences being identified.

Primary symptom;Aj<10 & Wf=36000pph.

POSSIBLE CAUSES
1.Nozzle positioning incorrect,
2.Nozzle position indication incorrect,
3.Fuel utilisation is substandard.

Primary symptom;Aj<10 & Wf<36000pph.

POSSIBLE CAUSES
These include those listed above with the addition of
4.Fuel flow supply below the required level.

Primary symptom;Aj=10 & Wf<36000pph.

POSSIBLE CAUSES
The causes of these symptoms are covered by those given above.

Primary symptom;EPR not attained.

It should be noted that the point considered most critical for EPR is at Military power. Hence it is unlikely that the engine would fail EPR requirements at Maximum afterburner power after passing the requirements at Military power. However for the sake of completness the EPR case will be examined.

POSSIBLE CAUSES
5.Engine efficiency below required level.

All of the events listed above under POSSIBLE CAUSES may be considered as the fault influences which were observed when the unserviceability was reported. The analysis may now procede by tracing the causal chains which could produce these observed influences.

3.Causal chain fault tracing.

The aim of this investigative step is to identify the set of faults which could produce each observed fault influence. This is achieved by determining the departures from correct operation which could cause the fault's observable influences. Examination of the roles of components which are involved in these suspect operations reveals the components which have the potential to produce the observed symptoms.

The investigative process involved in identifing the potential faulty component set is given in figure 1.

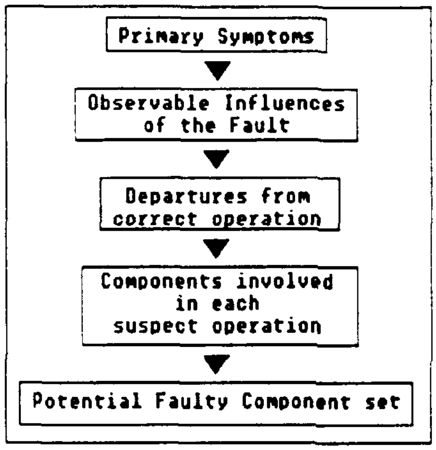

Figure 1.

Departures from correct operation.

By dealing with each observable influence in turn the responsible departures from correct operation may now be determined.

1.Nozzle positioning incorrect

Examination of the engine reveals the departures from correct operation which may be responsible for incorrect nozzle positioning. These have been listed out below.

EITHER:
1.1.Nozzle positioning system received incorrect instruction.
OR:
1.2.Nozzle positioning system incapable of correctly executing instruction.
OR:
1.3.Nozzle positioning system missinterprets state of Aj and/or other input parameters.

The departures from correct operation listed above, (1.1, 1.2, 1.3), may now be individually examined to determine the components involved in the operations. This will reveal the potentially faulty component set. Furthermore the effects of the failures listed may be traced to confirm the primary symptoms which should be expected for the listed failure.

1.1 Nozzle positioned incorrectly having received incorrect instructions.

The nozzle receives positioning instructions via the PLA input.
PLA request originates at the *throttle* and is transmitted via the *throttle linkages*. Hence it may be seen that the critical components are the throttle and throttle linkages.
The implications of missrigging may now be examined to confirm the possibility of these components being at fault.
IF throttle and throttle linkages are missrigged low THEN
120 degrees PLA not reqested
AND
 Aj<10,
AND
 Wf scheduled<36000pph

HENCE 1.1 =>THROTTLE & THROTTLE LINKAGES would belong
 to the Aj<10 & Wf<36000pph problem class.

1.2. Nozzle positioning system incapable of correctly executing instruction.

The nozzle is positioned by the *actuators* which are in turn positioned by the *ENC Nozzle positioning svstem.*
It may be seen therefore that if the nozzle is incapable of Aj=10 due to stuck actuators or ENC that Wf < 36000pph by feedback & Pb/Pt7 system which is operating correctly.

HENCE 1.2 =>ACTUATORS & POSITIONERS is in the Aj<10
 & Wf<36000pph problem class.

1.3 Nozzle positioned incorrectly due to incorrect parameter state input.

This must be further subdivided to account for the different inputs.

(a)Pt7 as the input parameter.
Pt7 is sensed by a *Pt7 probe* & transmited to *Pb/Pt7 system.*
The Pb/Pt7 system then commands nozzle positioning
IF Pt7 received is lower than actual THEN
 Pb/Pt7 system will lower Aj to compensate for the perceived Pt7 error. This will raise Pt7 above desirable levels, and may produce an unsustainable pressure ratio across the engine fan. This may result in a stall. *(Note this is an example of how the analysis can reveal other implications of a fault. In this case depending upon operating conditions this fault may result in a completely different unserviceability being reported i.e. "Engine Stalls at some Intermediate Zone of Afterburning".)*
HENCE 1.3.(a)=>Pt7 PROBE & LINE will result in Aj<10 &
 Wf=36000pph.

(b)Pb as the input parameter.
The Pb signal to ENC Pb/Pt7 system commands nozzle positioning
IF Pb received is above actual THEN
  Pb/Pt7 system will lower Aj
AND
  stall may result

HENCE 1.3.(b)BLOCKED ENC Pb LINE will result in Aj<10 &
  Wf=36000pph.

(c)Aj as the input parameter.
The feedback rigging transmits Aj to ENC which compares signal to requested Aj and Wf is rescheduled.
IF Feedback rigging indicates Aj higher than actual THEN
  Aj (actual) <10
AND
  Aj (indicated)=10
AND
  Wf<36000pph (due to down trimming by Pb/Pt7 system)
HENCE 1.3.(c)FEEDBACK RIGGING HIGH will result in the third class of problem Aj(indicated)=10,Wf<36000pph.

IF Feedback rigging indicates Aj lower than actual THEN
  Aj (indicated)<<10
AND
  Aj (actual)<10 (due to low Wf schedule and Pb/Pt7 system)
AND
  Wf<36000pph
  HENCE 1.3.(c)FEEDBACK RIGGING LOW will result in a problem of the Aj<10,Wf<36000pph class.

In summary of the findings so far, the potential faulty component set which is responsible for the observable fault influence of *incorrect nozzle positioning* is as follows.

- Throttle setting stops,
- Throttle linkage rigging,
- Nozzle actuators,
- ENC nozzle positioning system,
- Pt7 probe and sense line,
- ENC Pb line,
- Nozzle feedback rigging.

This same process may now be carried out for the remaining observable fault influences. The potential faulty component sets which were generated in this fashion are listed below.

Observable fault influence	Potential faulty component	Associated primary symptom
1.Nozzle positioned incorrectly:	*Throttle setting stops.	*Aj<10,Wf<36000pph
	*Throttle linkage rigging.	*Aj<10,Wf<36000pph
	*Nozzle actuators.	*Aj<10,Wf<36000pph
	*ENC nozzle positioning system.	*Aj<10,Wf<36000pph
	*Pt7 probe and sense line.	*Aj<10,Wf=36000pph
	*ENC Pb line.	*Aj<10,Wf=36000pph
	*Nozzle feedback rigging.	*Aj<10,Wf<36000pph
2.Nozzle position indication incorrect:	*Cockpit nozzle indicator.	*Aj<10,Wf=36000pph
3.Fuel utilisation is substandard:	*Fuel leak post AB pump.	*Aj<10,Wf=36000pph
	*Damaged zone rings or Flame holders.	*Aj<10,Wf=36000pph
4.Fuel flow below required level:	*Metering heads.	*Aj<10,Wf<36000pph
	*AB pump.	*Aj<10,Wf<36000pph
	*AB pump turn on switch.	*Aj<10,Wf<36000pph

4.Inferring additional observable symptoms associated with identified faults.

The faulty component set which describes the possible causes of *full afterburner power not available* has now been established. The components which make up the set may now be examined individually to identify any associated secondary symptoms. These secondary symptoms are required in order to differentiate between faulty components which exhibit identical primary symptoms.

The processes involved in inferring and deducing the secondary symptoms associated with a fault are shown in the figure below.

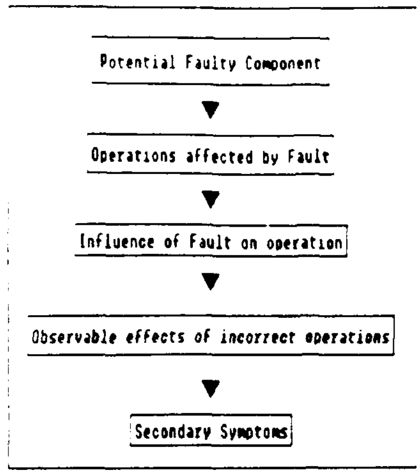

Figure 2

This procedure is demonstrated below for the fault of *Pt7 probe blocked and /or Pt7 sense line leak*.

Operations affected by fault

The Pt7 probe senses tailpipe pressure. The sensed pressure is transmitted to the ENC turbine pressure ratio controller via the Pt7 sense line.

Hence the immediate effect of a failure in the probe or sense line will be corruption of the ENC Pb/Pt7 ratio.

Corruption of the Pb/Pt7 ratio will in turn cause incorrect nozzle positioning.

Incorrect nozzle positioning will affect the tailpipe pressure which will change the EPR , such that the N1 & N2 spool speeds will alter. The changing of the N2 spool speed will be counteracted by the main fuel control, which will reschedule main engine fuel flow to maintain desired N2 RPM.

Influence of the fault upon affected operations.

The faults investigated here are of a blockage of the probe or a leak in the sense line.

If either of these conditions exist then the pressure transmitted to the ENC will be lower than the actual pressure.

Thus examination of the operation description given above reveals that

1.Nozzle will be positioned lower than required.
2.Tailpipe pressure will be higher than desired.
3.Engine EPR will be raised.
4.Pressure ratio across the fan will rise.

From this set of conditions the observable effects of the fault may be listed. These will be the Primary and Secondary symptoms.

Observable effects of the incorrect operations.

1.Nozzle will be positioned low. (ie $Aj < 10$ in this case a primary symptom.)
2.EPR may be high in comparison to the other engine.
3.The engine may stall due to increased fan pressure ratio.
4.Lightoff detection may be delayed, and stalling at AB initiation may occur.

Hence the secondary symptoms associated with a blocked Pt7 probe or a leaking Pt7 sense line are:

1.Comparatively high EPR,
2.Engine may stall at AB initiation, or at intermediate AB operation,
3.Nozzles may be slow to unlock at AB initiation.

This procedure was carried out for all of the components identified in the initial investigation phase. The secondary symptoms associated with the components are listed below.

Pt7 probe.	:Engine may stall;Pressure ratios incorrect; :Light-off detec & Noz unlock late;EPR high.
Pb line.	:Pressure ratios incorrect; Fuel in line.
Cockpit indicator.	:Measurement & indication do not agree; :Engine performance otherwise satisfactory.
Flame holders & rings.	:Visual inspection. :
Fuel leak.	:Visual inspection.
Throttle & linkages.	:PLA<120° When throttle at MAX;Throttles :split for various settings.
Nozzle actuators.	:Visual inspection;Rough noz motion;Noz does :not totally pop open below idle.
ABFC.	:Reduced Wf through certain zones; :Wf lower than 36000pph.
AB Pump.	:Wf lower than 36000pph;Fuel pressure at :ABFC zone outlets low.
Pump switch.	:As for AB pump and;If Wf<4000pph then :switch closed.
Nozzle Feedback.	:Noz pos indic not 0 at idle;Engine may :tend to stall.
7th & 12th Bleeds.	:Check their operation by 0.1 EPR rise.
Anti-iceing.	:Check their operation by observation. :Should be off.
Inlet.	:Check for fully open position.
ECS.	:If both engines in trouble and problem :disappears when ECS switched away.
ENC trim	:Engine may tend to stall;EPR may be high.Wf :& Aj may fluctuate if so ASSK may alleviate.

Appendix 2. Qualitative Fault Model of the TF30-P3 Afterburner.

This appendix details work done on the development of a qualitative fault model for the afterburner of the TF30-P3.

Modelling Goal.

The model was developed to demonstrate the concepts involved in building a fault model for diagnosis of faults in a gas turbine engine. The primary task of the fault model was to provide an indication of the behaviour of the engine when one component within the engine was not functioning correctly. Careful examination of the predicted engine behaviour then provides a set of observable symptoms which can be associated with the embedded fault.

Information Required for Modeling.

The structure and content of the model was determined by the knowledge and information which were available for its construction. The information required was a description of the behavior of all relevant components and of the interactions between the components. This information was required to be of sufficient detail so that the output of any system of components could be determined from the input to the system and the operational state of the components within the system.

The documented information available for the construction of this model consisted of the Field Maintenance Instructions for the TF30 (reference[4]), and the training notes for the RAAF F111 Engine and Fuel Control Unit courses (references[2],[3]). As these were the main sources of information they dictated that the model be qualitative as opposed to quantitative. Little if any quantitative data were given regarding the performance of the components, rather they supplied descriptions of the behavior and nature of the components.

Therefore a qualitative fault model was constructed which could indicate qualitative changes in engine parameters which were considered important.

Structure of Model.

The structure of the model was to a large extent determined by these knowledge sources, and their description of component behaviour.

The type of knowledge obtained allows the afterburner to be broken down into a collection of main-systems and then further into sub-systems. This process is continued until a level is reached where the input-output relationship for the sub-system is well defined for all input conditions to the sub-system.

The main-systems considered in the model were the Afterburner, Exhaust Nozzle Control (ENC), and the Afterburner Fuel Control (ABFC). An example of the reduction of a main-system into sub-systems which are in turn further detailed into smaller sub-systems is given below.

These diagrams display the reduction of the ENC into four sub-systems, and then the further reduction of one of these sub-systems to a level where the output of the sub-system may be determined, in qualitative terms, from the inputs to the sub-system.

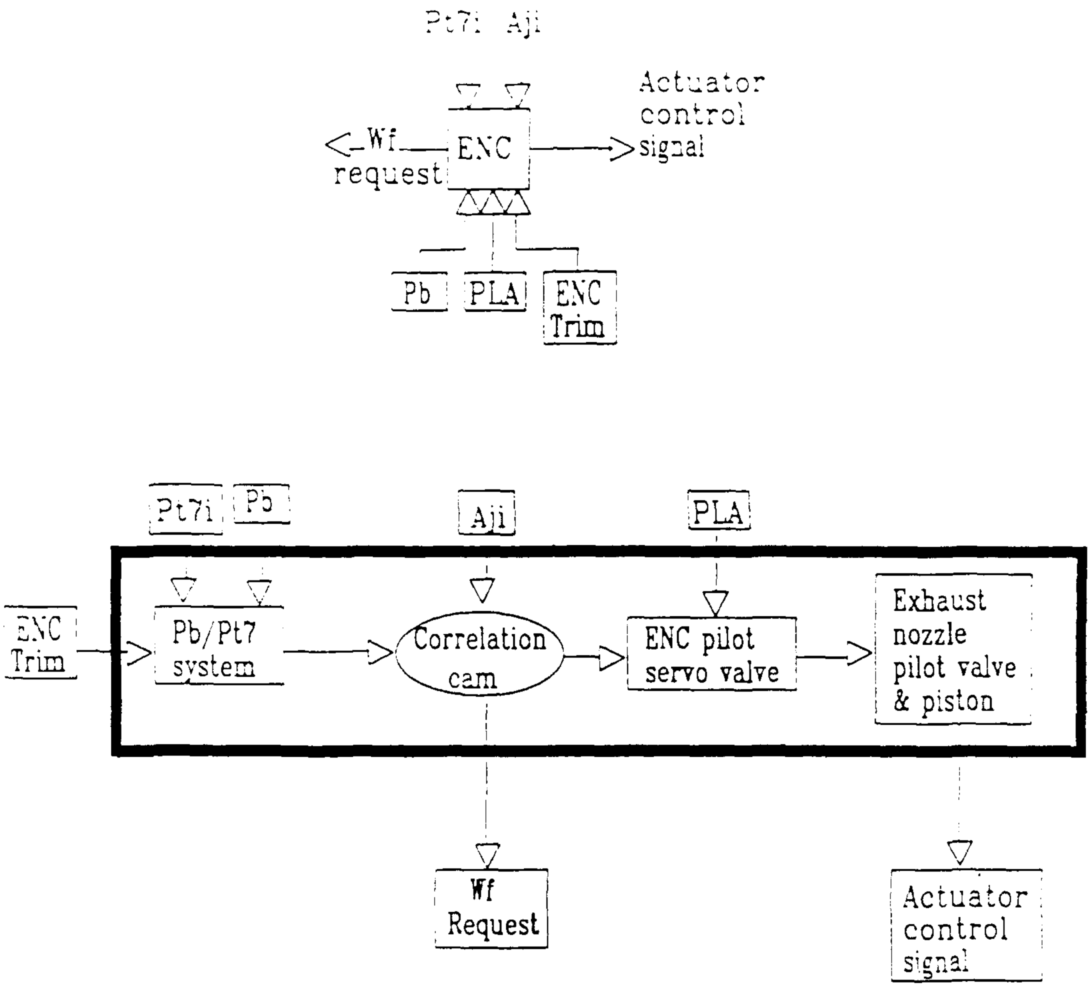

Figure 1.
ENC reduced to subsystems.

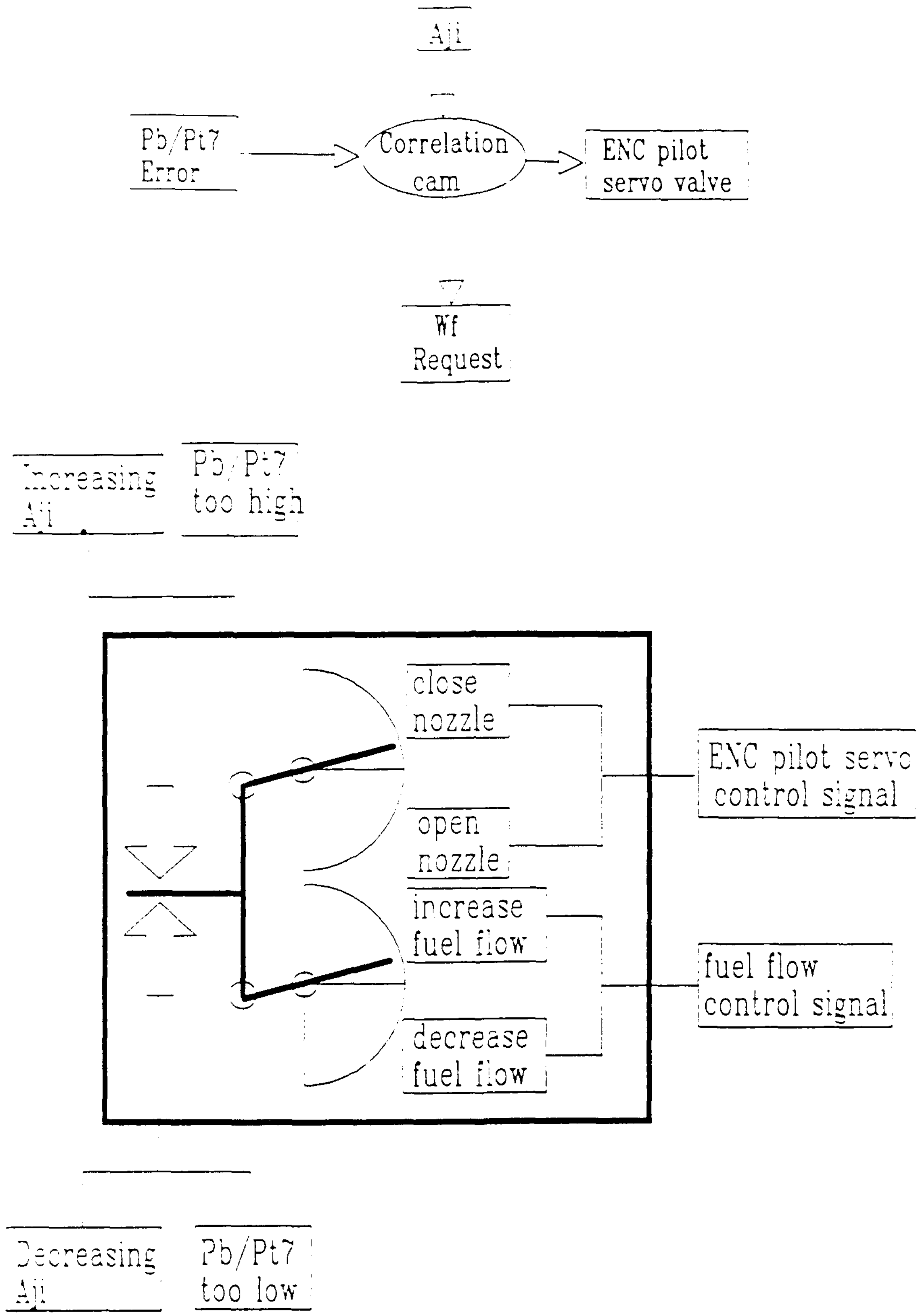

Figure 2.
ENC sub-system: Correlation Cam, Input to Output relationships.

Qualitative Modelling of Component Interaction.

To model component interaction the allowable signals which could be passed from one component to another were restricted to the following terms:

Increase, component A requests an increase in the parameter from component B,

Decrease, component A requests an decrease in the parameter from component B,

Null, component A requests no change in the parameter from component B,

Mu, The state of component A has no bearing on the parameter of component B at this point in time.

For example consider the signal from the ENC to the nozzle actuators. This signal is a flow of fuel from the ENC to the nozzle actuators which moves the actuators in the desired manner. However in this case the Nozzle Control Signal from the ENC is interpreted into one of the above options. i.e. when the ENC determines that an increase in nozzle size is required then the Nozzle Control Signal to the Nozzle Actuators is 'Increase'.

Sequencing of System Interactions.

The program developed for the qualitative model was writern in Turbo Pascal. The choice of Turbo Pascal was dictated by project time constraints and given a more complex modelling task, and more modelling resources the choice of another language would be desirable. Languages which would be more appropriate to qualitative modeling would be C or LISP , as these languages would allow the many concurent interactions in the engine to be modelled in a reasonably natural fashion. The use of Turbo Pascal however dictated that the interactions between systems had to be handled serially. This of course does not reflect what occurs in the engine. The system interaction within the engine occurs with much simultaneous feedback, where the response to an action affects the original ongoing action . In order to simulate the true state of affairs as acurately as possible a sequence for main-system interactions was developed. This sequence is shown in the figure below.

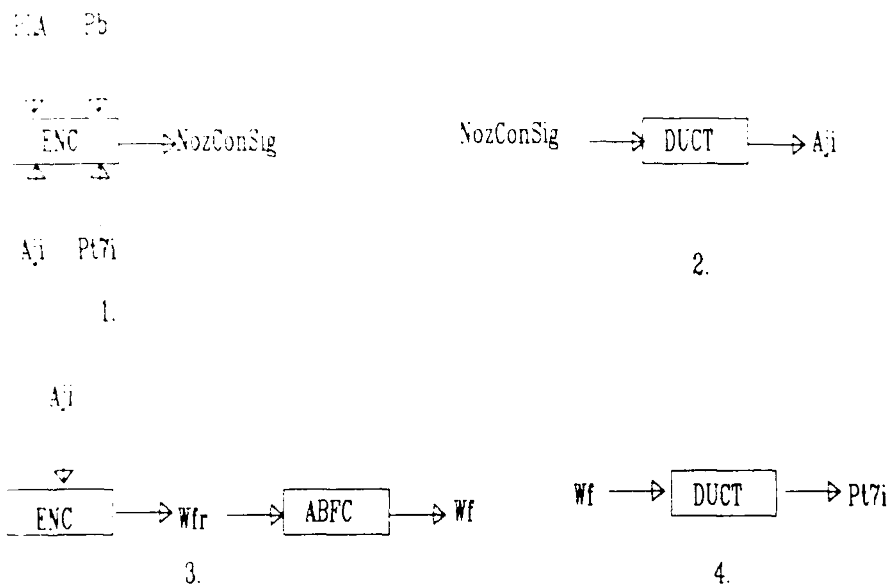

Figure 3.
Sequence of Main-system Interactions.

Adopting this sequence allows the action of the major feedback routes in the afterburner to be reproduced by the serial program.

<u>Embedding Faults and Outputing Symptoms.</u>

The model was developed to take the inputs to the main-systems and develop the outputs, in order, as required by the sequencing. This was achieved by considering the initial state of the inputs to the subsystems within the first main-system (ENC) and propagating the resultant state change requests throughout the sub-sysytems until the required output for the main-system had been developed. The main-system then supplies the other relevant main-system (Afterburner duct) with the input it requires. The process is then repeated until the total sequence of main-system interactions is completed. The entire sequence is then restarted with the new inputs which occurred as a result of the actions just taken. Thus the process continues until the system's response has evolved. This is indicated by an absence of change in the interaction parameters, or by the system settling into a repeated pattern response.

In order to keep track of the system changes all of the component interactions were passed as outputs to a file. This allowed the operation of the model to be examined in detail. This output provided the behaviour which the simulation predicted for the input and the current state of the entire system.

Embedding faults then became a matter of selecting a fault in a component, and determining how this fault would affect the input-output relationship for that component and hence the relevant sub-system. Once this had been done the model could be run for a variety of input conditions to determine the modified behaviour of the faulted model. Identifying and interpreting these modifications to the model's behaviour isolates the symptoms which the model predicts to be associated with the embedded fault.

As an example of the operation of the model the following case provides the model's reaction to a Power Lever Angle increase. The first output is for a simulation with no embedded fault. the second output is for the embedded fault of a malfunctioning fuel metering valve.

It can be seen from the first output that with no fault the model produces the normal expected engine behaviour in response to a PLA increase. The nozzle is opened , the fuel flow increases, and the tailpipe pressure is maintained at the desired level.

Referring now to the second output , the effect of the malfunctioning fuel metering valve which will not allow an increase in fuel flow is shown.
The PLA requests an increase in the nozzle size and fuel flow. The nozzle responds, however the fuel flow cannot. This leads to a reduction in tailpipe pressure. This reduction is sensed as a turbine pressure ratio error and the nozzle is commanded to close to counteract this problem.This brings the nozzle position into conflict with the PLA request, and an unsteady situation is created where the nozzle is forced to fluctuate in response to conflicting requirements.

Further examples which cover the range of PLA and ENC trim inputs and the model's response with malfunctioning metering valves , and slipping nozzle actuators are included at the end of the appendix.

Performance of the Qualitative Fault Model.
These results provide symptoms such as fluctuating nozzle positions, decreased nozzle sizes, and fluctuating fuel flows which are all possible and expected symptoms for the embedded fault and the action which the engine is called upon to perform. As such it is considered that a qualitative fault model has the potential to perform the role of expert system verifier and validator.

The TURBO PASCAL Code for the Qualitative Fault Model of the TF30-P3 Afterburner :

```
program Afterburner(I,E,O);
(* Global declarations *)
const
L = 14;
Blank = ' ';

type
 Chng = (MU,DEC,NUL,INC);
 Status =
 record
      CH: Chng;
     FLT: Char
  end;
Data = text;

label 99;
var
Pos,J,Count : 1..L;

Name :  array[1..L] of Char;
change :  array[1..3] of Char;

INCORRECT_INPUT_CH,INCORRECT_INPUT_NAME,
                THE_END_IS_NIEGH : Boolean;

I,E,O : Data;

PLAOLD,PbOLD,Noz_con_sigOLD,Pt7IOLD,AjiOLD,WfOLD : Chng;

 ENC_Trim,PLA,Pb,Fuel_tanks,PbPt7I,PbPt7R,PbPt7,
 Aji,Aj,PLANEW,Noz_con_sig,Pt7I,Pt7,Actuators,Metering_Heads,
 AB_Pump,AB_Pump_Switch,Pt7_Sense_Line,Wf,Dummy : Status;

function CON(Dummy: Chng) :String;
begin
case Dummy of
    DEC : CON := 'DEC';
    NUL : CON :='NUL';
    INC : CON := 'INC';
    MU : CON:='MU'
  end;
end;

procedure ENC_NOZZLE(var Pb,Pt7I,Aji,
                PLA, Noz_con_sig,PbPt7,PbPt7R: Status);

(* Local declarations *)
var
PbPt7I,PLANEW : Status;
```

```
begin
(* Determine ENC Pilot servo valve output *)
 (* combine Aji & PLA to produce relative pilot valve origin PLANEW *)
 case Aji.CH of
     MU : PLANEW.CH := PLA.CH;
    DEC : case PLA.CH of
           MU : PLANEW.CH := INC;
          DEC : PLANEW.CH := NUL;
          NUL : PLANEW.CH := INC;
          INC : PLANEW.CH := INC
        end;
    NUL : case PLA.CH of
           MU : PLANEW.CH := NUL;
          DEC : PLANEW.CH := DEC;
          NUL : PLANEW.CH := NUL;
          INC : PLANEW.CH := INC
        end;
    INC : case PLA.CH of
           MU : PLANEW.CH := DEC;
          DEC : PLANEW.CH := DEC;
          NUL : PLANEW.CH := DEC;
          INC : PLANEW.CH := NUL
        end
 end;(* case for PLANEW determination *)

 (* reset PLA to PLANEW *)
 PLA.CH := PLANEW.CH;

 (* determine PbPt7 for combination with PLANEW *)
   (* obtain  PbPt7I from Pb & Pt7I *)
   case Pt7I.CH of
        MU : case Pb.CH of

              MU : PbPt7I.CH := MU;
       DEC,NUL,INC : PbPt7I.CH := Pb.CH
            end;
       DEC : case Pb.CH of
              MU : PbPt7I.CH := INC;
             DEC : PbPt7I.CH := NUL;
          NUL,INC : PbPt7I.CH := INC
           end;
       NUL : case Pb.CH of
              MU : PbPt7I.CH := NUL;
       DEC,NUL,INC : PbPt7I.CH := Pb.CH
           end;
       INC : case Pb.CH of
              MU : PbPt7I.CH := DEC;
             INC : PbPt7I.CH := NUL;
          NUL,DEC : PbPt7I.CH := DEC
           end
   end;(* case to determine PbPt7I.CH *)
   Pb.CH:=NUL;

   (* compare PbPt7I with PbPt7R to produce PbPt7*)
```

```
case PbPt7I.CH of
      MU : case PbPt7R.CH of
             MU,NUL : PbPt7.CH := PbPt7R.CH;
               DEC : PbPt7.CH := INC;
               INC : PbPt7.CH := DEC
           end;
      DEC : case PbPt7R.CH of
           MU,NUL,INC : PbPt7.CH := DEC;
               DEC : PbPt7.CH := NUL
           end;
      NUL : case PbPt7R.CH of
             MU,NUL : PbPt7.CH := NUL;
               DEC : PbPt7.CH := INC;
               INC : PbPt7.CH := DEC
           end;
      INC : case PbPt7R.CH of
           MU,NUL,DEC : PbPt7.CH := INC;
               INC : PbPt7.CH := NUL
           end
end;(* PbPt7 determination *)
case PbPt7.CH of
     DEC : PbPt7R.CH := INC;
     INC : PbPt7R.CH := DEC;
   MU,NUL : PbPt7R.CH := PbPt7.CH
end;(* reset of requested PbPt7R *)

(* Combine PLANEW with PbPt7 to produce Noz_con_sig *)
case PLANEW.CH of
     MU : case PbPt7.CH of
            MU : Noz_con_sig.CH := MU;
           DEC : Noz_con_sig.CH := INC;
           NUL : Noz_con_sig.CH := NUL;
           INC : Noz_con_sig.CH := DEC
         end;
     DEC : case PbPt7.CH of
         NUL,MU,INC : Noz_con_sig.CH := DEC;
              DEC : Noz_con_sig.CH := NUL
         end;
     NUL : case PbPt7.CH of
            MU,NUL : Noz_con_sig.CH := NUL;
              DEC : Noz_con_sig.CH := INC;
              INC : Noz_con_sig.CH := DEC
         end;
     INC : case PbPt7.CH of
         MU,NUL,DEC : Noz_con_sig.CH := INC;
              INC : Noz_con_sig.CH := NUL
         end
 end (* determination of Noz_con_sig *)

end; (* ENC_NOZZLE *)
```

```
procedure NOZZLE(Noz_con_sig:Status;
           var Actuators. Aji,Aj:Status);
(* local declarations *)
begin
(* Determine effect of signal from Nozzle controller to actuators *)
 case Actuators.FLT of
(*'O' = operational *)
 'O' :  Actuators.CH := Noz_con_sig.CH;
(*'S' = slipping actuator *)
 'S' :  case Noz_con_sig.CH of
      MU,NUL,INC : Actuators.CH := INC;
      DEC : Actuators.CH := DEC
      end
 end;

(* Determine effect of Actuators on Aj*)
  Aj.CH := Actuators.CH;

(* Determine effect of Aj on Aji *)
  Aji.CH := Aj.CH

end;(*NOZZLE*)


procedure ENC_ABFC(Aji,PbPt7:status;
             var Wf:Status);
(* local declarations *)
var
WfR:Status;

begin

(* Determine Wf request from Aji & PbPt7 *)
  case Aji.CH of
     MU : WfR.CH := PbPt7.CH;
    NUL : case PbPt7.CH of
              MU : WfR.CH := NUL;
       DEC,NUL,INC : WfR.CH := PbPt7.CH
         end;
    DEC : case PbPt7.CH of
           MU,NUL : WfR.CH := Aji.CH;
             DEC : WfR.CH := DEC;
             INC : WfR.CH := NUL
         end;
    INC : case PbPt7.CH of
           MU,NUL : WfR.CH := INC;
             DEC : WfR.CH := NUL;
             INC : WfR.CH := INC
         end
  end;(*determination of WfR*)
```

```
(* Determine Wf from WfR effect on ABFC *)
  case Metering_Heads.FLT of
      'O'  Wf.CH  = WfR.CH ;
      'B'  case WfR.CH of
             DEC,MU: Wf.CH:=DEC,
                NUL,INC: Wf.CH:=NUL
           end
  end;


end;(* ENC_ABFC *)

procedure DUCT(Wf,Aj:Status;
           var Pt7I,Pt7:Status);
(* local declarations *)

begin
(* Determine Pt7 from Aj & Wf *)
  case Aj.CH of
  NUL,MU : Pt7.CH := Wf.CH;
    DEC : case Wf.CH of
      INC,NUL,MU : Pt7.CH := INC;
           DEC : Pt7.CH := NUL
         end;
    INC : case Wf.CH of
      DEC,NUL,MU : Pt7.CH := DEC;
           INC : Pt7.CH := NUL
         end
  end;(* determination of Pt7 *)

(* determine Pt7I from Pt7 *)

  Pt7I.CH := Pt7.CH
  end;(* DUCT *)

begin


(* Initialise components to MU state *)
 ENC_Trim.CH := MU;
 PLA.CH := MU;
 Pb.CH := MU;
 Fuel_tanks.CH := MU;
 PbPt7I.CH := MU;
 PbPt7R.CH := MU;
 PbPt7.CH := MU;
 Aji.CH := MU;
 Aj.CH := MU;
 PLANEW.CH := MU;
 Noz_con_sig.CH := MU;
 Pt7I.CH := MU;
  Pt7.CH := MU;
 Actuators.CH := MU;
 Actuators.FLT := 'S';
```

```
(* insert fault *)
 Metering_Heads.CH := MU;
 AB_Pump.CH := MU;
AB_Pump_Switch.CH := MU;
Pt7_Sense_Line.CH := MU;
Wf.CH := MU;
(* assign files *)
Assign( I, 'System_I.PAS');
 Assign( E, 'System_E.PAS');
 Assign( O, 'System_O.PAS');
(* Reset input files *)
Reset (I);
 Reset (E);
 Rewrite (O);
writeln(O,'ENC PLA Pb Pb/Pt7 Aji Aj  Noz Pt7I Pt7 Actu Wf');
writeln(O,'Trim                    sig        ator   ');

INCORRECT_INPUT_CH := false;
(* read & convert inputs & errors to internal type *)
while not EOF(I) do
begin
  for Pos := 1 to L do
    begin
     if EOLn(I) then
       Name[Pos] := Blank
     else
     begin
       Read(I,Name[Pos]);
       writeln('NamePos',Pos,Name[Pos])
     end
    end;
  Readln(I);
  for Pos := 1 to 3 do
    begin
     if EOLn(I) then
       Change[Pos] := Blank
     else
     begin
       Read(I,Change[Pos]);
       writeln('ChangePos',Pos,Change[Pos])
     end
    end;
  Readln(I);
  Readln;

     if Change[1]= 'I'then
      begin
      writeln('I');
       Dummy.CH :=INC
       end ;
     (* end*)
     if Change[1]= 'N'then
      begin
      writeln('N');
```

```
      Dummy CH :=NUL
      end ;
      if Change[1]= 'D'then
     begin
     writeln('D');
      Dummy.CH :=DEC
      end ;
  INCORRECT_INPUT_NAME := False;

  if Name = 'ENC_Trim      'then ENC_Trim.CH := Dummy.CH;
  if Name =  'PLA          'then PLA.CH := Dummy.CH;
  if Name =  'Pb           'then Pb.CH := Dummy.CH;
  if Name =  'Fuel_tanks   'then Fuel_tanks.CH := Dummy.CH;
  if Name =  'PbPt7l       'then PbPt7l.CH := Dummy.CH;
  if Name =  'PbPt7R       'then PbPt7R.CH := Dummy.CH;
  if Name =  'PbPt7        'then PbPt7.CH := Dummy.CH;
  if Name =  'Aji          'then Aji.CH := Dummy.CH;
  if Name =  'Aj           'then Aj.CH := Dummy.CH;
  if Name =  'PLANEW       'then PLANEW.CH := Dummy.CH;
  if Name =  'Noz_con_sig  'then Noz_con_sig.CH := Dummy.CH;
  if Name =  'Pt7l         'then Pt7l.CH := Dummy.CH;
  if Name =  'Pt7          'then Pt7.CH := Dummy.CH;
  if Name =  'Actuators    'then Actuators.CH := Dummy.CH;
  if Name =  'Metering_Heads'then Metering_Heads.CH := Dummy.CH;
  if Name =  'AB_Pump      'then AB_Pump.CH := Dummy.CH;
  if Name =  'AB_Pump_Switch'then AB_Pump_Switch.CH := Dummy.CH;
  if Name =  'Pt7_Sense_Line'then Pt7_Sense_Line.CH := Dummy.CH;
  if Name =  'Wf           'then Wf.CH := Dummy.CH;

end;
while not EOF(E) do
begin
  for Pos := 1 to L do
    begin
     if EOLn(E) then
       Name[Pos] := Blank
     else
     begin
       Read(E,Name[Pos]);
       writeln('NamePos',Pos,Name[Pos])
     end
    end;
  Readln(E);
  Readln(E,Dummy.FLT);
  writeln('Dummy flt ',Dummy.FLT);
  readln;
      if Name = 'ENC_Trim      'then ENC_Trim.FLT := Dummy.FLT;
  if Name =  'PLA          'then PLA.FLT := Dummy.FLT;
  if Name =  'Pb           'then Pb.FLT := Dummy.FLT;
  if Name =  'Fuel_tanks   'then Fuel_tanks.FLT := Dummy.FLT;
  if Name =  'PbPt7l       'then PbPt7l.FLT := Dummy.FLT;
  if Name =  'PbPt7R       'then PbPt7R.FLT := Dummy.FLT;
  if Name =  'PbPt7        'then PbPt7.FLT := Dummy.FLT;
  if Name =  'Aji          'then Aji.FLT := Dummy.FLT;
```

```
  if Name =  'Aj           'then Aj.FLT := Dummy.FLT;
  if Name =  'PLANEW       'then PLANEW.FLT := Dummy.FLT;
  if Name =  'Noz_con_sig  'then Noz_con_sig.FLT := Dummy.FLT;
  if Name =  'Pt7I         'then Pt7I.FLT := Dummy.FLT;
  if Name =  'Pt7          'then Pt7.FLT := Dummy.FLT;
  if Name =  'Actuators    'then Actuators.FLT := Dummy.FLT;
  if Name =  'Metering_Heads'then Metering_Heads.FLT := Dummy.FLT;
  if Name =  'AB_Pump      'then AB_Pump.FLT := Dummy.FLT;
  if Name =  'AB_Pump_Switch'then AB_Pump_Switch.FLT := Dummy.FLT;
  if Name =  'Pt7_Sense_Line'then Pt7_Sense_Line.FLT := Dummy.FLT;
  if Name =  'Wf           'then Wf.FLT := Dummy.FLT;
  writeln('Actuator flt',Actuators.FLT);

end;
PbPt7R.CH:=ENC_Trim.CH;
THE_END_IS_NIEGH := False;
(* Evolve system response to the conditions *)
while (*system response evolving*)Not(THE_END_IS_NIEGH) do
   begin
   (* ENC acts on current system state to send nozzle control signal *)
   ENC_NOZZLE(Pb,Pt7I,Aji,
         PLA,Noz_con_sig,PbPt7,PbPt7R);

   (* Nozzle responds and provides ENC with feedback *)
   NOZZLE(Noz_con_sig,Actuators,Aji,Aj);

   (* ENC combines all information and sends a signal to ABFC *)
   ENC_ABFC(Aji,PbPt7,Wf);

   (* Duct adjusts to current nozzle and Wf inputs *)
   DUCT(Wf,Aj,Pt7I,Pt7);

   (* check evolution of system *)
  case PLA.CH of
  NUL : case Pb.CH of
      NUL : case Noz_con_sig.CH of
          NUL : case Pt7I.CH of
              NUL : case Aji.CH of
                  NUL : case Wf.CH of
                      NUL :THE_END_IS_NIEGH := True;
                      MU,DEC,INC :THE_END_IS_NIEGH := False
                      end;
                  MU,DEC,INC :THE_END_IS_NIEGH := False
                  end;
              MU,DEC,INC :THE_END_IS_NIEGH := False
              end;
          MU,DEC,INC :THE_END_IS_NIEGH := False
          end;
      MU,DEC,INC :THE_END_IS_NIEGH := False
      end;
  MU,DEC,INC :THE_END_IS_NIEGH := False
  end;
```

```
if Not(THE_END_IS_NIEGH) then
  begin
  Count:=1;
  if( (PLA.CH) = (PLAOLD)) then Count:=Count+1;
  if(( Pb.CH) = (PbOLD)) then Count:=Count+1;
  if(( Noz_con_sig.CH) = (Noz_con_sigOLD)) then Count:=Count+1;
  if( (Pt7I.CH) =( Pt7IOLD)) then Count:=Count+1;
  if(( Aji.CH) =( AjiOLD)) then Count:=Count+1;
  if( (Wf.CH) = (WfOLD)) then Count:=Count+1;
  if( Count = 7) then THE_END_IS_NIEGH := True ;
  (* output current system state *)
  writeln(O,CON( ENC_Trim.CH):3,CON( PLA.CH ):4,CON( Pb.CH ):4,
   CON( PbPt7.CH ):4,CON( Aji.CH ):6,CON( Aj.CH ):4,
   CON( Noz_con_sig.CH):4,CON( Pt7I.CH ):5,CON( Pt7.CH ):4,
   CON( Actuators.CH):5,CON( Wf.CH):4);
   if  J =10 then THE_END_IS_NIEGH := True;
    J:=J+1;
        PLAOLD:=PLA.CH;
   PbOLD:=Pb.CH;
   Noz_con_sigOLD:=Noz_con_sig.CH;
   Pt7IOLD:=Pt7I.CH;
   AjiOLD:=Aji.CH;
   WfOLD:=Wf.CH;
   end;
   end;
99:
if INCORRECT_INPUT_CH then
write(O,'*********Incorrect change parameter entered.*********');
if INCORRECT_INPUT_NAME then
begin
writeln(O);
write(O,'*********Incorrect object name entered.*********');
writeln(O)
end;
(* Output final system state in full *)
 writeln(O,CON( ENC_Trim.CH):3,CON( PLA.CH ):4,CON( Pb.CH ):4,
   CON( PbPt7.CH ):4,CON( Aji.CH ):6,CON( Aj.CH ):4,
   CON( Noz_con_sig.CH):4,CON( Pt7I.CH ):5,CON( Pt7.CH ):4,
   CON( Actuators.CH):5,CON( Wf.CH):4);

close(I);
close(E);
close(O)
end. (* Afterburner *)
```

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The tasks involved in developing a fault diagnosis expert system for a gas turbine engine are examined. Particular attention is given to the options available to maximise the quality of the advice given by the expert system. All phases of system development from knowledge acquisition, through to system support are covered. A general example of diagnosis by engineering analysis is given to demonstrate the concepts involved. Using acquired knowledge, a limited qualitative fault model of the TF30-P3 gas turbine engine afterburner has been developed, and application to some fault case examples is described.

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