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Using Expert Systems in Maintenance Monitoring and Management.

Tahoomars Rastin
Louisiana State University and Agricultural & Mechanical College

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Rastin, Tahoomars, Ph.D.

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300 N. Zeeb Rd.
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Tahoomars Rastin
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M.S., Louisiana State University, 1984
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LIST OF SYMBOLS

Symbol	
$X = [x_1, x_2, \ldots, x_L]$	Feature vector
p	Probability density or "probability of"
ε	Is in
$A \mid B$	Event A conditioned on event B
$\boldsymbol{\Upsilon}$	Category space
$\mathcal{C}$	Class space
$\mathfrak{X}$	Feature space
$\mathcal{S}$	Total system
$\mathcal{S}_s$	Subsystem s within the total system
$\mathfrak{X}_s$	Feature space for subsystem $\mathcal{S}_s$
M_s	Number of categories in subsystem s of total system
M_{c_s}	Number of classes in subsystem s of total system
K_s	Number of subcategories for each category in subsystem s of total system
S	Number of subsystems in the total system
$\mathbf{x}_s = \{x_{s_j}\}$	x_{s_j} = 1 if jth primitive is included in subsystem s, 0 otherwise
$\boldsymbol{\gamma}_s^* = \{\gamma_{s_i}^*\}$	$\gamma_{s_i}^*$ = 1 if ith category is included 0 otherwise
$\mathbf{c}_s = \{c_{s_i}\}$	c_{s_i} = 1 if ith class included, 0 otherwise

$d^*_{s_i} = \{\gamma^*_{s_{i_{e_\xi}}}\}$	$\gamma^*_{s_{i_{e_\xi}}}$ = 1 if category $\gamma^*_{s_i}$ in subsystem s depends on category $\gamma^*_{e_\xi}$ in subsystem e
$\gamma^*_i \varepsilon \gamma$	ith category in category space
$\omega_i \varepsilon \mathscr{C}$	ith class in class space
(ω_i, ω_j)	Class w_i and Class w_j which the complex class
Ω^*_{ij}	Complex class incorporating classes w_i and w_j
:::>	The implication linking a concept description with a concept name
$\mid>$	Specialization (Deduction)
$\mid<$	Generalization (Induction)

ABSTRACT

In this research, a model for fault diagnosis of equipment is discussed. The model discusses the use of multi-variable monitoring for a more precise means of equipment malfunction trouble shooting. Also within this model means are discussed for automatically generating work-orders. Equipments are divided into subsystems. The subsystems are broken down into sub-subgroups and further down to individual parts. Preventive maintenance techniques, along with expert system technology, are used to develope the maintenance expert system (MES). Statistical pattern recognition techniques are used as a way to describe the relationship between categories of equipment. The relationships shown here are mostly that of E. A. Patrick. These relationships give an example of how different categories within each subsystem could be effected by each other. In order to achieve accuracy when this model is applied, new and original probability density functions applicable for that particular case should be used. A prototype MES is built.

CHAPTER ONE

1.1 Introduction

By simultaneous use of several performance parameters, the purpose of this research is to investigate a unique maintenance monitoring and management technique, to diagnose equipment malfunction. Once sources of malfunction are determined, the system generates pre-stored work-orders with pre-assigned priorities to be either printed or scheduled (users choice). The maintenance expert system (MES) combines artificial intelligence (AI) techniques with maintenance (particularly preventive and condition-based maintenance) procedures to organize an effort directed towards obtaining long, trouble-free service life of vital plant equipment; hence, guard against costly, unwarranted breakdowns and maintain efficient, productive plant operation.

Industrial maintenance of production and operational machinery is undergoing rapid and important changes. The need for on-line diagnostics has long been recognized [1]. As equipment increases in size and complexity, the difficulty of identifying potential problems increases. At the same time, growing capital investment in the equipment makes it more important to quickly locate a problem. As facilities are modernized and automated, every effort should be made to reduce costs and increase production. Because of this, maintenance becomes critical and downtime less tolerable [2].

The uninterrupted operation of today's plant and, often, a company's profit, depend on the skill, efficiency, and procedures of the maintenance department, which suggests the creation a Maintenance Expert System (MES). The purpose of this research is to develop a MES, for rotary equipment fault diagnosis. The relevant maintenance and computer theories will be described. Once the proper techniques have been discussed, a real-time example of the program will be developed.

The development of the MES is based on combined condition-based maintenance, preventive maintenance theories and artificial intelligence (AI), and particularly knowledge-base systems. The motive for development of MES is to obtain a computerized fault diagnostic system which contains the maintenance experts' characteristics, such as, problem solving approach, reasoning, learning, and decision making. Because qualified personnel are in short supply, the need for such systems seems necessary. Although, the purpose of this research is to develop the MES used for rotary equipment, emphasis is placed on the use of this system to analyze most of the equipment faults.

Preventive maintenance (PM) is the aspect of maintenance which relies on accurate equipment history to pre-schedule maintenance. The objective of PM is to minimize down-time by efficiently using "idle" times (if any) to check or replace parts, before an abnormality is observed, in other words, anticipating malfunctions. PM results in lower unexpected equipment shut-down, therefore, higher overall equipment and plant efficiency.

Condition-based maintenance can be described as the " if its not broken, don't fix it " maintenance. In condition-based maintenance, several performance parameters, such as vibration, temperature, or pressure can be monitored and, through these characteristic parameters, the malfunctions and abnormal equipment operation can be observed. Once an abnormality is encountered, the system is then attended to and problems are repaired. The advantage of this system is that equipment is attended to only on the "as needed" basis. This type of monitoring is applied especially on the continuous running machines, such as, process compressors, power generators, and turbines.

An expert system is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant expertise for their solutions. The knowledge necessary to perform at such a level, plus the inference procedures used, can be thought of as a simulated model of the expertise of the best practitioners in the field. The maintenance of complex equipment involves a diagnostic procedure incorporating many rules as well as judgment decisions by the maintenance personnel. Experience is an important factor in determining the ease with which a mechanic can locate a failure problem and implement the appropriate correction. Expert systems can be utilized to assist maintenance personnel in performing complex repairs by presenting menu-driven instruction guides for the diagnostic task. These expert systems incorporate the knowledge of experts who are experienced in maintenance and repair.

Condition health monitoring is becoming increasingly automated [36, 41]. Computer-controlled instruments and the use of computers to collect and record data has become commonplace. With the presence of computers to perform data reduction and processing, the task of decision making concerning the health of the machine in question has become more efficient.

The use of AI techniques is a natural extension of that trend. There is also a trend within the world of AI for more fault diagnosis application [35]. To date, most of these systems have been built around the rule-based framework on fairly expensive computers [32]. There are two important subtrends that are emerging. One is the availability of the knowledge-based systems and knowledge-based system toolkits on smaller and more inexpensive machines, and the other is a more direct coupling of knowledge-based systems with test and measurement instruments. Today, most knowledge-based systems for fault diagnosis or condition monitoring require the user to measure a particular set of values. The user then turns to the device, makes some measurements on the instrument and types the values into the machine. Users of test and measurement instruments, represent a wide range of sophistication, from those who desire simple systems to those who are capable of using complex instruments to develop their own complex diagnosis and health monitoring programs. Whatever the level of experience of the user, they all require the same foundation, that is, a knowledge-based system properly interfaced with test and measurement instruments which allow users to write their own rule bases.

In early expert systems, knowledge was represented in the form of production rules [32]. The inference engine was a simple mechanism. It merely found the set of rules which could conclude the current hypothesis, and tried each one in turn. Usually, to satisfy a rule, other rules would be needed. This led to recursion and backward chaining. This approach worked for simple problems. In the early days of expert systems, the field could only do simple problems. Expert systems could be developed because the inference engine gave a simple paradigm for solving problems. After a time, however, problems became too complex for simple rule bases. Especially in diagnostic reasoning, structure and function has begun to be used to guide the effort to isolate the region which contains the fault. Structure is used to isolate the region which contains the fault. Function is used in two ways, first to help isolate the fault in structure, and then to reason about possible faults. Milne [34] outlines one of the simplest forms of structure: "... By intersecting paths known to be good and bad, faults in some portions of system can be ruled out. This decision is based solely on GO/NOGO information. The simplest algorithm is to split the possible fault path in half. To pick the optimal test to perform next, information about the cost of each test and possible value of the test can be considered. " Cantone [32] has one of the most elaborate algorithms for this task. Scarl [38] describes a more complicated reasoning mechanism to declare the innocence of devices by inferring that their function could not have caused the possible fault. This work illustrates the reasoning and issues involved in using function in this way. Whit and Fredericsen [40] use a simple view of function in electrical circuits to rapidly guide a binary search for the fault. Their approach is at the other end of the spectrum from Scarl's work. Whereas Scarl uses a complex combination of reasoning, White's simpler method is just as effective although not as general.

By the use of structure and function of machines, this monitoring technique will combine information from several performance parameters simultaneously, which is unique to this research, to pin-point faults.

CHAPTER TWO
Literature Review

2.1 Traditional Maintenance Monitoring Techniques

Three maintenance philosophies, which can be implemented in the plant, are [3,30]:

(a) Corrective maintenance: This is maintenance carried out to restore an item which has ceased to meet an acceptable level of condition. Often it is referred to as emergency maintenance. Its cost may be higher than preventive and it may involve a high loss of production.

(b) Preventive maintenance (PM): This is maintenance carried out at predetermined intervals; it is planned in advance and normally requires a long shut-down (2 or more weeks depending on the machinery involved). Its cost is high, and does not include corrective or emergency maintenance.

(c) Condition-based maintenance: This is preventive maintenance initiated as a result of knowledge of the condition of equipment from inspection. It is planned and carried out only when necessary, and it prevents most emergencies.

The rapid increase in the size of petrochemical plants and chemical plants in recent times has led to the use of larger and more complex equipment. In addition, The time between turnarounds has now increased to two, three, and even five years. As a result of the increased output of product of these large plants, the losses which are experienced as a result of accidental hutdown are high. A loss of 100,000 dollars per day and even more are not unusual. As a result of this situation, it has become evident that there is a need for more systematic means to aid in trouble correction and to reduce shutdown times. Also, means are required to predict abnormalities in equipment performance so that unwarranted shutdowns would not hinder production and result in high downtime costs.

In any system, failures do happen causing loss of production. The task of maintenance is to minimize downtime, within economic constraints. To totally prevent failures would generally be economically prohibitive. The calculated risk of the probability of a certain number of failures is more economical.

Condition-based maintenance can help solve this problem by constant (sometimes continuous) monitoring of such parameters as temperature, noise, sound, vibration, color, etc. When a failure is approaching, the measurement of one or more of these parameters will alert maintenance; therefore, condition-based maintenance is a powerful tool in the hands of a maintenance manager enabling him to be in full control of the condition of the plant at all times so that he can:

(a) Plan a shut-down when materials and personnel are available.

(b) Plan a shut-down at the most appropriate moment considering production and delivery dates.

In summary, one can define the main feature distinguishing condition-based maintenance philosophy by stating: "in the case of condition-based maintenance, managers manage by data" [4]. One task of the proposed MES is to relieve the maintenance manager of some of the decisions.

2.1.1 Significance of Machine Diagnosis

The study of preventive maintenance (PM), which is the main stream of today's machine maintenance, has revealed the following [28].

(1) Because the determination of the overhaul and repair timings is made empirically and by use of stochastic method, these timings are not always appropriate.

(2) Because the check and inspection activities which lay foundation for maintenance actions rely mainly on sensory inspections by skilled labor, their outcome is deficient in providing quantitative and recordable data, and is strongly influenced by personal judgment.

(3) Because the PM technique does not incorporate any quality evaluation technique for repair work, the life and reliability of machines are seriously affected by latent defects overlooked at the time of repair.

On the other hand, the trend towards higher speed continuous operation, larger capacity, and more complex machinery, poses the risk of high production losses by unscheduled shutdowns, thus pushing up maintenance costs. In order to solve this problem, it is necessary to develop a technique which is capable of accurately and quantitatively determining the condition, strength, performance, etc. of machinery.

For this purpose, the systematic development of a technique for accurately and quantitatively checking the machine condition, namely, " machine diagnosis (MD)" should be developed. The maintenance method based on the accurate determination of machine condition is called condition-based maintenance or predictive maintenance, while the conventional PM conducted at regular time intervals is called time-based maintenance or hard-time maintenance.

2.1.2 Basic Structure of Machine Diagnostics

Machine diagnostic is a technique for accurately and quantitatively checking the condition of machinery and predicting its future. The determination of machine condition constitutes an essential function fundamental to all maintenance activities, therefore it must include the determination of:

(1) Stresses which cause machine deterioration and trouble

(2) Location, magnitude, and cause of machine deterioration and trouble

(3) Performance, strength, efficiency, etc. of machine

(4) Reliability and life of machine

Large numbers of machines are arranged in the production stream in such a way that considerable losses could occur if any of them should fail. Hence, it is necessary to diagnose a large number of machines efficiently, promptly, and accurately.

In order to satisfy these requirements, MD like human health control, needs to have the following two techniques:

(1) Machine survey technique, which is primarily a health examination of machinery. This is the technique for prompt and efficient survey of machinery and has the following functions:

(i) Trend control and early detection of abnormality

(ii) Monitoring and protection of machinery

(iii) Exposing machine problems

(2) Precision diagnostics

This technique of precision diagnosis of a machine whose abnormality or trouble is detected by machine survey technique is employed to determine the actions to be taken, and has the following functions:

(i) Calculation, measurement and estimation of various stresses

(ii) Analysis of extent, location and cause of trouble and deterioration

(iii) Quantification and estimation of performance, efficiency and strength

(vi) Prediction of life and reliability.

Accordingly, precision diagnostics is a technical package which includes stress estimation by calculation and life prediction as well as an observation technique.

2.1.3 Rotating Machinery Diagnostics

The rotary machine diagnostics is a technique applied for determining the best repair method by quantitatively detecting the degree and cause of the abnormality of general rotating machinery at early stages.

By this technique, vibrations and noise of the shaft and bearings are detected, for abnormalities in rotating machinery give rise to vibration and noise.

Rotating machinery diagnostics include (1) roller bearing diagnosis, (2) gear diagnosis, (3) rotating mechanism diagnosis, and (4) rotating machinery diagnosis which combines these machine element diagnostic techniques.

2.1.4 Reliability-Evaluation for Diagnostics of Rotary Machinery

When serious trouble occurs with an installation, one needs to know how to minimize cost of downtime. A given problem can be solved by a number of means, and the question is: which solution to try first, and how many steps to take simultaneously? To reach this decision one must evaluate the relative effect of each component on the overall picture. In other words, there must be a reliability guide to determine the amount of improvement which can be expected from a certain step [29].

As design speed increase, the reliability is usually reduced, unless reasonable provisions are made to offset this effect. Although, increasing the reliability of a machine is costly, the increase in efficiency of the equipment justifies this additional cost. This is accomplished with lower probabilities of unplanned shutdown and shorter equipment down-time. Usually the difference is balanced by a few days of high-efficiency operation resulting in greater profit. But in using high-speed machinery one must properly maintain the equipment, or considerable losses can occur.

2.2 Justifying Predictive Maintenance [31]

The chief advantage of predictive maintenance over other maintenance philosophies is that it saves money in maintenance costs and insurance costs as well as increase machine up-time.

Consequently, the most effective justification is the return on investment, and how the potential savings of the program offset the costs of the program. The potential savings as applied to the operations are as follows:

(i) Reduced Maintenance Cost

A predictive maintenance program offers the ability to schedule maintenance on rotating machinery only when it's needed, rather than on an arbitrary calendar basis.

The reduction in maintenance can occur in two areas, namely reduced overtime, and reduced repair costs.

Because with predictive maintenance, the need for maintenance can be anticipated, emergency repair are reduced [30]. By reducing emergency repairs, one is able to order parts and reduce overtime by making the repairs during the normal work period. Reductions of up to 30 percent have been reported by petrochemical companies during the first year of the use of predictive maintenance.

The ability to anticipate the machine problems before a major failure happens enables the personnel to repair the machine, such as replace the bearings, rather than completely rebuild it. Overhaul costs are typically less expensive than rebuilding costs, especially when the failure is catastrophic.

(ii) Improved Machine Availability and Process Productivity

The ability to predict mechanical problems improves machine availability in two ways: reduced unplanned down-time and fewer unnecessary repairs.

Major production interruptions can be avoided by planning the outages or turnarounds at the most convenient and cost-effective time for production.

Predictive maintenance techniques enable the maintenance personnel to monitor the mechanical status of the machines, therefore, avoiding any unnecessary inspections. Hence, machines can be safely operated beyond their normal maintenance intervals.

The increased machine availability achieved by an ammonia plant in the southeastern United States is an example of the types of results that can be gained from the a predictive maintenance program. The company increased its machine on-stream factor from 90.7 to 98.9 percent over a five-year period, using predictive maintenance techniques. Over the same period, the company experienced only three unplanned shutdowns that were directly attributed to unknown machinery malfunctions.

Improved product quality is also a natural consequence of improved machine availability. Product quality can suffer greatly with unexpected disturbance to major process flow. Well-monitored and maintained machines result in the production of a uniform, dependable product.

(iii) Extended Machinery Life

When machines are well maintained, they can be operated beyond their design life. By extending machinery life, one can minimize expenditures for new equipment.

A comparison of the cost of a steam turbine generator rotor in 1976 versus the cost of the same rotor in 1987, illustrates the type of savings that can be achieved by extending machine life. According to a major turbine manufacturer [1], a complete rotor for a

350-400 mega-Watts turbine generator for a fossil power plant cost $1.9 million in 1976. In 1987, The cost of the rotor was $3.7 million.

2.2.1 Increased Plant Safety and Controlled Insurance Costs

Safety is the most significant economic consideration for a predictive maintenance program. The ability to detect malfunctions before they reach catastrophic levels, enables the maintenance personnel to not only protect the equipment, but also to avoid possible human injuries [12].

By demonstrating a well-planned predictive maintenance program on all types of machinery: critical, essential, and general purpose - it is possible to maintain or lower the insurance expenditures for casualty, production, and capital equipment losses.

2.3 Artificial Intelligence And Its Relevance To Maintenance Monitoring [37]

One definition of AI is " The process by which one attempts to simulate human 'thinking' in machines" [5]. Expert systems are one of the areas of AI which has achieved considerable success recently.

Just what is an expert system? Feigenbaum, a pioneer in expert systems [6] states:

> An "expert system" is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. The knowledge necessary to perform at such a level, plus the inference procedures used, can be thought of as a model of the expertise of the best practitioners of the field.
>
> The knowledge of an expert system consists of facts and heuristics. The "facts" constitute a body of information that is widely shared, publicly available, and generally agreed upon by experts in a field. The "heuristics" are mostly private, little-discussed rules of good judgment (rules of plausible reasoning, rules of good guessing) that characterize expert-level decision making in the field. The performance level of an expert system is primarily a function of the knowledge base that it possesses.

A decision to utilize expert systems as the basic tool in the development of diagnostic systems is dictated by a number of factors. As compared to using conventional programming languages such as FORTRAN or BASIC, the development effort is considerably reduced with an AI approach. While expert knowledge can be written into conventional software, the program input process would require not only experts but also computer programmers as well. With AI it is possible to create a program, where non-programmers can create expert systems through interactive, menu-driven input sessions. This allows easier modification of an existing expert system. A conventional, decision tree analysis will not indicate the validity of the diagnosis, whereas an expert system gives the associated confidence factor for each of the results presented to the user. An expert system can display the methods it used to reach its conclusion. Therefore, it brings clarity to the diagnosis and provides an opportunity for training additional personnel in the field [39].

2.3.1 The Basic Structure of an Expert System

An expert system uses AI techniques to make inferences based on domain-specific knowledge supplied by experts. In the typical expert system the expertise that the system brings to bear on a problem is represented as a large collection of rules usually based on empirical associations. One example of such a rule might be " IF the display flickers, THEN examine the power supply." Domain experts, such as senior technicians, may be consulted for problems known to occur in an equipment. Their solutions and knowledge are codified into a set of condition-action rules which subsequently drives a program for inferential reasoning about the specified domain. Paraphrasing [27], the individual rules are usually specified as IF-THEN statements, each rule representing a small portion of the problem-solving or decision process. Each rule specifies a conclusion that follows from a given set of premises. The rules are usually in the form: If <condition> then <action>, with the condition composed of conjunctions or disjunctions of terms. These premises either refer to the facts given to the system or to the conclusions of previous rules using such facts. The conclusion of one rule could be used as a premise for other rules. In such a manner the simple rules comprising the program can be chained together to describe complex decision processes. Thus a rule-based system can be "data-directed", meaning that the flow of control is determined by the data rather than by rigidly fixed statements of program code [18].

Rule-based expert systems have several important properties that make them suitable for certain classes of application. They can focus on and handle significant amounts of detail, and their continual re-evaluation of the control state lends an environmental sensitivity unmatched in canonical procedural approaches. They are well-suited to real-world, multi-dimensional environments whose events and actions are richly interconnected. The rule versus data organization of the system allows the separation of data examination from action for data modification. Rule systems are highly modular and allow easy addition of new information, hence, easing the chore of knowledge acquisition. A complete treatment of rule-based systems can be found in [23, 24].

Expert systems consist of:

(1) a knowledge base(or knowledge source) of domain facts and heuristics associated with the problem;

(2) an inference procedure (or control structure) for utilizing the knowledge base in the solution of the problem;

(3) a working memory - "global data base" - for tracking the problem status, the input data for the particular problem, and the relevant history of what has thus far been done.

A human "domain expert" usually has input in developing the knowledge base. An expert system differs from more conventional programs in several important respects. Duda [7] observes that, in an expert system,

"... there is a clear separation of general knowledge about the problem (the rules forming a knowledge base) from information about the current problem (the input data) and methods for applying the general knowledge to the problem (the rule interpreter). In conventional computer programs, the knowledge about the problem and methods for utilizing this knowledge are all intermixed, so it becomes very difficult to change and update the program. In expert systems, the program itself is only an interpreter (or general reasoning mechanism) and ideally the system can be changed by simply adding or subtracting rules in the knowledge base."

A study by Gevarter [8] showed that the uses of expert systems are virtually limitless. They can be used to: diagnose, monitor, analyze, interpret, consult, plan, design, instruct, explain, learn, and conceptualize. Thus they are applicable to a wide spectrum of uses, such as, equipment design, monitoring, diagnosis, maintenance, and repair, the specific problem under consideration here.

2.3.2 Expert Systems Versus Algorithm-Based Systems

Expert systems differ in important ways from both conventional data processing systems and systems developed in other branches of AI. In contrast to traditional data processing systems, AI applications generally involve several distinguishing features, which include symbolic representation, symbolic inference, and heuristic search. In fact each of these corresponds to a well-studied core topic within AI, and a simple AI task often yields to one of the formal approaches developed for these core problems. But the expert systems differ from the broad class of AI tasks in several respects. First, they perform difficult tasks at expert levels of performance. Second, they emphasize domain-specific problem-solving over the more general "weak methods" of AI [21]. And third, they employ self-knowledge to reason about their own inference processes and provide explanations or justifications for conclusions reached.

Prior to availability of expert systems (knowledge-based systems), the only way to represent and organize knowledge was through the use of algorithm-based systems. These systems possess the following characteristics:

1. Deterministic and do not have redundancy.

2. Sharp distinction between code and data.

3. Opaque algorithms, thus difficult to modify or analyze.

4 Lack the ability to reason about or explain the techniques and mechanism that they employ.

Knowledge-based systems (KBS) are a body of knowledge and simple mechanisms for applying knowledge whenever possible to be useful. This feature is possible due to the rules that make up the rule set. KBS are applied to area s that rely on the judgment of human experts; in other words, where problems are complex and require the application of high-level rules that are judgments and evaluations of solutions. In contrast to algorithm-based systems, KBS have the following characteristics:

1. Knowledge is redundant, so the absence of one fact does not necessarily prevent the system from arriving at a result by another route.

2. A sharp distinction exists between the body of knowledge and inference engine.

3. Transparent algorithms with independent rules allow for modifications and analysis.

4. Provision of explanations to describe the reasoning path used to arrive at a given goal.

Many problems are amenable to algorithm-based systems, but many are not; those that are not, require experts to evaluate and assess situations, then make judgments based on those assessments. The selection of KBS over algorithm-based systems is basically a tradeoff between the ease of modification, and intelligibility offered by the former, and fast execution speed and low data base space requirements offered by the latter [25].

2.4 Stages In Building The Maintenance Expert System

MES will be used to monitor and diagnose on-line equipment, using condition-based maintenance techniques to acquire the necessary on-line information. For illustrative purposes, a compressor will be used to demonstrate the capabilities of MES. Compressors are one of the most common items of equipment used in most process plants. MES will be applicable to the on-line, sensor-based diagnosis of virtually any compressor irrespective of the plant operating conditions. The process of "teaching" the program is known as knowledge engineering [9]. This is done by creating a rule base, which contains the diagnostic knowledge used by human experts interviewed by the knowledge engineer. The rule base is then used by an inference engine, which attempts to simulate the thinking process of the human expert.

2.4.1 Diagnostic System Requirements

The following is a set of requirements which MES's diagnostic system should meet [10]:

Level of performance: The system must identify abnormal conditions accurately and not indicate abnormal conditions when none exist. Since on-line sensor evidence does t always lead to a perfect diagnosis, the degree of confidence (DOC) must be indicated. The system should also indicate several possible conclusions each with an associated DOC derived from the sensor input and the expert knowledge.

Adaptability: As human experts add to their knowledge in accordance of new experiences, it is important that the system be capable of being updated by the knowledge engineer. Therefore, the program's software should allow for easy changes.

Sensor Verification: In diagnosis of problems based on sensor indications, the system should be able to verify as much as possible that sensors are providing accurate data. Since, a faulty sensor, if not detected, can lead to an inaccurate diagnosis, the system should be capable of performing tests such as redundant sensing, self-testing, and logical verification.

Explanation of Diagnostics: In order to provide confidence in the person using the diagnosis, it is important that the system be able to describe how the diagnosis was determined. This explanation should be done in English and at a level which a plant operator can understand. This will enable the operator to query the system if he needs to understand how a diagnosis was reached.

Recommendations: An accurate diagnosis has limited value unless it is supplied with actionable information. Among the most important parameters are vibration, outlet pressure, and temperature. These are the parameters which will be used in this research. The use of a few parameters at a time will considerably reduce the complexity of the problem.

2.4.2 Diagnostic System Architecture[13,14,15,16,17]

The basic troubleshooting process includes failure detection, localization, diagnostic, analysis, monitoring, and fault comparison with maintenance standards. A key element is failure diagnosis. This element carries out a breakdown of the observations y Y (signals, images, etc) into individual failure modes E , E , ..., E , where E is the no-failure operating mode. Each diagnostic strategy, S, is a sequential search decision process:

$$D \;.\; L \;.\; Y \overset{S}{===>} (E\ ,T(E\ )) \qquad E \in \{E_0,\ldots,E_N\}$$

Where D: Functional decomposition of the system under test.

L: Learning information data base, e.g., operational environment, failure events, or maintenance actions.

Y: Diagnostic observations (signals from the probes).

T: Maintenance action required on the system under test.

The overall diagnostic system architecture as shown in Figure-1 includes knowledge representation, inference, decision, and action steps.

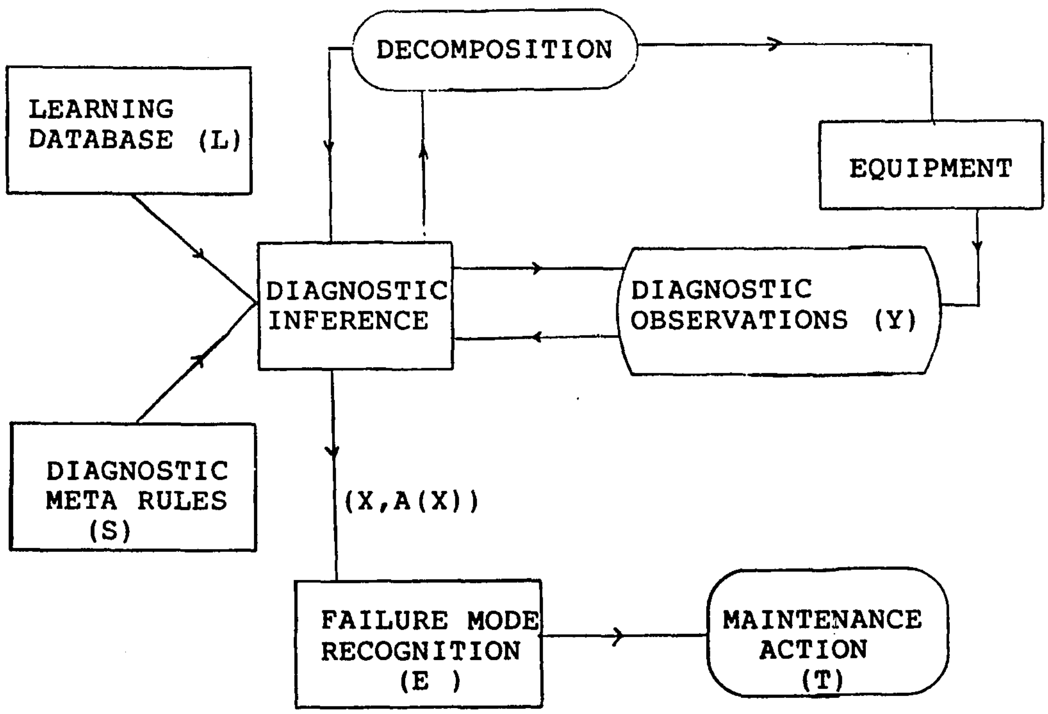

Figure-1. Diagnostic system architecture.

(i) Knowledge Representation (F)

This consists of a list frame data structure F, with an associated vector of attributes A(F), building together a script (F,A(F)). Frames are one of the key ideas for knowledge representation in artificial intelligence. A frame is a collection of facts and data about some thing or some concept. The use of frames along with production rules is particularly appropriate in MES's knowledge representation, since a frame of schema representation is based on the theory that previous situational experiences create certain expectations about objects and events associated with new situations, and provides a frame work within which new information can be interpreted. That is, a frame is a structure within which data or knowledge about stereotyped situations can be represented [26].

The equipment under test can be represented by a nested set of decision tables, constructed starting with basic modules and linked in hierarchical tree structure.

(ii) Learning Database (L)

This database specifies the operating environment, component characteristics, operating modes, and required actions or maintenance procedure.

(iii) Diagnostic Meta-Rules (S)

This unit specifies in predicate form the diagnostic or search strategy to identify the fault.

2.5 Artificial Intelligence Software

The design of the MES described here will incorporate the requirements of the previous section. MES will include a generic set of concepts such as sensors, rules, and hypotheses for representing expert knowledge. The knowledge engineer will use these concepts to create a rule base which contains the expert knowledge for diagnosing a specific fault. Once the rule base is defined, the MES inference engine software will use the rule base and the sensor inputs to compute the actual diagnosis.

The control structure in terms of the search and solution direction will utilize a "forward-chaining", or "data-driven" approach. This type of control structure works from sensor inputs towards possible conclusions, such as equipment conditions or problems. Similar to the MYCIN medical diagnosis system [11], MES will use a scale from -1 to +1 to represent the confidence or certainty of its conclusions. A confidence factor of -1 indicates that the conclusion is definitely false (i.e., a particular equipment condition is not present), while a confidence factor of +1 indicates that the problem is definitely present (i.e., the problem exists). It should be understood that most diagnosis cannot be 100% conclusive so the confidence factor will be between the two extremes. MES will be written in LISP. LISP and PROLOG are the primary programming languages used in AI.

These languages process lists in contrast to numerical or conventional programming languages. Such programming environment enables the creation of expert systems that follow closely to that of human experts.

In implementing the MES, it can be assumed that efficiencies can be attained which are in excess of those achieved by today's preventive and predictive maintenance systems. A diagnostic system based on AI should come to the same conclusion that a human expert would, given the same input. Therefore, theoretically, it can not be more accurate than its human counterpart when a problem situation arises. In reality, however, some improvement in its accuracy can be achieved since the rule base can be developed using the combined knowledge of several experts.

2.6 Strategies For Diagnosis

There are several dimensions of diagnostic strategies and information [35]. The key idea is that the basic knowledge used and its organization lead to the strategies which can be employed. By focusing on different levels of knowledge representation, one can develope very different diagnostic systems.

The basic knowledge required for diagnosis is the set of malfunctions and relations between the observations and the malfunctions. A problem solver may have these directly (e.g., MYCIN), or it may actually reason from some other knowledge (often called "causal" knowledge or "deep" models) to "compile" this diagnostic knowledge. Thus, the system which have this knowledge explicitly given to them are called "compiled knowledge systems" [34].

Typically, a diagnostic problem starts with the observation of some behavior which is recognized as a deviation from the expected or desirable, i.e., a malfunction behavior is observed. The problem solver at this stage needs to generate some hypotheses about the cause if the malfunction: typically, these are in terms of changes in the structure of the device from the specifications, i.e., a diagnostic hypothesis is of the form " component X and/or connection Y is incorrect and causing the set of deviant observations." In some domains, such as medicine, it may not always be possible to identify the problem structurally, i.e., not all disease names correspond to clearly identified structural causes.

In some domains, the initial generation of hypothesis may require a number of low-cost broad spectrum tests to be performed without a specific hypotheses in mind. For example, in medicine, physical examination and a battery of blood tests are often performed. In some cases the observed malfunction may be used to invoke one or more specific malfunction hypothesis. In either case, hypothesis invocation is done by using what one might call "precompiled" pieces of knowledge that relate behavioral observations to one or more hypotheses. This initial hypothesis-generation task can be more or less complex, and more or less controlled depending upon the domain and the knowledge the problem solver has. Whatever the particular method, they all involve going from behavioral observation (test values, signs and symptoms, etc.) to a number of hypotheses, possibly ranked. At this stage, typically, a small number of the more plausible hypotheses are considered the differential or candidate set. In a compiled system, knowledge may be explicitly available for each hypothesis in the differential about which further tests may be successfully used to confirm or reject that hypothesis. By comparing this knowledge for the different hypothesis in the differential, the problem solver can generate tests that have the potential for the greatest discrimination between the hypotheses [22].

If, however, this knowledge is not directly available to the problem solver, but the structure of the device is known, then the following reasoning can be very useful. Assume that the structure has changed in a way corresponding to each of the malfunction hypothesis in the differential list, and reason about what behavior will follow. This strategy amounts to introducing each possible fault and observing the impact on the overall system. One then matches the current state of the system with a fault library. This is commonly known as the approach of using faulty models. This information can be used to discriminate between different hypotheses in the differential. Since the human experts do this forward reasoning qualitatively, there has been substantial interest in a body of techniques called qualitative simulation in AI [40].

2.6.1 The Relationship Between Strategies

There are four basic types of overall strategies for knowledge representation. They are structural, behavioral, functional, and pattern matching. From each knowledge representation one is able to derive the next higher level of representation (refer to Figure 2). It is possible to build a diagnosis system based on knowledge which has been input at any level, stop at any output level of representation, and produce a diagnostic system. It is possible to enter at any level, derive information upwards through the model, and exit at any level with a problem-solving system [44].

Given a representation of the system and a representation of the structure of the equipment, i.e., the interconnection of the components, the ability to generate the behavioral description of the device or equipment as a whole is an important part of causal reasoning. Qualitative reasoning [47] and consolidation [42] have been methods to do this. In simple systems, this stage will generate enough information to understand the equipment. In general, however, this technique is useful for producing various fragments of behavior by ranges of values of components. Often these fragments may need to be further organized to explicitly represent the hierarchical structure of the device and also to capture the teleology of the device [45].

Given the ability to generate behavioral sequences for various assumptions about the components, the agent can often put together an account of the function of the device and its relationship to its structure. In simple cases the behavior that was mentioned earlier can be the function, but, generally, functional specification involves teleology, i.e., an account of the intentions for which the device is used. Often behavior may need to be abstracted to a level higher than that, at which the component is specified. For instance, in an electronic circuit the behavior of components, such as a transistor and a resistor may be in terms of voltage or currents, while a device containing them may be described as an amplifier or an oscillator. To go from the level of the description in terms of "currents" and "voltages" to one of "amplification" and "oscillation" requires an abstraction process. This abstraction process often involves a hierarchical organization of representation of the relation between function and structure [19].

The idea is that an agent's understanding of how a device or equipment works is organized as a representation that shows how an intended function is accomplished as a series of behavioral states of the equipment and how each behavior state transition can be understood as either due to a function of a component or in terms of further details of behavior states. This can be repeated at several levels so that, ultimately, all the functions of a device can be related to its structure and functionality of the components in the structure[20].

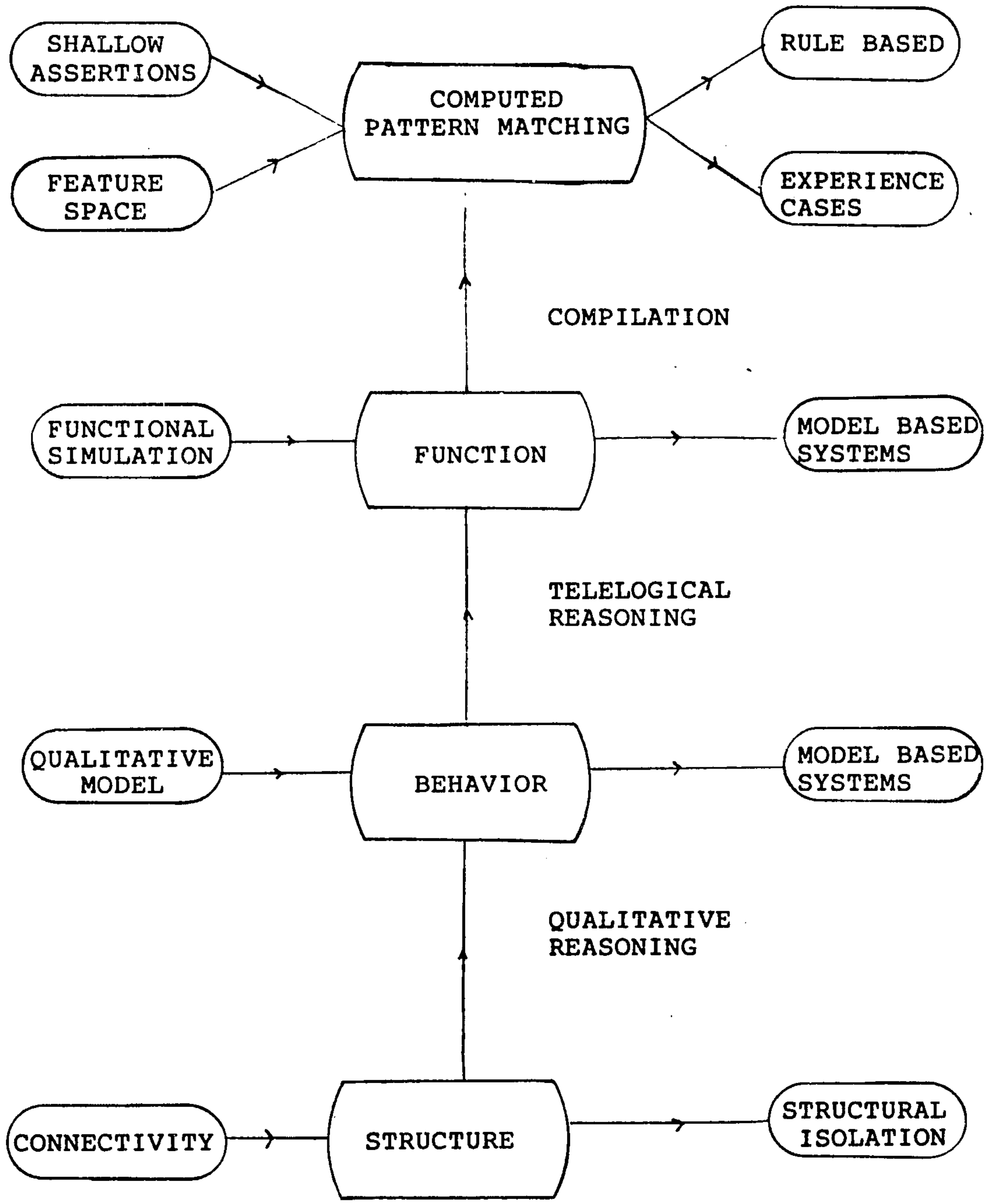

Figure 2. Levels of Diagnostic Reasoning.
(Source: Reference 53, pp. 334)

There are four levels of knowledge representation by which diagnostics systems can be built. At the lowest level is the structural or connectivity information. Next is the behavioral information. Following is the functional information. Finally, there is the compiled information suitable for pattern matching. Of these four levels, one can enter with knowledge at any point and exit at any point. For example, if only the knowledge of connectivity is available, the entering point of the model is at the structural level with the input being the knowledge of connectivity. With no further work the model can be exited at structural isolation state of the diagnostic model. However, through the process of qualitative reasoning , teleolgical reasoning, and compilation, the diagnostic model can be exited with a rule based expert system.

2.6.2 Multiple Faults and Composite Hypothesis

The real goal of the diagnostic process is to generate a diagnosis which can explain all the observation, especially those that differ from the norms. Since equipment can have multiple faults, the correct diagnostic answer will often consist of a number of malfunctions. Each explains some of the data, but together they account for all the observations in a "best" way. In general, the problem of picking the best subset of hypotheses is a version of the "set-covering" problem and as such is computationally complex.

Depending on the kinds of knowledge available, the multiple-fault problem can be complex. de Kleer [43] assumes only an input/output description of each component and connectivity information. Under these assumptions he describes a procedure which uses forward and backward propagations to accept or deny single, double, triple faults, and so on. Peng and Reggia [48] describe a probability-based approach to guide the composition of hypotheses such that more likely combinations are considered first. Their approach uses a merit function for partially completed hypotheses to guide itself to the provably most probable hypothesis or hypotheses. Ideally one wants to considerably reduce the number of hypotheses considered and at the same time still identify the most likely hypothesis.

Josephson et al. [49] describe another approach to this problem, an approach they call abductive assembly. Their paper describes a more natural approach toward diagnosis, than the more formal approaches of de Kleer and Peng/Reggia, who view diagnostic reasoning as the same as some of the information-processing activities that underlie other familiar cognitive activities, such as concept recognition, classification, and the reasoning of human experts. This type of approach is highly modular, and its parts have meaningful intelligent functionalities (i.e., recognition, classification, criticism, etc.).

Knowledge in a variety of forms is brought to bear to contribute to the various subtasks. Computational feasibility is of major design consideration from the start.

2.6.3 Compiled Knowledge Models

Because of the fact that no "deep" model, i.e., structural model, of the equipment under diagnosis is used in compiled knowledge systems, they are often referred to as "surface" or "shallow" knowledge systems. Rule-based systems, usually are made of shallow relationships. The use of either shallow assertions or some pattern-matcher is what comprise the rule-base systems. Most current diagnostic tools are built using the rule-base approach. In this approach a rule exists to conclude each known fault or malfunction of the system. The rules are organized so that one or more intermediate hypotheses are computed, and these intermediate hypotheses are then combined to provide the final analysis of the system.

In areas such as medicine and equipment maintenance where case history of malfunctions are available, a newer shallow reasoning exists. Case-based diagnostic systems use the stored diagnostic information in an indexed or pattern matching approach to identify the case in the past and relate it to the current situation. Standard pattern recognition techniques are often employed to get the best match. The solution is then either to apply the past remedy or try to make some analysis of the difference between the current information and the past knowledge and try to make a small differential or incremental improvement in the solution. This approach is an effective tool where the underlying causal relationships are very complicated and many case histories are available.

2.6.4 Structural Reasoning

Structural or connectivity reasoning is one of the simplest types of knowledge representation. In many systems it can be difficult to describe the behavior and function of the system but simple to describe the connectivity. Diagnostic experts use this type of structural information to guide a diagnosis, even when the function of the component is not clearly understood. Usually structural information is used to isolate the faulty region and then a more complex reasoning is used to identify the exact problem [20].

Structural information provides a boundary for diagnostic systems, therefore, completeness is achieved. This boundary is gained by using simple uniform inference mechanism to derive a large number of possible faults directly from the description of the system. Instead of writing hundreds of rules, the system generates the rules, and the system builder merely describes the connectivity. Completeness is achieved from examining all the structural connections and paths, guaranteeing that nothing is forgotten. Millan [34] describes one of the simplest use of the structure.

2.6.5 Qualitative Reasoning

Most diagnostic systems base their inference and work on real data coming in from the environment. In these systems the necessary first step is to translate the numerical data into qualitative values. These values then can be used throughout the diagnostic process of the expert system. This translation of numerical to qualitative data results in a major means of data reduction. Rather than having to deal with a wide range of numerical values, one can insytead focus and reason about the interesting qualitative states that the system may exhibit. Forbes [47] addresses this point directly. In his system, given a particular physical situation, a graph or chart of all possible behaviors for the system is generated. Then domain-specific criteria are applied to translate the numerical data into an initial qualitative description. By examining what is important to the system, clear guidance is obtained to such fundamental questions as "how should the initial numerical data be segmented, how many interpretation should be constructed for each segment, and how should global interpretations be constructed?" His work also shows how a qualitative model can be used to construct a complete diagnostic system.

2.6.6 Deep Models

In AI two types of models can be distinguished: 1) where an underlying mathematical description is used numerically or qualitatively to simulate the equipment, and 2) where a representation of the causal sequences by means of which the personnel understands the device's function is used for the simulation. The work by Nawab and Lesser [50] (numerically) and Kuipers [51] (qualitatively) are examples of the first model, while the work done by Scarl et al. [52], Patil [46], and Sembugamoorthy and Chandrasekaran [45] are examples of the later model. The second type enables the system to go beyond the input/output of the system and makes it possible to understand each of the underlying steps and the causal sequence which follows.

Models, whether behavioral, functional, or causal, are among the central mechanisms for organizing more powerful diagnostic systems. They provide a knowledge representation mechanism for the large quantity of information and its relationships needed to enable the more complex reasoning for a powerful diagnostic system.

CHAPTER THREE
Maintenance Model Overview

3.1 Introduction

The maintenance system architecture based on the combination of a maintenance plan for critical rotary plant equipment, and artificial intelligence techniques for knowledge representation and modeling will be discussed.

The design of the model will be divided into four steps:

(1) Divisions of the equipment

The machines can be divided into sub-groups based on the similarity of the functions of each group, e.g., structure, rotating elements, controls, and power generation.

(2) Determination of significant items

By dividing economically and precautionary items of each division from the non-significant items, the systems search for a solution can considerably be reduced.

(3) Classification of failures

The failure classification is according to the function of the significant item with respect to (1) safety, (2) operation, (3) economics, and (4) reduction of the risk of multiple or catastrophic failures. By employing this priority classification, the maintenance tasks can either be delayed or act upon immediately.

(4) Determination of maintenance task

By the use of the on-line monitoring data, maintenance tasks can be related to the failure mode. In this section the model will be built around equipment history of the machine plus the condition-based monitoring techniques such as temperature, pressure, and vibration data to specify a work-order for the specific task.

3.2 Division Of Equipment

Equipment can be broken down to divisions of sub-groups based on the similarity of the functions of each group. This enables the program to reduce the search space required to pin-point an abnormal behavior. Figure 3 depicts one such classification of equipment parts. The major divisions of the equipment are divided into subgroups of systems. Each system is further divided into it's subsystems. Subsystems are comprised of assemblies, and the assemblies are broken down into individual parts. It is evident that by categorization of critical machines, the expert systems's diagnostic procedure will be more efficient as compared to non-modular approach. These divisions are intended to divide and categorize rotary equipment according to their distinguishing functions. Hence, the above catagories should contain overall description of the equipment within the diagnostic domain.

3.2.1 Division of Significant Items

Determination of significant items will simplify the maintenance analysis. This is accomplished by reduction of the number of items to be analyzed during the diagnosis of the machine. The darker lines in Figure 3 displays the application of this procedure. Significant items are those items that have a direct effect on the safety, or a major economic consequences, e.g., operational inefficiency, since this could bring about unscheduled equipment down time.

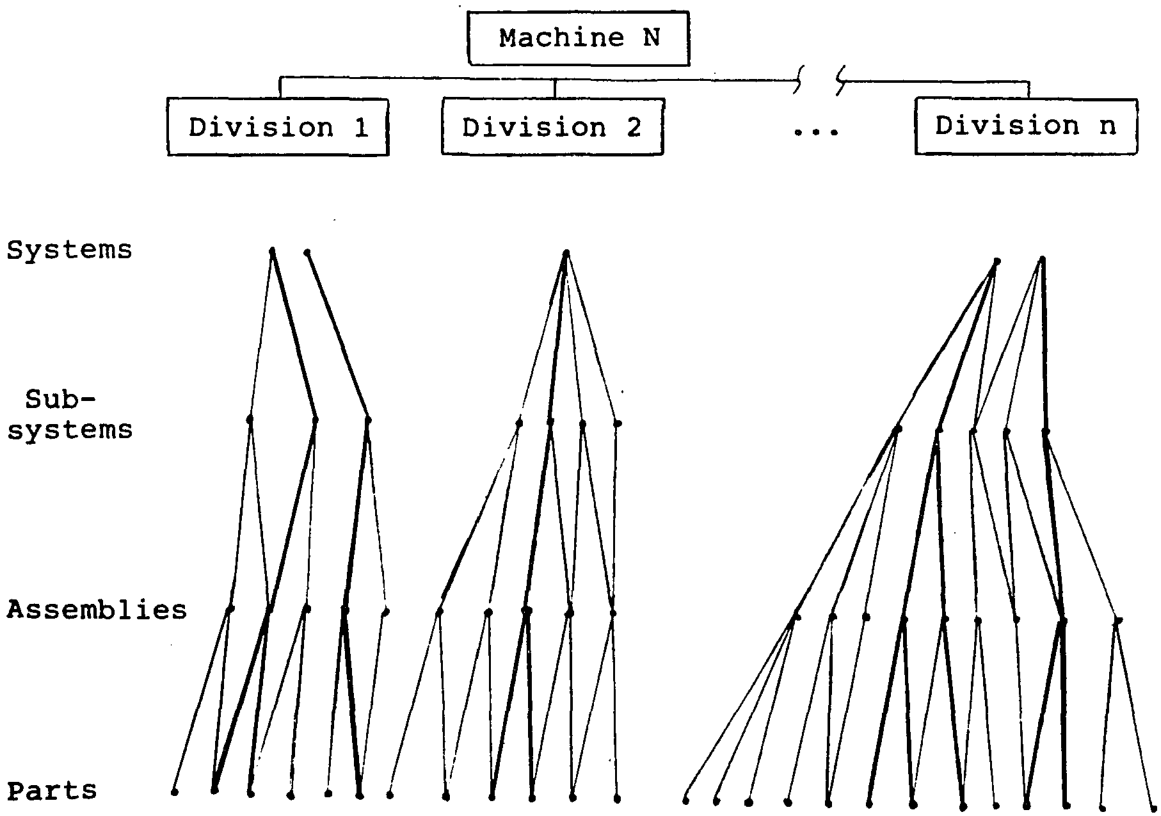

Figure 3. Divisioning of Machines into Major Parts.

3.3 Classification Of Failures

By classifying different failures according to their nature, an expert system can quickly determine the priority of different necessary maintenance actions. The significance of failures can be divided into the following catagories: safety related, operational related, and non-operational related.

Safety related failures are those failures by which the safety of crew and/or total loss of equipment could occur as the result of machine failure. The failures in this category are of the highest priority and the machine should be attended at once to resolve the abnormality. The operations related failures are those by which the output or the function of the machine is hindered. These failures can reduce the efficiency of the operating machine. The direct economic impact of these types of failures makes their priority second to those that are safety related. The non-operational failures are those in which the performance of the machine is not effected ; however, if left unattended the penalty could become severe. This type of failure is of the third priority level.

3.4 Maintenance Task Determination

The maintenance task determination is the heart of any maintenance planning model. It aims at relating each maintenance task to each failure mode distinguished.

The diagnostic reasoning is initiated by user-supplied information to the maintenance expert system, or by means of on-line data input. Some performance parameters, e.g., temperature, pressure, and vibration, are monitored. Once an abnormality is sensed, the system executes a diagnostic routine to choose what division of the machine is involved (see Figure 3). Once at the division level, by the use of diagnostic rules the fault is pin-pointed, and a remedy sought.

3.4.1 Architecture of Overall System

The architecture of overall system is depicted in Figure 4.

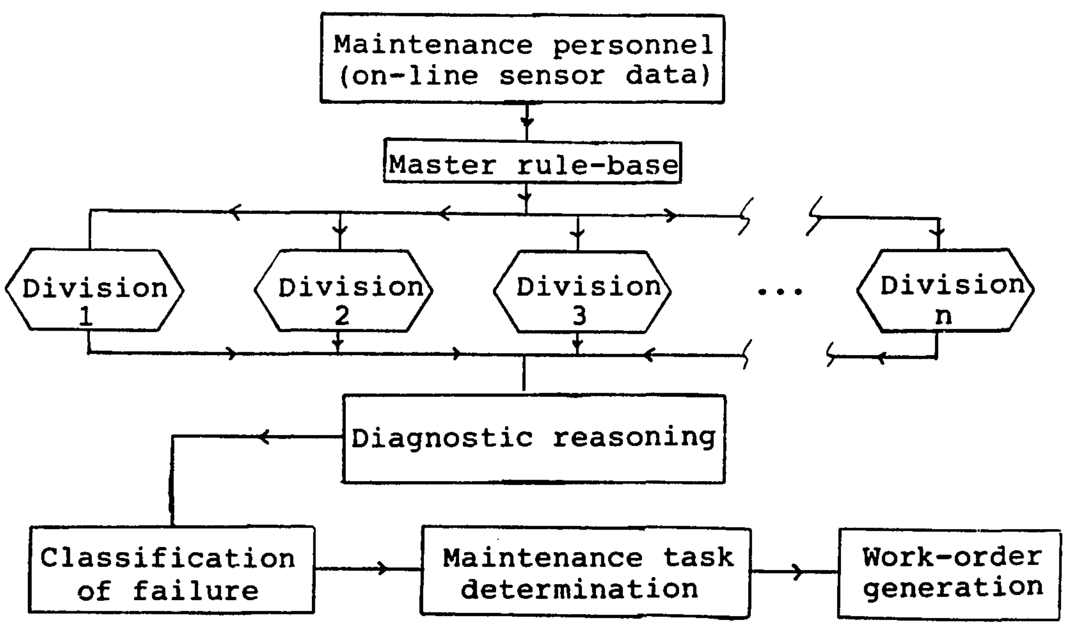

Figure 4. Overall System Architecture.

The system uses the data inputed either by maintenance personnel or by on-line hard-wire means to determine the location in of the equipment which is most likely to contain the problem. The master rule-base contains the fundamental distinguishing rules which enables the system to reduce its search to a particular division, i.e., location. These rules are based on the mode of operation and function of the different parts within the equipment. Once a division, or location, of the equipment is chosen, the system then, with application of that division's rule-base, attempts to pin-point the problem area. These rules are different from those in the master rule-base, since they are aimed toward specific parts operations. This rule base can be sub-partitioned to significant item rule-base and non-significant item rule-base. The advantage of such partitioning is that it reduces the search space to reach an specific fault, while, it still enable the system to contain a complete knowledge of the machine. The failure classification module is used to determine the priority of the fault. The priority of failures decrease in the following order: safety related, operations related, and non-operational type failures. The maintenance task specification module devises a correctional routine and this information is put into an work-order form and printed, or, if not an emergency, fitted automatically into the maintenance schedule.

3.5 Multi-Parameter Diagnosis

The use of several operating parameters in the diagnostic reasoning is unique to this research. In conventional monitoring techniques, operating parameters such as: temperature and outlet pressure are mostly used as warning signals to an abnormal machine condition. These parameters, which are an important indicator of machine condition, are primarily used to indicate that a threshold is exceeded or the output flow rate is not within the acceptable limits.

For diagnostic purposes, especially in rotary equipment, vibration analysis has been the foremost technique used in fault detection. The use of the shape of operating signature patterns as the basis of comparison leads to the detection of abnormal behavior.

Multi-parameter diagnosis is defined as the use of several operating parameters simultaneously to pin-point a malfunctioned behavior. Therefore, by consideration of all chosen performance parameters and their status at the time of diagnosis, faults can be more accurately pin-pointed. Figure 5 shows the use of three performance parameter in fault isolation. Note that this procedure can be expanded to any number of parameters. The machine is monitored until an abnormality is encountered. The operating range of each performance parameter is determined either by maintenance personnel, or on-line sensors which could use adaptive means of process control to deliver the most appropriate operating changes, and keeping the machine performance within acceptable limits.. The vibration signatures can be isolated and categorized with conventional vibration analyzers. Note that in diagnosis, the operating range of each performance parameter is considered. Once this information is supplied to the MES, it will use them simultaneously with the available data on the other performance parameters, therefore, maximizing the available information on hand.

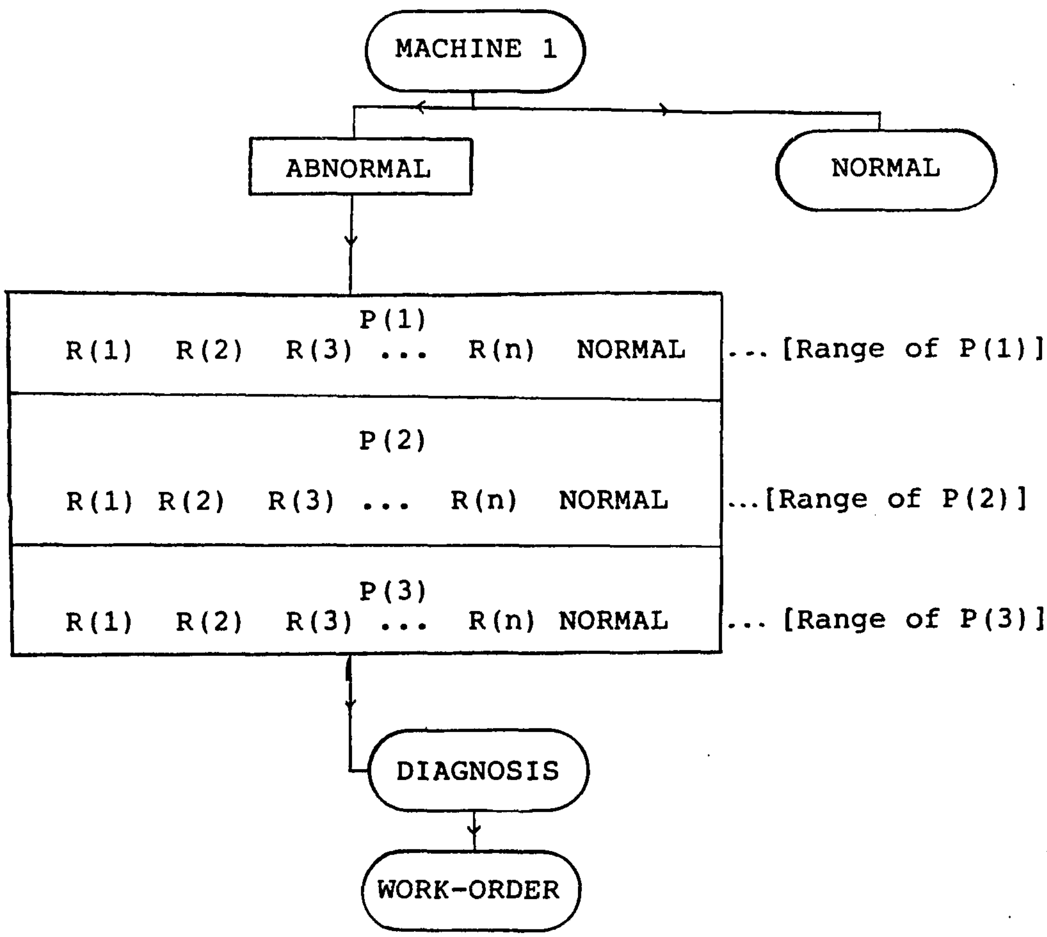

Figure 5. Simultaneous Use of All Parameters in Diagnosis

As the accuracy of diagnosis is increased, the length of equipment down-time along with probability of misdiagnosis is decreased. The effect of how incorrect diagnosis could increase the overall down-time of equipment can be seen in equation 1.

$$\% \ A = \frac{B}{B + C} \qquad \text{(eq. 1)}$$

Where: A is actual percent of down-time.
B is down-time given correct diagnosis.
C is down-time given incorrect diagnosis.

One goal of the MES is to reduce down-time caused by incorrect diagnosis (C). It can be seen that as this value nears the optimum value of zero, the time spend on the equipment become closer to the minimum time required to repair the machine, therefore, increasing both machine and production efficiencies.

3.6 Work-Order Generation

Work-orders contain all the necessary information to perform maintenance tasks, information such as material, tools, labor, and a description of work. The priority of work-orders determines their sequence in scheduling. Figure 6 illustrates a typical work-order. Chemical plants are usually divided into different geographic areas. With area classification and machine numbers, maintenance personnel are able to easily locate the machine specified in work-orders.

```
WORK-ORDER NUMBER: 102010
PRIORITY: 1
MACHINE no.: 324
AREA: J3
DESCRIPTION: crank case oil contains brass and nickel
             elements, pertaining to existence of bearing
             seal rub.

MATERIAL REQUIREMENT: Seal no. 345xy325P  (one)
TOOLS : 9-24 mm Socket set, crane (type B)
LABOR: 3 man hr.
COMMENTS:




COMPLETION DATE:
```

Figure 6. Information Contained in a Typical Work-order.

Completed work-orders are the source of equipment history. This information is catalogued according to the division of equipment. In MES, failures have a unique work-order assigned to them. Once a failure is diagnosed, the program will determine its priority according to criteria cited earlier, and then search a database of work-orders and assigns the proper work-order.

Work-orders are stored according to the major divisions of equipment (see Figure 3). This approach will reduce the search time for work-orders. By relieving maintenance personnel from work-order preparation, MES attempts to reduce machine turn-around time. Also, the maintenance department can perform their tasks at a more efficiently.

3.7 Diagnostic Analysis

3.7.1 Introduction

The principal concern of this research is the fault diagnosis of machines. The information acquired for such a task can be used in making decisions, therefore, the decision making process has to be examined before defining a failure system analysis.

Presumably, any decision that one makes is based on the present knowledge about the situation at hand. This information comes partly from the direct experience with the relevant situation or from related experience with similar situations. This knowledge may be increased by appropriate tests and proper analysis of the results, e.g., experimentation. To some extent the knowledge may be based on speculation and this will be conditioned by human's degree of optimism or pessimism. For example, one may be convinced that "all is for the best in this best of all possibilities." Or, conversely, one may believe in Murphy's Law: " If anything can go wrong, it will go wrong." Thus, knowledge may be obtained in several ways, but in vast majority of cases, it will not be possible to acquire all relevant information, so that it is almost never possible to eliminate all elements of uncertainty. The decision making task at the time of failure has to be conducted quickly to reduce downtime of the machine, therefore, utilizing only the information on hand and the knowledge of the past. Figure 7. provides a schematic representation of these considerations.

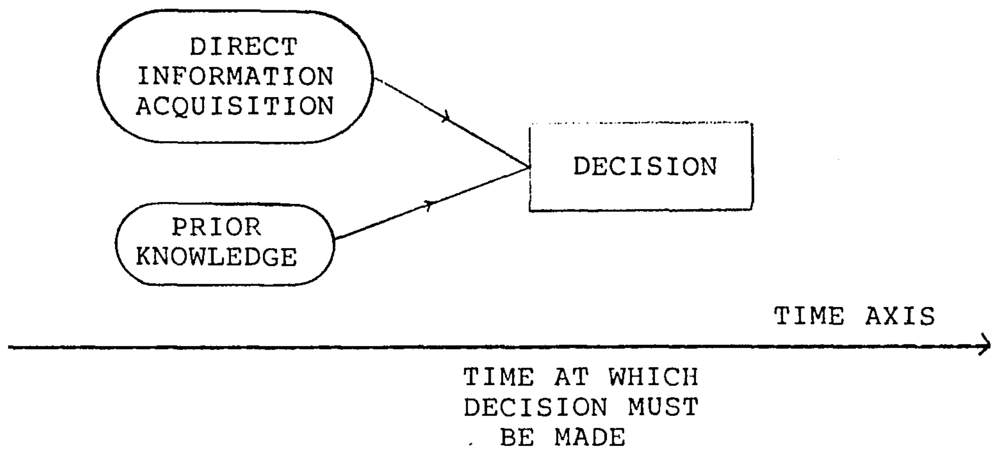

Figure 7. Schematic Representation of the Decision Making Process.

The existence of the time constraint on the decision making process leads one to distinguish between good decisions and correct decisions. With time and experience good decisions can turn to correct decisions. The main concern of this research is to set the basis for correct decision making. To do this one must:

(1) Identify that information (or data) which pertain to the anticipated decision.

(2) Create a systematic program for the acquisition of this pertinent information.

(3) Assess or analysis the data acquired.

Diagnostic analysis is a directed process for the orderly and timely acquisition and investigation of specific system information pertinent to a given decision. Accordingly, the primary function of the diagnostic analysis is the acquisition of information and not the generation of a system model. The emphasis (initially) will be on the process, i.e., the acquisition of information, and not on the product, i.e., the system model. This is important because, in the absence of a directed, manageable, and disciplined process, the corresponding system model will not usually be a very fruitful one.

The nature of the decision making process is shown in Figure 8. Block A represents certified reality. These are the available information about the system under study. A comprehensive review of the equipment history and an exhaustive interview of experts will comprise this step. These steps can also lead to building a system model shown as block B. Next, this model is analyzed to produce conclusions (block C) on which the decisions are based. Hence, the decision is a direct outcome of the model and if the model is grossly in error, so will the decision that is produced. Clearly, then, in this process the greatest emphasis should be placed on assuring that the system model provides as accurate a representation of reality as possible.

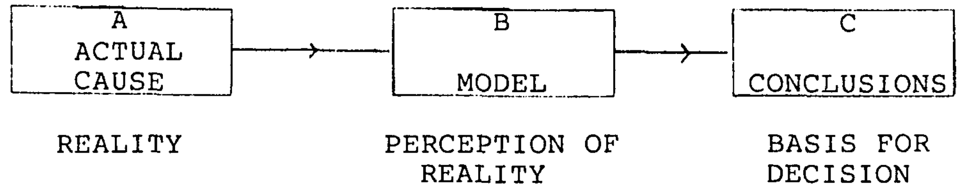

Figure 8. Relationship Between Reality, System Model, and Decision Process.

3.7.2 Definition of a System

A system can be described as a deterministic entity comprising an interacting collection of discrete elements. From a practical standpoint, this is not very useful and, in particular cases, one must specify what aspects of system performance are of immediate concern. A system performs certain functions and the selection of particular performance aspects will dictate what kind of analysis is to be conducted.

The word "deterministic" implies that the system in question be identifiable. The discrete elements of a systems must also be identifiable. Equipment operation , therefore, can comprise the overall system. Note that the discrete elements themselves may be regarded as systems. Thus a machine can consists of a power generation system, a piping system, a casing and foundation system, and so forth; each of these, in turn, may be further broken down into subsystems and sub-subsystems, etc.

Note also from the definition that, a system is made up of parts or subsystems that interact. This interaction, which may be very complex, generally insures that a system is not simply equal to the sum of its parts. Also, if the physical nature of any part changes, i.e., degradatin or failure, the system itself also changes. This is an important point because, should design changes be made as a result of a system analysis, the new system so resulting will have to be subjected to another baseline analysis.

It is important in any system definition to put external boundaries on the system. This decision will have to be partially made on the basis of what aspect of system performance is of concern. It is also important to establish a limit of resolution, i.e, how specific should the system be defined. Such system definition was shown in Figure 3.

3.8 Basic Model Concepts

3.8.1 Failure vs. Success

The operation of a system can be considered from two standpoints: enumeration of various ways for system success, or system failure. This concepts is shown in Figure 9.

One should note that certain identifiable points in success space coincide with analogous points in failure space. Thus, for instance, "maximum anticipated success" in the success space can be thought of as coinciding with "minimum anticipated failure" in failure space.

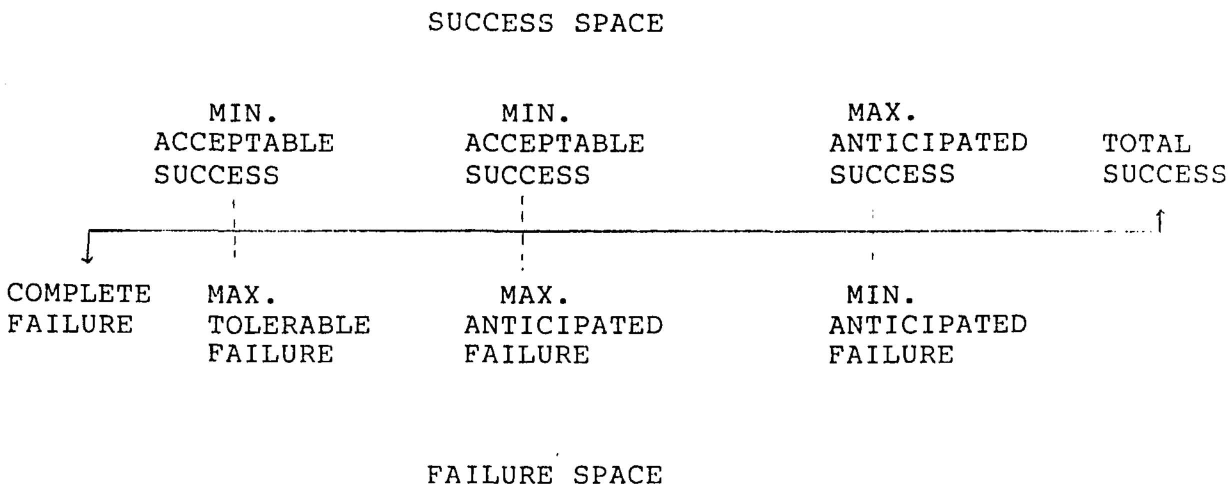

Figure 9. The Failure Space-Success Concept
(source: reference 21, pp.16)

From an analytical standpoint, there are several overriding advantages that occur to the failure space standpoint. First of all, it is generally easier to attain concurrence on what constitutes failure than it is to agree on what constitutes success. "Success" tends to be associated with the efficiency of a system, the amount of output, the degree of usefulness, and production and marketing features. These characteristics are describable by continuous variables which are not easily modeled in terms of simple discrete events, such as "valve does not open" which characterizes the failure space. Thus, the event "failure," in particular, "complete failure," is generally easy to define, whereas the event, "success," may be much more difficult to tie down. This fact makes the use of failure space in analysis much more valuable than the use of success space.

Another point in favor of the use of failure space is that, although theoretically the number of ways in which a system can fail and the number of ways in which a system can succeed are both infinite, from a practical standpoint there are generally more ways to success than there are to failure. Thus, purely from a practical point of view, the size of the population in failure space is less than the size of the population in success space. In analysis, therefore, it is generally more efficient to make calculations on the basis of failure space.

MES will utilize a deductive failure analysis which focuses on one particular undesired event and which provides a method for determining causes of this event. The undesired event constitutes the top event in the diagnostic reasoning of the system.

3.9 Diagnostic Model Construction

3.9.1 Faults vs. Failures

One must first make a distinction between the rather specific word "failure" and the more general word "fault". If a subsystem of an equipment is malfunctioning this could be considered the subsystem's "failure." However, if the malfunction is due to a problem upstream, then this is termed as a "fault." Therefore, generally all failures are faults but not all faults are failures. Failures are basic abnormal occurrences, whereas faults are "higher order" events. The proper definition of a fault requires a specification of not only what undesirable component state is but also when it occurs. These "what" and "when" specifications should be part of the event descriptions which are entered into the diagnostic procedure.

3.9.2 Fault Occurrence vs. Fault Existence

A fault may be repairable or not, depending on the nature of the component or the subsystem. Under the conditions of no repair, a fault that occurs will continue to exist. In a repairable subsystem a distinction must be made between the occurrence of a fault and its existence. This distinction is of importance, specially in cases where the equipment is able to function within threshold limits, but close attention to certain components must be given.

3.9.3 Active vs. Passive Components

Component of a system can be separated into two type: active and passive. A passive component contributes in more or less static manner to the functioning of the system. Such a component may act as transmitter of energy, i.e., steam lines transmitting heat energy, or it could act as a transmitter of loads, e.g., a structural member. To assess the operation of passive components, such tests as stress analysis can be performed. Further examples of passive components are: pipes, bearings, journals, welds, etc.

An active component can be considered as the transmitter of a "signal." This "signal" can be a force or current. A passive component may also be thought of as the mechanism, e.g., a wire, where the output of one active component becomes the input to a second active component. The failure of the passive component becomes the non-transmission, or partial transmission of its "signal."

In contrast, an active component originates or modifies a signal. Generally, such a component requires an input signal or trigger for its output signal. In such cases the active component acts as a "transfer function." If an active component fails, there may be no output signal or there may be an incorrect output signal.

3.9.4 Component Fault Catagories: Primary, Secondary, and Operator Related

The faults can be classified into three catagories: primary, secondary, and operator related. A primary fault is any fault of a component that occurs in an environment for which the component is qualified. A secondary fault is any fault of a component that occurs in an environment for which it has not been qualified. An operator related fault, involves the proper operation of a component or subsystem but at the wrong time or in the wrong place. These types of faults usually originate from some upstream device.

3.9.5 The Concept of Immediate Cause

An expert, in diagnosing a failure, first defines his system (its boundary) and then selects a particular system failure mode for further analysis. This constitutes the discovery of the causes which led to this effect (failure). He next determines the immediate, necessary, and sufficient causes for the occurrence of this failure. These are not the basic causes of the failure but the immediate causes or immediate mechanisms for the event.

The immediate, necessary, and sufficient causes of the break-down are then treated as sub-failures and diagnosis proceed to determine their immediate, necessary, and sufficient causes. In so doing, the diagnosis propagates to achieve finer resolution, until ultimately, the origin of the fault is discovered. This concept is one of essentials of diagnostic systems modeling, because it actually describes human experts behavior in problem solving.

3.10 DIAGNOSTIC MODEL

3.10.1 Introduction

The diagnostic model representation of the equipment failures is shown in Figure 10.

P1	P2	P3	...	Pn	Z
A11	A12	A13	...	A1n	Z1
A21	A22	A23	...	A2n	Z2
.	.	.	...	.	.
.	.	.	...	.	.
.	.	.	...	.	.
Am1	Am2	Am3	...	Amn	Zm

Figure 10: Fault Diagnosis Model.

Where P1 thru Pn are the performance parameters and Z is the cause of the status of the machine when such values by the performance parameters are exhibited. The performance parameters thresholds, e.g., A11, A21, A22, or Amn, are preset and give an indication of the status of the respective parameters. With list processing languages of artificial intelligence (AI) it is possible to assign parameter status as either qualitative or quantitative. For example, a qualitative assignment could be discoloring of oil, and a quantitative assignment could be temperature threshold of 100 to 125 (F). The parameters could also represent different vibration patterns, e.g., pattern-1 could represent a normal pattern, pattern-2 could be misalignment, etc. Signature analysis is a common method of isolating vibration signals from machine noise and other signals. As it will be discussed in the latter section, the model shown in Figure 10. can be regarded as a complete model (for smaller diagnostic applications), or a subsystem of a total model (more complex equipment or diagnosis, requiring the breakdown of the machine or diagnostic procedure into several subsystems). Each row or set of rows in conjunction with each other, could depict a class or pattern of machines behavior.

After a careful review of equipment history of the equipment one such model can be formulated. From Figure 10 it can be seen that this modeling approach is non-deterministic in nature. Also, in order to recognize different patterns of machine's performance parameters a pattern recognition technique is to be devised. The aim of this model is to apply AI along with statistical pattern recognition (SPR) techniques to recognize machine status and recommend the nature of faults with an assigned probability level or degree of confidence. Once this is accomplished then produce work-orders to remedy failures.

The methods and theory for classification systems apply to many problem areas. Considerable emphasis has been given to (1) medical decision making, referred to in AI as AIM (Artificial Intelligence in Medicine), (2) diagnosis in learning disorders [54], (3) signal recognition in communication, (4) agricultural pattern recognition, (5) recognition of military patterns, (6) process control, and many others. Other expert systems include PROSPECTOR for geology [55], DENDRAL for mass spectroscopy [56], MACSYMA for symbolic integration [57], DART for computer fault diagnosis [58], R1 [59] and R1-Soar [60] for configuration of computer systems and BATTLE for the military [61, 62].

3.10.2 Knowledge Base Structure

In order to describe the knowledge base structure one has to initially define how knowledge can be represented. The hierarchical representation of knowledge in this research is as follows:

- Primitives
- Features
    - Type 0 feature
    - Type 1 feature
- Complex feature
- Classes
    - Only class
    - Complex class
- Categories
- Complex categories
- Subsystems

A primitive denoted y_{ξ} is a basic characteristic (level 1) of a category. A feature value denoted x_{jr} (level 2) is the next higher level characteristic in the hierarchy. A feature x_j "owns" a set of feature values, one of which is true for a given pattern from a category. There are different kinds of features. A Type 0 feature is defined to have values which are mutually exclusive. A Type 1 feature is defined as a set of binary features where a binary feature is either true or false. The value of a Type 1 feature is one of the possible combinations of true or false values for all the features in the set (a probability function of these values). In the hierarchy there is a complex feature value (level 3), this is at the initial level in the hierarchy where concept formation can take place. A complex feature can be a ratio, sum, maximum, minimum, dependent output of a set of simultaneous linear or nonlinear equations, or a complex mathematical equation. Primitives and features are basic characteristics of a category. A complex feature value can be a category; but more generally it is a concept in the hierarchical description of a category. Define a category space γ consisting of mutually exclusive and exhaustive categories γ_1^*, γ_2^*, ... , γ_M^*. Being mutually exclusive, these categories are events which cannot occur together.

Let

$$\{ w_i^* \}_{i=1}^{M_1} = w_1^* , w_2^* , \ldots , w_{M_1}^* \qquad \text{(eq. 2)}$$

be a subset of the categories in the category space and name w_i^* " the only class w_i ." The notation only class w_i^* is used to distinguish this category from categories consisting of class w_i and one or more other classes. The M_1 only classes [eq. 2] are mutually exclusive and thus cannot occur together. Therefore, the event w_i^* means

$$w_i^* : \quad \text{only class } w_i \qquad \text{(eq. 3)}$$

Thus, w_i^* and w_j^* , i = j, cannot occur together because the former is only the class w_i while the latter is only the class w_j by definition.

Let

$$\{\Omega_\xi^*\}_{\xi=1}^{M_2} = \Omega_1^*, \Omega_2^*, \ldots, \Omega_{M_2}^* \qquad \text{(eq. 4)}$$

be a subset of categories. also events in the category space, and name Ω_ξ complex class ξ . The M_2 complex classes [eq. 4] are mutually exclusive and thus cannot occur together. The event Ω_ξ^* means:

$$\Omega_\xi^*: \quad \text{complex class } \Omega_\xi .$$

The practical significance of classes is that, in designing a classification system utilizing AI, the best starting point in development is to describe the patterns corresponding to " only classes." Even with a small number M_1 of classes, the number of complex classes can be very large. A knowledge of probability can be introduced to constrain this number to " possible" complex classes or " probable" complex classes.

The diagnostic systems vary with the applications; but in general the need for a model ranging from where the total system is a single subsystem, consists of two or three subsystems, or consists many subsystems. A total diagnostic system consists of L features, M categories, and M_i classes. Knowledge is grouped into S subsystems indexed by s = 1,2,...,S, where subsystem is characterized as follows:

Subsystem Λ_s

M_s : Number of categories in subsystem Λ_s
M_{c_s} : Number of classes in subsystem Λ_s
L_s : Number of features in subsystem Λ_s .

A method is needed to index all categories, classes, features, and other subsystems and categories of other subsystems associated with or affecting subsystem Λ_s. This is accomplished with vectors, where the term in { } indicate those items included:

$X_s = \{x_{s_j}\}$, $x_{s_j} = 1$	if the jth feature (primitive) is included in { }, insignificant otherwise
$\gamma_s = \{\gamma^*_{s_i}\}$, $\gamma^*_{s_i} = 1$	if ith category γ^*_i is included in { }, insignificant otherwise
$\mathcal{C}_s = \{\mathcal{C}_{s_i}\}$, $\mathcal{C}_{s_i} = 1$	if ith class is included in { }, insignificant otherwise
$S_s = \{S_s\}$, $S_{s_t} = 1$	if subsystem Λ_t is associated with reference subsystem Λ_s, insignificant otherwise.

In consideration of the concept of categories, classes, and primitives of a system, the MES knowledge base structure is divided in different modules or subsystems. Each subsystem represents different categories by which the operating behavior of the machine is modeled by means of production rules and heuristics. Within the categories the diagnostic inference is to derive at matching the present machines behavior to one of the previously stored patterns or classes, e.g. a row in Figure 10. This is accomplished by focusing on the status of each performance parameter (primitive) within that category. In the areas where the knowledge is not complete, for example an exact match is not found, then the system will refer to the nearest probable cause of the failure and state that the diagnosis is not fully supported with the available knowledge.

The complete knowledge base structure is depicted in Figure 11. The main module's task, similar to experts behavior, is to decide with general information about the nature of the problem. The completeness of this module is essential in speed and accuracy of the diagnostic procedure. This module is the interface between the user and the expert system.

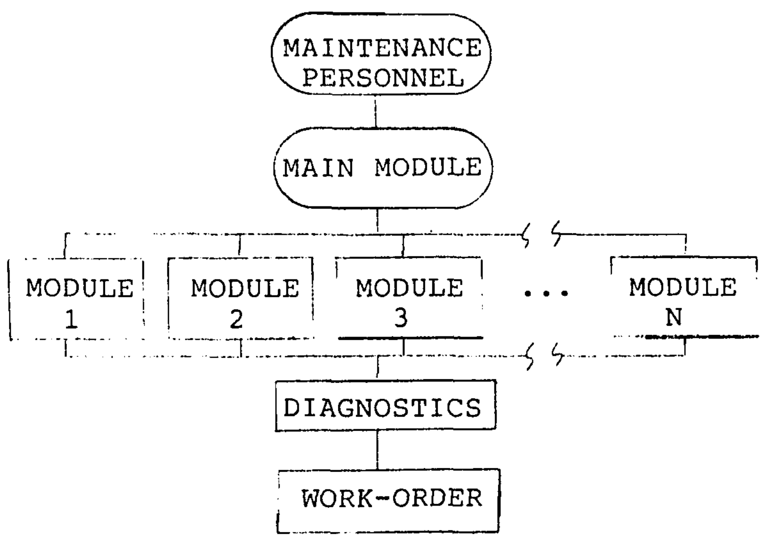

Figure 11- Knowledge Base Structure of MES

By accumulating necessary information the main module, decides which subsystem appears to be the leading cause of the symptoms. Then by transferring the control and the inference structure to the selected module the investigation continues. At times it is possible that certain knowledge about other subsystems is necessary, then either by direct or thru the main module, an access to another subsystem is accomplished. Hence, similar to the experts organization of knowledge, the knowledge within MES is separated, and at the same time interfaced with other "chunks" of knowledge, so that maximum use of the available information could be attained.

3.10.3 Constraints in Feature Space

The application of SPR in AI is pursued with construction of category conditional probability density function. This construction involves MES learning by instruction, learning from examples, and may involve learning by discovery. In this research the main mode of learning is restricted to learning from instruction. Rules can be used to describe relations between features in a subset of features. These relations can be reflexive, transitive, etc. Other interrelationships among features in a subset of features include product, ratio, sum of squares, simultaneous equations, etc.

3.10.3.1 Dropping Condition Rule

The underlying logic or heuristic behind the missing feature operation in MES can be described as follows:

The rule

A & S :::> K |< A :::> K

states that a concept description can be generalized by simply removing a conjunctivity linked expression (S). If the concept is a pattern, then this rule generates a whole class of patterns from one typical pattern (induction).

3.10.3.2 Adding Alternative Rule

The rule

A :::> K |< A:U:B :::> K

uses logical disjunction (OR) :U: to provide the alternative concept A:U:B to concept A. This rule applies extensively to Type 0 features.

3.10.3.3 Extending Reference Rule

If feature R1 is a sub-feature of R2 and both are in domain L, then

A & [L-R1] :::> K |< A & [L-R2] :::> K

R2-R1 might be insignificant features and utilizing these feature should not prevent result K.

3.10.3.4 Closing Interval Rule

The closing interval rule is like a fuzzy set operation used in a Type 0 feature. Suppose that Z is a Type 0 feature and "a" and "b" are two values; then

$$\left.\begin{array}{l} A \;\&\; [Z=a] \;:::>\; K \\ A \;\&\; [Z=b] \;:::>\; K \end{array}\right| \quad |< \quad A \;\&\; [\, Z=a:U:b \,] \;:::>\; K$$

is a rule stating the concept that if feature Z has value equal to either "a" or "b" then result K follows.

3.10.3.5 Climbing Generalization Tree Rule

This rule would indicate, for example, that if only class w_i^* occurred, then class w_i is at lowest level in that hierarchy. Let a, b, ..., i be nodes in a hierarchy as s represents the lowest parent node to the other node. The rule

$$\left.\begin{array}{l} A \;\&\; [Z = a] \;:::>\; K \\ A \;\&\; [Z = b] \;:::>\; K \\ \quad\quad \cdot \\ \quad\quad \cdot \\ \quad\quad \cdot \\ A \;\&\; [Z = i] \;:::>\; K \end{array}\right| \quad |< \quad A \;\&\; [Z = s] \;:::>\; K$$

A special case is a path along in a network.

3.10.3.6 Turning Constraints into Variable Rule

Let F(v) stand for some descriptive dependence on feature v, and let this description hold for v = a,b,...,and so on. Then a generalization is that the rule holds for all v. This is a common rule used in inductive inference. Patrick [63] proposed such rules for statistical dimensionality. For example, let $v = (x_1 \mid x_2)$ be the ratio of two features. If a functional F(v) can be found whose domain is an important attribute for a class (category), then F(v) is a significant feature for the category. In particular, F(v) is a complex feature because it is a function of two features.

3.10.3.7 Turning Conjunction into Disjunction Rule

Define the rule

$$F_1 \ \& \ F_2 \ :::> K \qquad |< \qquad F \ :U:F \ :::> K,$$

Which implies that iff F_1 & F_2 implies K then F_1 or F_2 implies K. The way this rule can be used in applications where F_2 is dependent on or correlated with F_1 . If it is known F_1 is true, then F_2 is true. This type of rules can be applied to embedded features in a Type 1 feature.

3.11 Total System: Integrating MES Subsystems

Subsystems are modular construction for acquiring a knowledge base and making decisions. There are problems where it is desired to process categories or features from another subsystem or even from complex classes that are complexed with classes in another subsystem. This problem is handled by constructing a knowledge base structure that crosses subsystems.

The key is that a category has insignificant features for features not in the subsystem. Ideally this is how a subsystem should be designed. An alternative is for one or more features of a category to have values which are called intermediate categories. An intermediate category is a decision from another subsystem which affects the subsystem. An intermediate category is a concept in knowledge base structure of the total system. It can be viewed as a complex feature for the subsystem although it is constructed in another subsystem.

3.11.1 Introduction to the Total MES System

A total diagnostic system has a knowledge base consisting of "all" categories and features. The total system is modular , see Figure 12 . The categories and category feature relationships are arranged in modules for ease of review and updating. The classes and categories suggest a natural hierarchy because "only classes" and "complex classes" are formed from classes. This hierarchy is a property of the feature space and category space and applies to the modules (subsystems) as well as the total system. At the bottom of the hierarchy are primitives, which are the basic components used to identify classes, only classes, and complex classes.

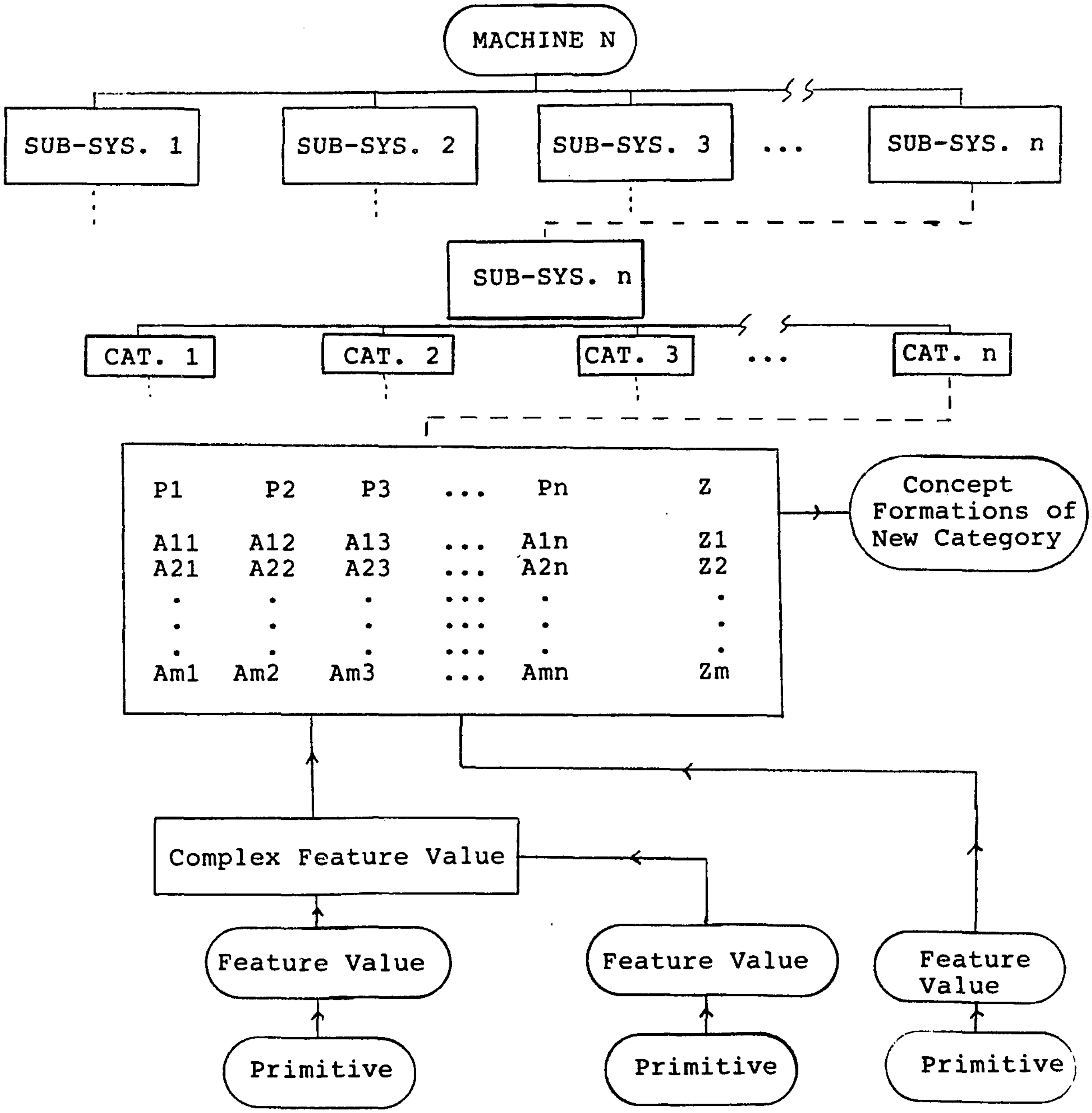

Figure 12. Diagram of Knowledge Representation from Primitive to Machine Division, with Possible Intermediate Concept Formation of a Complex Feature Value as a Category.

A primitive is a feature. Usually , a class, only class, or complex class are measured by a multivariate function of primitives (the inference function). However, a primitive can be the sole component of the inference for an "only class", class, or complex class. That is, a primitive can be a class or category.

This hierarchical structure is important for a total system design where it may be desirable to identify a primitive as a category. For example, increased vibration of the casing, a primitive, can be the category of structural looseness.

In practice a variety of diagnostic problems arise. There are instances when the problem is known to be confined to one or several subsystems. There can be problems where the total system must be considered, but some form of activation usually is required. To accomplish this , subsystem conditional density functions are required.

3.11.2 Parameters of the Total System

A total diagnostic system consist of M categories γ_i^*, $i = 1, 2, \ldots, M$, M_c classes, and L features. There exists an optimum decision strategy for the total system. The total system consists of S subsystems where the sth subsystem is characterized as follows:

Subsystem Λ_s s = 1, 2, ..., S
M_c : Number of categories in subsystem s.
M_{cs} : Number of classes in subsystem s.
L_s : Number of features in subsystem s.
K_s : Number of subcategories for categories or classes in subsystem s.

A method is needed to index all categories, classes, features, other subcategories of other subsystems associated with (affecting) subsystems Λ_s ; the latter is called the reference subsystem. This is accomplished with vectors for the sth subsystem:

$X_s = \{x_{sj}\}$, X_{sj} = 1 if jth feature (primitive) is included in the reference subsystem s, 0 otherwise.

$\gamma_s^* = \{\gamma_i^*\}$, $\gamma_{s_i}^*$ = 1 if ith category γ_i^* is included in the reference subsystem s, 0 otherwise.

$C_s = \{C_i\}$, C_{s_i} = 1 if ith class is included, 0 otherwise.

$S_s = \{S_{s_\varepsilon}\}$, S_{s_ε} = if subsystems Λ_ε is associated with the reference subsystem Λ_s otherwise.

A category $\gamma_{s_i}^*$ in reference subsystem Λ_s can depend on categories in other subsystems. The existence of this dependence is denoted by

$d_{s_i}^* = \{\gamma_{s_i e_\xi}\}$, 1 if category in the reference subsystem
$= 1$ depends on category $\gamma_{\varepsilon_\xi}^*$ in subsystem ε.

Categories $\gamma^*_{e_i}$ outside of the subsystem Λ_s, which can effect a category $\gamma^*_{s_i}$ in subsystem Λ_s are called "intermediate categories" and denoted by

$\gamma^*_{(s)}$: Set of intermediate categories for subsystem Λ_s .

These intermediate categories are used to interconnect subsystems. Optimally "interconnecting" two subsystems could require that all features of the second subsystem are involved in joint probability density functions for categories in the first reference subsystem. But this often is unrealistic and unnecessary and can contradict the reasons for defining subsystems in the first place. Intermediate categories are a practical model for obtaining joint probability density functions of a category affected by another subsystem (s).

3.11.3 Primitives in a Total System

A primitive is the basic characteristic of a category presentation. A feature value is the next higher level characteristic. A Type 1 embedded feature is a primitive that either is true or false. Each feature value of a Type 0 feature can be a primitive. A complex feature is at a higher level in the feature space hierarchy and is a function of primitives.

The primitive is important because it is the basic storage unit for features and complex features and is the basic building block of the knowledge base structure. The system incorporate primitives in grammar for user interaction; but the diagnostic routine operates on primitives, not the grammar.

A convenient way to order primitives is alphabetically; but associate with each primitive an integer p to indicate its order, the primitive's name, and the primitive Type (0 or 1).

Categories also are ordered by the index c when the category is referred to as in the total system and by index i within any subsystem. Associated with each category indexed by c is a set of primitives denoted P_c. Within a subsystem λ_s a category $\gamma^*_{s_i}$ has associated primitives P_{s_i} and associated categories d_{s_i}. Included in P_c (and P_{s_i}) is the primitive type.

3.11.4 Category Primitive Relationship

Consider the subsystem λ_s with categories $\gamma^*_{s_i}$ and features (primitives) χ. A complete subsystem is defined as a subsystem where decision making does not depend on any other subsystem. A category γ^*_i in this subsystem depends only on P and thus has a probability density function

$$p(X \mid \gamma^*_i, P_i) \text{ : For a complete subsystem.} \qquad \text{(eq. 5)}$$

If $\mathcal{X}_s$ is the feature space for subsystem Λ_s; then (eq. 5) can be rewritten as:

$$p(X \in \mathcal{X}_s \mid \gamma_i^* \ , P_i). \qquad \text{(eq. 6)}$$

To be more general, the probability density function in eq. 6 depends on d_s which contains those categories in other subsystems on which γ_i^* depends. Therefore, eq. 6 is redefine as

$$P(X \in \mathcal{X}_s \mid \gamma_i^*, P_i, d_s)$$

$\mathcal{X}_s$ = Feature space for subsystem Λ_s.
γ_i^* = ith category in subsystem Λ_s.
P = Primitives for ith category.
d = Categories in other subsystems on which category γ_i^* in subsystem Λ_s depends.

The vector d_s contains categories in other subsystems upon which category γ_i^* in reference subsystem Λ_s depends.

3.11.5 Development of MES Likelihood Functions

The category conditional probability density function is the inference function in MES that measures the "closeness" of a pattern, e.g., X (called recognition sample) to each category in { } in the knowledge base. Let K be the initial maximum number of probablistic presentations (subcategory) for a category. Then

$$
\begin{aligned}
p(X \mid \gamma_i^*) &= \sum_{k=1}^{K} p(X, \gamma_{i_k}^* \mid \gamma_i^*) \\
&= \sum_{k=1}^{K} p(X \mid \gamma_{i_k}^*, \gamma_i^*)\, p(\gamma_{i_k}^* \mid \gamma_i^*) \qquad \text{(eq. 7)} \\
&= \sum_{k=1}^{K} p(X \mid \gamma_{i_k}^*)\, p(\gamma_{i_k}^* \mid \gamma_i^*)
\end{aligned}
$$

The term $p(X \mid \gamma_{i_k}^*)$ is considered the subcategory conditional probability density function for the Kth subcategory of category γ_i^*. Since it is assumed that the subcategories are mutually exclusive, it follows that

$$\sum_{k=1}^{K} p(\gamma_{i_k}^* \mid \gamma_i^*) = 1 \qquad \text{(eq. 8)}$$

and each term $p(\gamma_{i_k}^* \mid \gamma_i^*)$ reflects the relative frequency that $\gamma_{i_k}^*$ occurs for category γ_i^*. The term $p(\gamma_i^*)$ is the category probability within MES, which is used by the main module in pursuing to the division modules of the equipment (see Figure 11).

Features x_r and x_j are statistically independent given category γ_i^* if

$$p(x_r, x_j \mid \gamma_i^*) = p(x_r \mid \gamma_i^*)\, p(x_j \mid \gamma_i^*). \qquad \text{(eq. 9)}$$

Features are comprised of independent features denoted X_I, and dependent features denoted X_D. That is,

$$X = [X_D, X_I] \qquad \text{(eq.10)}$$

where I and D denote the independent and dependent subsets. Then

$$\begin{aligned} p(X \mid \gamma_i^*) &= p(X_D, X_I \mid \gamma_i^*) \\ &= p(X_I \mid \gamma_i^*, X)\, p(X_D \mid \gamma_i^*) \qquad \text{(eq. 11)} \\ &= p(X_I \mid \gamma_i^*)\, p(X_D \mid \gamma_i^*). \end{aligned}$$

A set of statistically independent features $\{X_j\}$ given category γ_i^* satisfies

$$p(x_1, x_2, \ldots, x_{L_I} \mid \gamma_i^*) = \prod_{j=1}^{L} p(x_j \mid \gamma_i^*) \qquad \text{(eq. 12)}$$

where L is the number of features in the set I. The set of dependent features D have values that vary in a dependent way among themselves but do not depend on the statistically independent features. There are L_D features in the dependent subset. Let

$$x_{j_v} \qquad \text{(eq. 13)}$$

denote the vth value of feature X ; then

$$C * p(x_{1_v}, x_{2_v}, \ldots, x_{L_{D_v}} \mid \gamma_i^*) \qquad \text{(eq. 14)}$$

is the probability density for category γ_i^* at the particular point represented by

$$x_{1_v}, x_{2_v}, \ldots, x_{L_{D_v}}$$

where L_{D_v} is the number of dependent features, and C is the numerical value of equation (12) for the independent subset of features.

Under the assumption that subcategories $\{\gamma^*_{i_k}\}$ are mutually exclusive, it follows that (fuzzy operation)

$$p(X \ \gamma^*_i) = \max_k \{p(X \ \gamma^*_{i_k})\} \qquad \text{(eq. 15)}$$

since only one of the subcategories in $\{p(X \ \gamma^*_{i_k})\}$ can be true.

The set of dependent features D can be decomposed into mutually exclusive subsets

$$D = D_1 + D_2 + \ldots + D_U . \qquad \text{(eq. 16)}$$

Let

$$\{ x^u_i \} = D_u$$

be the dependent features in dependent subset D . Then

$$p(X_D \ \gamma^*_{i_k}) = \prod_{u=1}^{U} p(x^u_1, x^u_2, \ldots, x^u_{L_u} \mid \gamma^*_{j_k}) \qquad \text{(eq. 17)}$$

is the joint probability density function for subcategory $\gamma^*_{i_k}$ where

U : Number of dependent subsets
u : uth dependent subset
L_u : Number od dependent features in the uth subset.

The functionals (probabilities) in equation (17) can be viewed as packets of knowledge or production rules; but their "interconnection" is engineered by the direction provided in equation (17) for subcategory $\gamma^*_{i_k}$ of category γ^*_i . The construction includes "Bayes network" from AI.

The vector X can have both independent and dependent subsets, i.e.,

$$X = \{X_{D(k)}, X_{I(k)}\} \qquad \text{(eq. 18)}$$

for the kth subcategory.

Then, imposing equation (18), equations analogous to (11), (12), and (17) exist for the kth subcategory:

$$p(X \mid \gamma_{i_k}^*) = p(X_{I(k)} \mid \gamma_{i_k}^*)\, p(X_{D(k)} \mid \gamma_{i_k}^*) \qquad \text{(eq. 19)}$$

$$p(x_1, x_2, \ldots, x_{L_{I(k)}} \mid \gamma_{i_k}^*) = \prod_{\xi=1}^{L_{I(k)}} p(x_\xi \mid \gamma_{i_k}^*) \qquad \text{(eq. 20)}$$

$$p(X_{D(k)} \mid \gamma_{i_k}^*) = \prod_{u=1}^{U(k)} p(x_1^u, x_2^u, \ldots, x_{L_{u(k)}}^u \mid \gamma_{i_k}^*) \qquad \text{(eq. 21)}$$

and equation (7) becomes

(eq. 21)

$$p(X \mid \gamma_i^*) = \sum_{k=1}^{K} \left[\prod_{\xi=1}^{L_{I(k)}} p(x_\xi \mid \gamma_{i_k}^*) \prod_{u=1}^{U(k)} p(x_1^u, x_2^u, \ldots, x_{L_{u(k)}}^u \mid \gamma_{i_k}^*)\, p(\gamma_{i_k}^* \mid \gamma_i^*)\right]$$

where

$U(k)$ = Number of dependent subsets for kth subcategory.

$u(k)$ = uth dependent subset for subcategory k.
$L_{I(k)}$ = Number of independent features for subcategory k.
$\gamma_{i_k}^*$ = kth subcategory of category .

Therefore, for any category γ_i^* in the total MES system equation (21) can be written as

$$p(X \mid \gamma_i^*) = \qquad \text{(eq. 22)}$$

$$\sum_{k=1}^{K} \prod_{\xi=1}^{L_{I(k)}} p(x_\xi \mid \gamma_{i_k}^*) \left[\sum_{u=1}^{U(k)} \prod_{t=1}^{S(u)} (p_{i_{k_t}}^u)\right] p(\gamma_{i_k}^* \mid \gamma_i^*)$$

where

K : Number of subcategories.

$U(k)$: Number of dependent subsets for kth subcategory.

$L_{I(k)}$: Number of independent features for subcategory k.

$p(x_\eta \mid \gamma^*_{c_k})$: Probability density function of statistically independent feature x_η for kth subcategory.

$p(\gamma^*_{c_k} \mid \gamma^*_c)$: Mixing probability for the kth column; i.e, subcategory probability given category γ^*_c.

$\prod_{t=1}^{S(u)} (p)$: Probability density for uth subsubcategory of subcategory k involving S(u) packet probabilities.

$S(u)$: Number of features involved in the uth subsubcategory of subcategory K.

Equation (22) can be simplified by letting the statistically independent features I be decomposed into insignificant (ISIG) and significant (SIG) independent features:

$$I = I_{SIG} + I_{ISIG} \qquad \text{(eq. 23)}$$

That is,

$$\prod_{\eta=1}^{L_{I(k)}} p(x_\eta \mid \gamma^*_{c_k}) = \prod_{I_{SIG}} p(x_\eta \mid \gamma^*_{c_k}) \prod_{I_{ISIG}} p(x_\eta \mid \gamma^*_{c_k}) \qquad \text{(eq. 24)}$$

3.11.6 Developing MES

The theories and equations developed in the previous sections are used to outline a total maintenance expert system. Steps in this development are outlined below.

1. Create and Store Primitives. The creation of primitives is an ongoing process; but by storing them alphabetically, updating is simplified. The order of a primitive is indicated by an integer p, as discussed in section 11-3. When a primitive is created and stored, a vector X_s is updated for each subsystem Λ_s for which that primitive is significant. Often new primitives are created when developing or modifying a subsystem Λ_s. Automatic techniques can be used to add a new primitive to X_s of ant appropriate subsystem Λ_s or to transfer a subsystem primitive to the total system's primitive list.

2. Categories are indexed γ_c^* in the total system with γ_s^* indicating those categories in subsystem Λ_s. Classes associated with categories are part of the subsystem.

3. Subsystems are created in the total system through an initialization process whereby for each subsystem Λ_s, parameters M_s, M_{is}, L_s, and K_s are specified; appropriate data files are created or formatted. For subsystem Λ_s, a set of intermediate categories d_i is determined. The intermediate categories are indexed in the total system; and through

d_S , it is indirectly known that each subsystem having a category d_S as an intermediate category for subsystem Δ_S . Intermediate categories that can be feature values for the reference subsystem constitutes the links among subsystems.

4. Develope Category Feature Relationships. Using production rules and conditional probability functions, features within categories form classes which are used in conjunction to determine the cause of failure .

5. Decision Rule. Decisions are made by computing category likelihood functions as derived in section 11-5.

CHAPTER FOUR
PROTOTYPE MES

4.1 Introduction

This chapter contains a working prototype of MES (Appendix Three). The aim of this system is to illustrate the knowledge representation, utilizing the category, subcategory, and class approach. This approach is embedded within the rule base structure of the MES to perform diagnostic reasoning. The knowledge gathered for this system, was obtained by series of interviews conducted with DOW Chemical Company's preventive maintenance group (see Appendix One). A centrifugal air compressor was chosen due to its relatively narrow mode of application, as compared to process compressors. The secrecy laws also had an impact as to why an air compressor was allowed to be thoroughly investigated, as compared to process compressors.

Along with conducting interviews with the maintenance personnel, the relative frequency of some failures and their causes were obtained by a rigorous review of completed work orders. This is shown by a number in parenthesis in front of the causes of the failures listed in the following sections. Hence, by having (30) in front of the cause it is meant that: The cause, e.g., foundation distortion was noticed in %30 of pitted couplings (failure). The knowledge structure of

MES is shown in Figure 13. The user interface knowledge base is used by the system to gather information to be used in the diagnostic process. In order to keep knowledge separated in MES, and due to the nature of the available literature, it was decided to divide the knowledge into three separate categories: structural, mechanical, and electrical. The structural and mechanical categories were further broken down into two subcategories as shown in Figure 14. Appendix One contains the knowledge gathered for the prototype MES. Storing information with regards to similarity of applications significantly increase the response and efficiency of the system. Category three, due to the size of the knowledge available needed no further subcategories.

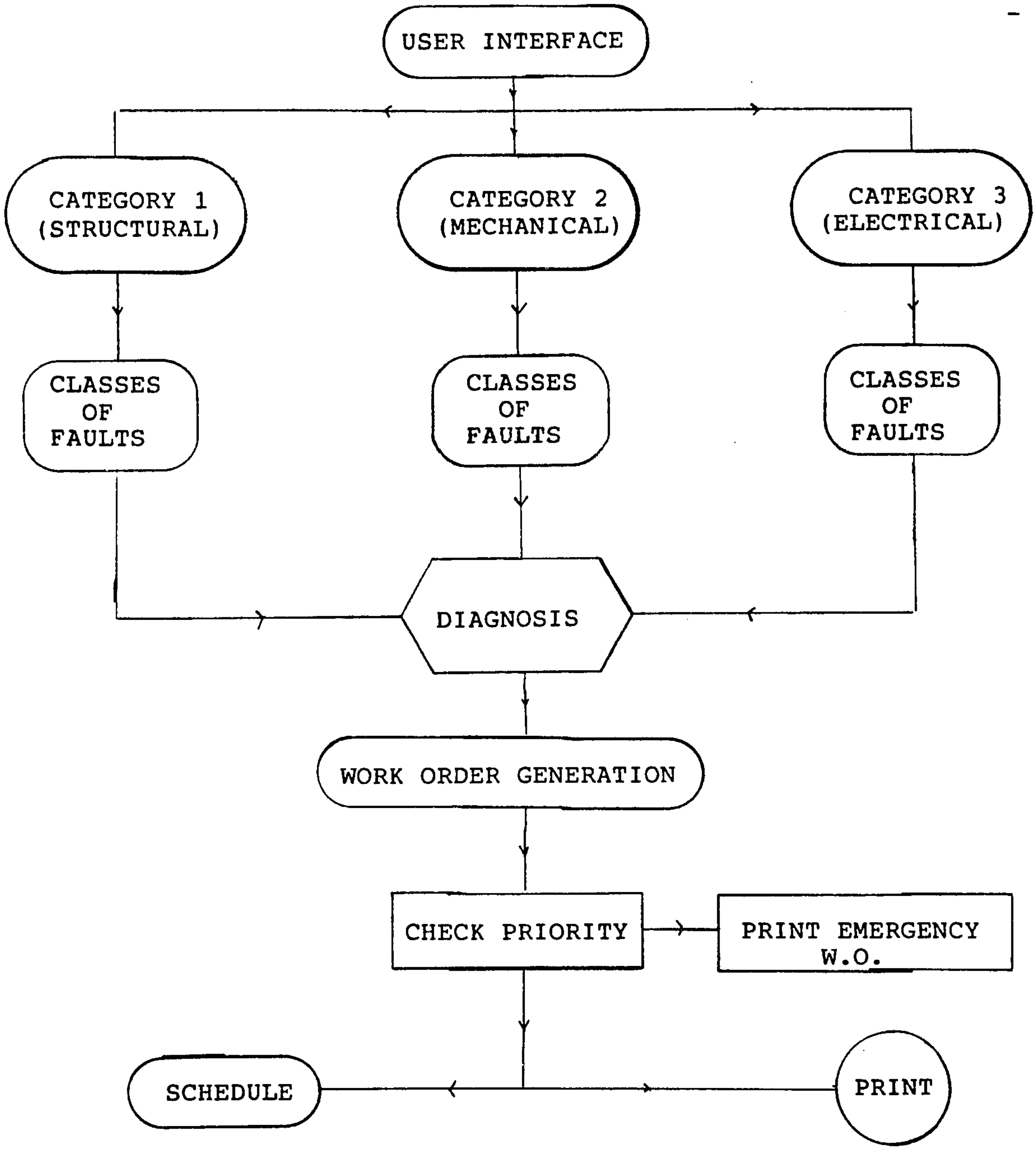

Figure 13. Knowledge Structure of the Prototype MES.

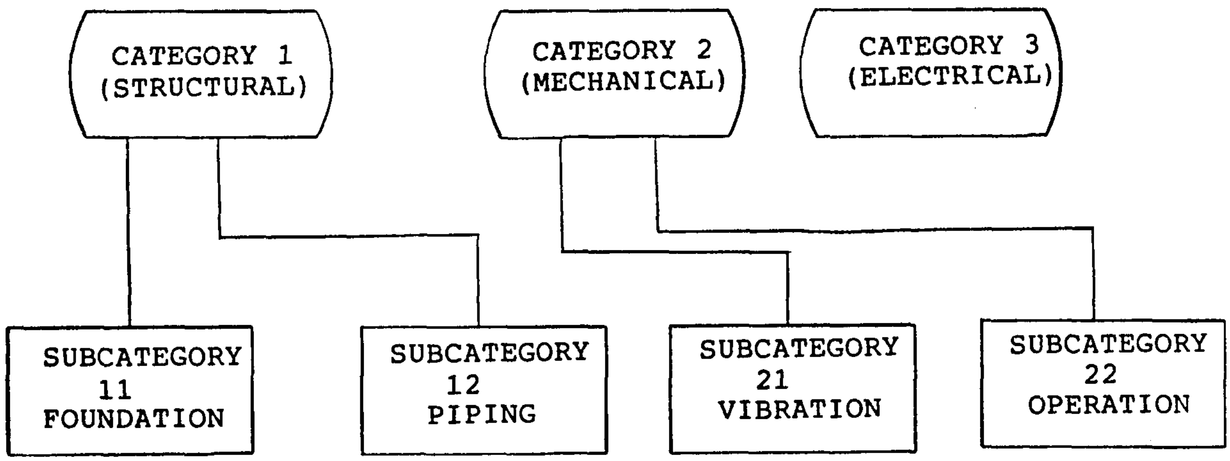

Figure 14. Knowledge Structure Within Categories.

4.1 How to Use MES

The maintenance expert system is a user friendly consulting environment, by which the user is instructed, step by step, how to proceed. It requires a double disk driven, IBM personal computer with at least 625 k RAM memory. The size of the total knowledge base of MES is 250 k, but due to modulization only a fourth of this amount occupies the computers memory at any given time. The response time of MES for the most time consuming diagnosis is about 45 seconds. The users is capable of asking the program "why", which leads to a generated report telling the user why MES is prompting for information. "What if" facilities enable the user to change the answers which he gave, therefore, the added ability to explore the effect of alternative answers on diagnosis. "What if" facility is available in the consult mode menu.

To examine the reasoning process for conclusions, the chart facility (or "how") is available. The "how" facility allows the user to examine the reasoning used by MES in obtaining a particular conclusion when pursuing a goal. This facility can be invoked at the end of the consulting session when the final conclusion is produced.

4.1.1 Example Session

The expert system requires two diskettes, labelled systems 1 & 2. The user first must boot up the system by inserting system 1 diskette into drive A and system 2 diskette into drive B. The purpose of these systems are to create the MES environment. The initial screen of the expert system is shown in Figure 16. The user must next replace system 1 diskette with MES diskett in drive A. The MES diskette contains the knowledge bases of the expert system. To initiate diagnosis, one must choose consult application from screen. MES will then initiate a series of questions to determine what category is the most probable cause of the malfunction.

```
Please select an item and proceed:
                                  > Consult application
                                    Build applicaation
                                    Run tutorial
                                    Exit system
```

Figure 15. Enabling MES Diagnostic Routine

If the user is aware of the nature of the problem, e.g., structural, mechanical, or electrical, MES will directly invoke the chosen category. If the user is not too sure of the nature of the problem, then thru the main module MES will begin a short consulting session, asking key questions to determine the most probable category of faults. Once the category is distinguished, the system then requires the user to supply the available information about the faults encountered. Then the system will conduct a through search of its knowledge base to reach a diagnosis, while prompting for more information if necessary. Once done with diagnosis, it will then direct the result to the work order module. In work order module, MES will then gives the user the opportunity of printing, scheduling, or both of some or all of the generated work orders. The work orders are automatically generated by the system, given it knows the cause. The emergency work orders are automatically prompted on the screen and printed. An example session of MES is as follows:

```
what is the most likely area of difficulty ?

Select one of..

          * structural
            mechanical
            electrical
            need help


==> You are now in the structural knowledge base.
```

```
     Select the most significant problem which you are
encountering:

     Select one of..

          excess moment and force on pipes
          water accumulating over valves
     *    traps not working
          resonant in foundation
          settling or shrinking foundation
          unevenly heated foundation
          grout swelling or shrinking or rust deterioration
          foundation soleplate looseness
          none of the above
```

At this time MES begins its diagnostic routine. Faults are prestored in the system. The knowledge of MES, organized in a cause and effect mode, is then searched and the most likely causes of difficulty are selected. The inference engine of MES is responsible for diagnostic propagation. The result of the trace facility of MES is shown in Appendix Two. Figure 16 shows the generated status report of MES after the diagnosis. It contains, the probable causes with priority. This priority can be a guide to the user as to whether a work order should be generated or not. The rules in MES were constructed in such a way to incorporate the probabilities of accuracy in diagnosis, by assigning higher priorities to higher probable causes. This method proved to be more effective in keeping the response time low and the efficiency of the system high. Also, MES includes a list of other problem which could be linked to the problem on hand. This information is of particular interest since it enable the maintenance personnel to be alert about problems which otherwise could become major breakdowns.

```
The probable cause of > > > traps not working are listed as following:

casing distortion ( c.d ) priority = = > three
seal rub ( s.r ) priority = = > zero
thrust bearing damage ( t.b.d ) priority = = > one
aerodynamic excitation ( a.e ) priority = = > one

Relating areas to be investigated are as follows:
                              piping not properly supported
                              drain pots undersize
                              pipe expansion restricted
                              insufficient foundation rigidity
                              expansion joints not properly installed
                              pipes not properly sloped and drained
                              drains running to common sewer
                              dead ends not drained
                              resonants of pipes

            PRESS PgDn KEY

NOTE: PRINT THIS REPORT OR WRITE DOWN THE ABBREVIATIONS
      OF CAUSES WHICH YOU WANT TO SEE A PRINTED WORK ORDER
```

Figure 16. Example of MES Status Report.

Seal rub is a priority zero, or an emergency fault, therefore, MES generates a work order of seal rub automatically and instructs the user to print the work order. The generated work order for seal rub is shown in Figure 17.

WORK ORDER NO. : DATE :

Priority : EMERGENCY
Problem : traps not working
Cause : seal rub
Comments: slight seal rubs may clear but trip unit immediately
if high speed rub gets worse
if rub did not clear itself out replace seal
with slight rubs turn until clear

Material : two seal no 2356
Labor : 8 man hour
Tools : seal replacement tool set
seal remover
type 1 seal adhesive

Figure 17. Generated Work Order for Seal Rub.

Once the emergency work orders are printed, MES will then prompt the user for instructions. The following is the continuation of the consulting session.

```
What do you want to do?
Select one of..
     * print work order
       schedule work order

Work orders for printing includes ?
> c.d,a.e
Enter one or more work orders
```

This instructions will cause MES to generate work orders for casing distortion (c.d) and aerodynamic excitation (a.e). Figures 18 and 19 illustrate the generated work orders.

```
WORK ORDER NC. :                                        DATE :
      Priority : three
       Problem : traps not working
         Cause : casing distortion
      Comments : often results to a need for complete rework or
                 a new casing some mild distortions correct themselves
                 look for excessive piping forces or wrong casing
                 design or wrong material or improper stress relief

      Material : new casing and supports
         Labor : 35 man hour
         Tools : crane
                 1.5 ton fork lift
                 casing tool set
```

Figure 18. Generated work order for casing Distortion

```
WORK ORDER NO. :                                      DATE :
      Priority : one
       Problem : traps not working
         Cause : aerodynamic excitation
      Comments: check moleweight and measure pressure drop across
                balance line and especially balance flow temperature
                check stage pressure and pressure fluctuations by
                installing pressure gages thermometers etc

      Material : none
         Labor : 12 man hour
         Tools : pressure gages
                 temperature gages
                 frequency analyzer
```

Figure 19. Generated Work order for Aerodynamic Excitation

MES in the current phase will keep a record of work orders submitted for scheduling. The file "schedule.rpt" contains the list of these work orders. The strength of MES lies in its user friendliness, and its response time. The knowledge base of MES can be easily modified and enlarged to be able to have the capacity of trouble shooting a family of machines, e.g., centrifugal equipments. MES can also be utilized as a powerful teaching aid for junior maintenance engineers.

CHAPTER FIVE
CONCLUSIONS and RECOMMENDATIONS

The goal of this research was to integrate artificial intelligence (AI), namely rule base expert systems, with maintenance monitoring techniques to design an efficient maintenance diagnostic tool. In addition, to design a system which upon diagnosing malfunctions could automatically generate work orders for the diagnosed causes, and also be user friendly enough so that maintenance personnel with minimum computer back ground could easily use the software. Chapter Two reviewed the latest literature of AI applications and methodology in maintenance. In Chapter Three, the ideas of equipment fault diagnostics through pattern recognition and classification were developed. The use of multi-parameter monitoring and classification is unique to this research. The rules developed are based on these principals (pattern recognition and fault classification). The divisioning of the equipment into sub-systems and categories, enabled the design to be modularized, hence, the enabling the use of personal computers (pc). In Chapter Four, a prototype maintenance expert system (MES) was developed. The capability of the system for adding, deleting, editing, and saving the rules and hypotheses that make up a rule base is a convenient tool for the personnel. The system is capable of automatically generating work orders for faults which it diagnoses.

MES relates specific "sets" of faults, considering the performance parameters, to a specific diagnosis and is capable of printing the resulting work orders. The work orders are pre-planned and stored for retrieval. The system can be easily expanded as the knowledge about the machine is increased. The ability to edit the knowledge base with minimum difficulty is a direct result of the use of AI technology. The user friendliness of MES and its operation leads to its use by personnel not familiar with computers, and such systems can become valuable to plant operation, especially when the expert trouble shooter is unavailable. MES can be used as a teaching aid for junior maintenance engineers. The system can be used as a consultant, the user could try different problems and see the results.

With the rapid advances in computer technology, a much larger version of MES can be developed on a pc. The advantage of a system capable of running on a pc is the abundance of personal computers in industry, and the familarity of personnel to these systems.

DOW chemical could use the results and approaches of this research to set up a more complete maintenance monitoring and management system. The initial step in this direction proved to be beter and more complete means of operational data logging of machines. By analysis of these data the company could adapt a AI based monitoring system with close resemblence of MES, hence, driving toward a higher overall plant efficency.

5.1 Recommendation

As an extension of this research, one could try to make MES an on-line system. Actual performance parameters can be monitored by the system, and a module could be built to comprehend the pattern of all performance parameters. Provisions should also be made to alter parameter limits as "bases" change. This system could also be interfaced with the maintenance management information system (MMIS). The MMIS is essentially a multi-domain knowledge acquisition system. The system should encompass at least six domains. Namely, diagnostics, maintenance, maintenance training, data collection, data analysis, and graphics. By use of a graphic package, the user could reply to question both graphically and as the example in this research. This could conisderably increse the speed of diagnosis. The graphics could also be used in generating work orders with parts printed and ways of correct assemblies. The old saying of " a picture speaks louder than 1000 words", correctly applies here. In building a system such as MMIS it is important that there be continuity within each domain and a relationship between domains. The method used must not only have the physical and functional knowledge of the item of equipment the expert is talking about, but also knowledge of what previous and related domain data has been inputed by the various experts during the building of the system. Probabilities, or degrees of confidence could also be incorporated in MMIS. Since information is never totally complete, probabilistic knowledge propagation can be used to rank causes according to the available information. These probabilities can be used to choose the most probable faults.

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APPENDIX ONE
Equipment History

The following is the results of interviews and reviews of available work orders at DOW chemical Company. Some of the material are also form J. S. Shore work on high speed turbomachinery [29]. The categories are as follows:

(1) Structural
 - a. piping
 - b. foundation

(2) Mechanical
 - a. operations
 - b. vibration analysis

(3) Electrical

The number in front of some of the causes indicates the relative frequency of occurrence. Higher numbers indicate higher probability of occurrence.

Subcategory 11: Foundation

Resonant in foundation is caused by:

- bearing and support excited vibration (oil whirl)
- rotor and bearing system critical
- structural resonance
- electrically excited vibration
- vibration transmission
- sub-harmonic resonance
- resonant vibration
- resonant whirl

Settling or shrinking of foundation is caused by:

- seal rub
- misalignment
- piping forces
- casing distortion
- bearing damage
- casing and support looseness

Unevenly heated foundation (hot lines too close) is caused by:

- seal rub
- misalignment
- piping forces
- bearing damage
- casing distortion

When foundation is not separated from building the following can occur:

- bearing and support excited vibration (oil whirl)
- electrically excited vibration
- vibration transmission
- sub-harmonic resonance
- harmonic resonance
- resonant vibration
- resonant whirl

Grout swelling or shrinking and rust deterioration under soleplate of the foundation is caused by:

- foundation distortion
- seal rub
- misalignment
- bearing damage
- bearing and support excited vibration
- unequal bearing stiffness, horizontal, and vertical
- coupling and support looseness
- coupling damage

- rotor and bearing system critical
- structural resonance in support
- structural resonance in foundation
- vibration transmission
- sub-harmonic resonance
- harmonic resonance
- friction induced whirl
- critical speeds

Foundation's soleplate looseness:

- bearing and support excited vibration (oil whirl)
- structural resonance of supports
- structural resonance of foundation
- sub-harmonic resonance
- resonant vibration
- resonant whirl
- clearance induced vibration

Foundation's rigidity insufficient:

- casing distortion
- foundation distortion
- seal rub
- rotor rub
- misalignment
- piping forces
- rotor bearing system critical
- sub-harmonic resonance
- resonant vibration
- resonant whirl

Subcategory 12: Piping

Excessive moments and forces on pipes is caused by:

- casing distortion
- seal rub
- misalignment
- insufficient tightness of casing support
- coupling damage
- clearance induced vibration

Expansion joints not properly installed can cause the following:

- seal rub
- misalignment
- piping forces
- insufficient tightness of casing support
- aerodynamic excitation
- structural resonance of supports
- structural resonance of foundation

Piping not properly supported can cause the following:

- casing distortion
- seal rub
- misalignment
- piping forces
- insufficient tightness in casing support
- structural resonance of casing
- structural resonance of supports
- structural resonance of foundation
- electrically excited vibration
- vibration transmission
- resonant vibration
- resonant whirl
- clearance induced vibration

Not properly sloped and drained can cause the following:

- permanent bow or lost rotor parts
- temporary rotor bow
- seal rub
- rotor rub, axial
- bearing damage
- thrust bearing damage
- insufficient tightness of rotor (shrink-fits)
- aerodynamic excitation
- friction induced whirl

Resonant of pipes can cause the following:

- aerodynamic excitation
- structural resonance of casing
- structural resonance of supports
- structural resonance of foundation

- electrically excited vibration
- vibration transmission
- resonant vibration
- resonant whirl

Not taking off at top of headers or water accumulating over valves is caused by:

- permanent bow or lost rotor
- temporary rotor bow
- seal rub
- rotor rub, axial
- bearing damage
- thrust bearing damage
- insufficient tightness in rotor (shrink fits)
- friction induced whirl

When casing drains run to common sewer or common header or into water can cause the following:

- temporary rotor bow
- seal rub
- insufficient tightness in rotor (shrink fits)
- friction induced whirl

Traps not working is caused by:

- temporary rotor loss
- casing distortion
- seal rub
- thrust bearing damage
- aerodynamic excitation
- friction induced whirl

Drain pots and lines undersize can cause:

- temporary rotor bow
- casing distortion
- seal rub
- rotor rub, axial
- thrust bearing damage
- insufficient tightness of rotor (shrink fits)
- aerodynamic excitation
- friction induced whirl

Pipe expansion restricted by contact with foundation or other pipes can cause:

- casing distortion
- seal rub
- misalignment
- piping forces
- bearing and support excited vibration (oil whirls)
- insufficient tightness of casing support
- structural resonance of casing

- structural resonance of supports
- structural resonance of foundation
- vibration transmission
- resonant vibration
- resonant whirl

Branch lines restricting expansion can cause the following:

- casing distortion
- seal rub
- misalignment
- piping forces
- structural resonance of casing
- structural resonance of supports

Dead ends not drained can cause the following:

- temporary rotor bow
- seal rub
- rotor rub, axial
- thrust bearing damage
- insufficient tightness of rotor (shrink fits)
- aerodynamic excitation

Rotor or stator resonant frequencies:

- initial unbalance (5)
- permanent bow or lost rotor parts (30)
- temporary rotor bow (20)
- casing distortion (10)
- seal rub (10)
- rotor rub, axial (20)
- misalignment (5)
- piping forces (5)
- journal and bearing eccentricity (60)
- bearing damage (20)
- bearing and support excited vibration (20)
- unequal bearing stiffness (80)
- thrust bearing damage (90)
- insufficient tightness of rotor (shrink fits) (40)
- insufficient tightness of bearing liner (90)
- insufficient tightness of bearing casing (90)
- insufficient tightness of casing support (50)
- coupling damage (10)
- aerodynamic excitation (60)
- rotor and bearing system critical (100)
- coupling critical (100)
- overhang critical (100)
- structural resonance of casing (100)
- structural resonance of supports (100)
- structural resonance of foundation (100)
- pressure pulsations (80)
- electrically excited vibrations (80)
- vibration transmission (30)
- oil seal induced vibration (30)
- sub-harmonic resonance (100)
- harmonic resonance (100)
- friction induced whirl (100)
- critical speed (100)
- resonant vibration (100)
- resonant whirl (100)
- dry whirl (100)
- clearance induced vibrations (50)
- torsional resonance (100)
- transient torsional (100)

Predominant frequencies are 1 X running frequency (R F)

- initial unbalance (90)
- permanent bow or lost rotor parts (90)
- temporary rotor bow (90)
- casing distortion (60)
- foundation distortion (40)
- seal rub (20)

- rotor rub, axial (30)
- misalignment (30)
- piping forces (30)
- journal and bearing eccentricity (60)
- bearing damage (20)
- thrust bearing damage (90)
- insufficient tightness of rotor (shrink fits) (10)
- insufficient tightness of bearing casing (30)
- insufficient tightness of casing support (30)
- coupling damage (20)
- aerodynamic excitation (20)
- rotor and bearing system critical (100)
- coupling critical (100)
- overhang critical (100)
- structural resonance of casing (70)
- structural resonance of supports (70)
- structural resonance of foundation (60)
- pressure pulsations (80)
- critical speed (100)
- resonant vibration (60)
- clearance induced vibrations (20)
- torsional resonance (40)
- transient torsional (50)

Predominant frequencies are 2 X R F

- initial unbalance (5)
- permanent bow or lost rotor parts (5)
- temporary rotor bow (5)
- casing distortion (10)
- foundation distortion (30)
- seal rub (10)
- rotor rub, axial (10)
- misalignment (60)
- piping forces (60)
- journal and bearing eccentricity (60)
- bearing damage (20)
- unequal stiffness of bearing (80)
- thrust bearing damage (90)
- insufficient tightness of rotor (shrink fits) (10)
- coupling damage (30)
- structural resonance of casing (10)
- structural resonance of supports (10)
- structural resonance of foundation (10)
- harmonic resonance (100)
- resonant vibration (60)
- clearance induced vibrations (30)
- torsional resonance (20)

Predominant frequencies are of higher multiples:

- initial unbalance (5)
- permanent bow or lost rotor parts (5)
- temporary rotor bow (5)
- casing distortion (10)
- foundation distortion (10)
- rotor rub, axial (10)
- misalignment (10)
- piping forces (10)
- unequal stiffness of bearing (20)
- insufficient tightness of rotor (shrink fits) (10)
- gear damage (20)
- coupling damage (10)
- harmonic resonance (100)
- resonant vibration (5)
- clearance induced vibrations (10)
- torsional resonance (20)

Predominant frequencies are 1/2 of R F:

- bearing and support excited vibration (10)
- structural resonance of casing (10)
- structural resonance of supports (10)
- structural resonance of foundation (10)
- sub-harmonic resonance (100)
- resonant vibration (10)
- oil whirl (10)

Predominant frequencies are 1/4 of R F:

- bearing and support excited vibration (10)
- sub-harmonic resonance (100)
- resonant vibration (5)
- oil whirl (5)

Predominant frequencies are of lower multiples:

- seal rub (10)
- rotor rub, axial (10)
- sub-harmonic resonance (100)

Predominant frequencies are of odd frequencies:

- foundation distortion (10)
- seal rub (10)
- rotor rub, axial (10)
- insufficient tightness of rotor (shrink fits) (10)
- insufficient tightness of bearing liner (10)
- insufficient tightness of bearing casing (10)
- insufficient tightness of casing support (50)
- gear damage (20)
- aerodynamic excitation (10)
- vibration transmission (40)

. transient torsional (50)

Predominant frequencies are very high frequencies:

. seal rub (10)
. rotor rub, axial (10)
. misalignment (10)
. piping forces (10)
. bearing damage (20)
. thrust bearing damage (10)
. gear damage (60)
. coupling damage (80)
. aerodynamic excitation (10)
. dry whirl (100)

Subcategory 22: OPERATIONAL EVIDENCE

Seals rubbed:

- initial unbalance (10)
- permanent bow or lost rotor parts (50)
- temporary rotor bow (90)
- casing distortion (90)
- foundation distortion (90)
- rotor rub, axial (90)
- misalignment (50)
- piping forces (50)
- bearing damage (90)
- bearing and support excited vibration (90)
- unequal bearing stiffness (10)
- thrust bearing damage (90)
- insufficient tightness of rotor (shrink fits) (90)
- insufficient tightness of bearing liner (90)
- insufficient tightness of bearing casing (50)
- insufficient tightness of casing support (20)
- coupling damage (20)
- aerodynamic excitation (10)
- rotor and bearing system critical (50)
- coupling critical (30)
- overhang critical (50)
- structural resonance of casing (20)
- structural resonance of supports (20)
- structural resonance of foundation (20)
- pressure pulsations (30)
- vibration transmission (20)
- oil seal induced vibration (90)
- sub-harmonic resonance (10)
- harmonic resonance (10)
- friction induced whirl (90)
- critical speed (50)
- resonant vibration (20)
- oil whirl (60)
- resonant whirl (80)
- dry whirl (80)
- clearance induced vibrations (90)
- torsional resonance (5)
- transient torsional (5)

Shaft bent:

- temporary rotor bow (10)
- casing distortion (10)
- foundation distortion (10)
- seal rub (10)
- rotor rub, axial (30)
- misalignment (10)
- piping forces (10)
- bearing damage (10)
- bearing and support excited vibration (10)
- thrust bearing damage (20)

- insufficient tightness of rotor (shrink fits) (10)
- insufficient tightness of bearing liner (10)
- insufficient tightness of bearing casing (5)
- rotor and bearing system critical (10)
- coupling critical (10)
- overhang critical (20)
- oil seal induced vibration (50)
- friction induced whirl (10)
- critical speed (10)
- oil whirl (10)
- resonant whirl (15)
- dry whirl (10)
- clearance induced vibrations (10)

Thrust bearing damage:

- rotor rub, axial (30)
- misalignment (30)
- gear damage (40)
- coupling damage (60)
- aerodynamic excitation (50)
- pressure pulsations (30)

Bearing failure due to wiping:

- initial unbalance (10)
- permanent bow or lost rotor parts (30)
- temporary rotor bow (50)
- casing distortion (50)
- foundation distortion (50)
- rotor rub, axial (50)
- seal rub (15)
- misalignment (10)
- piping forces (10)
- journal and bearing eccentricity (30)
- bearing and support excited vibration (80)
- unequal bearing stiffness (40)
- thrust bearing damage (50)
- insufficient tightness of rotor (shrink fits) (60)
- insufficient tightness of bearing liner (30)
- insufficient tightness of bearing casing (20)
- insufficient tightness of casing support (40)
- gear damage (20)
- coupling damage (20)
- aerodynamic excitation (20)
- rotor and bearing system critical (50)
- coupling critical (50)
- overhang critical (60)
- structural resonance of casing (20)
- structural resonance of supports (20)
- structural resonance of foundation (20)
- pressure pulsations (30)
- electrically excited vibration (20)
- vibration transmission (20)
- sub-harmonic resonance (20)

- harmonic resonance (20)
- friction induced whirl (60)
- critical speed (50)
- resonant vibration (20)
- oil whirl (80)
- resonant whirl (90)
- dry whirl (90)
- clearance induced vibrations (30)
- torsional resonance (5)
- transient torsional (5)

Bearing failure due to fatigue:

- initial unbalance (10)
- permanent bow or lost rotor parts (10)
- casing distortion (10)
- foundation distortion (30)
- seal rub (10)
- misalignment (20)
- piping forces (20)
- journal and bearing eccentricity (60)
- bearing and support excited vibration (60)
- unequal bearing stiffness (40)
- insufficient tightness of rotor (shrink fits) (60)
- insufficient tightness of bearing liner (30)
- insufficient tightness of bearing casing (20)
- insufficient tightness of casing support (60)
- gear damage (20)
- coupling damage (20)
- aerodynamic excitation (30)
- rotor and bearing system critical (50)
- coupling critical (50)
- overhang critical (60)
- structural resonance of casing (20)
- structural resonance of supports (20)
- structural resonance of foundation (20)
- pressure pulsations (30)
- electrically excited vibration (20)
- vibration transmission (20)
- oil seal induced vibration (90)
- sub-harmonic resonance (10)
- harmonic resonance (20)
- friction induced whirl (60)
- critical speed (50)
- resonant vibration (20)
- oil whirl (60)
- resonant whirl (80)
- dry whirl (20)
- clearance induced vibrations (30)
- torsional resonance (20)
- transient torsional (5)

Bearing failure because babbitt squeezed out:

- permanent bow or lost rotor parts (10)
- temporary rotor bow (20)
- casing distortion (10)
- seal rub (10)
- bearing and support excited vibration (30)
- thrust bearing damage (30)
- insufficient tightness of rotor (shrink fits) (40)
- insufficient tightness of bearing liner (40)
- insufficient tightness of bearing casing (30)
- insufficient tightness of casing support (10)
- overhang critical (10)
- oil seal induced vibration (10)
- friction induced whirl (40)
- oil whirl (30)
- resonant whirl (40)
- dry whirl (40)
- clearance induced vibrations (20)

Case distorted or cracked:

- seal rub (10)
- misalignment (20)
- piping forces (40)
- bearing damage (10)
- oil seal induced vibration (20)

Out of alignment:

- casing distortion (10)
- foundation distortion (50)
- seal rub (20)
- piping forces (40)
- structural resonance of foundation (30)
- pressure pulsations (20)
- vibration transmission (30)

Coupling burned or pitted:

- temporary rotor bow (20)
- casing distortion (20)
- foundation distortion (30)
- seal rub (10)
- rotor rub, axial (20)
- misalignment (40)
- piping forces (40)
- bearing damage (20)
- bearing and support excited vibration (20)
- insufficient tightness of rotor (shrink fits) (80)
- insufficient tightness of bearing liner (80)
- insufficient tightness of bearing casing (20)
- insufficient tightness of casing support (20)
- coupling damage (40)
- aerodynamic excitation (30)

. rotor and bearing system critical (30)
. coupling critical (30)
. overhang critical (40)
. structural resonance of supports (20)
. structural resonance of foundation (30)
. pressure pulsations (30)
. electrically excited vibration (30)
. vibration transmission (30)
. oil seal induced vibration (50)
. sub-harmonic resonance (10)
. harmonic resonance (20)
. friction induced whirl (80)
. critical speed (30)
. resonant vibration (20)
. oil whirl (20)
. resonant whirl (40)
. dry whirl (10)
. clearance induced vibrations (80)
. torsional resonance (40)
. transient torsional (30)

Gear teeth broken or pitted:

. temporary rotor bow (5)
. bearing damage (10)
. bearing and support excited vibration (10)
. insufficient tightness of rotor (shrink fits) (10)
. insufficient tightness of bearing liner (20)
. insufficient tightness of bearing casing (20)
. gear damage (40)
. aerodynamic excitation (20)
. electrically excited vibration (30)
. oil seal induced vibration (50)
. sub-harmonic resonance (10)
. harmonic resonance (20)
. friction induced whirl (40)
. oil whirl (20)
. resonant whirl (30)
. dry whirl (5)
. clearance induced vibrations (20)
. torsional resonance (80)
. transient torsional (80)

Gear teeth marked on the backside:

. temporary rotor bow (20)
. bearing damage (10)
. bearing and support excited vibration (10)
. insufficient tightness of rotor (shrink fits) (40)
. insufficient tightness of bearing liner (20)
. insufficient tightness of bearing casing (20)
. gear damage (20)
. aerodynamic excitation (30)
. rotor and bearing system critical (10)
. electrically excited vibration (10)

- sub-harmonic resonance (10)
- harmonic resonance (10)
- friction induced whirl (40)
- critical speed (10)
- oil whirl (10)
- resonant whirl (20)
- dry whirl (5)
- clearance induced vibrations (20)
- torsional resonance (80)
- transient torsional (80)

Shaft cracked or broken:

- temporary rotor bow (5)
- rotor rub, axial (10)
- bearing damage (10)
- bearing and support excited vibration (10)
- thrust bearing (10)
- insufficient tightness of rotor (shrink fits) (20)
- insufficient tightness of bearing liner (10)
- insufficient tightness of bearing casing (10)
- aerodynamic excitation (5)
- friction induced whirl (20)
- oil whirl (10)
- resonant whirl (20)
- dry whirl (30)
- clearance induced vibrations (10)
- torsional resonance (40)
- transient torsional (50)

Galling or fretting marks under disks or hubs:

- bearing damage (20)
- bearing and support excited vibration (10)
- insufficient tightness of rotor (shrink fits) (50)
- insufficient tightness of bearing liner (5)
- insufficient tightness of bearing casing (5)
- aerodynamic excitation (20)
- friction induced whirl (50)
- oil whirl (10)
- resonant whirl (20)
- dry whirl (5)
- clearance induced vibrations (5)
- torsional resonance (5)
- transient torsional (10)

Coupling bolts loose:

- temporary rotor bow (5)
- rotor rub, axial (10)
- misalignment (10)
- piping forces (10)
- bearing damage (20)
- thrust bearing damage (10)
- insufficient tightness of rotor (shrink fits) (10)

- insufficient tightness of bearing liner (10)
- insufficient tightness of bearing casing (10)
- aerodynamic excitation (10)
- electrically induced vibration (5)
- oil seal induced vibration (10)
- sub-harmonic resonance (5)
- harmonic resonance (5)
- friction induced whirl (10)
- resonant whirl (10)
- dry whirl (70)
- clearance induced vibrations (10)
- torsional resonance (40)
- transient torsional (50)

Foundation settled or cracked:

- seal rub (10)
- misalignment (50)
- bearing damage (20)
- aerodynamic excitation (30)
- structural resonance of supports (30)
- structural resonance of foundation (30)
- pressure pulsations (30)
- oil seal induced vibration (40)
- sub-harmonic resonance (10)
- harmonic resonance (10)
- resonant vibration (30)
- resonant whirl (10)

Soleplates loose or rusted:

- foundation distortion (30)
- seal rub (10)
- misalignment (50)
- piping forces (10)
- bearing damage (20)
- aerodynamic excitation (30)
- structural resonance of supports (20)
- structural resonance of foundation (10)
- pressure pulsations (20)
- oil seal induced vibration (40)
- sub-harmonic resonance (10)
- harmonic resonance (10)
- resonant vibration (10)

Sliding surfaces binding:

- casing distortion (30)
- foundation distortion (30)
- rotor rub, axial (10)
- seal rub (20)
- misalignment (10)
- piping forces (20)
- bearing damage (20)
- structural resonance of supports (10)

- structural resonance of foundation (10)
- resonant vibration (10)

Thermal expansion restricted:

- casing distortion (30)
- foundation distortion (10)
- rotor rub, axial (10)
- seal rub (40)
- misalignment (50)
- piping forces (50)
- bearing damage (20)
- structural resonance of foundation (20)
- resonant vibration (20)

Fluid marks on internals:

- permanent bow or lost rotor parts (20)
- seal rub (10)
- bearing damage (40)
- thrust bearing damage (60)
- insufficient tightness of rotor (shrink fits) (40)
- friction induced whirl (40)

Rotor components eroded:

- permanent bow or lost rotor parts (20)
- bearing damage (10)
- thrust bearing damage (30)
- insufficient tightness of rotor (shrink fits) (10)
- aerodynamic excitation (40)
- friction induced whirl (10)

Solids accumulated on vanes or rotor:

- initial unbalance (20)
- permanent bow or lost rotor parts (60)
- seal rub (10)
- bearing damage (10)
- thrust bearing damage (60)
- aerodynamic excitation (40)

Salt deposits on internals:

- initial unbalance (20)
- permanent bow or lost rotor parts (60)
- seal rub (10)
- bearing damage (10)
- thrust bearing damage (60)
- aerodynamic excitation (20)

Main flanges leaks:

- casing distortion (50)
- foundation distortion (20)
- piping forces (50)
- bearing damage (10)

Seals leaking:

- permanent bow or lost rotor parts (10)
- temporary rotor bow (20)
- casing distortion (20)
- foundation distortion (10)
- rotor rub, axial (50)
- seal rub (50)
- misalignment (10)
- piping forces (10)
- bearing damage (10)
- bearing and support excited vibration (10)
- thrust bearing damage (50)
- insufficient tightness of rotor (shrink fits) (30)
- insufficient tightness of bearing liner (30)
- insufficient tightness of bearing casing (10)
- insufficient tightness of casing support (10)
- coupling damage (10)
- aerodynamic excitation (20)
- rotor and bearing system critical (20)
- overhang critical (25)
- structural resonance of casing (10)
- structural resonance of supports (10)
- structural resonance of foundation (10)
- pressure pulsations (15)
- vibration transmission (10)
- oil seal induced vibration (90)

Category 3: ELECTRICAL

Short circuit or synchronized, out of phase or phase fault are caused by:

- unbalance
- permanent bow or rotor loss
- foundation distortion
- misalignment
- bearing damage
- bearing and support excited vibration (oil whirls)
- insufficient tightness in rotor (shrink fits)
- insufficient tightness in bearing liner
- insufficient tightness in bearing casing
- insufficient tightness in casing support
- gear damage
- coupling damage
- electrically excited vibration
- sub-harmonic vibration
- harmonic vibration
- friction induced whirl
- oil whirl
- resonant whirl
- clearance induced vibration
- torsional resonance
- transient torsional

Reverse current relays can fail because of the occurrence of the following:

- Temporary rotor bow
- casing distortion
- seal rub
- rotor rub, axial
- misalignment
- bearing damage
- insufficient tightness in rotor (shrink fits)
- insufficient tightness in bearing liner

Synchronous motor starting pulsations excessive for system can be caused by:

- permanent bow or rotor loss
- transient torsional

Starting cycle improperly timed can be caused by:

- torsional resonance

APPENDIX TWO
Results of Trace Facility

The following is the result of the trace facility of the expert system. The user has indicated a structural problem of "traps not working." The inference engine then by the use of the knowledge available as facts, demons, and rules conducts a through search of the knowledge base. Demons are rules, which fire automatically once their condition part (" IF ") becomes true. The search strategy in backward chaining is " left to right", and " depth first " on goals. This means that each condition in a rule is fully evaluated before the next is begun (i.e. the first condition is started and completed before the second is started, etc.). To evaluate a condition, the search is focused to prove that condition. Forward chaining is enabled whenever data is supplied by the user, or inferences are made, or certain other control conditions are true.

The following is the set of events by which MES conducts its search of knowledge to reach its goal of diagnosing the structural problem of traps not working properly:

Current knowledge Base: main

FORWARD CHAINING ON RULES AND DEMONS using: query work with main module

FORWARD CHAINING ON RULES AND DEMONS using: check work with main module

BACKWARD CHAINING to find: work with main module

********** QUESTION for: users choice

FORWARD CHAINING ON DEMONS using: users choice is structural

Demon 1 succeeds

FORWARD CHAINING ON RULES AND DEMONS using: query working with cat1

FORWARD CHAINING ON RULES AND DEMONS using: check working with cat1

BACKWARD CHAINING to find: working with cat1

FORWARD CHAINING ON RULES AND DEMONS using: check go

BACKWARD CHAINING to find: go

********** QUESTION for: problem

FORWARD CHAINING ON DEMONS using: problem is traps not working

Using fact 72
NEW DATABASE ITEM
cause of traps not working includes t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of expansion joints not properly installed does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of piping not properly supported does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of pipes not properly sloped and drained does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of resonants_of_pipes does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of drains running to common sewer does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of drain pots undersize does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of pipe expansion restricted does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of dead ends not drained does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of foundation not separated from building does not include t.r.1

FORWARD CHAINING ON RULES AND DEMONS using: results of insufficient foundation rigidity does not include t.r.1

Using fact 73
NEW DATABASE ITEM
cause of traps not working includes c.d

FORWARD CHAINING ON RULES AND DEMONS using: results of expansion joints not properly installed does not include c.d

Using fact 32
NEW DATABASE ITEM
results of piping not properly supported includes c.d

Using rule 1
NEW DATABASE ITEM
go includes piping not properly supported

FORWARD CHAINING ON DEMONS using: go includes piping not properly supported

NEW DATABASE ITEM
count is on

FORWARD CHAINING ON DEMONS using: count is on

NEW DATABASE ITEM
c includes c.d

FORWARD CHAINING ON DEMONS using: c includes c.d

FORWARD CHAINING ON RULES AND DEMONS using: results of pipes not properly sloped and drained does not include c.d

FORWARD CHAINING ON RULES AND DEMONS using: results of resonants_of_pipes does not include c.d

FORWARD CHAINING ON RULES AND DEMONS using: results of drains running to common sewer does not include c.d

Using fact 79
NEW DATABASE ITEM
results of drain pots undersize includes c.d

Using rule 1
NEW DATABASE ITEM
go includes drain pots undersize

FORWARD CHAINING ON DEMONS using: go includes drain pots undersize

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes c.d

Using fact 86
NEW DATABASE ITEM
results of pipe expansion restricted includes c.d

Using rule 1
NEW DATABASE ITEM
go includes pipe expansion restricted

FORWARD CHAINING ON DEMONS using: go includes pipe expansion restricted

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes c.d

FORWARD CHAINING ON RULES AND DEMONS using: results of dead ends not drained does not include c.d

FORWARD CHAINING ON RULES AND DEMONS using: results of foundation not separated from building does not include c.d

Using fact 151
NEW DATABASE ITEM
results insufficient foundation rigidity includes c.d

Using rule 1
NEW DATABASE ITEM
go includes insufficient foundation rigidity

FORWARD CHAINING ON DEMONS using: go includes insufficient foundation rigidity

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes c.d

Using fact 74
NEW DATABASE ITEM
cause of traps not working includes s.r

Using fact 25
NEW DATABASE ITEM
results of expansion joints not properly installed includes s.r

Using rule 1
NEW DATABASE ITEM
go includes expansion joints not properly installed

FORWARD CHAINING ON DEMONS using: go includes expansion joints not properly installed

```
  NEW DATABASE ITEM
  count is on

  NEW DATABASE ITEM
  c includes s.r


 FORWARD CHAINING ON DEMONS using: c includes s.r

 Using fact 33
  NEW DATABASE ITEM
  results of piping not properly supported includes s.r

 Using rule 1
  NEW DATABASE ITEM
  go includes piping not properly supported

 NEW DATABASE ITEM
  count is on

 NEW DATABASE ITEM
  c includes s.r

 Using fact 45
  NEW DATABASE ITEM
  results  of  pipes  not properly  sloped  and  drained
  includes s.r

 Using rule 1
  NEW DATABASE ITEM
  go includes pipes not properly sloped and drained


 FORWARD CHAINING ON DEMONS using: go includes pipes not
 properly sloped and drained

NEW DATABASE ITEM
  count is on

NEW DATABASE ITEM
  c includes s.r


 FORWARD CHAINING ON RULES AND DEMONS using:  results of
 resonants_of_pipes does not include s.r

 Using fact 69
  NEW DATABASE ITEM
  results of drains running to common sewer includes s.r

 Using rule 1
  NEW DATABASE ITEM
  go includes drains running to common sewer
```

FORWARD CHAINING ON DEMONS using: go includes drains running to common sewer

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes s.r

Using fact 80
NEW DATABASE ITEM
results of drain pots undersize includes s.r

Using rule 1
NEW DATABASE ITEM
go includes drain pots undersize

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes s.r

Using fact 87
NEW DATABASE ITEM
results of pipe expansion restricted includes s.r

Using rule 1
NEW DATABASE ITEM
go includes pipe expansion restricted

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes s.r

Using fact 98
NEW DATABASE ITEM
results of dead ends not drained includes s.r

Using rule 1
NEW DATABASE ITEM
go includes dead ends not drained

FORWARD CHAINING ON DEMONS using: go includes dead ends not drained

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes s.r

FORWARD CHAINING ON RULES AND DEMONS using: results of foundation not separated from building does not include s.r

Using fact 153
NEW DATABASE ITEM
results of insufficient foundation rigidity includes s.r

Using rule 1
NEW DATABASE ITEM
go includes insufficient foundation rigidity

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes s.r

Using fact 75
NEW DATABASE ITEM
cause of traps not working includes t.b.d

FORWARD CHAINING ON RULES AND DEMONS using: results of expansion joints not properly installed does not include t.b.d

FORWARD CHAINING ON RULES AND DEMONS using: results of piping not properly supported does not include t.b.d

Using fact 48
NEW DATABASE ITEM
results of pipes not properly sloped and drained includes t.b.d

Using rule 1
NEW DATABASE ITEM
go includes pipes not properly sloped and drained

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes t.b.d

FORWARD CHAINING ON DEMONS using: c includes t.b.d

FORWARD CHAINING ON RULES AND DEMONS using: results of resonants_of_pipes does not include t.b.d

FORWARD CHAINING ON RULES AND DEMONS using: results of drains running to common sewer does not include t.b.d

Using fact 82
NEW DATABASE ITEM
results of drain pots undersize includes t.b.d

Using rule 1
NEW DATABASE ITEM
go includes drain pots undersize

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes t.b.d

FORWARD CHAINING ON RULES AND DEMONS using: results of pipe expansion restricted does not include t.b.d

Using fact 100
NEW DATABASE ITEM
results of dead ends not drained includes t.b.d

Using rule 1
NEW DATABASE ITEM
go includes dead ends not drained

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes t.b.d

FORWARD CHAINING ON RULES AND DEMONS using: results of foundation not separated from building does not include t.b.d

FORWARD CHAINING ON RULES AND DEMONS using: results of insufficient foundation rigidity does not include t.b.d

Using fact 76
NEW DATABASE ITEM
cause of traps not working includes a.e

Using fact 29
NEW DATABASE ITEM
results of expansion joints not properly installed includes a.e

Using rule 1
NEW DATABASE ITEM
go includes expansion joints not properly installed

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes a.e

FORWARD CHAINING ON DEMONS using: c includes a.e

FORWARD CHAINING ON RULES AND DEMONS using: results of piping not properly supported does not include a.e

Using fact 50
NEW DATABASE ITEM
results of pipes not properly sloped and drained includes a.e

Using rule 1
NEW DATABASE ITEM
go includes pipes not properly sloped and drained

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes a.e

Using fact 52
NEW DATABASE ITEM
results of resonants_of_pipes includes a.e

Using rule 1
NEW DATABASE ITEM
go includes resonants_of_pipes

FORWARD CHAINING ON DEMONS using: go includes resonants_of_pipes

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes a.e

FORWARD CHAINING ON RULES AND DEMONS using: results of drains running to common sewer does not include a.e

Using fact 84
NEW DATABASE ITEM
results of drain pots undersize includes a.e

Using rule 1
NEW DATABASE ITEM
go includes drain pots undersize

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes a.e

FORWARD CHAINING ON RULES AND DEMONS using: results of pipe expansion restricted does not include a.e

Using fact 102
NEW DATABASE ITEM
results of dead ends not drained includes a.e

Using rule 1
NEW DATABASE ITEM
go includes dead ends not drained

NEW DATABASE ITEM
count is on

NEW DATABASE ITEM
c includes a.e

FORWARD CHAINING ON RULES AND DEMONS using: results of foundation not separated from building does not include a.e

FORWARD CHAINING ON RULES AND DEMONS using: results of insufficient foundation rigidity does not include a.e

Using fact 77
NEW DATABASE ITEM
cause of traps not working includes f.i.w

FORWARD CHAINING ON RULES AND DEMONS using: results of expansion joints not properly installed does not include f.i.w

FORWARD CHAINING ON RULES AND DEMONS using: results of piping not properly supported does not include f.i.w

Using fact 51
NEW DATABASE ITEM
results of pipes not properly sloped and drained includes f.i.w

```
Using rule 1
 NEW DATABASE ITEM
 go includes pipes not properly sloped and drained

NEW DATABASE ITEM
 count is on

NEW DATABASE ITEM
 c includes f.i.w


FORWARD CHAINING ON DEMONS using: c includes f.i.w


FORWARD CHAINING ON RULES AND DEMONS using:  results of
resonants_of_pipes does not include f.i.w

Using fact 71
 NEW DATABASE ITEM
 results of drains running to common sewer includes f.i.w

Using rule 1
 NEW DATABASE ITEM
 go includes drains running to common sewer

NEW DATABASE ITEM
 count is on

NEW DATABASE ITEM
 c includes f.i.w

Using fact 85
 NEW DATABASE ITEM
 results of drain pots undersize includes f.i.w

Using rule 1
 NEW DATABASE ITEM
 go includes drain pots undersize

NEW DATABASE ITEM
 count is on

NEW DATABASE ITEM
 c includes f.i.w


FORWARD CHAINING ON RULES AND DEMONS using:  results of
pipe expansion restricted does not include f.i.w


FORWARD CHAINING ON RULES AND DEMONS using:  results of
dead ends not drained does not include f.i.w
```

FORWARD CHAINING ON RULES AND DEMONS using: results of foundation not separated from building does not include f.i.w

FORWARD CHAINING ON RULES AND DEMONS using: results of insufficient foundation rigidity does not include f.i.w

FORWARD CHAINING ON RULES AND DEMONS using: done go

NEW DATABASE ITEM
priority of c.d is three

NEW DATABASE ITEM
c.d is casing distortion

Demon 3 succeeds
NEW DATABASE ITEM
priority of s.r is zero

NEW DATABASE ITEM
s.r is seal rub

Demon 3 succeeds
NEW DATABASE ITEM
priority of t.b.d is one

NEW DATABASE ITEM
t.b.d is thrust bearing damage

Demon 3 succeeds
NEW DATABASE ITEM
priority of a.e is one

NEW DATABASE ITEM
a.e is aerodynamic excitation

Demon 3 succeeds
NEW DATABASE ITEM
priority of f.i.w is one

Demon 4 succeeds

Demon 5 succeeds

NEW DATABASE ITEM
comment of s.r includes slight seal rubs may clear but trip unit immediately

NEW DATABASE ITEM
comment1 of s.r includes _if high speed rub gets worse

NEW DATABASE ITEM
remedy of s.r includes _if rub did not clear itself out replace seal

NEW DATABASE ITEM
remedy1 of s.r includes with slight rubs turn until clear

NEW DATABASE ITEM
material of s.r includes two seal no_2356

NEW DATABASE ITEM
labor of s.r includes 8 man_hour

NEW DATABASE ITEM
tool of s.r includes seal replacement tool set

NEW DATABASE ITEM
tool1 of s.r includes seal remover

NEW DATABASE ITEM
tool2 of s.r includes type_1 seal adhesive

Rule 2 succeeds

NEW DATABASE ITEM
emergency is finished

FORWARD CHAINING ON DEMONS using: emergency is finished

********** QUESTION for: users choice

FORWARD CHAINING ON DEMONS using: users choice is print work order

Using rule 3

FORWARD CHAINING ON RULES AND DEMONS using: check emergency

BACKWARD CHAINING to find: emergency

FORWARD CHAINING ON RULES AND DEMONS using: done emergency

FORWARD CHAINING ON RULES AND DEMONS using: check work orders for printing

BACKWARD CHAINING to find: work orders for printing

********** QUESTION for: work orders for printing

FORWARD CHAINING ON DEMONS using: work orders for printing includes f.d

NEW DATABASE ITEM
priority of f.d is three

NEW DATABASE ITEM
f.d is foundation distortion

NEW DATABASE ITEM
comment of f.d includes caused by poor material under foundation_or thermal

NEW DATABASE ITEM
comment1 of f.d includes stress_hot spots

NEW DATABASE ITEM
remedy of f.d includes if_distortion_is extensive_then replace material

NEW DATABASE ITEM
remedy1 of f.d includes under the foundation also check the structural base plates

NEW DATABASE ITEM
material of f.d includes 600 pounds of cement_six 12x18 inch baseplates

NEW DATABASE ITEM
labor of f.d includes 160 man_hour

NEW DATABASE ITEM
tool of f.d includes crane

NEW DATABASE ITEM
tool1 of f.d includes 1.5 ton fork lift

NEW DATABASE ITEM
tool2 of f.d includes foundation tool set

Demon 6 succeeds

FORWARD CHAINING ON DEMONS using: work orders for printing includes a.e

NEW DATABASE ITEM
comment of a.e includes check moleweight_and measure pressure drop across

NEW DATABASE ITEM
comment1 of a.e includes balance line and_especially balance flow temperature

NEW DATABASE ITEM
remedy of a.e includes check stage pressure_and pressure fluctuations by

NEW DATABASE ITEM
remedy1 of a.e includes installing pressure gages_thermometers_etc

NEW DATABASE ITEM
material of a.e includes none

NEW DATABASE ITEM
labor of a.e includes 12 man_hour

NEW DATABASE ITEM
tool of a.e includes pressure gages

NEW DATABASE ITEM
tool1 of a.e includes temperature gages

NEW DATABASE ITEM
tool2 of a.e includes frequency analyzer

Demon 6 succeeds

FORWARD CHAINING ON RULES AND DEMONS using: done work orders for printing

NEW DATABASE ITEM
working with cat1 is finished

FORWARD CHAINING ON DEMONS using: working with cat1 is finished

FORWARD CHAINING ON RULES AND DEMONS using: done working with cat1

APPENDIX THREE
Maintnenance Expert System Listing

The following contains the knowledge base of the maintenance expert system (MES). Three categories, CAT1, CAT2, and CAT3 contain the structural, mechanical, and electrical categories. Due to the software used to create MES, the use of key words, such as " or ", " and ", " of ", etc., within rules had to be preceded by " _ " in order to ensure the inference engine not confusing these words as commands. Knowledge base WORKO performs the work order printing and scheduling of MES.

Knowledge Base : cat1

fact 1

resonant in foundation is a foundation problem

fact 2

settling_or_shrinking_of_foundation is a foundation problem

fact 3

unevenly heated foundation is a foundation problem

fact 4

grout swell_or_shri_rust deter under sole is a foundation problem

fact 5

foundations soleplate looseness is a foundation problem

fact 6

insufficient foundation rigidity is a foundation problem

fact 7

excess moment and force on pipes is a piping problem

fact 8

expansion joints not properly installed is a piping problem

fact 9

piping not properly supported is a piping problem

fact 10

resonant in pipes is a piping problem

fact 11

water accumulating over valves is a piping problem

fact 12

casing drains run to common sewer is a piping problem

fact 13

traps not working is a piping problem

fact 14

drain pots or lines undersize is a piping problem

fact 15

pipe expansion restricted due to foundation is a piping problem

fact 16

piping dead ends not drained is a piping problem

fact 17

piping problem is a structural subcategory

fact 18

foundation problem is a structural category

fact 19

cause of excess moment and force on pipes includes c.d

fact 20

cause of excess moment and force on pipes includes s.r

fact 21

cause of excess moment and force on pipes includes m

fact 22

cause of excess moment and force on pipes includes i.t.o.c.s

fact 23

cause of excess moment and force on pipes includes c.d

fact 24

cause of excess moment and force on pipes includes c.i.v

fact 25

results of expansion joints not properly installed includes s.r

fact 26

results of expansion joints not properly installed includes m

fact 27

results of expansion joints not properly installed includes p.f

fact 28

results of expansion joints not properly installed includes i.t.o.c.s

fact 29

results of expansion joints not properly installed includes a.e

fact 30

results of expansion joints not properly installed includes s.r.o.s

fact 31

results of expansion joints not properly installed includes s.r.o.f

fact 32

results of piping not properly supported includes c.d

fact 33

results of piping not properly supported includes s.r

fact 34

results of piping not properly supported includes m

fact 35

results of piping not properly supported includes p.f

fact 36

results of piping not properly supported includes i.t.o.c.s

fact 37

results of piping not properly supported includes s.r.o.c

fact 38

results of piping not properly supported includes j.s.r.o.s

fact 39

results of piping not properly supported includes s.r.o.f

fact 40

results of piping not properly supported includes e.e.v

fact 41

results of piping not properly supported includes v.t

fact 42

results of piping not properly supported includes r.w

fact 43

results of piping not properly supported includes c.i.v

fact 44

results of pipes not properly sloped and drained includes p.b.o.l.r.p

fact 45

results of pipes not properly sloped and drained includes s.r

fact 46

results of pipes not properly sloped and drained includes r.r.a

fact 47

results of pipes not properly sloped and drained includes b.d

fact 48

results of pipes not properly sloped and drained includes t.b.d

fact 49

results of pipes not properly sloped and drained includes i.t.o.r

fact 50

results of pipes not properly sloped and drained includes a.e

fact 51

results of pipes not properly sloped and drained includes f.i.w

fact 52

results of resonants_of_pipes includes a.e

fact 53

results of resonants_of_pipes includes s.r.o.c

fact 54

results of resonants_of_pipes includes s.r.o.s

fact 55

results of resonants_of_pipes includes s.r.o.f

fact 56

results of resonants_of_pipes includes e.e.v

fact 57

results of resonants_of_pipes includes v.t

fact 58

results of resonants_of_pipes includes r.v

fact 59

results of resonants_of_pipes includes r.w

fact 60

cause of water accumulating over valves includes p.b.o.l.r

fact 61

cause of water accumulating over valves includes t.r.b

fact 62

cause of water accumulating over valves includes s.r

fact 63

cause of water accumulating over valves includes r.r.a

fact 64

cause of water accumulating over valves includes b.d

fact 65

cause of water accumulating over valves includes t.b.d

fact 66

cause of water accumulating over valves includes i.t.o.r

fact 67

cause of water accumulating over valves includes f.i.w

fact 68

results of drains running to common sewer includes t.r.b

fact 69

results of drains running to common sewer includes s.r

fact 70

results of drains running to common sewer includes i.t.o.r

fact 71

results of drains running to common sewer includes f.i.w

fact 72

cause of traps not working includes t.r.l

fact 73

cause of traps not working includes c.d

fact 74

cause of traps not working includes s.r

fact 75

cause of traps not working includes t.b.d

fact 76

cause of traps not working includes a.e

fact 77

cause of traps not working includes f.i.w

fact 78

results of drain pots undersize includes t.r.b

fact 79

results of drain pots undersize includes c.d

fact 80

results of drain pots undersize includes s.r

fact 81

results of drain pots undersize includes r.r.a

fact 82

results of drain pots undersize includes t.b.d

fact 83

results of drain pots undersize includes i.t.o.r

fact 84

results of drain pots undersize includes a.e

fact 85

results of drain pots undersize includes f.i.w

fact 86

results of pipe expansion restricted includes c.d

fact 87

results of pipe expansion restricted includes s.r

fact 88

results of pipe expansion restricted includes m

fact 89

results of pipe expansion restricted includes p.f

fact 90

results of pipe expansion restricted includes o.w

fact 91

results of pipe expansion restricted includes i.t.o.c.s

fact 92

results of pipe expansion restricted includes s.r.o.c

fact 93

results of pipe expansion restricted includes s.r.o.s

fact 94

results of pipe expansion restricted includes s.r.o.f

fact 95

results of pipe expansion restricted includes v.t

fact 96

results of pipe expansion restricted includes r.w

fact 97

results of dead ends not drained includes t.r.b

fact 98

results of dead ends not drained includes s.r

fact 99

results of dead ends not drained includes r.r.a

fact 100

results of dead ends not drained includes t.b.d

fact 101

results of dead ends not drained includes i.t.o.r

fact 102

results of dead ends not drained includes a.e

fact 103

cause of resonant in foundation includes o.w

fact 104

cause of resonant in foundation includes r.a.b.s.c

fact 105

cause of resonant in foundation includes s.r

fact 106

cause of resonant in foundation includes e.e.v

fact 107

cause of resonant in foundation includes v.t

fact 108

cause of resonant in foundation includes s.h.v

fact 109

cause of resonant in foundation includes r.w

fact 110

cause of settling_or_shrinking foundation includes s.r

fact 111

cause of settling_or_shrinking foundation includes m

fact 112

cause of settling_or_shrinking foundation includes p.f

fact 113

cause of settling_or_shrinking foundation includes c.d

fact 114

cause of settling_or_shrinking foundation includes b.d

fact 115

cause of settling_or_shrinking foundation includes c.a.s.l

fact 116

cause of unevenly heated foundation includes s.r

fact 117

cause of unevenly heated foundation includes m

fact 118

cause of unevenly heated foundation includes p.f

fact 119

cause of unevenly heated foundation includes b.d

fact 120

cause of unevenly heated foundation includes c.d

fact 121

results of foundation not separated from building includes o.w

fact 22

results of foundation not separated from building includes e.e.v

fact 123

results of foundation not separated from building includes v.t

fact 124

results of foundation not separated from building includes s.h.r

fact 125

results of foundation not separated from building includes h.r

fact 126

results of foundation not separated from building includes r.v

fact 127

results of foundation not separated from building includes r.w

fact 128

cause of grout_swell_or_shri_rust deter under sole includes f.d

fact 129

cause of grout_swell_or_shri_rust deter under sole includes s.r

fact 130

cause of grout_swell_or_shri_rust deter under sole includes m

fact 131

cause of grout_swell_or_shri_rust deter under sole includes b.d

fact 132

cause of grout_swell_or_shri_rust deter under sole includes o.w

fact 133

cause of grout_swell_or_shri_rust deter under sole includes u.b.s

fact 134

cause of grout_swell_or_shri_rust deter under sole includes c.a.s.l

fact 135

cause of grout_swell_or_shri_rust deter under sole includes c.da

fact 136

cause of grout_swell_or_shri_rust deter under sole includes r.a.b.s.c

fact 137

cause of grout_swell_or_shri_rust deter under sole includes s.r.i.s

fact 138

cause of grout_swell_or_shri_rust deter under sole includes s.r.i.f

fact 139

cause of grout_swell_or_shri_rust deter under sole includes v.t

fact 140

cause of grout_swell_or_shri_rust deter under sole includes s.h.r

fact 141

cause of grout_swell_or_shri_rust deter under sole includes h.r

fact 142

cause of grout_swell_or_shri_rust deter under sole includes f.i.w

fact 143

cause of grout_swell_or_shri_rust deter under sole includes c.s

fact 144

cause of foundations soleplate looseness includes o.w

fact 145

cause of foundations soleplate looseness includes s.r.o.s

fact 146

cause of foundations soleplate looseness includes s.r.o.f

fact 147

cause of foundations soleplate looseness includes s.h.r

fact 148

cause of foundations soleplate looseness includes r.v

fact 149

cause of foundations soleplate looseness includes r.w

fact 150

cause of foundations soleplate looseness includes c.i.v

fact 151

results of insufficient foundation rigidity includes c.d

fact 152

results of insufficient foundation rigidity includes f.d

fact 153

results of insufficient foundation rigidity includes s.r

fact 154

results of insufficient foundation rigidity includes m

fact 155

results of insufficient foundation rigidity includes p.f

fact 156

results of insufficient foundation rigidity includes r.b.s.c

fact 157

results of insufficient foundation rigidity includes s.h.r

fact 158

results of insufficient foundation rigidity includes r.v

fact 159

results of insufficient foundation rigidity includes r.w

```
question 1
  problem is
    excess moment and force on pipes ,
    water accumulating over valves ,
    traps not working ,
    resonant in foundation ,
    settling_or_shrinking foundation ,
    unevenly heated foundation ,
    grout_swell_or_shri_rust deter under sole ,
    foundations soleplate looseness ,
    none of the above
  question text Select the most significant problem
question 2
  users choice is
    print work order ,
    schedule work order
  question text What do you wnat to do ?
```

```
rule 1
   if   problem is Any_problem
    and cause of Any_problem includes Any_cause
    and results of A_s_p includes Any_cause
   then go includes A_s_p
    and count is on
    and c includes Any_cause
rule 2
   if   done go
    and c includes Any_c
    and priority of Any_c is zero
    and Any_c is An_abb
    and comment of Any_c includes C
    and comment1 of Any_c includes C1
    and remedy of Any_c includes R
    and remedy1 of Any_c includes R1
    and material of Any_c includes M
    and labor of Any_c includes L
    and tool of Any_c includes T
    and tool1 of Any_c includes T1
    and tool2 of Any_c includes T2
   then report "4" DUE TO * * EMERGENCY * *
```

```
    and report " " THE FOLLOWING WORK ORDER ( S )
    and report "-" WORK ORDER NO. : "
    and report "        " Priority : EMERGENCY
    and report "         " Problem : [problem]
    and report "           " Cause : [An_abb]
    and report "         " Comments: [C]
    and report "                   " [C1]
    and report "                   " [R]
    and report "                   " [R1]
    and report "  "
    and report "        " Material : [M]
    and report "           " Labor : [L]
    and report "           " Tools : [T]
    and report "                   " [T1]
    and report "                   " [T2]
    and emergency is finished
rule 3
   if   done go
    and users choice is print work order
   then check emergency
    and check work orders for printing
    and working with cat1 is finished
```

```
rule 4
   if   done go
    and users choice is schedule work order
   then check emergency
    and check work orders for scheduling
    and working with cat1 is finished
```

Knowledge Base : cat2

fact 1

rotor_or stator resonant frequency of i.u is very low

fact 2

rotor_or stator resonant frequency of p.b.o.r.l is low

fact 3

rotor_or stator resonant frequency of t.r.b is low

fact 4

rotor_or stator resonant frequency of c.d is low

fact 5

rotor_or stator resonant frequency of s.r is very low

fact 6

rotor_or stator resonant frequency of r.r.a is low

fact 7

rotor_or stator resonant frequency of m is very low

fact 8

rotor_or stator resonant frequency of p.f is very low

fact 9

rotor_or stator resonant frequency of j.a.b.e is high

fact 10

rotor_or stator resonant frequency of b.d is low

fact 11

rotor_or stator resonant frequency of o.w is low

fact 12

rotor_or stator resonant frequency of u.b.s is mid

fact 13

rotor_or stator resonant frequency of t.b.d is very high

fact 14

rotor_or stator resonant frequency of i.t.o.r is mid

fact 15

rotor_or stator resonant frequency of i.t.o.b.l is very high

fact 16

rotor_or stator resonant frequency of i.t.o.b.c is very high

fact 17

rotor_or stator resonant frequency of i.t.o.c.s is mid

fact 18

rotor_or stator resonant frequency of c.da is low

fact 19

rotor_or stator resonant frequency of a.e is mid

fact 20

rotor_or stator resonant frequency of r.a.b.s.c is sure

fact 21

rotor_or stator resonant frequency of c.c is sure

fact 22

rotor_or stator resonant frequency of o.h.c is sure

fact 23

rotor_or stator resonant frequency of s.r.o.c is sure

fact 24

rotor_or stator resonant frequency of s.r.o.s is sure

fact 25

rotor_or stator resonant frequency of s.r.o.f is sure

```
fact 26
    rotor_or stator resonant frequency of p.p is high
fact 27
    rotor_or stator resonant frequency of e.e.v is high
fact 28
    rotor_or stator resonant frequency of v.t is low
fact 29
    rotor_or stator resonant frequency of o.s.i.v is low
fact 30
    rotor_or stator resonant frequency of s.h.r is sure
fact 31
    rotor_or stator resonant frequency of h.r is sure
fact 32
    rotor_or stator resonant frequency of f.i.w is sure
fact 33
    rotor_or stator resonant frequency of c.s is sure
fact 34
    rotor_or stator resonant frequency of r.v is sure
fact 35
    rotor_or stator resonant frequency of r.w is sure
fact 36
    rotor_or stator resonant frequency of d.w is sure
fact 37
    rotor_or stator resonant frequency of c.i.v is mid
fact 38
    rotor_or stator resonant frequency of t.r is sure
```

fact 39

rotor_or stator resonant frequency of t.t is sure

fact 40

predominant frequency equaling 1 x running frequency of i.u is very high

fact 41

predominant frequency equaling 1 x running frequency of p.b.o.r.l is very high

fact 42

predominant frequency equaling 1 x running frequency of t.r.b is very high

fact 43

predominant frequency equaling 1 x running frequency of c.d is mid

fact 44

predominant frequency equaling 1 x running frequency of f.d is mid

fact 45

predominant frequency equaling 1 x running frequency of s.r is low

fact 46

predominant frequency equaling 1 x running frequency of r.r.a is low

fact 47

predominant frequency equaling 1 x running frequency of m is low

fact 48

predominant frequency equaling 1 x running frequency of p.f is low

fact 49

predominant frequency equaling 1 x running frequency of j.a.b.e is mid

fact 5 0

predominant frequency equaling 1 x running frequency of b.d is low

fact 51

predominant frequency equaling 1 x running frequency of t.b.d is very high

fact 52

predominant frequency equaling 1 x running frequency of i.t.o.r is very low

fact 53

predominant frequency equaling 1 x running frequency of i.t.o.b.c is low

fact 54

predominant frequency equaling 1 x running frequency of i.t.o.c.s is low

fact 55

predominant frequency equaling 1 x running frequency of c.d is low

fact 56

predominant frequency equaling 1 x running frequency of a.e is low

fact 57

predominant frequency equaling 1 x running frequency of r.a.b.s.c is sure

fact 58

predominant frequency equaling 1 x running frequency of c.c is sure

fact 59

predominant frequency equaling 1 x running frequency of o.h.c is sure

fact 60

predominant frequency equaling 1 x running frequency of s.r.o.c is mid high

fact 61

predominant frequency equaling 1 x running frequency of s.r.o.s is mid high

fact 62

predominant frequency equaling 1 x running frequency of s.r.o.f is mid high

fact 63

predominant frequency equaling 1 x running frequency of p.p is high

fact 64

predominant frequency equaling 1 x running frequency of c.s is sure

fact 65

predominant frequency equaling 1 x running frequency of r.v is mid high

fact 66

predominant frequency equaling 1 x running frequency of c.i.v is low

fact 67

predominant frequency equaling 1 x running frequency of t.r is mid low

fact 68

predominant frequency equaling 1 x running frequency of t.t is mid

fact 69

predominant frequency equaling 2 x running frequency of i.u is very low

fact 70

predominant frequency equaling 2 x running frequency of p.b.o.r.l is very low

fact 71

predominant frequency equaling 2 x running frequency of t.r.b is very low

fact 72

predominant frequency equaling 2 x running frequency of c.d is very low

fact 73

predominant frequency equaling 2 x running frequency of f.d is low

fact 74

predominant frequency equaling 2 x running frequency of s.r is very low

fact 75

predominant frequency equaling 2 x running frequency of r.r.a is very low

fact 76

predominant frequency equaling 2 x running frequency of m is mid high

fact 77

predominant frequency equaling 2 x running frequency of p.f is mid high

fact 78

predominant frequency equaling 2 x running frequency of j.a.b.e is mid high

fact 79

predominant frequency equaling 2 x running frequency of b.d is low

fact 80

predominant frequency equaling 2 x running frequency of u.b.s is high

fact 81

predominant frequency equaling 2 x running frequency of t.b.d is very high

fact 82

predominant frequency equaling 2 x running frequency of i.t.o.r is very low

fact 83

predominant frequency equaling 2 x running frequency of c.d is low

fact 84

predominant frequency equaling 2 x running frequency of s.r.o.c is very low

fact 85

predominant frequency equaling 2 x running frequency of s.r.o.s is low

fact 86

predominant frequency equaling 2 x running frequency of s.r.o.f is low

fact 87

predominant frequency equaling 2 x running frequency of h.r is sure

fact 88

predominant frequency equaling 2 x running frequency of r.v is mid high

fact 89

predominant frequency equaling 2 x running frequency of c.i.v is low

fact 90

predominant frequency equaling 2 x running frequency of t.r is low

fact 91

predominant frequency higher multiple than 2 of i.u is very low

fact 92

predominant frequency higher multiple than 2 of p.b.o.r.l is very low

fact 93

predominant frequency higher multiple than 2 of t.r.l is very low

fact 94

predominant frequency higher multiple than 2 of c.d is very low

fact 95

predominant frequency higher multiple than 2 of f.d is very low

fact 96

predominant frequency higher multiple than 2 of r.r.a is very low

fact 97

predominant frequency higher multiple than 2 of m is very low

fact 98

predominant frequency higher multiple than 2 of p.f is very low

fact 99

predominant frequency higher multiple than 2 of u.b.s is low

fact 100

predominant frequency higher multiple than 2 of i.t.o.r is very low

fact 101

predominant frequency higher multiple than 2 of g.d is low

fact 102

predominant frequency higher multiple than 2 of c.da is very low

fact 103

predominant frequency higher multiple than 2 of h.r is sure

fact 104

predominant frequency higher multiple than 2 of r.v is very low

fact 105

predominant frequency higher multiple than 2 of c.i.v is very low

fact 106

predominant frequency higher multiple than 2 of t.r is low

fact 107

predominant frequency eqauling 0.5 x running frequency of o.w is very low

fact 108

predominant frequency eqauling 0.5 x running frequency of s.r.o.c is very low

fact 109

predominant frequency eqauling 0.5 x running frequency of s.r.o.s is very low

fact 110

predominant frequency eqauling 0.5 x running frequency of s.r.o.f is very low

fact 111

predominant frequency eqauling 0.5 x running frequency of s.h.r is sure

fact 112

predominant frequency eqauling 0.5 x running frequency of r.v is very low

fact 113

predominant frequency eqauling 0.25 x running frequency of o.w is very low

fact 114

predominant frequency eqauling 0.25 x running frequency of s.h.r is sure

fact 115

predominant frequency eqauling 0.25 x running frequency of r.v is very low

fact 116

predominant frequency lower than 0.25 of s.r is very low

fact 117

predominant frequency lower than 0.25 of r.r.a is very low

fact 118

predominant frequency lower than 0.25 of s.h.r is sure

fact 119

predominant frequency_are odd frequencies of f.d is very low

fact 120

predominant frequency_are odd frequencies of s.r is very low

fact 121

predominant frequency_are odd frequencies of r.r.a is very low

fact 122

predominant frequency_are odd frequencies of i.t.o.r is very low

fact 123

predominant frequency_are odd frequencies of i.t.o.b.l is very low

fact 124

predominant frequency_are odd frequencies of i.t.o.b.c is very low

fact 125

predominant frequency_are odd frequencies of i.t.o.c.s is mid

fact 126

predominant frequency_are odd frequencies of g.d is mid

fact 127

predominant frequency_are odd frequencies of a.e is very low

fact 128

predominant frequency_are odd frequencies of v.t is mid low

fact 129

predominant frequency_are odd frequencies of t.t is mid

fact 130

predominant frequency_are very high frequencies of s.r is very low

fact 131

predominant frequency_are very high frequencies of r.r.a is very low

fact 132

predominant frequency_are very high frequencies of m is very low

fact 133

predominant frequency_are very high frequencies of p.f is very low

fact 134

predominant frequency_are very high frequencies of b.d is low

fact 135

predominant frequency_are very high frequencies of t.b.d is very low

fact 136

predominant frequency_are very high frequencies of g.d is mid high

fact 137

predominant frequency_are very high frequencies of c.da is high

fact 138

predominant frequency_are very high frequencies of a.e is very low

fact 139

predominant frequency_are very high frequencies of d.w is sure

fact 140

cause of s.r includes p.b.o.r.l

fact 141

cause of s.r includes t.r.b

fact 142

cause of s.r includes c.d

fact 143

cause of s.r includes f.d

fact 144

cause of s.r includes b.d

fact 145

cause of s.r includes o.w

fact 146

cause of s.r includes t.b.d

fact 147

cause of s.r includes i.t.o.r

fact 148

cause of s.r includes i.t.o.b.l

fact 149

cause of s.r includes o.s.i.v

fact 150

cause of s.r includes f.i.w

fact 151

cause of s.r includes r.w

fact 152

cause of b.s includes r.r.a

fact 153

cause of b.s includes t.b.d

fact 154

cause of b.s includes o.h.c

fact 155

cause of b.s includes o.s.i.v

fact 156

cause of b.s includes r.w

fact 157

cause of t.b.d includes r.r.a

fact 158

cause of t.b.d includes m

fact 159

cause of t.b.d includes g.d

fact 160

cause of t.b.d includes c.d

fact 161

cause of t.b.d includes a.e

fact 162

cause of t.b.d includes p.p

fact 163

cause of b.f.d.t.w includes t.r.b

fact 164

cause of b.f.d.t.w includes c.d

fact 165

cause of b.f.d.t.w includes f.d

fact 166

cause of b.f.d.t.w includes r.r.a

fact 167

cause of b.f.d.t.w includes j.a.b.e

fact 168

cause of b.f.d.t.w includes o.w

fact 169

cause of b.f.d.t.w includes u.b.s

fact 170

cause of b.f.d.t.w includes t.b.d

fact 171

cause of b.f.d.t.w includes i.t.o.r

fact 172

cause of b.f.d.t.w includes i.t.o.c.s

fact 173

cause of b.f.d.t.w includes r.a.b.s.c

fact 174

cause of b.f.d.t.w includes f.i.w

fact 175

cause of b.f.d.t.w includes r.w

fact 176

cause of b.f.d.t.f includes o.w

fact 177

cause of b.f.d.t.f includes u.b.s

fact 178

cause of b.f.d.t.f includes i.t.o.r

fact 179

cause of b.f.d.t.f includes i.t..o.c.s

fact 180

cause of b.f.d.t.f includes r.a.b.s.c

fact 181

cause of b.f.d.t.f includes c.c

fact 182

cause of b.f.d.t.f includes o.h.c

fact 183

cause of b.f.d.t.f includes o.s.i.v

fact 184

cause of b.f.d.t.f includes f.i.w

fact 185

cause of b.f.d.t.f includes r.w

fact 186

cause of b.f.d.t.f includes d.w

fact 187

cause of b.f.b.b.s.o includes t.r.b

fact 188

cause of b.f.b.b.s.o includes o.w

fact 189

cause of b.f.b.b.s.o includes i.t.o.r

fact 190

cause of b.f.b.b.s.o includes i.t.o.c

fact 191

cause of b.f.b.b.s.o includes i.t.o.c.s

fact 192

cause of b.f.b.b.s.o includes f.i.w

fact 193

cause of b.f.b.b.s.o includes d.w

fact 194

cause of c.d.o.c includes s.r

fact 195

cause of c.d.o.c includes m

fact 196

cause of c.d.o.c includes p.f

fact 197

cause of c.d.o.c includes b.d

fact 198

cause of c.d.o.c includes o.s.i.v

fact 199

cause of m includes c.d

fact 200

cause of m includes f.d

fact 201

cause of m includes s.r

fact 202

cause of m includes p.f

fact 203

cause of m includes s.r.o.f

fact 204

cause of m includes p.p

fact 205

cause of m includes v.t

fact 206

cause of c.b.o.p includes m

fact 207

cause of c.b.o.p includes p.f

fact 208

cause of c.b.o.p includes i.t.o.r

fact 209

cause of c.b.o.p includes i.t.o.b.l

fact 210

cause of c.b.o.p includes c.d

fact 211

cause of c.b.o.p includes o.h.c

fact 212

cause of c.b.o.p includes o.s.i.v

fact 213

cause of c.b.o.p includes f.i.w

fact 214

cause of c.b.o.p includes r.w

fact 215

cause of c.b.o.p includes c.i.v

fact 216

cause of c.b.o.p includes t.r

fact 217

cause of g.t.b.o.p includes b.d

fact 218

cause of g.t.b.o.p includes o.w

fact 219

cause of g.t.b.o.p includes g.d

fact 220

cause of g.t.b.o.p includes o.s.i.v

fact 221

cause of g.t.b.o.p includes f.i.w

fact 222

cause of g.t.b.o.p includes r.w

fact 223

cause of g.t.b.o.p includes t.r

fact 224

cause of g.t.b.o.p includes t.t

fact 225

cause of g.t.m.b.s includes t.r.b

fact 226

cause of g.t.m.b.s includes i.t.o.r

fact 227

cause of g.t.m.b.s includes g.d

fact 228

cause of g.t.m.b.s includes a.e

fact 229

cause of g.t.m.b.s includes f.i.w

fact 230

cause of g.t.m.b.s includes t.t

fact 231

cause of g.t.m.b.s includes t.r

fact 232

cause of s.c.o.b includes i.t.o.r

fact 233

cause of s.c.o.b includes d.w

fact 234

    cause of s.c.o.b includes f.i.w

fact 235

    cause of s.c.o.b includes t.t

fact 236

    cause of s.c.o.b includes t.r

fact 237

    cause of g.o.f.m.u.d.o.h includes b.d

fact 238

    cause of g.o.f.m.u.d.o.h includes i.t.o.r

fact 239

    cause of g.o.f.m.u.d.o.h includes f.i.w

fact 240

    cause of g.o.f.m.u.d.o.h includes i.t.o.b.c

fact 241

    cause of g.o.f.m.u.d.o.h includes f.i.w

fact 242

    cause of g.o.f.m.u.d.o.h includes a.e

fact 243

    cause of c.b.l includes b.d

fact 244

    cause of c.b.l includes i.t.o.r

fact 245

    cause of c.b.l includes i.t.o.b.l

fact 246

    cause of c.b.l includes i.t.o.b.c

fact 247

cause of c.b.l includes f.i.w

fact 248

cause of c.b.l includes t.r

fact 249

cause of c.b.l includes t.t

fact 250

cause of f.s.o.c includes m

fact 251

cause of f.s.o.c includes a.e

fact 252

cause of f.s.o.c includes s.r.o.s

fact 253

cause of f.s.o.c includes s.r.o.f

fact 254

cause of f.s.o.c includes p.p

fact 255

cause of f.s.o.c includes o.s.i.v

fact 256

cause of s.l.o.r includes f.d

fact 257

cause of s.l.o.r includes m

fact 258

cause of s.l.o.r includes b.d

fact 259

cause of s.l.o.r includes a.e

fact 260

cause of s.l.o.r includes o.s.i.v

fact 261

cause of s.s.b includes c.d

fact 262

cause of s.s.b includes f.d

fact 263

cause of s.s.b includes s.r

fact 264

cause of s.s.b includes p.f

fact 265

cause of s.s.b includes b.d

fact 266

cause of t.e.r includes c.d

fact 267

cause of t.e.r includes f.d

fact 268

cause of t.e.r includes s.r

fact 269

cause of t.e.r includes m

fact 270

cause of t.e.r includes p.f

fact 271

cause of t.e.r includes b.d

fact 272

cause of f.m.o.i includes p.b.o.l.r

fact 273

cause of f.m.o.i includes s.r

fact 274

cause of f.m.o.i includes b.d

fact 275

cause of f.m.o.i includes t.b.d

fact 276

cause of f.m.o.i includes i.t.o.r

fact 277

cause of f.m.o.i includes f.i.w

fact 278

cause of r.c.e includes p.b.o.l.r

fact 279

cause of r.c.e includes b.d

fact 280

cause of r.c.e includes t.b.d

fact 281

cause of r.c.e includes i.t.o.r

fact 282

cause of r.c.e includes a.e

fact 283

cause of s.a.o.v.o.r includes i.u

fact 284

cause of s.a.o.v.o.r includes p.b.o.r.l

fact 285

cause of s.a.o.v.o.r includes s.r

fact 286

cause of s.a.o.v.o.r includes b.d

fact 287

cause of s.a.o.v.o.r includes t.b.d

fact 288

cause of s.a.o.v.o.r includes a.e

fact 289

cause of s.d.o.i includes i.u

fact 290

cause of s.d.o.i includes p.b.o.r.l

fact 291

cause of s.d.o.i includes t.b.d

fact 292

cause of s.d.o.i includes a.e

fact 293

cause of m.f.l includes c.d

fact 294

cause of m.f.l includes f.d

fact 295

cause of m.f.l includes p.f

fact 296

cause of m.f.l includes b.d

fact 297

cause of s.l includes t.r.b

fact 298

cause of s.l includes c.d

fact 299

cause of s.l includes r.r.a

fact 300

cause of s.l includes s.r

fact 301

cause of s.l includes t.b.d

fact 302

cause of s.l includes i.t.o.r

fact 303

cause of s.l includes i.t.o.b.l

fact 304

cause of s.l includes a.e

fact 305

cause of s.l includes r.a.b.s.c

fact 306

cause of s.l includes p.p

fact 307

cause of s.l includes o.s.i.v

fact 308

b.s means bent shaft

fact 309

b.f.d.t.w means bearing failure due to wiping

fact 310

b.f.d.t.f means bearing failure due to fatigue

fact 311

b.f.b.b.s.o means bearing failure because babbitt squeezed out

fact 312

c.d.o.c means case distorted_or cracked

fact 313

c.b.o.p means coupling burned_or pitted

fact 314

g.t.b.o.p means gear teeth broken_or pitted

fact 315

g.t.m.b.s means gear teeth marked on the backside

fact 316

s.c.o.b means shaft cracked_or broken

fact 317

g.o.f.m.u.d.o.h means galling_or fretting marks under disks_or hubs

fact 318

c.b.l.o.r means coupling bolts loose_or rusted

fact 319

f.s.o.c means foundation setteled_or cracked

fact 320

s.l.o.r means soleplates loose_or rusted

fact 321

s.s.b means sliding surfaces binding

fact 322

t.e.r means thermal expansion restricted

fact 323

f.m.o.i means fluid marks on internals

fact 324

r.c.e means rotor components eroded

fact 325

s.a.o.v.o.r means solids accumulated on vanes_or rotor

fact 326

s.d.o.i means salt deposits on internals

fact 327

m.f.l means main flanges leaks

fact 328

s.l means seals leaking

fact 329

s.r means seal rub

fact 330

m means misalignment

fact 331

t.b.d means thrust bearing damage

fact 332

no means no

question 1

frequency is

rotor_or stator resonant frequency ,

predominant frequency equaling 1 x running frequency ,

predominant frequency equaling 2 x running frequency ,

predominant frequency higher multiple than 2 ,

predominant frequency equaling 0.5 x running frequency ,

predominant frequency equaling 0.25 x running frequency ,

predominant frequency lower multiple than 0.25 ,

predominant frequency_are odd frequencies ,

predominant frequency_are very high frequencies ,

vibration analysis showed no abnormal signs

question text Choose the most applicable statement :

```
question 2
  evidence includes
    case distorted_or cracked ,
    galling_or fretting marks under disks_or hubs ,
    sliding surfaces binding ,
    thermal expansion restricted ,
    fluid marks on internals ,
    salt deposits on internals ,
    no
  question text Are you experiencing any of the following problem :
question 3
  evidence for seals includes
    seal rub ,
    seals leaking ,
    main flanges leaking ,
    no
  question text Do you have any seal problems ?
question 4
  evidence for rotor includes
    bent shaft ,
    shaft cracked_or broken ,
    misalignment ,
    rotor components eroded ,
    solids accumulated on internals ,
    no
  question text Do you have any rotor problems ?
```

```
question 5
  evidence for bearing includes
    thrust bearing damage ,
    bearing failure because babbitt squeezed out ,
    bearing failure due to fatigue ,
    bearing failure due to wiping ,
    no
  question text Do you have any bearing problems ?
question 6
  evidence for coupling includes
    coupling burned_or pitted ,
    coupling bolts loose_or rusted ,
    no
  question text Do you have any coupling problems ?
question 7
  evidence for gear includes
    gear teeth broken_or pitted ,
    gear teeth marked on the back side ,
    no
  question text Do you have any gear problems ?
demon 1
   when done go
    and go includes c.d.o.c or g.o.f.m.u.d.o.h or t.e.r or s.d.o.i
    and go includes no
   then report "5" = = = > no , should only be used as a singular response
```

```
    and command reset evidence
    and command reset go
    and check evidence
    and command query go1
demon 2
   when done go1
    and go1 includes s.r or s.l or m.f.l
    and go1 includes no
   then report "5" = = = > no , should only be used as a singular response
    and command reset evidence for seals
    and command reset go1
    and check evidence for seals
    and command query go2
demon 3
   when done go2
    and go2 includes b.s or s.c.o.b or m or r.c.e or s.a.o.i
    and go2 includes no
   then report "5" = = = > no , should only be used as a singular response
    and command reset evidence for rotor
    and command reset go2
    and check evidence for rotor
    and command query go3
```

```
demon 4
   when done go3
    and go3 includes t.b.d or b.f.b.b.s.o or b.f.d.t.f or b.f.d.t.w or b.f.d.t.w
    and go3 includes no
   then report "5" = = = > no , should only be used as a singular response
    and command reset evidence for bearing
    and command reset go3
    and check evidence for bearing
    and command query go4
demon 5
   when done go4
    and go4 includes c.b.o.p or c.b.l.o.r
    and go4 includes no
   then report "5" = = = > no , should only be used as a singular response
    and command reset evidence for coupling
    and command reset go4
    and check evidence for coupling
    and command query go5
demon 6
   when done go5
    and go5 includes g.t.b.o.p or g.t.m.o.t.b.s
    and go5 includes no
   then report "5" = = = > no , should only be used as a singular response
    and command reset evidence for gear
```

```
  and command reset go5
  and check evidence for gear
  and check sum
  and command query rock
demon 7
 when done go
  and go includes c.d.o.c or g.o.f.m.u.d.o.h or t.e.r or s.d.o.i
  and go does not include no
 then command query go1
demon 8
 when done go1
  and go1 includes s.r or s.l or m.f.l
  and go1 does not include no
 then command query go2
demon 9
 when done go2
  and go2 includes b.s or s.c.o.b or m or r.c.e or s.a.o.i
  and go2 does not include no
 then command query go3
demon 10
 when done go3
  and go3 includes t.b.d or b.f.b.b.s.o or b.f.d.t.f
  and go3 does not include no
 then command query go4
```

```
demon 11
   when done go4
    and go4 includes c.b.o.p or c.b.l.o.r
    and go4 does not include no
   then command query go5
demon 12
   when done go5
    and go5 includes g.t.b.o.p or g.t.m.o.t.b.s
    and go5 does not include no
   then check sum
    and command query rock
demon 13
   when done go
    and go does not include c.d.o.c and g.o.f.m.u.d.o.h and t.e.r
    and go includes no
   then command query go1
demon 14
   when done go1
    and go1 does not include s.r and s.l and m.f.l
    and go1 includes no
   then command query go2
```

```
demon 15
   when done go2
    and go2 does not include b.s and s.c.o.b and m and r.c.e
    and go2 includes no
   then command query go3
demon 16
   when done go3
    and go3 does not include t.b.d and b.f.b.b.s.o and b.f.d.t.f
    and go3 includes no
   then command query go4
demon 17
   when done go4
    and go4 does not include c.b.o.p and c.b.l.o.r
    and go4 includes no
   then command query go5
demon 18
   when done go5
    and go5 does not include g.t.b.o.p and g.t.m.o.t.b.s
    and go5 includes no
   then check sum
    and command query rock
```

```
demon 19
   when frequency is vibration analysis showed no abnormal signs
    and sum includes Any_s
    and cause of Any_s includes Any_c
    and Any_s means An_abb
   then c includes Any_c
    and problem includes An_abb
demon 20
   when frequency is vibration analysis showed no abnormal signs
   then choice is made
rule 1
   if   evidence for seals includes Any_e
    and An_abb means Any_e
   then go1 includes An_abb
rule 2
   if   evidence for rotor includes Any_e
    and An_abb means Any_e
   then go2 includes An_abb
rule 3
   if   evidence for bearing includes Any_e
    and An_abb means Any_e
   then go3 includes An_abb
```

```
rule 4
   if   evidence for coupling includes Any_e
    and An_abb means Any_e
   then go4 includes An_abb
rule 5
   if   evidence for gear includes Any_e
    and An_abb means Any_e
   then go5 includes An_abb
rule 6
   if   done go5
    and go includes Ag
    and go1 includes Ag1
    and go2 includes Ag2
    and go3 includes Ag3
    and go4 includes Ag4
    and go5 includes Ag5
   then sum includes Ag
    and sum includes Ag1
    and sum includes Ag2
    and sum includes Ag3
    and sum includes Ag4
    and sum includes Ag5
```

```
rule 7
   if   frequency is Any_f
    and sum includes Any_s
    and cause of Any_s includes Any_c
    and Any_f of Any_c is mid high or high or very high or sure
    and Any_s means An_abb
   then c includes Any_c
    and problem includes An_abb
    and choice is made
rule 8
   if   evidence includes Any_e
    and An_abb means Any_e
   then go includes An_abb
rule 9
   if   choice is made
   then command load worko
    and rock is fin
query 1
  go
  query options auto , noreply
```

Knowledge Base : cat3

fact 1

    cause of ph.f includes i.u

fact 2

    cause of ph.f includes f.d

fact 3

    cause of ph.f includes i.t.o.c.s

fact 4

    cause of s.c includes g.d

fact 5

    cause of s.c includes c.da

fact 6

    cause of s.c includes r.w

fact 7

    cause of s.c includes t.t

fact 8

    cause of r.c.f includes t.r.b

fact 9

    cause of r.c.f includes c.d

fact 10

    cause of r.c.f includes s.r

fact 11

    cause of r.c.f includes s.r

fact 12

    cause of r.c.f includes r.r.a

fact 13

    cause of r.c.f includes i.t.o.r

```
fact 14
    cause of p.e includes p.b.o.r.l
fact 15
    cause of p.e includes t.t
fact 16
    cause of i.t includes t.r
fact 17
    s.c means short circuited
fact 18
    ph.f means phase fault
fact 19
    r.c.f means reverse current relays failure
fact 20
    p.e means synchronous motor starting pulsualtions excessive
fact 21
    i.t means starting cycle improperly timed
question 1
  choice includes
    short circuited ,
    phase fault ,
    reverse current relays failure ,
    synchronous motor starting pulsations excessive ,
    starting cycle improperly timed ,
    none of the above
  question text what is your electrical system difficiulities ?
```

```
question 2
  next action is
    go back to the main module ,
    check mechanical evidence ,
    check structural evidence ,
    quit
  question text choose what you want to do ?
demon 1
   when problem includes none of the above
   then check next action
rule 1
   if   choice includes Any_c
    and Any_t means Any_c
    and cause of Any_t includes C
   then c includes C
    and problem includes Any_c
    and diagnosis is on
rule 2
   if   next action is go back to the main module
   then command load main
rule 3
   if   next action is check mechanical evidence
   then command load cat2
rule 4
   if   next action is check structural evidence
   then command load cat1
```

```
rule 5
   if   next action is quit
   then report "15          " sorry could'nt be of any help
    and command reset kb
rule 6
   if   done diagnosis
   then command load worko
query 1
  diagnosis
  query options auto , noreply
```

Knowledge Base : worko

fact 1

p.b.o.l.r is permanent bow_or_lost rotor parts

fact 2

t.r.b is temporary rotor bow

fact 3

c.d is casing distortion

fact 4

f.d is foundation distortion

fact 5

s.r is seal rub

fact 6

r.r.a is rotor rub_axial

fact 7

m is misalignment

fact 8

p.f is piping forces

fact 9

j.a.b.e is journal_and_bearing eccentricity

fact 10

b.d is bearing damage

fact 11

o.w is oil whirl

fact 12

t.b.d is thrust bearing damage

fact 13

    i.t.o.r is insufficient tightness_of_rotor

fact 14

    i.t.o.c.s is insufficient tightness_of_casing support

fact 15

    a.e is aerodynamic excitation

fact 16

    r.a.b.s.c is rotor_and_bearing system critical

fact 17

    s.r.o.c is structural resonance_of casing

fact 18

    s.r.o.s is structural resonance_of support

fact 19

    s.r.o.f is structural resonance_of foundation

fact 20

    e.e.v is electrically excited vibration

fact 21

    v.t is vibration transmission

fact 22

    s.h.r is sub harmonic resonance

fact 23

    h.r is harmonic resonance

fact 24

    c.da is coupling damage

fact 25

    r.w is resonant whirl

fact 26

r.v is resonant vibration

fact 27

comment of p.b.o.l.r includes hot spotting can be used as a short term

fact 28

comment1 of p.b.o.l.r includes solution_check for corrosion fatigue

fact 29

remedy of p.b.o.l.r includes overhaul of rotor assembly at the most

fact 30

remedy1 of p.b.o.l.r includes appropriate time

fact 31

labor of p.b.o.l.r is 8 man hour for rotor

fact 32

tool of p.b.o.l.r includes 9 to 40 mm socket set

fact 33

tool1 of p.b.o.l.r includes crane

fact 34

tool2 of p.b.o.l.r includes rotor tool set

fact 35

material of p.b.o.l.r includes rotor kit 4536_0001

fact 36

comment of t.r.b includes if_rub occurs trip unit immediately and keep rotor

fact 37

comment1 of t.r.b includes turning 90 degrees by shaft wrench every 5 min

fact 38

remedy of t.r.b includes resume lower operating speed_straighten bow

fact 39

remedy1 of t.r.b includes by running in low gear it may take 24 hrs

fact 40

labor of t.r.b includes one man up to 24 hrs

fact 41

tool of t.r.b includes rotor wrench

fact 42

tool1 of t.r.b includes rotor tool set

fact 43

tool2 cf t.r.b includes heating unit

fact 44

material of t.r.b includes no material required

fact 45

comment of c.d includes often results to a need for complete rework_or

fact 46

comment1 of c.d includes a new casing some mild distortions correct themselves

fact 47

remedy of c.d includes look for excessive piping forces_or wrong casing

fact 48

remedy1 of c.d includes design_or wrong material_or improper stress relief

fact 49

labor of c.d includes 35 man_hour

fact 50

material of c.d includes new casing_and_supports

fact 51

tool of c.d includes crane

fact 52

tool1 of c.d includes 1.5 ton fork lift

fact 53

tool2 of c.d includes casing tool set

fact 54

comment of f.d includes caused by poor material under foundation_or thermal

fact 55

comment1 of f.d includes stress_hot spots

fact 56

remedy of f.d includes if_distortion_is extensive_then replace material

fact 57

remedy1 of f.d includes under the foundation also check the structural base

fact 58

labor of f.d includes 160 man_hour

fact 59

material of f.d includes 600 pounds of cement_six 12x18 inch baseplates

fact 60

tool of f.d includes crane

fact 61

tool1 of f.d includes 1.5 ton fork lift

fact 62

tool2 of f.d includes foundation tool set

fact 63

comment of s.r includes slight seal rubs may clear but trip unit immediately

fact 64

comment1 of s.r includes _if high speed rub gets worse

fact 65

remedy of s.r includes _if rub did not clear itself out replace seal

fact 66

remedy1 of s.r includes with slight rubs turn until clear

fact 67

labor of s.r includes 8 man_hour

fact 68

material of s.r includes two seal no_2356

fact 69

tool of s.r includes seal replacement tool set

fact 70

tool1 of s.r includes seal remover

fact 71

tool2 of s.r includes type_1 seal adhesive

fact 72

comment of r.r.a includes rapid changes of load and temperature

fact 73

comment1 of r.r.a includes rub also check thrust bearing damages

fact 74

remedy of r.r.a includes check_thrust bearing status

fact 75

remedy1 of r.r.a includes do not allow rapid load changes

fact 76

labor of r.r.a includes 24 man_hour

fact 77

material of r.r.a includes two rotor seal no_xze2371

fact 78

tool of r.r.a includes seal remover

fact 79

tool1 of r.r.a includes two seal no_2356

fact 80

tool2 of r.r.a includes type_1 seal adhesive

fact 81

comment of m includes caused by excessive pipe strain and_or inadequate

fact 82

comment1 of m includes mounting_and foundation

fact 83

remedy of m includes check_for local heating from pipes_or sun on the

fact 84

remedy1 of m includes foundation_also check if thermal expansion is allowed

fact 85

labor of m includes 15 man_hour

fact 86

material of m includes no material required

fact 87

tool of m includes alignment tool set

fact 88

tool1 of m includes vibograph

fact 89

tool2 of m includes frequency analyzer

fact 90

comment of p.f includes most trouble_is_caused by poor piping support

fact 91

comment1 of p.f includes and improperly used expansion joints

fact 92

remedy of p.f includes see_if_ proper expansion joints are used also

fact 93

remedy1 of p.f includes if_poor pipe line up exists at casing connection

fact 94

labor of p.f includes 15 man_hour

fact 95

material of p.f includes six expansion joints no_46980

fact 96

tool of p.f includes crane

fact 97

tool1 of p.f includes pipe wrench

fact 98

tool2 of p.f includes piping tool set

fact 99

comment of j.a.b.e includes bearings may get distorted from heat make

fact 100

comment1 of j.a.b.e includes hot checks

fact 101

remedy of j.a.b.e includes provide for thermal expansion and install

fact 102

remedy1 of j.a.b.e includes heat shields

fact 103

labor of j.a.b.e includes 4 man_hour

fact 104

material of j.a.b.e includes heat shields cat_no wqa1265

fact 105

tool of j.a.b.e includes bearing setter type trefi3123

fact 106

tool1 of j.a.b.e includes heat gloves

fact 107

tool2 of j.a.b.e includes bearing grease type_xrt0097

fact 108

comment of b.d includes usually preceded by brown discoloration before

fact 109

comment1 of b.d includes failure check rotor for vibration

fact 110

remedy of b.d includes improve bearing design_do not ope. .te under

fact 111

remedy1 of b.d includes high vibration_of rotor_and extreme temperatures

fact 112

labor of b.d includes 6 man_hour

fact 113

material of b.d includes bearing_type rewq2133_and lubricant xsrw8765

fact 114

tool of b.d includes pressure gauge

fact 115

tool1 of b.d includes bearing remover wwe4312

fact 116

tool2 of b.d includes bearing tool set

fact 117

comment of o.w includes check for clearance_and_roundness_of_journal

fact 118

comment1 of o.w includes also check for resonant_of_pipes_or_foundation

fact 119

remedy of o.w includes correct clearance of bearing and journal also

fact 120

remedy1 of o.w includes check running frequency_may require tilt shoe bearings

fact 121

labor of o.w includes 4 man_hour

fact 122

material of o.w includes tilt shoe bearing

fact 123

tool of o.w includes frequency analy[illegible]r

fact 124

tool1 of o.w includes bearing tool set

fact 125

tool2 of o.w includes vibograph

fact 126

comment of u.b.s includes can excite resonance and criticals_and combination

fact 127

comment1 of u.b.s includes _or thereof at 2xrunning frequency

fact 128

remedy of u.b.s includes increase horizontal bearing support stiffness

fact 129

remedy1 of u.b.s includes or_mass depending on severity

fact 130

labor of u.b.s includes 10 man_hour

fact 131

material of u.b.s includes bearing supports type_asw33309

fact 132

tool of u.b.s includes bearing tool set

fact 133

tool1 of u.b.s includes alignment tool

fact 134

tool2 of u.b.s includes bearing wrench

fact 135

comment of i.t.o.r includes disks_and_sleeves may have lost their fit due

fact 136

comment1 of i.t.o.r includes temperature changes

fact 137

remedy of i.t.o.r includes replace disks_and_sleeves check the rotor and

fact 138

remedy1 of i.t.o.r includes support criticals frequency

fact 139

labor of i.t.o.r includes 15 man_hour

fact 140

material of i.t.o.r includes disk no_234rty sleeve no_wer29800

fact 141

tool of i.t.o.r includes rotor tool set

fact 142

tool1 of i.t.o.r includes frequency analyzer

fact 143

tool2 of i.t.o.r includes vibograph

fact 144

comment of i.t.o.b.l includes make sure everything in the bearing

fact 145

comment1 of i.t.o.b.l includes assembly_is_tight

fact 146

remedy of i.t.o.b.l includes seal the horizontal joint_but_do not use

fact 147

remedyl of i.t.o.b.l includes silicon_rubber_rtv_to seal bearing casing

fact 148

labor of i.t.o.b.l includes 12 man_hour

fact 149

material of i.t.o.b.l includes sealing rubber_type4345ttr

fact 150

tool of i.t.o.b.l includes seal tool set

fact 151

tool1 of i.t.o.b.l includes sealer machine

fact 152

tool2 of i.t.o.b.l includes frequency analyzer

fact 153

comment of i.t.o.b.c includes make sure to check attachment bolts

fact 154

comment1 of i.t.o.b.c includes and_splits with torque wrench

fact 155

remedy of i.t.o.b.c includes check tightness of casing and also review

fact 156

remedyl of i.t.o.b.c includes casing design

fact 157

labor of i.t.o.b.c includes 3 man_hr

fact 158

material of i.t.o.b.c includes no material required

fact 159

tool of i.t.o.b.c includes bearing tool set

fact 160

tool1 of i.t.o.b.c includes torque wrench

fact 161

tool2 of i.t.o.b.c includes casing tool set

fact 162

comment of i.t.o.c.s includes usually involves sliding pedestats_and

fact 163

comment1 of i.t.o.c.s includes casing feet_check for friction

fact 164

remedy of i.t.o.c.s includes reduce friction if necessary also

fact 165

remedy1 of i.t.o.c.s includes check proper clearance and piping strains

fact 166

labor of i.t.o.c.s includes 8 man_hour

fact 167

material of i.t.o.c.s includes four casing support no_qw3214

fact 168

tool of i.t.o.c.s includes slider wrench

fact 169

tool1 of i.t.o.c.s includes crane

fact 170

tool2 of i.t.o.c.s includes frequency analyzer

fact 171

comment of g.d includes strong axial vibration indicates pitch line

fact 172

comment1 of g.d includes runout_bent shaft_or_gear wheel cracking

fact 173

remedy of g.d includes to get frequencies tape microphone to gear casing

fact 174

remedy1 of g.d includes and play back through vibograph

fact 175

labor of g.d includes 6 man_hour

fact 176

material of g.d includes 12x 4 in bevel gears

fact 177

tool of g.d includes gear remover

fact 178

tool1 of g.d includes gear tool set

fact 179

tool2 of g.d includes frequency analyzer

fact 180

comment of c.da includes loose coupling sleeves are notorious trouble

fact 181

comment1 of c.da includes makers specially with long heavy spacers

fact 182

remedy of c.da includes check tooth fit by placing indicator on top then

fact 183

remedy1 of c.da includes lift with jack_or hand_and note looseness

fact 184

material of c.da includes heavy spacers type_1234aasw

fact 185

labor of c.da includes 10 man_hour

fact 186

tool of c.da includes jack

fact 187

tool1 of c.da includes level indicator

fact 188

tool2 of c.da includes clearance gage

fact 189

comment of a.e includes check moleweight_and measure pressur drop across

fact 190

comment1 of a.e includes balance line and_especially balance flow temperature

fact 191

remedy of a.e includes check stage pressure_and pressure fluctuations by

fact 192

remedy1 of a.e includes installing pressure gages_thermometers_etc

fact 193

labor of a.e includes 12 man_hour

fact 194

material of a.e includes none

fact 195

tool of a.e includes pressure gages

fact 196

tool1 of a.e includes temperature gages

fact 197

tool2 of a.e includes frequency analyzer

fact 198

comment of r.a.b.s.c includes difficult to correct in field sometimes

fact 199

comment1 of r.a.b.s.c includes adding mass at bearing helps_over 8000rpm

fact 200

remedy of r.a.b.s.c includes try more viscous oil larger_and longer bearings

fact 201

remedy1 of r.a.b.s.c includes with min clearance and_tight fit

fact 202

labor of r.a.b.s.c includes 10 man_hour

fact 203

material of r.a.b.s.c includes lubricant type 123er4

fact 204

tool of r.a.b.s.c includes stabilizer wrench

fact 205

tool1 of r.a.b.s.c includes frequency analyzer

fact 206

tool2 of r.a.b.s.c includes vibograph

fact 207

comment of c.c includes these criticals_of the spacer overhang sub_system

fact 208

comment1 of c.c includes often encountered with long spacers

fact 209

remedy of c.c includes make sure of_tight fitting teeth with slight

fact 210

remedy1 of c.c includes interference at stand still

fact 211

labor of c.c includes 12 man_hour

fact 212

material of c.c includes tubular spacer_and solid couplings

fact 213

tool of c.c includes spacer wrench

fact 214

tool1 of c.c includes coupling tool set

fact 215

tool2 of c.c includes frequency analyzer

fact 216

comment of o.h.c includes can be exceedingly troublesome this can make

fact 217

comment1 of o.h.c includes the criticals so rough that they can not be passed

fact 218

remedy of o.h.c includes shorten overhang or_put in an outboard bearing

fact 219

remedy1 of o.h.c includes for stabilization

fact 220

labor of o.h.c includes 12 man_hour

fact 221

material of o.h.c includes aluminum and_titanium coupling_and spacer

fact 222

tool of o.h.c includes spacer wrench

fact 223

tool1 of o.h.c includes coupling tool set

fact 224

tool2 of o.h.c includes frequency analyzer

fact 225

comment of s.r.o.c includes so called case drumming can bevery presistant

fact 226

comment1 of s.r.o.c includes but its sometimes harmless

fact 227

remedy of s.r.o.c includes check for diaphragm drumming also for rotor_casing

fact 228

remedy1 of s.r.o.c includes interaction

fact 229

labor of s.r.o.c includes 7 man_hour

fact 230

material of s.r.o.c includes none

fact 231

tool of s.r.o.c includes frequency analyzer

fact 232

tool1 of s.r.o.c includes vibograph

fact 233

tool2 of s.r.o.c includes casing tool set

fact 234

comment of s.r.o.s includes local drumming is_usually harmless but major

fact 235

comment1 of s.r.o.s includes resonances can cause rubs and_component failure

fact 236

remedy of s.r.o.s includes stiffness of_supports will dampen vibration

fact 237

remedy1 of s.r.o.s includes therefore apply correct amount of stiffness

fact 238

labor of s.r.o.s includes 6 man_hour

fact 239

material of s.r.o.s includes damper type_345trfg

fact 240

tool of s.r.o.s includes torque wrench

fact 241

tool1 of s.r.o.s includes frequency analyzer

fact 242

tool2 of s.r.o.s includes vibograph

fact 243

comment of s.r.o.f includes cracking and_misalignment can result plus

fact 244

comment1 of s.r.o.f includes piping trouble and_casing warpage material

fact 245

remedy of s.r.o.f includes add stiffness by properly choosing the

fact 246

remedy1 of s.r.o.f includes proper foundation material

fact 247

labor of s.r.o.f includes 20 man_hour

fact 248

material of s.r.o.f includes foundation dampers type 345ytg

fact 249

tool of s.r.o.f includes crane

fact 250

tool1 of s.r.o.f includes vibration analyzer

fact 251

tool2 of s.r.o.f includes alignment tool

fact 252

comment of p.p includes can excite other vibrations possibly with

fact 253

comment1 of p.p includes serious consequences

fact 254

remedy of p.p includes eliminate vibration by using restraints_flexible

fact 255

remedy1 of p.p includes pipe supports_sway braces_and shock absorbers

fact 256

labor of p.p includes 10 man_hour

fact 257

material of p.p includes sway brace type 2343ret5

fact 258

tool of p.p includes brace remover tool

fact 259

tool1 of p.p includes frequency analyzer

fact 260

tool2 of p.p includes vibograph

fact 261

comment of e.e.v includes mostly 2xline frequency coming from motor

fact 262

comment1 of e.e.v includes and generator fields turn field off to verify

fact 263

remedy of e.e.v includes shaft failures are likely if_torsional criticals

fact 264

remedy1 of e.e.v includes coincides with line frequency

fact 265

labor of e.e.v includes 3 man_hour

fact 266

material of e.e.v includes electrical relay type 9876qwe

fact 267

tool of e.e.v includes electrical tool kit

fact 268

tool1 of e.e.v includes frequency analyzer

fact 269

tool2 of e.e.v includes vibograph

fact 270

comment of v.t includes can excite serious vibrations _and bearing failure

fact 271

comment1 of v.t includes use vibration absorbers where possible

fact 272

remedy of v.t includes isolate piping_and foundation and use sway braces

fact 273

remedy of v.t includes to disallow the transmission

fact 274

labor of v.t includes 6 man_hour

fact 275

material of v.t includes sway brace type 45532

fact 276

tool of v.t includes brace tool kit

fact 277

tool1 of v.t includes frequency analyzer

fact 278

tool2 of v.t includes vibograph

fact 279

comment of o.s.i.v includes most likely caused by damage to seal faces

fact 280

comment1 of o.s.i.v includes and_or poor face lubrication

fact 281

remedy of o.s.i.v includes use baked_on or_bonded solid_film lubricant

fact 282

remedy1 of o.s.i.v includes to avoid excessive vibration

fact 283

labor of o.s.i.v includes 3 man_hour

fact 284

material of o.s.i.v includes lap seals type 65re4

fact 285

tool of o.s.i.v includes frequency analyzer

fact 286

tool1 of o.s.i.v includes seal tool kit

fact 287

tool2 of o.s.i.v includes lubricant tool set

fact 288

comment of s.h.r includes vibration at exactly half_quarter_eighth of_

fact 289

comment1 of s.h.r includes exciting frequency can only be in none linear

fact 290

remedy of s.h.r includes look fir such things as looseness_aerodynamic_or

fact 291

remedy1 of s.h.r includes hydrodynamic excitations

fact 292

labor of s.h.r includes 12 man_hour

fact 293

material of s.h.r includes none

fact 294

tool of s.h.r includes clearance gages

fact 295

tool1 of s.h.r includes rotor tool kit

fact 296

tool2 of s.h.r includes frequency analyzer

fact 297

comment of h.r includes vibrations at exactly 2x_3x_4x exciting frequency

fact 298

comment1 of h.r includes look for looseness and aerodynamic excitations

fact 299

remedy of h.r includes change frequency add damping and_reduce aerodynamic

fact 300

remedy1 of h.r includes and hydrodynamic excitation_if either exists

fact 301

labor of h.r includes 12 man_hour

fact 302

material of h.r includes damper type 23ewr

fact 303

tool of h.r includes frequency analyzer

fact 304

tool1 of h.r includes rotor tool kit

fact 305

tool2 of h.r includes damping tool kit

fact 306

comment of f.i.w includes if intermittent look into temperature variations

fact 307

comment1 of f.i.w includes and fluid slugging are the cause

fact 308

remedy of f.i.w includes usually rotor must berebuilt_increase stator mass

fact 309

remedy1 of f.i.w includes and_use larger bearings

fact 310

labor of f.i.w includes 15 man_hour

fact 311

material of f.i.w includes tilt shoe bearing stator type 123wer

fact 312

tool of f.i.w includes bearing tool kit

fact 313

tool1 of f.i.w includes stator tool kit

fact 314

tool2 of f.i.w includes frequency analyzer

fact 315

comment of c.s includes basically a design problem but often aggravated by

fact 316

comment1 of c.s includes poor balancing and_foundation

fact 317

remedy of c.s includes try to field balance rotor at operating speed lower

fact 318

remedy1 of c.s includes oil temperature use larger and_tighter bearings

fact 319

labor of c.s includes 15 man_hour

fact 320

material of c.s includes tilt shoe bearing

fact 321

tool of c.s includes frequency analyzer

fact 322

tool1 of c.s includes bearing tool kit

fact 323

tool2 of c.s includes balancing machine

fact 324

comment of r.v includes reducing mass or_stiffness can leave the amplitude

fact 325

comment1 of r.v includes the same even if_resonant frequency shifts

fact 326

remedy of r.v includes add mass or_change stiffness to shift frequency

fact 327

remedy1 of r.v includes out of resonance

fact 328

labor of r.v includes 10 man_hour

fact 329

material of r.v includes damper type sdf451

fact 330

tool of r.v includes frequency analyzer

fact 331

tool1 of r.v includes damper tool kit

fact 332

tool2 of r.v includes vibograph

fact 333

comment of r.w includes check for loose bearings first and improve

fact 334

comment1 of r.w includes system isolation

fact 335

remedy of r.w includes find resonant members and source of excitation

fact 336

remedy1 of r.w includes use tilt shoe bearings

fact 337

labor of r.w includes 4 man_hour

fact 338

material of r.w includes tilt shoe bearing

fact 339

tool of r.w includes bearing tool kit

fact 340

tool1 of r.w includes frequency analyzer

fact 341

tool2 of r.w includes vibograph

fact 342

comment of c.i.v includes usually rocking motions_and beating within clearance

fact 343

comment1 of c.i.v includes serious especially in bearing assembly

fact 344

remedy of c.i.v includes frequencies are often below running frequency make

fact 345

remedy1 of c.i.v includes sure everything is_absolutely tight

fact 346

labor of c.i.v includes 13 man_hour

fact 347

material of c.i.v includes lubricant type qwe3245

fact 348

tool of c.i.v includes frequency analyzer

fact 349

tool1 of c.i.v includes rotor tool kit

fact 350

tool2 of c.i.v includes clearance gage

fact 351

comment of d.w includes the squeal of_bearing or_seal may be ultrasonic

fact 352

comment1 of d.w includes and_very destructive

fact 353

remedy of d.w includes check for rotor vanes hitting stator especially

fact 354

remedy1 of d.w includes if clearances is tight

fact 355

labor of d.w includes 8 man_hour

fact 356

material of d.w includes none

fact 357

tool of d.w includes clearance gage

fact 358

tool1 of d.w includes frequency analyzer

fact 359

tool2 of d.w includes noise charts

fact 360

comment of t.r includes very destructive and_difficult to identify

fact 361

comment1 of t.r includes isolate the source

fact 362

remedy of t.r includes causes include_loose coupling bolts and_fretting

fact 363

remedy1 of t.r includes properly tuned torsional vibration dampers

fact 364

labor of t.r includes 15 man_hour

fact 365

material of t.r includes torsional vibration damper

fact 366

tool of t.r includes damper tool kit

fact 367

tool1 of t.r includes frequency analyzer

fact 368

tool2 of t.r includes coupling tool set

fact 369

comment of t.t includes encountered only during start up and_shut down due

fact 370

comment1 of t.t includes to very strong torsional pulsations

fact 371

remedy of t.t i ludes check for torsional cracks use properly tuned

fact 372

remedy1 of t.t includes torsional vibration damper

fact 373

labor of t.t includes 13 man_hour

fact 374

material of t.t includes torsional vibration damper

fact 375

tool of t.t includes damper tool kit

fact 376

tool1 of t.t includes frequency analyzer

fact 377

tool2 of t.t includes torsion tool set

fact 378

priority of i.u is two

fact 379

priority of p.b.o.l.r is one

fact 380

priority of t.r.b is two

fact 381

priority of c.d is three

fact 382

priority of f.d is three

fact 383

priority of s.r is zero

fact 384

priority of r.r.a is two

fact 385

priority of m is three

fact 386

priority of p.f is four

fact 387

priority of j.a.b.e is three

fact 388

priority of b.d is two

fact 389

priority of o.w is two

fact 390

priority of u.b.s is three

fact 391

priority of t.b.d is one

fact 392

priority of i.t.o.r is two

fact 393

priority of i.t.o.b.l is three

fact 394

priority of i.t.o.b.c is three

fact 395

priority of g.d is one

fact 396

priority of a.e is one

fact 397

priority of r.a.b.s.c is zero

fact 398

priority of c.c is one

fact 399

priority of o.c is zero

fact 400

priority of s.r.o.c is zero

fact 401

priority of s.r.o.s is three

fact 402

priority of s.r.o.f is three

fact 403

priority of p.p is two

fact 404

priority of e.e.v is two

fact 405

priority of v.t is one

```
fact 406
    priority of o.s.i.v is three
fact 407
    priority of s.h.r is three
fact 408
    priority of h.r is two
fact 409
    priority of f.i.w is one
fact 410
    priority of r.v is one
 act 411
    priority of d.w is three
fact 412
    priority of c.i.v is three
fact 413
    priority of t.r is zero
fact 414
    priority of t.t is zero
fact 415
    comment of t.b.d includes this may result from slugging the machine with fluid
fact 416
    comment1 of t.b.d includes or_solid build up on rotor_or off design operation
fact 417
    remedy of t.b.d includes aviod surging_since this is a leading cause also
fact 418
    remedy1 of t.b.d includes check rotors and clean them if necessary
```

fact 419

material of t.b.d includes thrust bearing type 4356xccr

fact 420

labor of t.b.d includes 7 man_hour

fact 421

tool of t.b.d includes bearing tool set

fact 422

tool1 of t.b.d includes frequency analyzer

fact 423

tool2 of t.b.d includes clearance gage

```
demon 1
   when users choice is print work order
    and work orders for printing includes Any_c
    and priority of Any_c is P
    and Any_c is An_abb
    and comment of Any_c includes C
    and comment1 of Any_c includes C1
    and remedy of Any_c includes R
    and remedy1 of Any_c includes R1
    and material of Any_c includes M
    and labor of Any_c includes I
    and tool of Any_c includes T
    and tool1 of Any_c includes T1
    and tool2 of Any_c includes T2
    and problem includes Problem
   then report "-" WORK ORDER NO. : "
    and report "       " Priority : [P]
    and report "       " Evidence : [Problem]
    and report "          " Cause : [An_abb]
    and report "        " Comments: [C]
    and report "                  " [C1]
    and report "                  " [R]
    and report "                  " [R1]
    and report "  "
    and report "       " Material : [M]
    and report "          " Labor : [L]
    and report "          " Tools : [T]
    and report "                  " [T1]
    and report "                  " [T2]
```

```
demon 2
   when users choice is schedule work order
    and work orders for scheduling includes Any_c
    and Any_c is An_abb
    and priority of Any_c is P
    and problem includes Problem
   then report to file schedule.rpt W.O no. "    " Evidence = = > [Problem]
    and report to file schedule.rpt : [An_abb] ( [Any_c] ) ... Priority : [P]
    and report "8" File: schedule.rpt contains the submitted W.O
demon 3
   when users choice is list work orders
    and c includes Any_c
    and Any_c is An_abb
    and priority of Any_c is P
   then report " " write or print this page for later reference
    and report " " [An_abb] - - ( [Any_c] ) - - priority : [P]
demon 4
   when users choice is list work orders
   then command reset users choice
    and check users choice
```

```
rule 1
  if   c includes Any_c
   and priority of Any_c is zero
   and Any_c is An_abb
   and comment of Any_c includes C
   and comment1 of Any_c includes C1
   and remedy of Any_c includes R
   and remedy1 of Any_c includes R1
   and material of Any_c includes M
   and labor of Any_c includes L
   and tool of Any_c includes T
   and tool1 of Any_c includes T1
   and tool2 of Any_c includes T2
   and problem includes Problem
  then report "4" DUE TO * * EMERGENCY * * PRIORITY YOU MUST PRINT
   and report " " THE FOLLOWING WORK ORDER ( S )
   and report "-" WORK ORDER NO. : "
   and report "        " Priority : EMERGENCY
   and report "        " Evidence : [Problem]
   and report "           " Cause : [An_abb]
   and report "         " Comments: [C]
   and report "                   " [C1]
   and report "                   " [R]
   and report "                   " [R1]
   and report "  "
   and report "        " Material : [M]
   and report "           " Labor : [L]
   and report "           " Tools : [T]
   and report "                   " [T1]
   and report "                   " [T2]
   and emergency is finished
```

```
rule 2
   if   users choice is print work order
   then check emergency
    and check work orders for printing
    and go is fin
rule 3
   if   users choice is schedule work order
   then check emergency
    and check work orders for scheduling
    and go is fin

question 1
  users choice is
    print work order ,
    schedule work order ,
    list work orders
  question text what do you want to do ?
```

VITA

Tahoomars Rastin was born in Tabriz, Iran on July 16, 1960, the son of Kiomars and Khadijeh Rastin. He recieved his high school diploma form Acadiana high school in Lafayette and graduated in May, 1977. In september of that year he enrolled at Louisiana State University form which he recieved the bachelor of science in mechanical engineering in December, 1981, and master of science in industrial engineering in December, 1984. Through out his years at LSU, he was an active member of LSU Bayou Water polo team.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Tahomars Rastin

Major Field: Engineering Science

Title of Dissertation: Using Expert Systems in Maintenance Monitoring and Management

Approved:

Lawrence Mann, Jr.

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Ralph W. Pike

M. Zohdi

Date of Examination:

9/16/88