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Network Theory for AI-Based Equipment Failure Diagnosis

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Application of Expert Systems for Diagnosing Equipment Failures at Central Energy Plants

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FOREWORD

This study was performed under Project 4A161102AT23, "Basic Research in Military Construction"; Work Unit BO-031, "Network Theory for AI-Based Equipment Failure Diagnosis."

This research was conducted by the Energy and Utility Systems Division (FE) of the Infrastructure Laboratory (FL), of the U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Ralph Moshage. Mark Metea and Christopher Blazek are associated with the Institute of Gas Technology. Special thanks go to Rama Katz, Younggook Jun, and Frank Johnson of USACERL for their assistance in preparing this report. Thanks also go to Stanley Briggs and Lawrence L. Yost of York-Shipley, York, PA; Charles Schmidt of Schmidt & Associates, Cleveland, OH; and Sid Snow of Cleaver Brooks, Inc., Milwaukee, WI, for providing expert knowledge engineering information. Dr. David Joncich is Chief, CECER-FE, and Dr. Michael O'Connor is Chief, CECER-FL. The USACERL technical editor was William Wolfe, Information Management Office.

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CONTENTS

TABLES

FIGURES

APPLICATION OF EXPERT SYSTEMS FOR DIAGNOSING EQUIPMENT FAILURES AT CENTRAL ENERGY PLANTS

1 INTRODUCTION

Background

The Army operates and maintains a large number of fossil fuel-powered central heating plants for supplying energy to its facilities. As the cost of running these plants continues to grow, the Army is seeking alternative ways to do labor-intensive tasks. Recent advances in computer technology may help to automate many of the tasks now performed manually. One task especially well suited to computer automation is the diagnosis of equipment malfunction. An automated diagnostic tool could free personnel for higher priority work, and could also reduce downtime for repair, promote thermal efficiency, and improve on-line reliability.

Microcomputer-based expert systems technology provides a means to develop such a tool. To complete the task, an artificial intelligence (AI) based expert system would need to incorporate the expertise of a select group of consultants known for their ability to anticipate and diagnose equipment and operational problems in heating plants, in the form of a database, from which the system would acquire its "inference" ability.

Objectives

The objectives of this project were to evaluate the application of expert system technology to diagnosing equipment problems in Army central energy plants, and to develop and test a system prototype.

Approach

The approach to this project was threefold. First, to evaluate expert systems in general, a literature search and analysis was conducted to explore and define the current state of AI technology. Second, to test and experiment with an expert system, state-of-the-art development tools including computer languages (such as LISP and PROLOG) and commercially available expert system shells were investigated. More than 30 of these shells were evaluated for their ability to handle large knowledge bases, operate in real time, and interface with process equipment. Information to be used in the expert system was gathered from personal interviews with experts in the field, and from a review of equipment operation and maintenance manuals. Finally, based on this investigation, an expert system shell developed by Texas Instruments (called PCPLUS) was selected for testing. Computer hardware as well as software components were then evaluated to find those best suited for the application and a prototype expert system was developed using the equipment selected for monitoring and diagnosing typical Army boiler central heating plants.

Mode of Technology Transfer

The results of this research project will be applied in ongoing project 4A162784AT41, Work Unit EQ-XK3, "Central Energy Supply: Advanced Operations." It is anticipated that an Army Engineer Technical Note (ETN) will be prepared from the results of this study when field application of the system is feasible.

2 EXPERT SYSTEMS TECHNOLOGY

Artificial Intelligence

Artificial Intelligence (AI) is a field of computer science concerned with understanding intelligence and developing computer programs that exhibit intelligence. The aim of AI software and hardware is to create computers that will be able to mimic some of the functions of the human brain. Expert systems is one of the major application areas of AI.

"Intelligence" includes such elements as the ability to learn or understand from experience, to acquire and retain knowledge, and to use reasoning in solving problems (Hunt 1986, pp 1-2). A fundamental component of intelligence is knowledge. In AI, knowledge representation focuses on methods for efficiently modeling knowledge to make it easily accessible for application to problem solving within the context of an artificial intelligence computing system. A great deal of early AI research focused on development of systems that had general problem solving knowledge.

Artificial intelligence problem solving can be viewed as a search among alternative solutions to a problem to determine the best solution. The search proceeds under the guidance of one or more control strategies, or search techniques, from an initial state to a goal state. The implicit set of all possible paths the search might take is called the "search space" (Hunt, pp 231-232; Rich and Knight 1991, pp 29-31). One of the greatest challenges in AI research has been to develop efficient and effective methods of limiting the enormous search spaces associated with real-world problems. Techniques have been designed to limit the search space by using a variety of formal search strategies or by building in shortcuts derived from information about the nature and structure of problems or tasks associated with a particular domain of knowledge. Such limiting strategies and shortcuts are called "heuristics." Heuristic problem solving is one of the most important concepts in AI (Hunt, p 125; Rich and Knight, p 41).

Programming languages for artificial intelligence have constituted an important area of AI research. The two most well known AI programming languages are LISP (**LIS**t Processing) and PROLOG (**PRO**gramming **LOG**ic). These languages can accommodate the specialized requirements of AI for symbol manipulation, deduction, and implementation of various strategies for searching alternative paths from an initial state to goal states. In addition to these and other AI programming languages, specialized programming environments known as knowledge engineering languages are widely used (Tanimoto 1990, pp 494-499).

Hardware for artificial intelligence applications is of two types: conventional computer systems at the mainframe, minicomputer, and microcomputer levels, and specialized computing systems known as AI workstations or LISP machines. Most early AI development was carried out on conventional mainframe computer or minicomputer systems, and these classes of computers are still used heavily today. In addition, a wide assortment of AI programming and knowledge engineering language software is available for use on microcomputers. AI technology became available for PCs in 1985 and has seen much success since then. Although still limited when compared with large mainframe applications, the performance of the PC-based AI and expert system applications are adequate for many purposes. Consequently, many individuals and smaller businesses can now deploy expert systems using relatively inexpensive PCs that cost between $3K and $6K, rather than relying on expensive mainframe hardware or specialized LISP machines.

AI workstations are computing systems designed with specialized features that facilitate AI work. For example, their high-speed processors and large memory capabilities enable them to deal with the heavy demands of AI search and knowledge representation. Their high-resolution, bit-mapped displays allow for development of sophisticated graphics. Their advanced software environments, which include AI programming languages, knowledge engineering languages, and extensive programming support facilities, address the specialized programming needs of AI development (Tanimoto, pp 496-497).

Expert Systems

An expert system is an artificial intelligence computer program that uses knowledge and inference to address problems that would normally require human expertise to solve. The knowledge in an expert system consists both of the commonly accepted facts in the domain and the heuristic knowledge, or rules of thumb, that the best experts use to facilitate decisionmaking. Expert systems typically function as advisors or consultants to assist human users in making decisions or solving problems within a given domain.

Components of an Expert System

An expert system consists of five basic components:

1. A **knowledge base** of facts related to the domain

2. An **inference engine**, or rule interpreter, which controls the search of the knowledge base

3. A **working memory**, or data base, which keeps track of the data input, new facts inferred, and the like, in the solution of the problem at hand

4. A **user interface**, which allows for easy interaction with the system by its intended users and by the system developers. A very important feature of the user interface is an **explanation facility**, which allows a user to query the system's reasoning process and facilitates system debugging (Hunt, pp 106, 147, 133-135, 261, 270).

Differences Between Expert Systems and Conventional Programs

The mere fact that a computer program yields a result comparable to that which an intelligent person would achieve does not make it an expert system. Expert systems differ from conventional programs in several important respects:

1. **Knowledge:** A conventional program manipulates data while an expert system manipulates knowledge. In an expert system, knowledge is represented symbolically, using strings of characters that represent real-world concepts such as: "main entry," "infection," or "H7101 regulator." These symbols are organized into a knowledge base of facts about the domain. An expert system uses this knowledge base to solve problems by searching through and pattern-matching among the symbols.

2. **Heuristic problem solving:** A conventional program solves problems through a repetitive algorithmic process, whereas an expert system uses heuristic and inferential reasoning. Heuristic reasoning is a shortcut or rule-of-thumb learned through experience that an expert applies to eliminate unproductive paths toward the solution of a problem. The algorithmic approach is intended to guarantee a solution; the heuristic approach does not guarantee a solution, but it allows problem solving to take place in domains where the search space is so large that an algorithmic approach would be impossible. It is the use of heuristics, for example, which allows human beings to successfully complete a game of chess despite the fact that there are an estimated 10^{120} possible combinations of moves.

3. **Program structure:** In a conventional program, factual knowledge about the problem being addressed tends to be implicit and intermixed in the program code with procedural instructions for processing data. In an expert system, the knowledge base, and the control structure (the inference engine) are separate. The expert system knowledge base can therefore be updated without affecting the inference engine, making program modification and debugging much easier than in conventional programs. In addition, it is possible for different knowledge bases to function with the same inference engine (although for large-scale problems, the inference engine will probably need at least some tailoring to each knowledge base).

4. **Self-knowledge:** An expert system can keep track of and display to the system user the logical path it used to arrive at a problem solution. A conventional program does not explain how it achieved its results, and the logical process it followed is often difficult to track through its code (Hayes-Roth, Waterman, and Lenat 1983, pp 3-6).

Benefits of Using Expert Systems

Expert systems technology has the potential to offer many benefits:

1. Expert systems make scarce expertise more widely available within the organization, thereby helping nonexperts achieve expert-like results.

2. They free human experts for other activities instead of repeatedly solving the problems an expert system could resolve.

3. They promote a standardized, consistent approach to solving relatively unstructured tasks.

4. They enhance organizational effectiveness and efficiency by making readily available solutions to difficult problems that might otherwise require time-consuming research or consultation with experts to solve.

5. They provide a way to capture and store valuable knowledge that might be lost if an expert left the organization.

6. Because machine knowledge does not deteriorate with time or disuse as human knowledge can, they provide a means for permanent retention of highly complex knowledge.

7. They perform consistently even at high level tasks without fatigue or loss of concentration (Beerel 1987, pp 31-33; Waterman 1986, pp 32-39).

Uses of Expert Systems

Expert systems have been developed to perform a variety of functions in a wide range of domains. Table 1 lists the broad functional categories of expert systems application and gives an example application area for each (Hayes-Roth, Waterman, and Lenat, pp 13-16; Waterman, pp 32-33).

Table 1

Functional Categories of Expert Systems

Category	Application
Interpretation	Image analysis
Prediction	Weather forecasting
Diagnosis	Medical diagnosis
Design	Computer configuration
Planning	Job-shop scheduling
Monitoring	Power plant regulation
Debugging	Software correction
Repair	Automobile maintenance
Instruction	Intelligent tutoring
Control	Battlefield management

Some examples of the broad domain categories in which expert systems have been developed are (Waterman, p 40):

- aerospace
- agriculture
- chemistry
- computers
- education
- electronics
- engineering
- energy management
- finance
- geology
- law
- information management
- mathematics
- manufacturing
- medicine
- meteorology
- military science.

Existing expert systems range from small-scale efforts to very large and carefully documented research projects and production systems. Since many systems are known only within the organizations where they originated, it is impossible to estimate how many expert systems have been developed or are in use today. One source that includes "commercially available, proprietary programs used in house, and projects still in the prototype stage" identifies 475 systems (Walker and Miller 1986, p 13). Some expert systems in the area of boiler heating plants are:

1. An expert system in its developmental stages by Northern Indiana Public Service Co. (NIPSCO) (Kozlik, Bleakley, and Skinner 1988, p 44)

2. FUELCON, a prototype system developed for optimization of fuel reload configurations (Galperin, Kimhi, and Segev 1989, p 52)

3. An expert system for electric power systems fault analysis developed and now in use by Kyushu Electric Power of Japan (Moriguchi, Tanaka, and Ishikawa 1988, p 590)

4. A prototype system developed to aid in the mechanical design of Tubular Exchanger Manufactures Association (TEMA) type shells and tube heat exchangers (Wang and Soler 1989, p 147)

5. ESCARTA, a protype system in testing that helps analyze boiler tube failures, developed by EPRI/University of Texas (*Proceedings: 1987 Conference on Expert-System Applications in Power Plants* 1987, pp 1-29 [for items 5 through 8])

6. TUBEFAIL (Boiler Tube Failure Analysis System), a prototype system in testing developed by Central and Southwest Services

7. EXACT, a system sponsored by EPRI and developed to troubleshoot gas turbine faults, was field tested in 1987 at the Jersey Central Power and Light, Gilbert Power Station.

8. TIP, a system developed by New York State Electric & Gas Corporation to monitor heat rate in thermal plants.

How Expert Systems Function

The Knowledge Base

Knowledge can be considered a collection of related facts, procedures, models, and heuristics that can be used in problem solving or inference systems. Knowledge varies widely in both its content and appearance. It may be specific, general, exact, fuzzy, procedural declarative, etc.

The *knowledge base* is the component of an expert system where facts and rules pertinent to problem solving in the domain are represented. Methods for representing expert knowledge in the knowledge base may be either declarative (representing facts or assertions) or procedural (representing actions) or a combination of the two (Hunt, pp 146-149). There are several commonly used methods to organize and represent knowledge in a knowledge base. Some examples of declarative methods are semantic networks, logical representation schemes, object-attribute-value triplets, and frames. The leading example of the procedurals method is the production rule approach (Hunt, pp 151-152; Tanimoto, p 152).

Semantic nets were originally designed to represent the meanings of English words. In a semantic net, information is represented as a set of nodes connected to each other by labeled arcs, that represent relationships among the nodes. It is useful to think about semantic nets using a graphical notation even though they cannot be represented as such inside a program. Figure 1 shows a fragment of a typical semantic net.

The relationships represented in this net include the following:

"FTX01 is a firetube boiler"
"A firetube boiler is a boiler"
and "Boilers have burners."

Examples of arcs illustrated in the net are "is-a" and "has-part." These express how the nodes that they connect relate and allow for the inference of new facts. For example, from this semantic net one could infer that FTX01 is a boiler and that FTX01 has burners, even though neither of these facts was explicitly stated.

An important property of the semantic net is "property inheritance"; nodes lower in the net can inherit properties from higher nodes so that properties applying to all levels of a hierarchy need not be

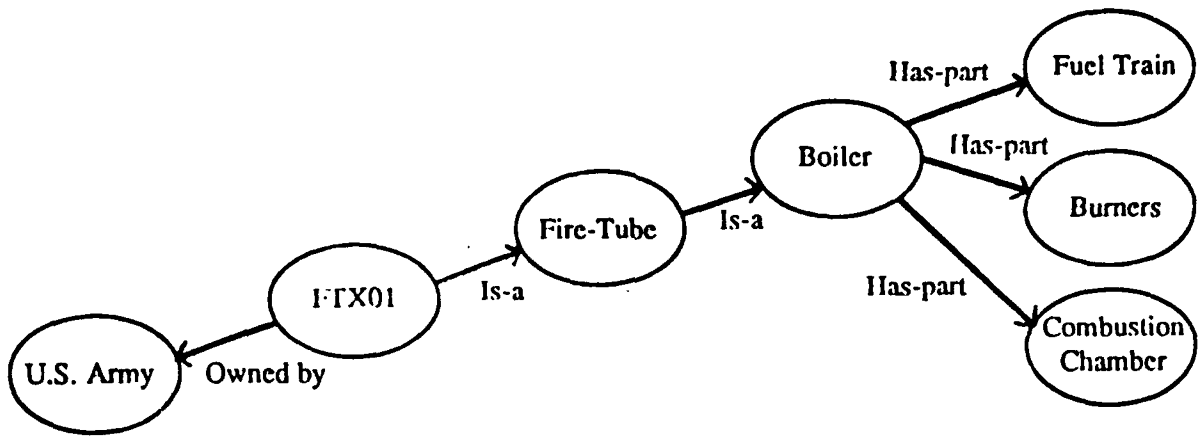

Figure 1. Semantic Net.

repeated at each level. In Figure 1 for example, the parts of a boiler can be stored once at the "Boiler" level rather than having to be repeated at the type of boilers and the individual boiler levels (Rich and Knight, pp 203-204).

The most commonly used logical representation scheme is predicate logic. In predicate logic a proposition consists of objects, persons, concepts, and the like (arguments) about which something is stated (the predicate). For example, the proposition "A component of Boiler is the burner" might be stated in the form of predicate logic as:

has component (boiler, burner)

where "boiler" and "burner" are the arguments and "has component" is the predicate, which in this case expresses a relationship between the arguments. Predicate logic lends itself well to inferences. For example, if we add another proposition "A component of the burner is the flame," stated as:

has component (burner, flame)

it can be inferred from these two propositions that flame is a component of boiler, although this was not explicitly stated (Rich and Knight, pp 131-139).

In the object-attribute-value triplet method of representing factual knowledge, *objects* are entities in the domain, *attributes* are properties associated with the object, and these attributes may possess *values*. For example, in the triplet:

boiler-efficiency-76 percent

"76 percent" is the value of the attribute "efficiency" associated with the object "boiler." An advantage of this method of knowledge representation is that it facilitates data gathering by the system through questions posed to the user in the form "What is the [value] of [attribute x] of [object y]?" (Hunt, p 183)

Frames are very powerful and versatile data structures that are especially good for representing stereotyped knowledge about an object, concept, or event. Like a semantic net, frames can be readily organized into a hierarchial network of nodes and relationships, with a frame constituting each node. A frame is subdivided into a collection of attributes called "slots." Values may then be associated with the attributes. In some cases, default values may be assigned. Slots can also be associated with procedural attachments that are executed when information in the slot changes. Examples of such procedural attachments are the "if-added" procedure, which executes when new information is placed in the slot, and the "if-needed" procedure, which executes when information is needed in the slot but is not available (Hunt, p 113; Tanimoto, pp 134-137).

To consider how a system using frames might work, suppose that a frame-based fuel order system included a frame called "Special Order." Such a frame would include slots for the elements of information needed to process a special order, such as order number, description of the fuel type, price, vendor code, and claim date. In most of these slots, explicit values would be inserted. Slots whose initial values could be predicted, such as claim date, might have such values generated by default. Some slots might have procedural attachments. For example, an "if-added" procedure attached to the vendor code slot could search a vendor data base for the full name and address associated with the code.

The production rule method is the most commonly used technique for expert system knowledge representation. Production rules typically take the form IF-THEN where the IF portion describes a condition, antecedent, or situation, and the THEN portion describes the resulting action, consequence, or response (Hunt, p 203). Production rules are formal representations of heuristics. For example, a personal heuristic could be stated as a production rule as follows:

IF the chance of rain is higher than 50%, THEN take an umbrella.

In a rule-based expert system, facts known about the current situation are compared against the domain knowledge expressed as a set of such rules. When the IF portion of a rule is satisfied, the THEN portion is executed. This may result in a new fact being inferred and added to the working memory for possible matches with the IF portion of other rules, or may cause the action specified by the THEN portion to be taken (Rich and Knight, p 36).

Knowledge Engineering

Expert systems use knowledge derived from human experts to guide the analysis and decisionmaking process. (When combined with a natural language computer program, this system results in a powerful learning tool that performs many valuable functions for its user.) Surpassing mere storage and retrieval functions of conventional computer programs, expert systems provide an "expert-in-a-can" that helps the user in all facets of the relevant analysis. Diagnostic functions, monitoring, analyzing, planning, and explaining are all features of expert systems.

Codification of the chain of rules provided by human experts is a function of the "knowledge engineer." Knowledge engineering is a very conceptual field since human experts tend to have a level of pragmatic expertise developed over time that is not easily recalled in detail. Knowledge engineering requires the expert to step back to a basic stage of learning, recall a concept, and restate it in explicit form. As the knowledge of multiple human experts is incorporated into the "knowledge base," the level of system expertise rises above that of the individual expert.

The programming goals of the knowledge engineer are: first, to program in modular format to allow for ease of modification, and second, to explain in the program why a logic structure was evoked at any given time. For example, when the program uses a rule to explain a certain set of facts that a human expert questions, the program should be able to explain why that rule was evoked instead of another one. This type of reiteration provides constructive feedback; it highlights inconsistencies in procedures and data, and frees the human expert to redefine rules while learning from the program.

The simplest expert strategy is to reference each entity separately. Under this scheme of knowledge representation, all entities are independent of each other and may or may not be connected by rules. Therefore, if an entity is assigned a value dependent on other values, t would have to be connected by a rule. Then these rules themselves can be executed in a different order by "metarules," rules that control other rules.

Another scheme is based on the fact that classes of entities share similarities. A particular entity will have a certain characteristic by virtue of being a member of a class, and would be automatically assigned a value when the class is assigned a value without the use of an exclusive rule to do so. Under the simplistic scheme of representation, different properties of the same physical object would be separate entities, thus giving the programmer the entire set of entities to track without any grouping to make information storage and retrieval easier. The class/member kind of representation is useful for expert systems developed for process plants.

The Inference Engine

The inference engine is the control structure that organizes, controls, and executes the steps followed by the expert system in searching its knowledge base for a solution to the current problem. Two basic search approaches may be employed: blind search and heuristic search.

In the absence of a guiding search strategy, the blind search involves consideration of all possible paths from the problem's initial state to a goal state. This might be acceptable for small problems, but would be inefficient for large-scale problems. To make them more efficient, blind searches are guided by search strategies. These include depth-first search, breadth-first search, and forward and backward chaining (Tanimoto, p 177; Hunt, p 62).

The depth-first search pursues a single path in the search tree until either a goal state, a dead end, or an arbitrarily designated cutoff depth is reached. If a dead end or cutoff point is reached, the system will backtrack to a point where another path can be pursued. Depth-first search is potentially more economical in its use of computer memory than breadth-first search. However, a serious deficiency of this method is that it does not ensure an optimal solution. In a large-scale problem, an arbitrary cutoff depth is necessary to prevent the system from using tremendous amounts of time pursuing unproductive search paths to great depths. But if the cutoff point is too shallow, a solution will never be reached, and if the cutoff point is too deep, the solution path will be non-optimal (Shapiro 1990, p 996). Figure 2 provides an example of a depth-first search.

The breadth-first search examines all nodes in each level of the search tree before moving on to the next level. This method will find the shortest path to a solution, if one exists, but is not practical if the solution is deep in the search tree because successively deeper levels of the search tree are subject to combinatorial explosion and each level must be generated before the next level can be examined (Shapiro, p 995; Hunt, p 64). Figure 3 illustrates an example of a breadth-first search.

Forward chaining is a data-driven search method. The inference engine starts with known facts that it attempts to match with facts in the knowledge base. When such matches occur, new facts are inferred, that can then be matched with other facts. This process continues until no new conclusions can be reached. At this point either a goal state has been reached or, if there were no facts to support a goal state, the search has failed. In either case additional goals can then be sought (Hunt, pp 112-113; Shapiro, p 824).

The backward chaining method starts from a potential goal state and works backward through the search tree seeking facts that support that goal. If the available facts do not support the goal, the search

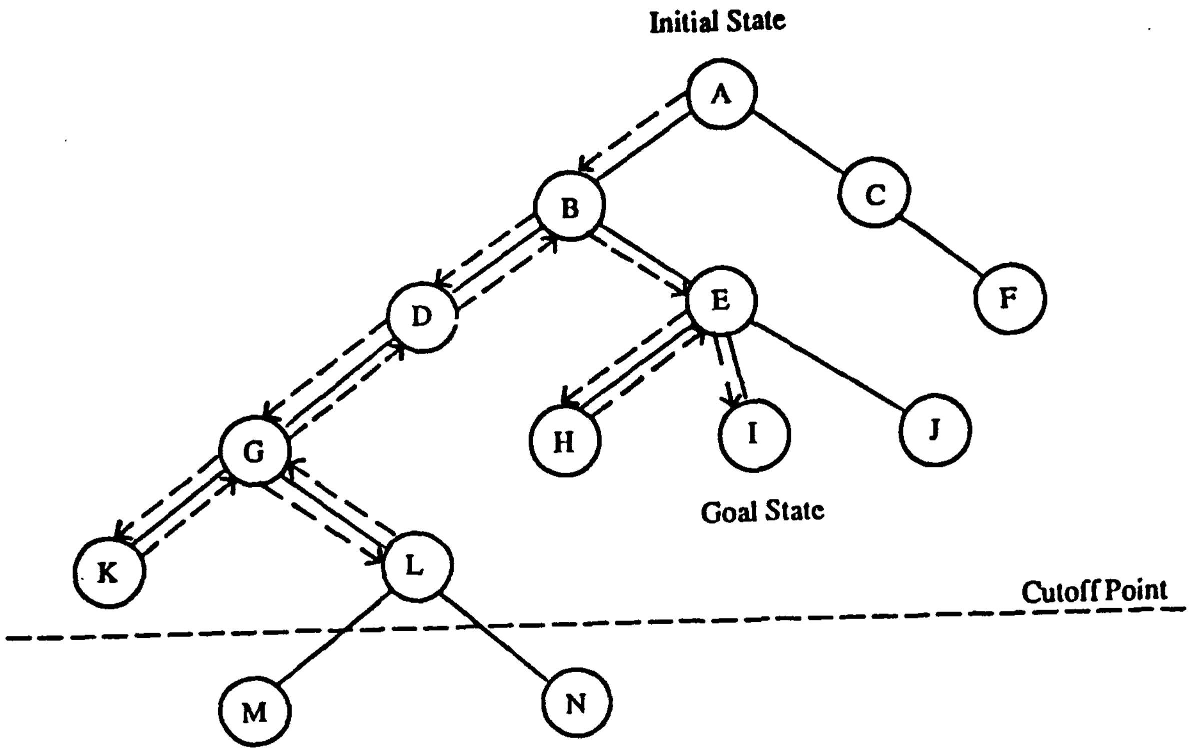

Figure 2. Depth-First Search.

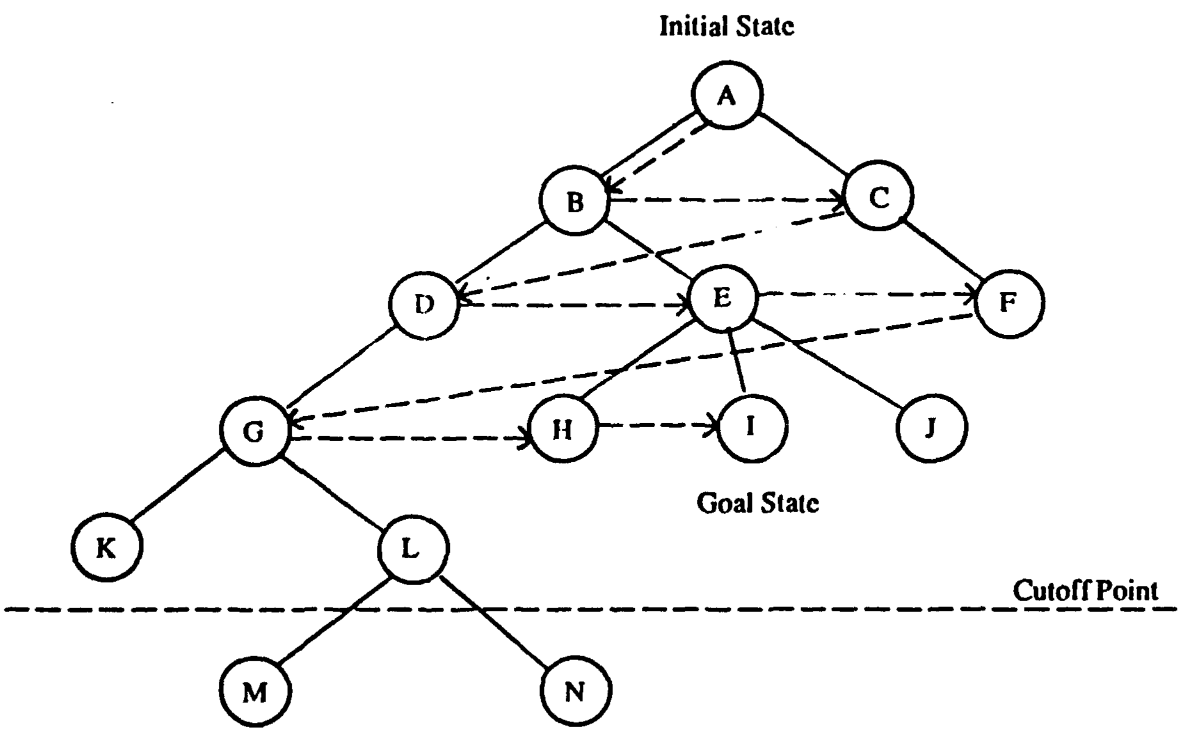

Figure 3. Breadth-First Search.

fails, at which point another potential goal is selected, and the search is tried again. Forward chaining is more appropriate when the number of initial states is greater than the number of goal states. When the number of goal states exceeds the number of possible initial states, backward chaining is more efficient (Hunt, pp 58-59; Shapiro, p 824).

Although the blind search techniques discussed above are sometimes used, the expert systems searching process is generally modified by the use of heuristic search to limit the number of alternative solution paths that must be considered. A heuristic search generally involves a process of evaluating the current node in the search tree and predicting the quality of succeeding nodes by their desirability as subsequent nodes in the path to the goal. Two possible heuristic search techniques are *difference reduction* and *hill climbing* (Shapiro, pp 578, 996-997).

Difference reduction (also referred to as "means-ends analysis") uses a combination of forward and backward chaining to shorten the distance between the current node and a goal state by setting subgoals. For example, suppose that a certain heuristic would attain the desired goal state. Suppose further that it is not possible to apply the heuristic from the current node, but that there is a nearby node from which it could be applied. Employing the concept of difference reduction, the ultimate goal would be temporarily set aside in favor of the subgoal of reaching the nearby node enabling use of the desired heuristic. By applying this process repeatedly, smaller and smaller subproblems, each with search spaces much smaller than the original problem, can be solved. When all the subproblems are solved, the main problem is also solved (Hunt, p 89; Rich and Knight, pp 94-97).

In a hill climbing approach, when the evaluation of a node reveals that it is not the goal state, the difference between that node and the goal state is calculated. A comparison of the sequence of calculated differences indicates whether the search is moving closer to or farther away from the goal state. If movement is away from the goal state, the search backtracks until a new search path can be taken (Rich and Knight, p 65-67).

Working Memory

The working memory is the dynamic memory where the current status of an expert system consultation is stored. It contains the initial information provided to the system to enable the search process to start. As rules are examined and executed, the working memory is updated to contain new facts inferred, values established and the like, which are then available for further use in the decisionmaking process. The working memory also keeps track of which rules the system has examined and executed and in what sequence so that it can give the reasoning process employed to the user if required.

User Interface

The user interface software permits interaction between the user and the expert system. The interface may contain pre-formulated questions and menus to facilitate the collection of data needed by the system to conduct the search of its knowledge base. The interface also provides a way to display the solution the system reaches.

For the expert system to be most useful, the user interface should include an explanation facility. This permits the user to ask the system to display the reasoning process used to achieve a particular result. The explanation facility not only enhances the system's credibility but also greatly helps debugging in case of unexpected or erroneous results.

Expert System Development Processes

Suitable Problem Definition

Before starting on an expert system development project, a problem suitable for application of this technology must be identified. Expert systems are not well suited for many types of problems and should be applied only when they are possible, justified, and appropriate (Waterman, p 127).

For an expert system to be possible, the task to be carried out must have certain characteristics:

1. The task must require only cognitive (i.e., not physical) skills and must not require "common sense" reasoning

2. There must exist human expertise related to the problem. There should be experts in the domain who can articulate their methods and who are in general agreement as to what constitutes solutions to the problems the expert system would be intended to solve

3. The task must fall within a reasonable range of difficulty. If it is so difficult that it cannot be taught to a novice by an expert or that it takes days or weeks for an expert to carry out, the size and cost of an expert system to tackle the task would be prohibitive. If a large problem, on the other hand, can be segmented, its component parts might be suitable for expert systems.

Expert System Building Tools

Many programming environments, or expert system building tools, are now available to assist the knowledge engineer in constructing an expert system. These tools fall into two main classes: *programming languages* and *knowledge engineering languages* (or shells). These programming environments are supported by a variety of facilities.

<u>Programming Languages</u>. Two types of programming languages are used in building expert systems:

1. Problem-oriented languages, such as C and PASCAL, which were designed for conventional software development

2. Symbol-manipulation languages, such as LISP and PROLOG, which were designed to represent and perform operations upon concepts expressed as symbols, for example as list structures or logical representations of concepts.

Expert systems have been developed using virtually all the major programming languages. For example, C, with its speed and flexibility, has become increasingly popular as an expert system building tool (Frenzel 1987, pp 113-115). However, the symbolic manipulation languages possess special characteristics that make them especially suitable for use as expert system development tools. LISP, for example, features flexible symbol manipulation, automatic memory management, and uniform treatment of program code and data.

In the United States, LISP is the most widely used AI programming language. Developed in the 1950s by John McCarthy, one of the pioneers of AI, LISP has retained its popularity due to its versatility and powerful capabilities. Many versions of LISP are available for all classes of hardware, and, as noted above, there exists a special class of computer known as the LISP machine that has specialized features to support LISP programming. In Europe, PROLOG is the most popular AI language. PROLOG is based on predicate logic and contains its own built-in inference engine. As with LISP, many versions of PROLOG are available. Besides these two, a number of other AI programming languages have been developed.

Knowledge Engineering Languages. Knowledge engineering languages, sometimes referred to as "shells," are specialized programming environments tailored for expert system development. The basic components of an expert system shell include a knowledge representation facility, an inference engine, and a variety of support capabilities. Some shells, such as those that were developed by removing the knowledge base from an existing expert system, are relatively specialized, emphasizing one particular knowledge representation scheme and one principal inferencing technique. Large hybrid tools are more generalized and versatile shells that support multiple knowledge representation schemes and inferencing techniques, and feature very sophisticated support facilities.

Shells can be very useful for rapidly prototyping expert systems. These shells can facilitate knowledge-base construction by providing good knowledge-representation facilities. However, the work of actually formulating the knowledge is not the job of a shell; this generally requires interactive dialogues between a knowledge-base building tool and one or more humans.

Commercially available knowledge engineering languages may have their own hardware requirements, knowledge representation methods, and inferencing techniques employed. Furthermore, existing tools are subject to modification, and new tools are being brought onto the market. Selection of a tool for a development project must therefore be based on a careful analysis of most current information (Rolston 1988, pp 169-178).

Selection of Software and Hardware. For this project, the prototype development system was envisioned as being PC-based, using a commercially available expert system shell. The design of the software structure (including the information input, knowledge engine, alternative selection process, rule modification process, and output format) was to reflect the expertise of a select group of individuals known for their abilities in diagnosing equipment problems at heat plants. Monitoring and diagnosing such problems can be an involved, complex task. Initially a prototype system might perform only modest fault diagnosis. More vigorous diagnostic capabilities would be added in the future.

For this reason, an IBM PC/AT or equivalent was considered adequate. Other equally capable, more expensive, and higher performance workstations do exist, but the superfluous increase in speed could not justify the higher cost for this particular application. Intel's 80386 and Motorola's 68020 microprocessors (CPUs) are now commonly available for the PC environment and will soon be available for less than $5K. The high performance workstations mentioned, include those manufactured by Sun, Apollo, Dec, NEC, and Hewlett-Packard.

Before implementating an expert system, the user must choose between creating the expert system development tools in-house, and buying commercial software. In the past, the need for very powerful, extensive, or specialized expert systems usually demanded user-created development tools. Today, this situation persists at the extreme end of the spectrum, but is rapidly fading out. Commercially available PC software and hardware has become more powerful and versatile. This new wave of PC software and hardware can create increasingly specialized, extensive expert systems, offering the extra advantage of compatibility with standard business software.

This raises the question of economic feasibility. An absolute need for user-created expert systems development tools will make the system costly. Programming in LISP is expensive, as knowledgeable LISP programmers are in short supply. Many expert systems developers have tried to circumvent this shortage by programming in C language, but this creates problems, for AI, since C is a less efficient operating environment than LISP. This is due to C's limited capabilities for symbolic manipulation. These functions, then, must be programmed on top of C, and thus increase complexity and memory requirements (Barber 1987, pp 28-31). Another reason for the high cost of user-developed expert systems tools is the extravagant price of LISP-dedicated machines and similar systems. For these reasons, commercially available expert system software packages were investigated for their potential in developing the prototype in this project.

In evaluating the available expert system shells, a number of features that would enhance task efficiency and provide flexibility for future modifications were considered:

- an ability to create real-time graphics, producing a user friendly interface
- an ability to interact with combustion equipment, sensors, and instrumentation
- an ability to access external databases
- ease of interface with external software
- speed of execution in a run-time environment
- a math library and an ability to evaluate math equations
- an explanation of how the knowledge representation paradigm relates to the monitoring and diagnosing task.

3 BOILER TECHNOLOGY

To develop a prototype, it was necessary to understand the fundamental principles of packaged boiler operation as well as the elements of combustion. Boiler operation fundamentals and an understanding of efficiency issues form the basis of the expert system.

Fundamentals of Combustion

"Combustion" is an exothermic (heat-releasing) chemical reaction that occurs during the rapid oxidation of fuel. Fuel, for this application, refers to oil or gas substances that consist primarily of carbon and hydrogen. Small amounts of other chemical substances such as sulfur may also be present and may react during the combustion process. The chemical reactions involved are:

C (carbon) + O_2 (oxygen) → CO_2 (carbon dioxide) + heat

2 H_2 (hydrogen) + O_2 → H_2O (as water vapor) + heat

S (sulfur) + O_2 → SO_2 (sulfur dioxide) + heat.

Oxygen for the combustion process is derived from air, which is approximately 21 percent oxygen and 79 percent nitrogen by volume. Nitrogen, being relatively unreactive, plays only a small role in the chemical reactions that occur during oxidation. However, nitrogen does play a significant role in boiler efficiency. During the combustion process, nitrogen is heated to high temperatures and releases only part of this heat to the water/steam. The remaining heat escapes up the stack along with the heat carried by the other combustion products. The relatively large amount of nitrogen entering the combustion zone lowers the temperature of the flame somewhat, thereby reducing heat transfer to the boiler water.

Perfect or stoichiometric combustion occurs when the exact proportion of oxygen and fuel react for complete conversion to carbon dioxide and water vapor. If too little oxygen is available for perfect combustion, incomplete or substoichiometric combustion occurs. Besides carbon dioxide (CO_2) and water vapor, products of combustion during substoichiometric conditions include carbon monoxide (CO), hydrogen (H_2), unburned hydrocarbon compounds (uC_xH_x), carbon and hydrogen sulfide (H_2S if sulfur is present). These pollutants can escape through the flue to contribute to air pollution.

When more than enough oxygen is present during combustion, the excess is not used. Like nitrogen, it is a source of inefficiency when it exits the boiler. Too much oxygen is commonly referred to as "excess air" or "excess oxygen." The term excess oxygen or air should not be confused with the terms primary and secondary air. Primary air is defined as the air mixed with the fuel at or in the burner. Secondary air or tramp air diffuses into the flame from the surrounding atmosphere.

The fuel and air introduced into the boiler are ignited by an external heat source that heats part of the mixture to the ignition temperature. Upon combustion, heat is released to the surrounding heat exchange surfaces and, in turn, to the steam or hot water. Each fuel type has a heating value unique to the fuel's constituents. The heating value of the fuel is typically expressed in terms of gross, higher heating value (HHV), or net, lower heating value (LHV). The gross heating value is the total heat released during the combustion reaction. The term net heating value refers to heat released during combustion minus the heat of vaporization (the energy required to vaporize the water formed during combustion). This energy can be recovered only when the combustion products are cooled to below the temperature of condensation, but this cooling is seldom allowed as the condensibles are typically corrosive and damaging to the stack.

Although the total heat released is a critical factor, equally important is the intensity of the flame temperature generated by combustion. Typical fuels have flame temperatures in the range of 3200 to 3800 °F. The maximum flame temperature theoretically occurs at stoichiometric conditions (where there is no excess oxygen). Flame temperatures are affected by the extent of heat radiation to the surrounding heat exchange surfaces, dilution with combustion products backmixing into the flame, incoming cooler fuel and air, the degree of excess air, and the chemical reactions occurring within the flame. Heat transfer is greatest at the highest flame temperatures.

Boiler Equipment

A boiler is a device that uses the heat of combustion to produce steam or hot water. The steam can be either saturated or superheated. Saturated steam is defined as that which exists at its saturation temperature or, the boiling point of water at the system operating pressure. Due to the liquid-to-gas phase change that occurs during boiling and the increase in volume created by the steam generation, unless steam is vented, the system operating pressure will increase as heat is added. Part of the boiler's function is to regulate the steam pressure near a desired value while maintaining an adequate level of water and steam space above the water inside the boiler.

Boilers are classified by design. Watertube design boilers circulate water and steam through tubes that are in contact with the combustion products. Firetube boilers generate steam by circulating combustion products through tubes immersed in water. Regardless of design, boilers generally contain the following components:

1. Fuel handling equipment
2. Air handling equipment
3. Burner
4. Combustion chamber
5. Heat exchange element
6. Controls
7. Stack.

The <u>fuel handling system</u> typically consists of components that condition the fuel in terms of volume, pressure, and temperature prior to introduction into the combustion system. Whereas natural gas is a relatively easy fuel to burn, special considerations must be taken when burning fuel oils. The most important parameter is fuel viscosity. Since viscosity varies with the type of fuel oil and temperature, heaters are used to maintain the fuel oil within a specified viscosity range that is a function of the burner design. Should the preheat temperature be too high, viscosity will be lower, and in turn, affect atomization of the fuel. This condition will result in poor flame stability and noisy operation. Too high a viscosity from too low a preheat temperature produces incomplete combustion and allows soot and oil to form within the boiler. In addition to viscosity, other constituents of the fuel oil can cause problems. Sulfur, trace metals, and ash, for example, can cause slag deposits, corrosion, and air pollution.

The <u>air handling equipment</u> includes both the devices that introduce combustion air into the burner and equipment that removes or regulates the flow of combustion gases out of the boiler. "Draft" is a common term used to indicate the movement of air and static pressure within the boiler's combustion chamber.

The four types of draft are: natural, forced, induced, and balanced. Natural draft relies on the buoyancy of the hot gases in the flue to draw combustion air into the fire box. Air registers and stack dampers can be used to balance the draft to the desired static pressure. When natural draft is insufficient to draw combustion air into the fire box or remove combustion products from the boiler (which is typically the case), draft fans are employed. These fans can be used to blow air into the boiler (forced draft) and/or out of the boiler (induced draft). Air control is a critical component of efficient boiler operation. Excessive draft can increase stack temperature, whereas inadequate draft can lead to incomplete combustion and, in the case of oil, smoke generation. Proper draft control produces a slightly negative pressure (around 0.1 in. wg [water gauge]*) in the combustion chamber. However, this condition can be affected by the height of the stack and the magnitude and velocity of ambient wind conditions.

Air and fuel entering the boiler are mixed in the <u>burner</u>, where ignition and combustion occur. Burner characteristics include turndown ratio, flame shape, and stability. The turndown ratio is the ratio of the maximum to minimum fuel and air input rate that produces satisfactory operation. The maximum firing rate is a function of the burner size and the velocity of the air and fuel stream. Too high a mixture velocity will produce a condition called blow-off, in which the mixture velocity exceeds the flame velocity. The minimum input rate is limited by proper mixing of the fuel and air, and a condition called flashback, which occurs when the flame velocity exceeds the mixture velocity. The term "flame stability" refers to the consistency of the flame. Stability is affected when the unit is cold or the flame is quenched by impingement on cooler heat exchange surfaces.

Flame shape is strongly influenced by burner design. However, for a given design, flame shape changes with mixture pressure and the amount of primary air. Increasing pressure typically broadens the flame shape while increasing primary air shortens it. Flame shape also reflects the degree of fuel-to-air mixing. A short, bushy flame is produced by high gas turbulence and velocity. Long, slender flames are the result of poor mixing and lower fuel/air mixture velocities. When the boiler is operating on oil, a longer flame is produced due to the high atomization pressures that tend to throw the flame away from the burner.

Atomization reduces fuel oil liquid to a very fine spray to ensure proper ignition and rapid combustion. Atomization is performed either mechanically or through the use of compressed gases such as air or steam. Rapid expansion of the steam or air mixed with the fuel produces the required atomization. When steam is used for atomization, it should be dry steam to prevent pulsations caused by moisture accumulation, which can lead to loss of ignition.

The <u>combustion space or firebox</u> of the boiler provides a contained area where complete combustion should occur. Incomplete combustion can result if the combustion chamber does not maintain the high temperatures and residence times required for the combustion reactions. Incomplete combustion can also occur when the flame impinges on the combustion chamber walls or when the combustion chamber is not conducive to complete mixing of the fuel and air. When the flame impinges on the cooler chamber walls or burner nozzle, the fuel is quenched and does not burn completely. Flame and spray patterns can be adjusted somewhat to prevent flame impingement. In the case of oil, the spray or atomization pattern is also affected by the viscosity of the oil. Changes in fuel oil viscosity can result from fuel changes or fluctuations in the fuel oil preheat temperature.

<u>Heat exchange</u> occurs when heat generated in the combustion chamber is transferred to the steam or hot water in the convective section. In a firetube boiler, this section consists of fire tubes running through a water drum. Baffles are usually used to redirect the flue gases through the drum for multiple

* 1 in. of water (60 °C) = $2.488^4 \times 10^{-2}$ pascal (Pa).

passes. In a watertube boiler, the combustion gases pass over various types of tubes that contain steam and hot water. These tubes can be for steam generation, superheated steam generation, or economizers. Most small boilers consist of only the main boiler tubes and perhaps an economizer.

Control and monitoring systems contain elements such as control and safety valves, measuring devices, and monitors. Typical control systems regulate the air-to-fuel ratio and rate of fire to meet steam demand while operating efficiently and safely. Parameters that are constantly monitored include draft and steam pressures, steam and flue temperatures, fuel and air flow, and, in more sophisticated systems, flue oxygen and unburned hydrocarbon levels.

Theory of Automatic Operation

The prototype system was initially developed for troubleshooting automatically operated boilers. Apart from minor differences between manufacturers and models, most automatically operated boilers incorporate the following processes.

The forced draft fan and the induced draft fan, if present, start and run for a while prior to fuel introduction into the combustion chamber and ignition. In addition, when the main flame is shut off, either on purpose or by accident, the fans remain on for a period before they are switched off. These periods of blower operation are called pre-purge and post-purge, and are meant to remove any unburned fuel that may be present in the combustion chamber.

Automation is achieved by using a sequencer, or master controller, which ensures that certain functions are executed only if certain other functions have been executed. In this manner, operations that require safety precautions can begin only after the required safety conditions are met. The mechanisms that ensure that conditions are met, are known as "limit" or "interlock" switches. These switches convert temperature, pressure, movement, position, and operational status into electrical signals that are then used to control boiler operation.

Master Controller

The relays responsible for automatic sequencing of different functions are collectively called by a variety of names. The controller may be called the flame sequencing control, the master controller, the flame safeguard system, or the flame safety system. In this report, this equipment is called the master controller. Besides relays and switches, there is another very important component in any master controller, a timer. From the moment the timer is energized, it keeps track of the elapsed time and controls the operation of certain devices through the opening and closing of relay contacts. These devices may include fans, pumps, dampers or valves.

Switches

Physically actuated switches or process switches can be classified as limit or interlock switches. Limit switches are placed before everything else; i.e., the timer cannot be started if any one of these switches is open. The blower motor, which is started by the master controller, cannot start unless all these switches are closed. The switches typically in this group are low water and high water level switches, high and low fuel pressure switches, the oil pump switch (used while firing oil), and the main steam pressure switch. A very important switch in this category is the proof-of-closure switch. This switch closes when the main fuel on-off valves are closed. It is a way to ensure that no fuel leaks into the combustion chamber, thereby reducing the chances of an accident.

Interlock switches are closed when some of the drivers required for the overall process have started. In other words, these switches ensure that the initially powered drivers have started and are delivering at their expected levels. An example of this set is the combustion air proving switch. This switch is placed downstream of the blower and is closed by the draft created by the operation of the fan. This switch ensures that the blower is indeed running normally and only then allows drivers further down the line to be energized. These switches are often referred to as the running interlocks. If, while firing light oil, an oil pump motor is switched on by the master controller, then the fuel pressure switches downstream of the pump should be placed in the interlock circuit. In short, these switches verify that initial steps of the start-up process are completed before proceeding with subsequent steps.

Flame Detector

At the heart of automatic operation is the flame detector. If a flame is present, this device holds in a relay that keeps the fuel solenoid valves open. The signal from the flame detector is actually used to hold in a relay that ensures a number of different conditions, one of which is power to the fuel solenoid valves. Another one could be to keep the timer stationary by cutting off power to it. The moment flame is not detected, this relay drops. This closes the fuel valves and starts the timer to complete the shutdown portion of the cycle. The detector works on the principles of photo-electricity, and the electrical signal produced by it can be tested at a specified point. While the flame detecting sensor is placed in the boiler at a suitable point, the amplifier circuit for the primary signal and the flame relay are placed in the master controller. Most commercial master controllers have the relay and amplifier circuitry built into them. Care should be taken to ensure that the flame sensor matches the flame detection part of the master controller.

Boiler Lockout

Note that all the limit switches and the interlock switches must retain their status for the boiler to be in operation. The boiler would stop if any one of these were to change status. Different switches, however, stop the boiler in different ways.

Some switches cause a lockout if their status changes. Usually, the limit switches do not cause lockouts except for the proof of valve closure switch. The interlock switches, on the other hand, cause lockouts that must be manually reset before the boiler can start again. Manual resetting is necessary because failure under certain conditions requires inspection before the boiler can be considered safe to restart.

For instance, gas supply pressure varies continuously. When the gas supply pressure is very low, the boiler is not expected to run smoothly. So a low limit is established on the supply pressure and is used with a gas low pressure cutoff switch. When the supply pressure goes below the switch set point, this switch stops the boiler. But because this condition is expected, the system is configured in a safe manner that does not cause a lockout.

On the other hand, once the blower is started, it is always expected to blow air into the combustion chamber. Therefore, if the proof of combustion air switch were to open and stop the boiler, the failure could be considered to be due to unforeseen reasons. Thus the master controller is configured in a manner such that the opening of the combustion air proving switch causes a lockout.

In most cases of lockout, after the failure, certain parameters will be outside their desired value ranges. Automatically restarting the boiler, without manually checking and correcting excessively deviated parameters, can result in unsafe operation. There are some parameters for which normal value ranges are *always* to be expected. An alarm should result for these parameters if value deviations occur. But because the deviation of many parameters from their normal ranges is expected to a limited degree, changes in the status of the switches that track these parameters should not create an alarm condition.

Boiler Output

The boiler's master controller functions only as a supervisor during start-up and shutdown; once the main flame is established, a second controller, which is responsible for control while the boiler is in operation, takes over. This second controller is required essentially because it is not practical to operate a boiler in an on/off manner. If a boiler were designed to operate in an on/off manner only, it would be limited to only two discrete outputs—zero and the maximum boiler capacity. Requirements for steam, however, vary continuously. This is why a variable firing rate boiler is designed to deliver different loads.

Some boilers are designed to deliver three discrete loads: high fire, low fire, and no fire. Others have the capability of delivering at these levels while continuously varying the load between high fire and low fire. The ratio of the firing rate at low fire to the firing rate at high fire is called the "turndown ratio." The turndown ratio is a function of the burner while the act of turning down is achieved by the modulating control. If the firing rate were to be reduced below the maximum turndown ratio, flame instability, inefficient operation, and potentially unsafe conditions could occur.

The variation of firing rate between high fire and low fire is termed here as "modulating control." Modulating control is achieved by varying the fuel flow and air flow rate continuously between two limits. In most units, this is done with a modulating motor. While air flow is varied by changing the position of an air damper, fuel flow is varied by a cam and valve assembly. Since this project's prototype system will only troubleshoot start-up failures and accidental shutdowns the modulating mode of operation will not be discussed here in detail.

Boiler Efficiency

Significant savings in fuel cost would result if the efficiency of a boiler could be constantly monitored and adjustments made to ensure that the boiler was not allowed to operate inefficiently. To do this one must first define efficiency and then look for methods by which efficiency could be estimated under different circumstances. Once a definite measure is established, efficiency must be computed and compared with the best that could be achieved given a particular boiler.

The efficiency of a boiler can be defined as the ratio of the heat output in the steam to the heat input of the fuel. Measurements typically made to monitor the combustion and boiler efficiency include fuel flow, flue gas analysis, stack temperature, smoke, and draft, as well as steam temperature and pressure. The difference between heat input and steam output is defined as boiler losses. Heat exiting the stack is the most significant loss, with losses from boiler walls and steam drum blowdown playing a minor role. Stack losses typically range from 10 percent in large, well designed boilers with economizers and air preheaters to 30 percent in poorly designed, maintained, or operated boilers. These losses are also a function of the fuel burned. The more water vapor the fuel generates upon combustion (a function of the hydrogen content of the fuel), the greater the latent heat exiting the stack. Minimum losses without recovering the latent heat of condensation are 8 percent for oil and 13 percent for natural gas.

Stack losses can be minimized by reducing the amount of excess combustion air. A certain degree of excess air is required, however, to ensure complete combustion, control steam temperature, compensate for imperfect mixing at reduced boiler loads, or maintain a balanced draft in multiple burner boilers. Other sources of excess (tramp) air include leaks in the firebox, leaks through unused burner doors, and measurement errors caused by leaks in the stack piping prior to the point of measurement. Measurements such as those involved in stack gas analysis indicate the degree to which combustion has been completed. The presence of constituents such as CO and CO_2 show how complete combustion has been. Oxygen in the flue is a function of the amount of excess combustion air. Perfect combustion is obtained when CO and oxygen are zero and CO_2 is maximized. However, since combustion is never perfect, there are no single values for these constituents that can be used to determine a boiler's optimal efficiency. The proper amount of these components is boiler-specific and varies with boiler load. Figures 4 and 5 present "typical" carbon monoxide and oxygen curves as a function of boiler load, which were used in developing the expert system for this project.

In addition to excess air in the flue gas, high stack gas temperatures also reduce boiler efficiency. The net stack temperature is the boiler outlet temperature minus the inlet combustion air temperature and should be kept as low as possible without entering the acid dew point temperature range. Excessive stack temperatures may indicate design or operation problems. Design problems include poor design of the heat exchange surfaces or an undersized combustion chamber. Operating problems that can lead to high net stack temperatures include poor draft regulation, overfiring of the boiler, excessive draft, or dirty heat exchange surfaces (from soot buildup on the fire side and/or scale buildup on the water side). Also, note that the net stack temperature on boilers without economizers or air preheaters is a function of the generated steam pressure and temperature. In this case, for saturated steam, the stack gas temperature should be within 25 to 150 °F above the saturated steam temperature (Figure 6).

Another indicator of efficiency for oil-fired units is the amount of smoke produced during combustion. Maximum production of CO_2 should be limited to a point where excessive smoke is not produced. The acceptable amount of smoke is sometimes referred to as the "haze" factor. Excessive smoke indicates air leaks, defective or incorrect burner nozzles, improper oil pump operation, incorrect fuel viscosity, low draft, and improper air-to-fuel ratios.

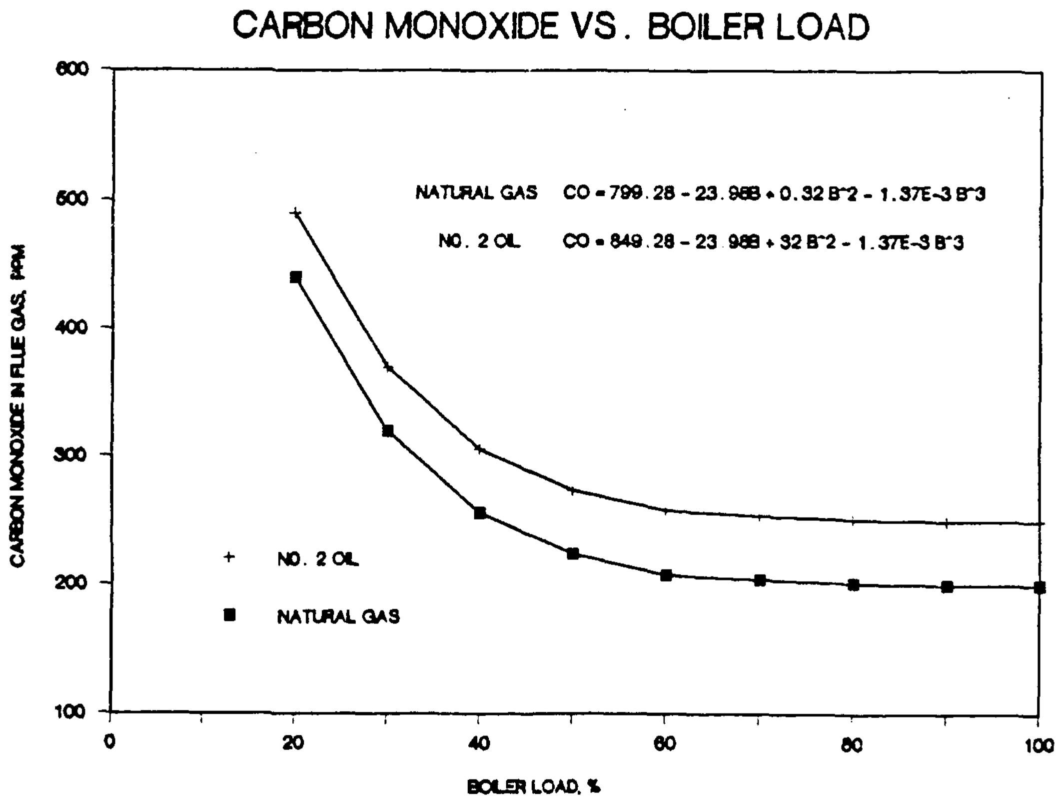

Figure 4. Typical Carbon Monoxide Curve.

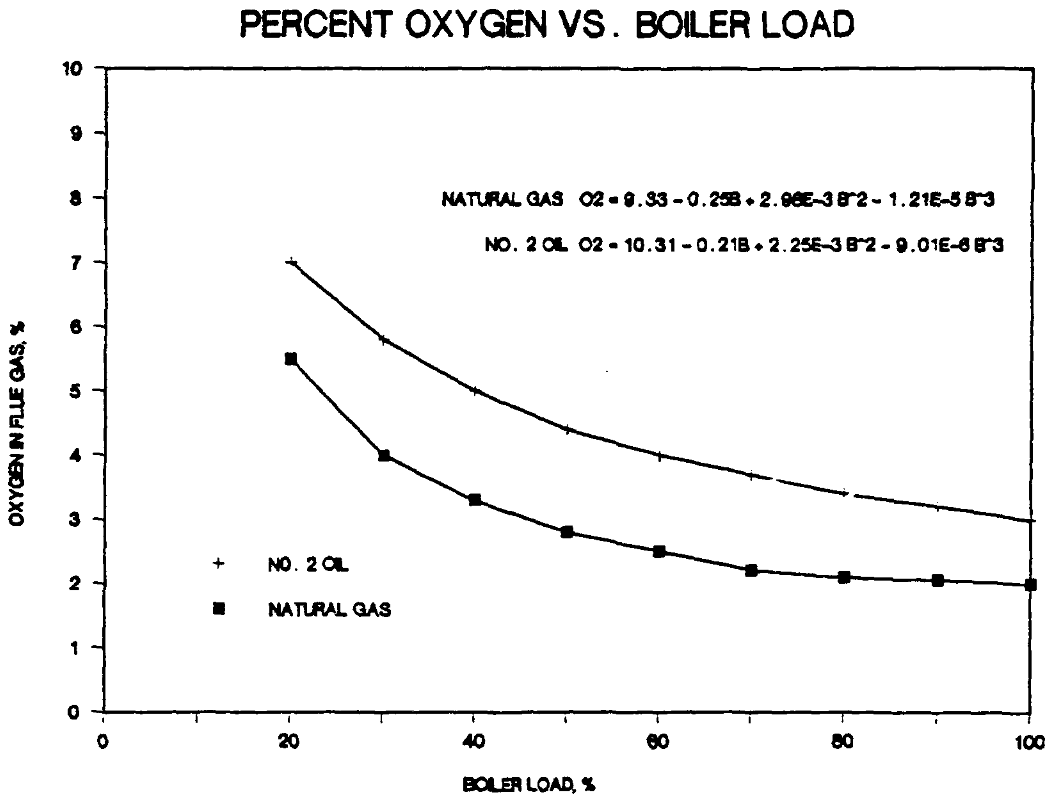

Figure 5. Typical Oxygen Curve.

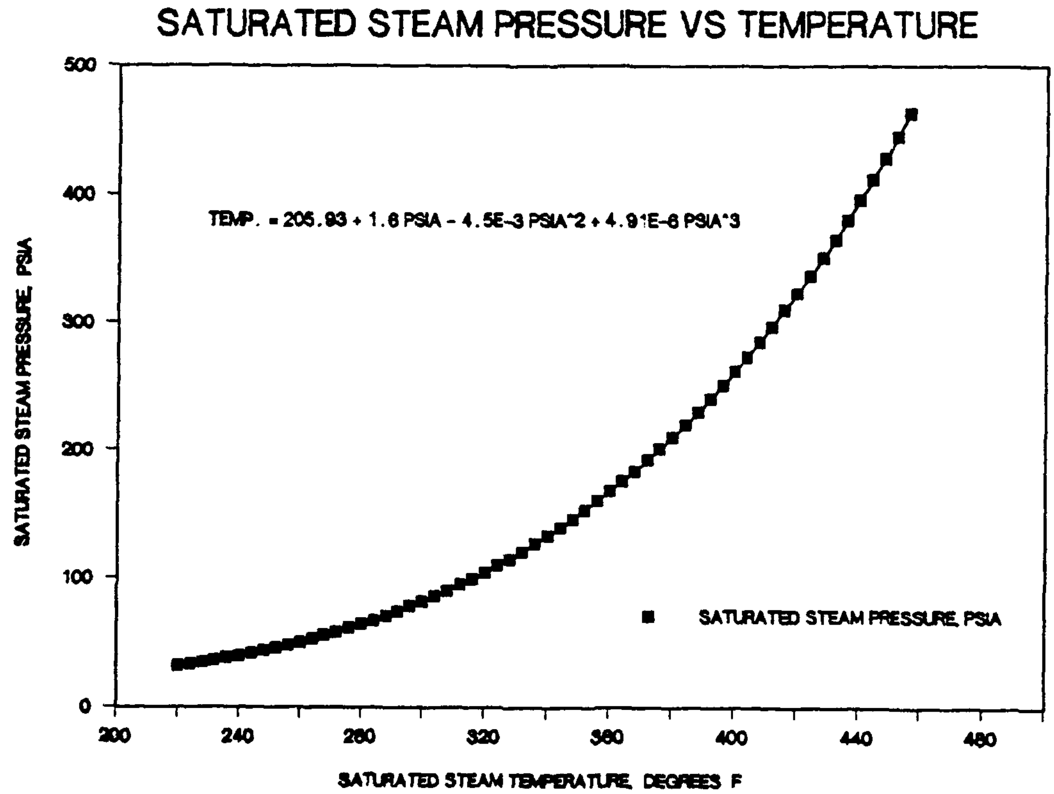

Figure 6. Saturated Steam.

4 PROTOTYPE DEVELOPMENT

Traditional AI languages (LISP, PROLOG) were not considered for prototype application due to the long development time involved in their use. Existing expert system tools are adequate for monitoring and diagnosing combustion technology machinery without the need for extensive custom coding. Indeed, if custom enhancement is required, many of the following shells allow for access to LISP, if not "standard" languages such as C, PASCAL, FORTRAN, and even assembler.

Field Evaluation

More than 100 PC AI tools are currently available on the market. Appendix A lists currently available expert system shells and their features. After evaluating both the requirements of the programming task in this project and features of most of these tools, nine were selected as a field of candidates. Table 2 lists the selected programs and the features evaluated for selection.

The **Aion Development System** (ADS) by Aion of Palo Alto, CA., has graphics capabilities that allow it to draw simple displays. Also, ADS can call and be called from external software programs, allowing it to be embedded in a larger control system. Its math capabilities include arithmetic, logarithmic, and trigonometric functions, and the system or end user can associate a certainty with a result. ADS supports reading and writing from dBASE III, Rbase 5000, and LOTUS 1-2-3. It does not, however, support combustion technology sensors and instrumentation.

First Class Fusion (Programs in Motion, Wayland, MA) is written in PASCAL, with speed-critical functions written in assembly language for better system performance. Four different algorithms allow for some flexibility in controlling the flow of execution. The system is developed by supplying First Class Fusion with examples it learns from, which makes development easier. It is relatively inexpensive at $1300 (the runtime software and license are supplied at no charge), but explanations of how the system achieves its conclusion are limited to a summary rather than a detailed account. More importantly, however, is the fact that First Class Fusion does not easily interface with machine sensors and instrumentation.

A very powerful new PC-based expert system is **GOLDWORKS** by Gold Hill Computers. Programmed in Common LISP, GOLDWORKS was designed to create very extensive expert systems and can interface with LOTUS 1-2-3, dBase, C, and networks. Thus, its manufacturer contends that "it will enhance and extend the scope of current hardware and software resources." GOLDWORKS uses object programming, which is a technique for describing problem domains as collections of objects, as well as rule-based and frame-based reasoning, all in one system. Priced at $7500, GOLDWORKS will probably establish the standard for compatibility with general business equipment and perhaps will increase acceptance of expert systems in the business community. It requires 5 Mb of extended random access memory (RAM) and does not extensively support machine sensor input.

Guru (Micro Data Base Systems, Inc., Lafayette, IN) combines features central to the development of expert systems with useful and familiar tools such as databases, spreadsheets, graphics, text processing, and communications. Although GURU is moderately expensive at nearly $6500, its versatility is viewed as being important in the development of expert systems for the general business community (Myers 1986, pp 28-32). The firm probably has shipped more than 4000 units of Guru, making it a very widespread AI tool (Schwartz 1987, pp 73-80). It does not, however, offer extensive support for input from machine sensors and display of those data.

Table 2

Summary of PC AI Tools Evaluated

Product/Company	Graphics	Senior Inputs	Access Externals	Access Data Base	Math Capabilities	Program Language	Knowledge Representation	Explanation Ability	Certainty	Modularity	Flow Control	Trace	Graphic Representation of Knowledge Base
Aion Dev. Sys.	Yes	No	Yes	Yes	Yes	n/a	rules, objects	Yes	Yes	Yes	Yes	Yes	No
First Class Fusion Programs in Motion	Yes	No	Yes	Yes	Yes	Pascal assembler	rules, examples	summary	Yes	n/a	four methods	Yes	Yes
Goldworks Gold Hill Computers	Yes	No	C files	Yes	n/a	LISP	rules, frames	n/a	n/a	multiple agencies	agendas	Yes	Yes
Guru Micro Data Based Systems	Yes	No	Yes	Yes	Yes	n/a	rules	Yes	Yes	rule sets	five methods	n/a	Yes
Insight 2 Level Five Research	No	No	Yes	No	Yes	Turbo Pascal	rules	No	No	Yes	metar-ules	n/a	Yes
KDS3 KDS Corporation	Yes	No	Yes	No	Yes	8086 Assembler	examples	n/a	Yes	Yes	Yes	No	No
KES Software A&E	n/a	inter-face	Yes	interface	Yes	C	rules, hyp. and test, bayes	Yes	Yes	Yes	Yes	Yes	n/a
Nextpert Neuron Data	No	No	Yes	Yes	n/a	C	objects	No	Yes	n/a	n/a	No	Yes
Personal Consultant Texas Instruments	Yes	Yes	Yes	Yes	Yes	LISP	rules, frames	Yes	Yes	frame descriptors	metar-ules	n/a	n/a

Level 5 / Insight 2+ (Level Five Research, Indialantic, FL) is a rule-based system written in Turbo PASCAL. Metarules allow for control of execution, while similar rule group displays provide for some modularity. Relationships between various rules are easily viewed during development via a knowledge tree. What-if scenarios allow the user to see what would happen in a hypothetical situation. Graphics are not supported extensively, however, and access to the outside world (programs, databases, sensor inputs) is achieved by passing parameters through RAM or via disk. This implies that the expert system developer would have to spend considerable time creating the software to implement this parameter passing.

KDS3 (KDS Corporation, Wilmette, IL) is a versatile system with many appealing features. Graphics can be created during development, and then captured from the disk during run-time. Using an $89 graphics package, it becomes possible to simulate instrumentation in graphical form in real time. Real-time execution is possible because the software is entirely written in 8086 assembly language, possibly making KDS3 the fastest executing expert system environment on the market. Modularity is encouraged naturally and the flow of execution is controlled through the use of selective inference suppression, speeding development and execution times. However, there is no graphical representation of the knowledge base to aid developers, who must write the software to access sensor input data, thereby increasing development time.

KES (Software Architecture and Engineering, Arlington, VA) allows sensor input and access to databases through an interface. It can be embedded in a larger system, allowing KES to supply the reasoning to a much larger system. It provides for modularity and control flow through the use of demons (actions taken when specific values are seen) and deals with uncertainty through using confidence factors. It provides explanations for the user, while the trace feature aids the developer during debugging sessions. In addition, knowledge can be represented in three different ways, allowing the developer to tailor the knowledge representation scheme to the application at hand. The three paradigms include: Production Rules (PS), Hypothesis and Test (HT), and Bayes Theorems for statistical applications. KES, however, does not extensively support graphics, databases, or input from sensors. The firm apparently has sold about 300 copies of KES (Schwartz, pp 73-80).

Nexpert (Neuron Data, Palo Alto, CA) is an object-oriented development tool written in C (originally written in PASCAL and assembler), which allows integration to external programs and databases (excel, LOTUS 1-2-3, Dbase III). Under Microsoft Windows, data can be passed between two concurrently running programs. Certainty of a conclusion can be calculated within each rule, and the object network and rule network browsers allow the developer to view the relationships among objects and rules during development. Support for graphics and data input from sensors is not extensive, however, requiring the developer to provide the software for these functions.

Personal Consultant (Texas Instruments, Dallas, TX) is offered in two versions: Easy and Plus. PC Easy is a limited, but compatible, version of the larger PC Plus. PC Easy can be used to determine the feasibility of developing the expert system using Texas Instruments technology and its cost ($435) can be applied toward the purchase price of PC Plus.

PC Plus is a comprehensive development tool that offers graphics, sensors input, and database support. Pictures can be captured from disk, and can be displayed or drawn at run-time using Texas Instruments' graphics package, PC Images. Simultaneous multiple images can also be displayed.

In addition, readings from machine sensors are supported through PC Online, a Texas Instruments product that includes interfaces to existing data acquisition and analysis programs, process synchronization (event-driven, sample-driven, or continuous looping), and reporting and trend analysis capabilities. Special operator interface features can suppress screen output or alert a human operator when intervention is required. Expert recommendations can be reported back to the process. PC Plus can call or be called by external programs, including LISP, C, .EXE, and .COM files. It can also access DOS files, LOTUS 1-2-3, Dbase II, III, and AII Plus. PC Plus can be compiled into LISP or C code for delivery and uses frame descriptors with inheritance for modularity. Flow control is achieved via metarules with inheritance; the expert system tool allows certainty factors to enter into the rules and has explanation capabilities. It appears to have all features needed for development of a diagnostic and monitoring expert system on combustion technology equipment. An estimated 3000 to 4000 copies of PC Plus have reportedly been sold, making it one of the more popular AI tools on the market (Schwartz, pp 73-80).

MAD Development

A prototype expert system to Monitor And Diagnose packaged boiler operations (MAD), was developed using commercially available hardware and software. All data entry and display in MAD is performed through graphics interfaces. The current version of the prototype collects sensor data via user inputs or directly from sensors on the boiler through a Texas Instruments* Personal Consultant Plus companion product called "On-line." The current version of MAD can recognize inefficient firetube packaged boiler operation and recommend action to produce optimal combustion efficiency. Appendix B contains an example of the diagnosing rules in LISP, English, and Abbreviated Rule Language (ARL).

Equipment Recommendations

The expert system development shell chosen for the expert systems prototype development was Personal Consultant Plus (PC Plus). Developed by Texas Instruments, it uses a dialect of Lisp called "PC Scheme." Texas Instrument's Personal Consultant series of AI software tools was selected for development and delivery of the expert system for combustion technologies because of its accessory software. Specifically, the PC Online package will eliminate substantial in-house developmental work on software for reading combustion technology sensors. The Images package enables the data display in graphical form, again with minimal in-house effort. Also, databases are easily read and accessed from within the expert system so that a history of sensor input data can be maintained. Finally, a large number of copies of PC Plus have been distributed, ensuring support and commonality with existing expert systems.

4.2.1.1 Hardware. MAD was developed on a 80386-based machine with 640K base memory and 1024K extended memory. It would also work well with any AT-class (80286- or 80386-based) PC. The present version of MAD can be used either with the developmental version or the run-time version of Personal Consultant Plus. Due to the relative simplicity of the initial prototype, researchers decided that an Intel 80286-based PC could provide for both development and delivery of the prototype system (although an upgrade to an Intel 80386 or 80486-based machine would be both faster as well as easily compatible).

4.2.1.2 System Requirements. The minimum system configuration will include:

- a 1.4 megabyte double sided, double density, diskette drive
- a fixed disk drive with at least 1.5 Mb available workspace
- at least 640K base memory and 1 megabyte extended or expanded memory
- a color monitor with Color Graphics Adapter (CGA), Enhanced Graphics Adapter (EGA), or Video Graphics Array (VGA).

*Texas Instruments, Inc., Data Systems Group, PO Box 2909, Dept TR, Austin, TX 78769, tel. 512/250-6591.

MAD could run on IBM PC-AT and AT compatibles, which require PCDOS version 3.0 or greater. Texas Instruments computers in particular require MS-DOS version 3.0 or greater.

MAD's General Theory of Operation

MAD can use a variety of techniques to determine the value of parameter, while testing the premise of a rule. It first checks the conclusions of other rules to see if any of them have the parameter whose value it is trying to find (this is in fact the default method of variable value assignment). If the parameter in question does appear in the conclusion of a rule, MAD checks its premise. If the premise is correct, the parameter is assigned the value specified by the conclusion of that rule. Besides having values assigned to them in rule conclusions, parameters can be assigned values by prompting the user, retrieving from databases, calling numeric type functions, or by specifying defaults. The method by which a parameter is assigned a value is usually specified by the developer while defining a parameter. MAD can decide during execution what method should be used to assign a value to a parameter.

In a knowledge base there have to be some parameters that are assigned values by methods other than rule conclusions. In MAD, most parameters are assigned values by prompting the user. In the on-line version of MAD adapted for implementation in real time, these parameters are assigned values from the locations of the computer's memory that are accessed by the DMA (direct memory management) channels to the data acquisition hardware.

Assumptions made by MAD regarding the control and safety features available on the boiler are:

- that the low water level switch is assumed to be in the limit circuit
- that switches in the limit circuit do not cause lockout
- that the fuel pressure switches are in the limit circuit.

MAD establishes the remaining variables by user prompts. See Appendix C for a sample program session.

System Development Knowledge Acquisition

This section will discuss the technical resources used during the knowledge acquisition phase.

The expert interviewed most extensively was Stanley Briggs of Control Associates, an independent consultancy specializing in instrumentation and control. Mr. Briggs personally has over 25 years of experience with boilers, and contributed information on all aspects of boiler operation and maintenance, although the areas most extensively covered related to instruments and controls. Mr. Briggs gave very valuable information about different types of switches, most common causes of their malfunctioning, as well as the different manufacturers and their respective market shares.

Lawrence L. Yost, the Engineering Manager at York-Shipley, York, PA, has over 30 years of experience with boilers, and was interviewed extensively about different aspects of firetube boiler manufacturing, installation, and operation. Mr. Yost gave very valuable information about the flame safeguard and the master control system, and also discussed the different flame detection systems and the commonly occurring faults with the draft control system. He probably had the most significant contribution towards the troubleshooting section of MAD.

Charles Schmidt, of Schmidt Associates, has over 30 years of experience with boilers, and was interviewed along with Stan Briggs. Mr. Schmidt's principal area of expertise is coal-fired boilers, and he contributed much valuable information about existing conditions in the industry. His knowledge about sensor placement for collecting inputs to the control system could not be incorporated into the present version of MAD's inefficiency diagnosis section due to project limitations. He also had a few words of caution about how to word suggestions in MAD and the possibility of accidents occurring due to misinterpretation of instructions. The clinical nature of the conclusions in MAD are mainly a result of this caution.

Sid Snow, a senior consultant with Cleaver Brooks, Milwaukee, WI, with over 40 years of boiler experience, contributed significantly to the troubleshooting section of MAD. He discussed the electrical side of troubleshooting shutdowns and start-up failures, and gave a detailed account of normal operating procedures.

Many individuals within IGT were also interviewed. These individuals also helped to review various rules and portions of the expert system. IGT boiler operators also provided valuable "hands on" experience.

Several supplemental sources were used to develop MAD, including the operation and maintenance manuals of the leading boiler manufacturers. USACERL workshop presentations held for boiler operators were reviewed. Finally, various technical references on steam generation and use were studied.

Manufacturers' manuals were studied for their parts lists, information on ideal operating conditions, and for their detailed discussion of maintenance procedures. Differences between the parts supplied by different manufacturers were noted. This also contributed significantly to the information regarding the malfunction of the various components of the flame detection system.

A detailed study was made of how maintenance affects performance and of those aspects of maintenance that affect specific aspects of performance. Each analysis began with a symptom that would appear if a certain maintenance procedure was not strictly adhered to. The entire study focused on acquiring information that would be relevant to identifying problems.

MAD's Areas of Expertise

MAD covers five basic areas of boiler operation and evaluation. These areas form the menu options that begin each session:

1. Efficiency check
2. Troubleshoot
3. Simulation
4. Setup
5. Education.

The "efficiency check" section is both expert knowledge and model based. Correlations known to exist between certain key boiler variables were used to develop numerical models for the process. These numerical models were developed from tune-up data entered in the Setup section of MAD, which is collected during initial setup of the boiler or during tune-ups. This information is entered into the program via the Setup section.

The efficiency option compares the values of certain key monitored variables against the values from the numerical models. The relative positions are used to identify inefficiency. Expert knowledge is the basis of these comparisons. A physical process model is used to make a numerical efficiency estimate. Since the physical process model is restricted to a theoretical mode of operation, its applicability is somewhat limited. This physical model was developed for complete combustion, so the model does not apply to situations with a high level of unburnt combustibles in flue gases.

The "efficiency check" is the most complete option in the current version of MAD. It requires the input of various parameters that include, but are not limited to: fuel type, flue gas temperature, amount of oxygen and combustibles exiting the stack, and steam pressure. Once the input data have been entered, MAD determines if the boiler is running efficiently. If not, it will display the general reason leading to this conclusion. In reaching the conclusion, MAD calculates the optimal value of a parameter (for a given boiler under the operating conditions specified), factoring in a certain tolerance before concluding that the boiler is or is not in a state of inefficiency. For example, it might state that the input value of 4.0 percent excess oxygen in the stack is more than 1 percent greater than the optimal amount of 2.1 percent for that particular boiler.

In essence, a consultation with MAD informs the user if the demand for steam is being met in the most cost effective manner given the limitations of a particular boiler. When a boiler is found to be operating inefficiently, MAD suggests possible causes of inefficient operation. The user can use MAD's suggestions to make adjustments required to bring the boiler back to an efficient mode of operation.

After MAD has been fully developed, it will receive input data automatically from sensors (with the aid of a Texas Instruments software package developed exclusively for real-time data acquisition), and if the boiler is running inefficiently, determine the malfunctioning component.

"Troubleshoot" determines which malfunctioning component might be causing the boiler to operate incorrectly or inefficiently. The areas most extensively addressed in the present version of MAD are unexpected shutdowns and start-up failures. Besides the nuisance factor involved, shutdowns can contribute significantly to operating expenses in various ways. Very often, shutdowns can be fixed without calling in service personnel.

The principle objective of troubleshooting is to help boiler room personnel identify the cause of shutdown and hence reduce the time required to get the boiler back on line. The user must realize the difficulty of troubleshooting all boilers with one generic program. MAD attempts to locate the problem by a process of elimination and in this endeavor narrows down the set of possibilities, which would in turn reduce the time taken to locate a problem even by an experienced boiler individual. The troubleshoot section of MAD assumes that the boiler is not operational and thus cannot be used to identify problems that may exist while the boiler is in operation.

Operator interaction with MAD is essential in troubleshooting due to the prohibitive cost of installing feedback sensors to check the integrity of every valve, electrical wiring assembly, moving part, and noise associated with the boiler. A criterion crucial to accurate evaluation of a boiler is that input data be gathered rigorously. MAD, therefore, asks the user a series of about six questions on the procedures used in gathering the data. The operator's responses are used to determine the degree of confidence that the system (and the user) has in it's analysis of the boiler's malfunction. If the data acquisition method is careless or unknown, MAD prints a qualifying statement that any opinion rendered must be deemed unreliable due to the fact that the input is unreliable. Otherwise, MAD prints a message that the opinion rendered is only trustworthy to the percent indicated at the end of that message.

The troubleshoot option does not currently cover all possible conditions that might exist in an operating boiler. The most important parameters in easily determining boiler efficiency are the temperature, oxygen, and combustibles found in the flue gas. At a given time, each of these parameters might be either at an excessively high level, a normal or acceptable level, or an abnormally low level. Since each of these three parameters has three possible conditions, there are 27 possible conditions (Table 3). MAD will accommodate conditions where two of the three input parameters are at normal levels and the third is abnormal. Not yet covered are conditions where more than one parameter is abnormal. An exception to this limitation is the condition in which oxygen and temperature are high while combustibles are normal.

Table 3

Firing Combinations Between Unburned Carbon Monoxide, Oxygen, and Flue Temperature

Carbon Monoxide	Oxygen	Flue Temperature	Number
High	High	High	1
High	High	Normal	2
High	High	Low	3
High	Normal	High	4
High	Normal	Normal	5
High	Normal	Low	6
Normal	High	High	7
Low	High	High	8
High	Low	High	9
High	Low	Normal	10
High	Low	Low	11
Normal	Normal	High	12
Normal	Low	High	13
Normal	Normal	Normal	14
Normal	Normal	Low	15
Normal	High	Normal	16
Normal	High	Low	17
Low	Normal	Normal	18
Low	High	Normal	19
Low	High	Low	20
Low	Normal	High	21
Low	Normal	Low	22
Low	Low	High	23
Low	Low	Normal	24
Low	Low	Low	25
Normal	Low	Normal	26
Normal	Low	Low	27

It is anticipated that future versions of this option will include extensive use of graphics such as the isometric drawing presented in Figure 7. By using such graphics, the expert system will be able to indicate what the problem might be, and to show the operator where to look for the problem or check for proper operation.

The "Simulation" section is essentially a smaller version of the main program that gathers data from a simulation rather than from sensors or operator interaction. This section gives an online demonstration of the expert system. The present version of MAD does not undertake any control functions although future versions of MAD can be developed to incorporate control functions.

Simulation is meant to demonstrate the real time capabilities of the expert system. This section contains an efficiency evaluator and functions in the following manner. Data that should be coming from a real boiler is instead imported from the simulation. (The simulation was developed in LISP exclusively for use in this section.) The simulated boiler is assumed to burn only gas. Once data is imported from the simulation, the efficiency evaluator estimates boiler percentage efficiency as well as qualitative efficiency. The main significance of this section is that it uses a physical model of the combustion process to estimate percentage efficiency from some user inputs. To initialize the simulation, the user must enter the boiler operating steam pressure, the condition of the firetubes that one wants the simulated boiler to

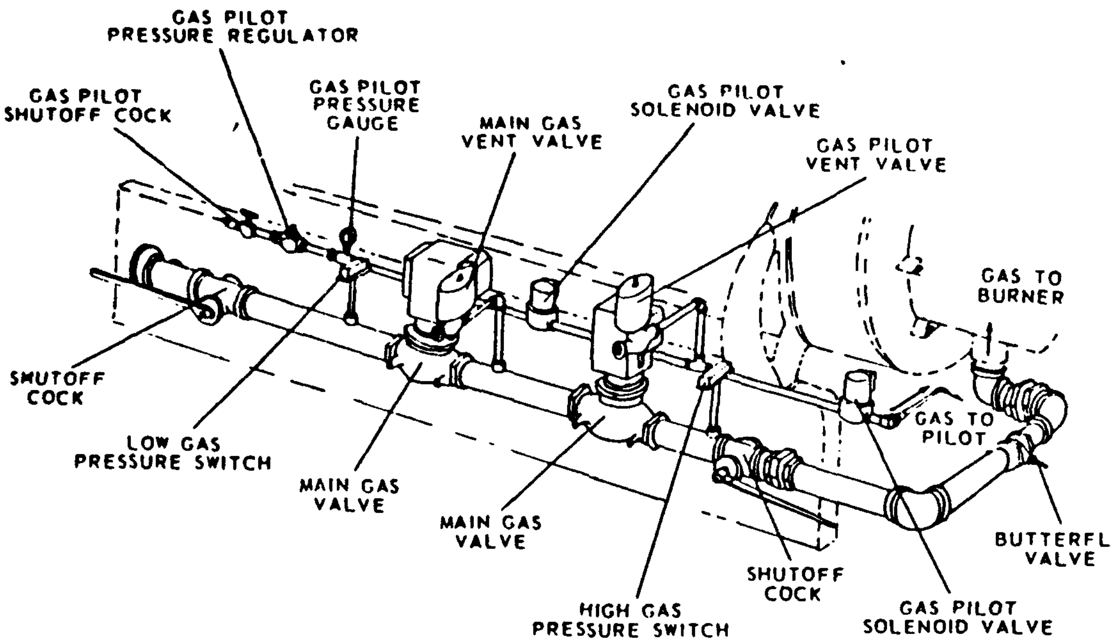

Figure 7. Isometric Drawing of Typical Gas Fuel Train.

have, and the quantity of excess air that the user wants for combustion. The load on the boiler is continuously modulated between a 20 and 100 percent load, in increments of 5 percent. The simulation can run indefinitely, as would a process monitor. The data collected from the simulation (percentage excess oxygen and flue gas exit temperature), along with the simulation independent variable load and MAD's estimate of boiler percentage efficiency, are displayed on the same screen. This screen also displays the expert system's qualitative estimate of boiler efficiency.

"Setup" customizes MAD for a particular boiler. This includes setting up of the optimal excess oxygen curves, and the optimal excess combustibles curve, for gas and/or oil firing. These curves are set up by executing an external program from within MAD that uses data entered in the setup section of MAD. The curves provide the inferencing mechanism of MAD with the numerical models required by the efficiency evaluating section of MAD.

"Education" is an option intended to educate boiler personnel—regardless of level of experience—to understand more about boilers. Experts who never require assistance are rare. In light of the U.S. Army's high turnover in boiler room staff in recent decades, it is expected that many young, inexperienced personnel would benefit greatly from an easily available educational tool of negligible operational cost.

The education option will serve as a colorfully illustrated, online textbook covering the principles of combustion technology, boiler operation, and maintenance. The user will be able to study an area of interest by choosing one of various options offered on multiple menus. The system could alternatively quiz the user by setting up various scenarios, requesting an answer, and then giving and explaining the correct answer as well as giving feedback on the incorrect answers. These sessions would include diagrams (Figure 8) that could graphically illustrate the proper procedures for installation or maintenance of boiler components.

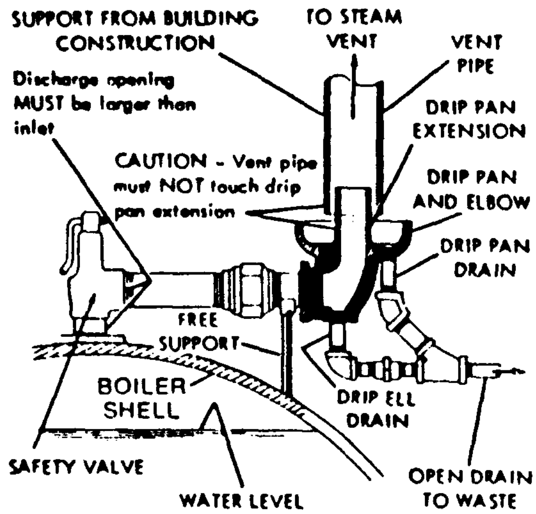

Figure 8. Example Recommended Safety Valve Installation Procedure.

The education option is not yet fully developed, and if selected, note that it is under development. However, a rudimentary educational system has been incorporated into the current version of MAD to demonstrate the degree and level of knowledge that would be transferred to the user. Many of the prompts (questions) include a note stating that a further explanation of the prompt is available by pressing the F1 key. This F1 help key has two purposes: to teach the user how to enter input for the prompt displayed and to educate as described above. This "extra" educational feature will be left in after full development of this option so the user can access the material through the various avenues of the system. Appendix C includes a sample MAD program session.

Future Development

MAD has been designed to accommodate future additions in its diagnostic section. The diagnostic section currently uses only very basic information, and consequently does not always give the user definite reasons for inefficient operation. However sufficient information was gathered during the knowledge acquisition phase to modify and expand this section to help the user locate the exact cause of inefficient operation. The present version has a separate diagnostics frame to diagnose process malfunctions. It may be difficult for an inexperienced individual to relate a process malfunction to an individual component malfunction. Since it requires a very detailed analysis of the causal relationships between various symptoms, the current version of MAD does not try to relate process malfunctions to component malfunctions except where the relationships are relatively simple.

MAD was developed with the final objective of implementing it in real time on an Intel 386- based computer alongside other control programs. MAD can be embedded in a master program that could be used to execute the boiler control programs. While the boiler is in operation, MAD would be monitoring boiler efficiency and making its assessments available to the user via the video display. At the user's request, MAD would start diagnosis whenever inefficient operation is detected. Note that, if the micro-computer is used in a feedback manner to send signals to the actuators, it may not be possible to use the diagnostic section of MAD in real time. The Troubleshoot section, however, can be used even if the machine it is implemented on is used in a feed back manner to send control signals to the actuators. This is possible because the troubleshooting section can only be used when the boiler is not operational.

The final implementation of MAD would follow one of two possible scenarios, depending on the capabilities of the equipment on which it is implemented and of the associated instrumentation. In the first case, a microcomputer could be used in conjunction with a bus board and signal conditioning hardware to import and display sensor data on the monitor. In this mode, the machine would constantly infer and display its assessment of boiler efficiency. If inefficient operation is detected MAD would list process faults that might cause such inefficiency. Through prompts, MAD will offer the user help to fix the problem. If so desired, the computer would leave the monitor mode and interact with the user to identify the malfunctioning component. As soon as MAD reaches a conclusion (which may or may not fix the problem) it would automatically enter the monitor mode again and resume displaying sensor data. In the time it takes to physically fix the problem, the user could exit the program and restart it when the problem was fixed. In this scenario, the computer is not used to control the process in a feedback manner at all. If MAD's help is not desired to identify the problem, MAD would continue displaying sensor data, its assessment of boiler efficiency, and the basic causes of inefficient operation. If the boiler needs to be brought off-line to fix the problem, the program would have to be restarted when the boiler is again put on line. Rules could be added in the monitor frame that would display additional information to help the user decide if the boiler should be taken off-line for maintenance. While MAD is in the diagnostic mode, data imported from the process is neglected or no data is acquired at all. Texas Instruments Personal Consultant Plus, the software MAD was developed on, can support all these functions.

The alternate scenario is where the computer that runs MAD is also used to control the boiler. A master program could be written using the expert system development shell to monitor sensor inputs. The inputs would then be sent to a control program, which would calculate the numerical values of the control signals, send them out, and return execution to the master program. The master program would again send data to the control program, and the sequence would continue. Before the imported data is sent to the control program, the master program would try to estimate boiler efficiency and discontinue normal execution if inefficiency is detected. MAD would then enter the diagnostic mode. The control program would be called regularly after fixed intervals of time to calculate and send signals out to the actuators while the machine would diagnose with user interaction. This would require a fast 386 or 486-based computer and an operating environment that supports multitasking.

The troubleshooting section of MAD would be at the user's disposal in both of the above cases. The user would choose Troubleshoot from the first menu before entering the data acquisition mode. Since it is assumed that the user would only enter the troubleshoot mode when the boiler is not operating, the computer would not be required to function as a controller when in this mode, so the entire resources of the computer would be devoted to troubleshooting.

5 CONCLUSIONS

This study investigated the application of AI using knowledge-based expert systems technology to the problem of monitoring CHP boiler operations. Two principal avenues for development were identified: to program an expert system "from scratch" using an AI-specific programming language like LISP or PROLOG, or to develop a system using a commercially available expert system. Because of the great time and expense involved in initiating a new programming project, and because currently available expert-system software is both sophisticated and flexible enough to address the problem under study, it was concluded that a commercial expert system would serve the needs of this project.

A number of expert system shells were reviewed and evaluated on the basis of:

1. Cost
2. Hardware requirements
3. Programming strategy
4. Software capabilities and features
5. Ability to interface with other software
6. Ability to interface with machine sensors and instrumentation.

It was concluded that Texas Instrument's PC Plus best met the needs for a diagnostic and monitoring expert system for combustion technology equipment.

MAD's knowledge base was derived from a broad literature search, and from interviews with a variety of combustion technology experts, including independent combustion consultants, representatives of leading boiler manufacturers, manufacturers' field personnel, and in house combustion researchers and boiler operators.

Using PC Plus and the knowledge base of information on CHP boiler technology, a real time prototype expert system, MAD, was developed to Monitor And Diagnose package boiler combustion inefficiencies and to recommend appropriate corrective action. MAD also incorporates an on-line "education" option that explains many facets of boiler operation. The MAD prototype is a cost effective tool that not only monitors, diagnoses, and troubleshoots smaller combustion units, but simultaneously educates boiler personnel in operation and maintenance practices.

To compensate for the fact that some boiler personnel may have little experience with microcomputers, MAD uses a graphics package to create a "friendly" user interface. Real time data can be displayed in the familiar form of digital or analog gauges. Automated data acquisition via remote sensors is scheduled for implementation in a second development phase. Currently, input data is entered through a keyboard.

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APPENDIX A:

Expert System Shell Suppliers and Manufacturers

Company Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
General Research Corp. 7655 Old Springhouse Rd McLean, VA 22102 Ph: (703) 893-5900	TIMM	-	-	-	-	-	-	-	-
Automated reasoning Cor 1800 Northern Blvd., Ste. Roslyn, N.Y. 11576 Ph: (516) 484-6254	I-CAT	-	-	-	-	-	MAC OS, UNIX X-WIndows	-	$18,000 - $60,
Jeffery Perrone & Associates Inc. 3685 17th St. San Francisco, CA 94114	Expert-Ease Expert Edge needs to be chec	-	-	-	-	-	IBM PC/XT IBM PC/XT, PS/2	-	$695 $1,495
Softsync Inc. 162 Madison Ave. New York, NY 10016 Ph: (212) 685-2080	Superexpert	-	-	-	-	-	IBM PC/XT/AT	-	$199.95
Logicware Inc. 2065 Dundas St. E., Ste. 204 Mississauga, Ontario, Canada L4X 1M	Mechano Set source code vers Ph: (416) 629-88	-	-	-	-	-	IBM PC/XT/AT	-	$500 $2,000
Bell Atlantic Knowledge Systems Group 34 Washington Rd. Princeton Junction, NJ 08	Laser Ph: (609) 275-45	-	-	-	-	-	IBM RT/PC Mac, DEC VAX	-	$900 - $25,000
Berkshire Software Co. 44 Madison St. Lynbrook, NY 11563 Ph: (516) 593-8019	Turbo Shell	-	-	-	-	-	IBM PC/XT/AT	-	$119

Comapny Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
Paradigm Software P.O. Box 2995 Cambridge, MA 02238 Ph: (617) 542-4245	Object Logo	-	Yes	Yes	No	No	Mac +	1 MB	$149
Advanced A.I. Systems, I P.O. Box 39-0360 Mountain View, CA 9403 Ph: (415) 948-8658	AAIS Prolog	No	Yes	Yes	-	No	Mac	1 MB	$298
A.I. Corp, Inc. 138 Technology Drive Waltham, MA 02254 Ph: (617) 891-6500	KBMS	Yes	Yes	Yes	Yes	avail	IBM/PC	8 MB	$7,500 - $10,000
Pathfinder Advanced Computer Tech. Inc. 66214 Southpoint Dr. N Suite 310 Jacksonville, FL 32216 Ph: (904) 296-1685	Keystone	-	-	Yes	Yes	No	IBM/PC GCLISP	512 K 10 Meg HD	-
Emerald Intelligence 3159-A1 Research Park Ann Arbor, MI 48108 Ph: (313) 663-8757	Mahogany Professional	Yes	Yes	Yes	No	No	IBM/PC Mac	640 K 1 MB	$495
Cosmic University of Georgia 382 East Broadstreet Athens, GA 30602 Ph: (404) 542-3265	NASA	-	Yes	-	-	-	IBM/PC Mac	1 MB	$490

Company Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
Software Plus 1652 Albermarle Dr. Crofton, MD 21114 Ph: (301) 261-0264	CxPERT	Yes	Yes	Yes	Yes	No	IBM PC MS-DOS	-	$795 (object code) $2,000 - 44,00 (source code)
Transform Logic 3502 E. Dia De Ventura Scottsdale, AZ 85258 Ph: (602) 948-2600	Transform	No	No	No	Yes	2 weeks	IBM mainfr. MVS/IMS/CICS	N/A	325,000 - $350,000
Umecorp 45 San Clemante Dr. Cprte Madera, CA 94925 Ph: (415) 883-1500	Expert Controller	Yes	Yes	Yes	Yes	1-2 days	IBM PC/AT KEOS	-	$10,000
Xerox Special Info. Sys. 250 N. Halstead St. Pasadena, CA 91107 Ph: (818) 351-2351	Humble 2.0	Yes	Yes	Yes	-	-	80386	7 MB	-
1st-Class Expert Systems 526 Boston Post Rd. Wayland, MA 01778 Ph: (617) 891-6500	1st-Class Fusion 1st-Class HT	Yes	Yes	Yes hyper- graphics	-	avail	IBM PC/XT/AT, VAX, VMS	-	$1,495 $2,495
IntelliCorp. 1975 El Camino Real Mountain View, CA 9404 Ph: (415) 965-5500	KEE Kappa Tool	Yes (with KEE) Yes	Yes Yes	Yes Yes	Yes Yes	9 days No	Lisp mach. DEC VAX, Sun Applo MS DOS	-	$30,000 - $50,000
Neuron Data 156 University Ave. Palo Alto, CA 94301 Ph: (415) 321-4488	Nexpert Object	Yes (with KEE)	Yes	Yes	Yes	9 days	Lisp mach. DEC VAX, Sun Applo	2 MB	$30,000 - $50,000

Company Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
Intelligent Environments P.O. Box 388 Chehmsford, MA 01824 Ph: (508) 640-1080	Crystal	Yes	Yes	Yes	Yes	avail not req	MS-DOS	-	$995
Keystone Technologies 7400 Bay Meadows Way Jacksonville, Fl 32256 Ph: (904) 296-9634	Keystone Developer's Package	almost completed	No	in devel	yes (very much)	1 week $1200-$2000	IBM PC/XT	-	$9,750 $7,000
Knowledge Garden Inc. 473A Malden Bridge Rl, Nassau, NY 12123 Ph: (518) 766-3000	Knowledge-Maker Knowledge-Pro	Yes	Yes	Yes	-	-	IBM PC/XT/AT	64 K	$99 $495
Lightwave P.O. Box 16858 Tampa, FL 33617 Ph: (813) 988-5033	ESIE	No	No	No	Yes	2 hrs	IBM PC MS-DOS	128 K	$145
Mountain View Press Inc. P.O. Drawer X Mountain View, CA 9404 Ph: (415) 961-4103	EXPERT-2	No	Yes	No	Yes	No	IBM PC, PS/2	-	$70 - $1,180
Park Row 4640 Jewel St. Ste. 232 San Diego, CA 92109 Ph: (619) 581-6778	Easy Expert	-	-	No	Yes	No	IBM PC MS-DOS	-	$49.95
Software Artistry 3500 Depauw Blvd. Indianapolis, IN 46268 Ph: (317) 876-3042	PC Expert Professional App. Software expert	Yes Yes	Yes Yes	Yes Yes	No Yes	No No	IBM PC/XT/AT, PS/2, 80386	-	$495 $5,000 - $36,000

Company Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
Expert Systems Internatio 1700 Walnut St. Philadelphica, PA 19103 Ph: (215) 735-8510	ESP Advisor	Yes dBase III	Yes	Yes	Yes	2 days	MS-/PC-DOS Dec Vax/Vms	-	$895
Harris & Hall Associates P.O. Box 1900 Port Angeles, WA 98362 Ph: (206) 457-4907	ALEX	No	Yes	Yes	Yes	No	Smalltalk/V	-	$695
Human Intellect Systems 1670 S. Amphlett Blvd. # San Mateo, CA 94402 Ph: (415) 571-5939	Instant Expert Instant Expert Pl NEXUS	Yes	Yes	No	Yes	No	IBM PC/XT/AT MAC IBM, MAC IBM PC/XT/AT	-	$69.95 $99.95 $498 $698
Information,Builders Inc. 1250 Broadway New York, NJ 10001 Ph: (212) 736-4433	Level5	Yes	Yes	Yes	Yes	3 days	IBM PC, Mac	640 K	$995-3,000
Intelligence Manufacturin 340 Bridge Pl. W. Sacramento, CA 9669 Ph: (916) 372-6680	IBIS	No	Yes	Yes	Yes	avail	IBM PC/XT/AT	-	$250
IntelligenceWare Inc. 9800 S. Sepulveda Blvd. Los Angeles, CA 90045-5 Ph: (213) 417-8896	Auto-Intelligenc Intellig./Compile IXL: Machine L	Yes Yes	Yes Yes	Yes Yes	Yes Yes	None 1-5 days	 IBM PC VAX IBM PC, VAX	512K 512K	$490 $490 $7,500 $490, 7,500
Intelligent Computer Eng 17A Landing Ln. Hopedage, MA 01747 Ph: (508) 478-5517	X-Mare Appl. software expert	Yes	Yes	Yes	Yes	avail	MS-DOS AS/400	-	$495 $5,000 - $36,000

Company Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
Software A&E 1600 winson Blvd, Suite Arlington, VA 22209 Ph: (703) 276-7910	KES II	Yes	Yes	No (DBDraw DBTools available)	Yes (with C)	5 days	IBM PC; DEC Applo; Sun Micro; CDC; H-L IBM mainfr.	-	$4,000 $7,000-$15,00 $60,000
Texas Instruments Data Systems Group Dallas, TX 75380 Ph: (214)995-2011	Personal Consulant Plus PC Easy	Yes dBase II, III Yes dBase II, III	-	Yes	Yes	1 week	PC-/MS-DOS; T.I. Explorer PC-/MS-DOS	640K 2Mb ext. 512K	$2,950 $495
Baldur Systems Corp. 3423 Investment Blvd., St Hayward, CA 94545 Ph: (415) 732-9715	IQ-200	No	yes	No	Yes	No	IBM PC/XT/AT MS-DOS	-	$495
CAM Software 750 N. 200 West, Ste. 20 Provo, Utah 84601 Ph: (801) 373-4080	Logic Tree	-	-	Yes	No	-	IBM PC/XT/AT, PS/2, MS-DOS	512 K	$495
Cimflex Teknowledge Co 1810 Embarcadero Rd. Palo Alto, CA 94303 Ph: (415) 424-0500	M.1 COPERNICUS	Yes	Yes	Yes	Yes	No	IBM PC/XT/AT VAX, Applo Sun	512 K 3 MB	$5,000 $30,000
Cognition Technology Co 55 Wheeler St. Cambridge, MA 02138 Ph: (617) 492-0246	MacSMARTS	Yes	Yes	Yes	Yes	No	Mac, Mac OS	-	$195
Digital Equipment Corp. 290 Donald Lynch Blvd. Marlboro, MA 01752-024 Ph: (508) 467-5111	Decision Expert	Yes	Yes	Yes	Yes	No	DEC VAX VMS	-	$7,900

Company Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
IBM Armonk, NY 10604 Ph: (914) 288-2080	Expert system Environment	No (user can write)	Yes GDDM	Yes	Yes	16-20 hr	MVS; VM	N/A	$26,000 - $35,000
Inference Corp. 5300 W. Century Blvd. Los Angeles, CA 90045 Ph: (312) 558-1540	Art-IM CBR Express	Yes	Yes	Yes	Yes	2 weeks	Lisp, Unix, DEC VAX/VMS	-	$65,000 (first copy)
KDS Corp. 934 Hunter Rd. Wilmette, IL 90091 Ph: (708) 251-2621	KDS	Yes dBase II/III	Yes	Yes	Yes	3 days	PC-/MS-DOS	512K	$1,495
Knowledgeware 1650 Tysons Blvd. McLeary, VA 22102 Ph: (703) 506-0800	IEW/WS	Yes	Yes	Yes	Yes	2 days	PC-DOS	640K	$7,500
Level Five Research 503 Fifth Ave. Indialantic, FL 32902 Ph: (407) 729-9046	COCOMO1, Insight2	Yes Yes dBase II/III	Yes Yes	NO Yes	No Yes	2-3 days 2-3 days	PC-/MS-DOS PC-DOS	512K 192K	$485 $485
Micro Data Base Systems P.O. Box 220 Lafayette, IN 47902 Ph: (317) 447-1122	Guru	Yes Mdbs 3	Yes C	Yes	Yes	3 days	PC-DOS Ultrix	640K	$6,500
Paperback Software 2830 Ninth St. Berkeley, CA 94710 Ph: (415) 644-2116	VP-Expert	Yes dBase II/III VP-Info	Yes	Yes	No	2 days	MS-/PC-DOS	256K	$99.95

Company Name	Product Name	DBMS Interface Available	Access External Programs	Graphic Support Included	Customize Screens	Training Required	Hardware Requirement	Minimum Memory Requiremen	Price
Aion Corporation 1010 University Avenue Palo Alto, CA 94301 Ph: (415) 328-9595	ADS	Yes	Yes	Yes	Yes	3 days	PC-DOS VS/TSO, CICS VM/CMS	512K	$15,000 $60,000 - $100,000
Arity Corp. 358 Bakers Ave. Concord, Ma 01742 Ph: (508) 371-1243	Arity Systems Development Package	Yes dBase III	Yes C, Pascal	Yes	Yes	3 days	PC/MS-DOS	512K	$295
Carnegie Group 650 Commerce Ct. Station Square Pittsburgh, PA 15219 Ph: (412)642-6900	Knowledge Craft	Yes (Vax only)	Yes	Yes	Yes	2 weeks	Lisp machines; DEC VAX, MicroVAX, Sun 3	N/A	$25,000 - $50,000
Exsys Inc. P.O. Box 75158 Albuquerque, NM 87194 Ph: (505) 256-8356	Exsys	Yes	Yes	Yes	Yes	3 days	PC-DOS	640K	$795
Gold Hill Computers 163 Harvard St. Cambridge, MA 02134 Ph: (617) 621-3300	Goldworks II	Yes	Yes	Yes	Yes	3 days	PC-/MS-DOS Advanced PC's (286, 386)	512K 8Mb extend memory required	$7,500
Help/38 Systems 210 Baker Rd. Minnetonka, MN 55345 Ph: (612) 944-2252	Genesis V	Yes	Yes	No	Yes	2 days	IBM/38 CPF	100K	$14,950

Note: Information not available: -
Not Applicable: N/A

APPENDIX B

Diagnosis Frame Rules: LISP, English, and ARL Versions

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==========================
Frame :: DIAGNOSIS
==========================

IDENTIFIER :: DIAGNOSIS-
PARENTS :: (SUPERVISOR)
PROMPT1ST :: (:LINE :ATTR (CYAN HIGH) " The Boiler is operating
        inefficiently" :LINE 2 :ATTR (YELLOW HIGH) " Would you like
        to find out why ?" )
RULEGROUPS :: (DIAGNOSIS-RULES)
0 :: ()
DIAGNOSIS-RULES :: (RULE315 RULE316 RULE317 RULE356 RULE357 RULE358
            RULE359 RULE360 RULE361 RULE362 RULE363 RULE364
            RULE365 RULE366 RULE367 RULE368 RULE369 RULE370
            RULE371 RULE372 RULE373 RULE374 RULE375 RULE376
            RULE377 RULE378 )

  ====================
  DIAGNOSIS-RULES
  ====================

RULE315
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 1))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :ATTR
         ('
          (YELLOW)) :LINE 3 " The boiler is operating inefficiently
        as the stack temperature is higher than normal , the level of
        excess oxygen is above normal and the level of combustibles
        is also above normal ." :LINE " REASONS FOR HIGH TEMPERATURE
        READING " :LINE "(1) Check the level of water in the gauge
        glass . If the water level seems fine make sure that the
        level indication is not false by blowing down the water
        column . The water level should bounce back as soon as you
        close the blowdown valve . " :LINE "(2) If the water level is
        normal then either you have excessive soot on the insides of
        your firetubes or you have too much scale on the outside of
        the tubes . If you are sure that your water treatment program
        is being followed rigorously then you need to soot blow the
        inside of the tubes . If you have blown the soot off the
        firetubes then you could need a stricter water treatment
        program ." :LINE " (3) If both sides of you fire tubes are
        free of junk {soot and scale} then you may have collected mud
        around the morrison tube . You need to blow down immediately
        { bottom Blowdown } . " :LINE " (4) If even this does not
        solve the problem then there is a chance that there is a leak
        in the baffles between passes . This would mean that some of
        the hot combustion gases are not going through all the passes
        and this is showing up as high stack temperature . " :LINE "
```

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        REASONS FOR HIGH EXCESS OXYGEN AND HIGH EXCESS COMBUSTIBLES
        " :LINE "(1) There is inadequate mixing between fuel and air
        before combustion . Bad mixing can be caused by incorrect
        air-fuel ratio . "))

RULE316
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 2))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently though the stack temperature is normal because
        the level of excess oxygen is above normal and the level of
        combustibles is also above normal ." :LINE "INEFFICIENCY IS
        PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "(1) The air
        damper is letting in too much air and this is causing
        insufficient mixing between fuel and air before combustion .
        " :LINE "(2) If you are firing oil then you are not atomizing
        properly ."))

RULE317
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 3))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is lower than normal ,
        the level of excess oxygen is above normal and the level of
        combustibles is also above normal ." :LINE "INEFFICIENCY IS
        PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "(1) There is
        insufficient mixing of fuel and air before combustion ."
        :LINE "(2) If you are firing oil then the problem is with
        atomization ." :LINE "(3) The air damper is letting in too
        much air and this is preventing the fuel and air from mixing
        properly . "))

RULE356
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 4))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is higher than normal
        and the level of combustibles is also above normal ." :LINE
        "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
        There is a thick layer of soot covering the fire side of fire
        tubes " :LINE "(2) There is too much mud around the morrison
        tube and the flame is fuel rich . " :LINE "(3) There is an
```

excessive amount of scale on the water side of the fire tubes
. " :LINE "(4) If your boiler has four or more passes then
there may be a leak in the baffles that seperate the passes .
"))

RULE357
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
PREMISE :: ($AND
(SAME FRAME SET 5))
ACTION :: (DO-ALL
(MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the level of combustibles is above normal .
" :LINE "INEFFICIENCY IS PROBABLY BECAUSE OF THE FOLLOWING ;
" :LINE "(1) The flame is fuel rich . " :LINE "(2) The
combustibles sensor is giving an incorrect reading . "))

RULE358
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
PREMISE :: ($AND
(SAME FRAME SET 6))
ACTION :: (DO-ALL
(MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is lower than normal
and the level of combustibles is above normal ." :LINE "
INEFFICIENCY IS PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "
(1) The flame could be fuel rich and outside air is mixing wit
h the flue gases before it reaches the sensors ." :LINE "(2)
The temperature sensor could be malfunctioning . "))

RULE359
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
PREMISE :: ($AND
(SAME FRAME SET 7))
ACTION :: (DO-ALL
(MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is higher than normal
and the level of excess oxygen is also above normal ." :LINE
"INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
There is excessive scale on the water side of the fire tubes
." :LINE "(2) There is too much mud around the morrison tube
." :LINE "(3) If your boiler has four or more passes then
there may be a leak in the baffles that seperate the passes .
" :LINE "(4) The fireside of the fire tubes are coated with
soot . " :LINE "(5) The linkages connecting the mod motor
shaft to the air damper are not functioning properly and this
is letting in too much air ."))

```
RULE360
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 8))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is higher than normal
        , the level of excess oxygen is also above normal level and
        the level of combustibles is below normal ." :LINE "
        INEFFICIENCY IS PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "

(1) There is excessive scale on the waterside of the fire tubes ." :LINE "(2)
        There is too much mud around the morrison tube . " :LINE "(3)
        If your boiler has four or more passes then there could be a
        leak in the baffles seperating the passes ." :LINE "(4) The
        air damper is letting in too much air . The linkages
        connecting the modulating motor shaft to the air damper are
        not functioning properly . "))

RULE361
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 9))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is higher than normal
        , the level of excess oxygen is below normal and the level of
        combustibles is above normal ." :LINE "INEFFICIENCY IS
        PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1) There is
        excessive soot on the fireside of the firetubes . " :LINE "
        (2) The flame is excessively fuel rich ." :LINE "(3) There is
        too much mud around the morrison tube ." :LINE "(4) If your
        boiler has four or more passes then there may be a leak in
        the baffles seperating the passes ."))

RULE362
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 10))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the level of excess oxygen is below normal
        and the level of combustibles is above normal ." :LINE "
        INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
        The air damper could be letting in too little air ." :LINE "
        (2) The excess oxygen sensor could be malfunctioning . "))
```

```
RULE363
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 11))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is lower than normal ,
        the level of excess oxygen is also below normal and the level
        of combustibles is above normal ." :LINE "INEFFICIENCY IS
        PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1) The air damper is
        letting in too little air ." :LINE "(2) The temperature
        sensor is malfunctioning . "))

RULE364
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 12))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is higher than normal
        ." :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;"
        :LINE "(1) There is excessive scale on the water side of the
        fire tubes ." :LINE "(2) There is too much mud around the
        morrison tube ." :LINE "(3) If your boiler has four or more
        passes then there may be a leak in the baffles between the
        passes . "))

RULE365
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 13))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 "  The boiler is
        operating inefficiently as the stack temperature is higher
        than normal and the level of excess oxygen is below normal .
        " :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;"
        :LINE "(1) There is excessive scale on the waterside of the
        fire tubes ." :LINE "(2) There is a lot of mud around the
        morrison tube ." :LINE "(3) If your boiler has four or more
        passes then there may be a leak in the baffles which seperate
        the passes ." :LINE "(4) You may have underestimated load ."
        ))
```

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RULE366
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 15))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is lower than normal
        ." :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;"
        :LINE "(1) The temperature sensor is malfunctioning " :LINE
        "(2) You overestimated boiler load . "))

RULE367
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 16))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the level of excess oxygen is above normal
        ." :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;"
        :LINE "(1) The air damper is not moving freely . The linkages
        between the modulating motor shaft and the air damper is
        either too tight or too loose . "))

RULE368
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 17))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is lower than normal
        and the level of excess oxygen is above normal ." :LINE "
        INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING" :LINE "(1)
        Outside air is mixing with the flue gases before it reaches
        the sensors . "))

RULE369
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 18))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the level of combustibles is below normal .
        " :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;"
        :LINE "(1) The combustibles measuring device is faulty . "))
```

```
RULE370
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 19))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently though the stack temperature is normal because
        the level of excess oxygen is above normal and the level of
        combustibles is below normal ." :LINE "INEFFICIENCY IS
        PROBABLY DUE TO THE FOLLOWING " :LINE "(1) Outside air is
        mixing with the flue gases before it reaches the sensors . "
        ))

RULE371
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 20))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is lower than normal ,
        the level of excess oxygen is above normal and the level of
        combustibles is below normal ." :LINE "INEFFICIENCY IS
        PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1) Outside air is
        mixing with the flue gases before it reaches the sensors .")
       )

RULE372
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
        (SAME FRAME SET 21))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is higher than normal
        and the level of combustibles is below normal ." :LINE "
        INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
        There is excessive scale on the waterside of the firetubes "
        :LINE "(2) There is too much mud around the morrison tube"
        :LINE "(3) If your boiler has four or more passes then there
        may be a leak in the baffles . " :LINE "(4) You
        underestimated boiler load ."))
```

RULE373
=======

SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
PREMISE :: ($AND
(SAME FRAME SET 22))
ACTION :: (DO-ALL
(MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating inefficiently as the stack temperature is lower than normal and the level of combustibles is also below normal ." :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1) The combustibles meter is faulty ." :LINE "(2) You have overestimated boiler load or your temperature reading is incorrect "))

RULE374
=======

SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
PREMISE :: ($AND
(SAME FRAME SET 23))
ACTION :: (DO-ALL
(MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating inefficiently as the stack temperature is higher than normal , the level of excess oxygen is below normal and the level of combustibles is also below normal ." :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING" :LINE "(1) There is excessive scale on the water-side of the fire tubes ." :LINE "(2) There is too much mud around the morrison tube " :LINE "(3) If your boiler has four or more passes then there could be a leak in the baffles . " :LINE "(4) The combustibles meter is faulty " :LINE "(5) The air damper or the linkage connecting it to the modulating motor's shaft is faulty . " :LINE "(6) You have underestimated boiler load "))

RULE375
=======

SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
PREMISE :: ($AND
(SAME FRAME SET 24))
ACTION :: (DO-ALL
(MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 "The boiler is operating inefficiently as the level of excess oxygen is below normal and the level of combustibles is also below normal ." :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING" :LINE "(1) Both the excess oxygen metering device and the combustibles metering device are faulty "))

```
RULE376
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
         (SAME FRAME SET 25))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is lower than normal ,
        the level of excess oxygen is below normal and the level of
        combustibles is also below normal ." :LINE "INEFFICIENCY IS
        PROBABLY DUE THE FOLLOWING" :LINE "(1) Air from outside is
        mixing with the flue gase before its temperature is measured
        or its composition analysed and the oxygen metering device is
        faulty ." :LINE "(2) The temperature measuring device is
        faulty and the flue gas analysers are also faulty . "))

RULE377
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
         (SAME FRAME SET 26))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 "The boiler is operating
        inefficiently as the level of excess oxygen is below normal
        ." :LINE "THE FOLLOWING COULD BE CAUSES OF INEFFICIENCY "
        :LINE "(1) Your excess oxygen metering device is faulty . ")
       )

RULE378
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 PREMISE :: ($AND
         (SAME FRAME SET 27))
 ACTION :: (DO-ALL
        (MPRINTT :LEFT 10 :RIGHT 70 :LINE 3 "The boiler is operating
        inefficiently as the stack temperature is lower than normal
        and the level of excess oxygen is also below normal ." :LINE
        "THE FOLLOWING COULD BE THE CAUSE OF INEFFICIENCY ; " :LINE
        "(1) You overestimated boiler load " :LINE "(2) The flue gas
        temperature measuring device is faulty or its positioning is
        faulty . " :LINE "(3) The excess oxgen reading is incorrect .
        "))
```

```
=========================
 Frame :: DIAGNOSIS
=========================

 IDENTIFIER :: DIAGNOSIS-
 PARENTS :: (SUPERVISOR)
 PROMPT1ST :: (:LINE :ATTR (CYAN HIGH) " The Boiler is operating
        inefficiently" :LINE 2 :ATTR (YELLOW HIGH) " Would you like
        to find out why ?" )
 RULEGROUPS :: (DIAGNOSIS-RULES)
 () :: ()
 DIAGNOSIS-RULES :: (RULE315 RULE316 RULE317 RULE356 RULE357 RULE358
            RULE359 RULE360 RULE361 RULE362 RULE363 RULE364
            RULE365 RULE366 RULE367 RULE368 RULE369 RULE370
            RULE371 RULE372 RULE373 RULE374 RULE375 RULE376
            RULE377 RULE378 )

  ====================
   DIAGNOSIS-RULES
  ====================

 RULE315
 =======
  SUBJECT :: DIAGNOSIS-RULES
  ANTECEDENT :: YES
If SET is 1,
Then inform the user of this decision.

 RULE316
 =======
  SUBJECT :: DIAGNOSIS-RULES
  ANTECEDENT :: YES
If SET is 2,
Then inform the user of this decision.

 RULE317
 =======
  SUBJECT :: DIAGNOSIS-RULES
  ANTECEDENT :: YES
If SET is 3,
Then inform the user of this decision.

 RULE356
 =======
  SUBJECT :: DIAGNOSIS-RULES
  ANTECEDENT :: YES
If SET is 4,
Then inform the user of this decision.
```

RULE357
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 5,
Then inform the user of this decision.

RULE358
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 6,
Then inform the user of this decision.

RULE359
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 7,
Then inform the user of this decision.

RULE360
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 8,
Then inform the user of this decision.

RULE361
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 9,
Then inform the user of this decision.

RULE362
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 10,
Then inform the user of this decision.

RULE363
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 11,
Then inform the user of this decision.

RULE364
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 12,
Then inform the user of this decision.

RULE365
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 13,
Then inform the user of this decision.

RULE366
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 15,
Then inform the user of this decision.

RULE367
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 16,
Then inform the user of this decision.

RULE368
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 17,
Then inform the user of this decision.

RULE369
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 18,
Then inform the user of this decision.

RULE370
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 19,
Then inform the user of this decision.

RULE371
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 20,
Then inform the user of this decision.

RULE372
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 21,
Then inform the user of this decision.

RULE373
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 22,
Then inform the user of this decision.

RULE374
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 23,
Then inform the user of this decision.

RULE375
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 24,
Then inform the user of this decision.

RULE376
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 25,
Then inform the user of this decision.

RULE377
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 26,
Then inform the user of this decision.

RULE378
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
If SET is 27,
Then inform the user of this decision.

DIAGNOSIS FRAME RULES: ABBREVIATED RULE LANGUAGE (ARL) VERSION

```
========================
Frame :: DIAGNOSIS
========================

IDENTIFIER :: DIAGNOSIS-
PARENTS :: (SUPERVISOR)
PROMPT1ST :: (:LINE :ATTR (CYAN HIGH) " The Boiler is operating
        inefficiently" :LINE 2 :ATTR (YELLOW HIGH) " Would you like
        to find out why ?" )
RULEGROUPS :: (DIAGNOSIS-RULES)
() :: ()
DIAGNOSIS-RULES :: (RULE315 RULE316 RULE317 RULE356 RULE357 RULE358
            RULE359 RULE360 RULE361 RULE362 RULE363 RULE364
            RULE365 RULE366 RULE367 RULE368 RULE369 RULE370
            RULE371 RULE372 RULE373 RULE374 RULE375 RULE376
            RULE377 RULE378 )


 ===================
  DIAGNOSIS-RULES
 ===================

RULE315
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 IF :: (SET = 1)
 THEN :: (PRINT :LEFT 10 :RIGHT 70 :ATTR (QUOTE (YELLOW)) :LINE 3 " The
      boiler is operating inefficiently as the stack temperature is
      higher than normal , the level of excess oxygen is above normal
      and the level of combustibles is also above normal ." :LINE "
      REASONS FOR HIGH TEMPERATURE READING " :LINE "(1) Check the
      level of water in the gauge glass . If the water level seems
      fine make sure that the level indication is not false by
      blowing down the water column . The water level should bounce
      back as soon as you close the blowdown valve . " :LINE "(2) If
      the water level is normal then either you have excessive soot
      on the insides of your firetubes or you have too much scale on
      the outside of the tubes . If you are sure that your water
      treatment program is being followed rigorously then you need
      to soot blow the inside of the tubes . If you have blown the
      soot off the firetubes then you could need a stricter water
      treatment program ." :LINE " (3) If both sides of you fire
      tubes are free of junk {soot and scale} then you may have
      collected mud around the morrison tube . You need to blow down
      immediately { bottom Blowdown } . " :LINE " (4) If even this
      does not solve the problem then there is a chance that there is
      a leak in the baffles between passes . This would mean that
      some of the hot combustion gases are not going through all the
      passes and this is showing up as high stack temperature . "
      :LINE "REASONS FOR HIGH EXCESS OXYGEN AND HIGH EXCESS
      COMBUSTIBLES " :LINE "(1) There is inadequate mixing between
      fuel and air before combustion . Bad mixing can be caused by
      incorrect air-fuel ratio . " )
```

RULE316
=======

```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 2)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
      inefficiently though the stack temperature is normal because
      the level of excess oxygen is above normal and the level of
      combustibles is also above normal ." :LINE "INEFFICIENCY IS
      PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "(1) The air damper
      is letting in too much air and this is causing insufficient
      mixing between fuel and air before combustion ." :LINE "(2) If
      you are firing oil then you are not atomizing properly ." )
```

RULE317
=======

```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 3)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
      inefficiently as the stack temperature is lower than normal ,
      the level of excess oxygen is above normal and the level of
      combustibles is also above normal ." :LINE "INEFFICIENCY IS
      PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "(1) There is
      insufficient mixing of fuel and air before combustion ." :LINE "
      (2) If you are firing oil then the problem is with atomization
      ." :LINE "(3) The air damper is letting in too much air and
      this is preventing the fuel and air from mixing properly . " )
```

RULE356
=======

```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 4)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
      inefficiently as the stack temperature is higher than normal
      and the level of combustibles is also above normal ." :LINE "
      INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
      There is a thick layer of soot covering the fire side of fire
      tubes " :LINE "(2) There is too much mud around the morrison
      tube and the flame is fuel rich . " :LINE "(3) There is an
      excessive amount of scale on the water side of the fire tubes .
      " :LINE "(4) If your boiler has four or more passes then there
      may be a leak in the baffles that seperate the passes . " )
```

RULE357
=======

```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 5)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
      inefficiently as the level of combustibles is above normal ."
      :LINE "INEFFICIENCY IS PROBABLY BECAUSE OF THE FOLLOWING ;"
      :LINE "(1) The flame is fuel rich . " :LINE "(2) The
```

combustibles sensor is giving an incorrect reading . ")

RULE358
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 6)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is lower than normal and
the level of combustibles is above normal ." :LINE "
INEFFICIENCY IS PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "(1)
The flame could be fuel rich and outside air is mixing with the
flue gases before it reaches the sensors ." :LINE "(2) The
temperature sensor could be malfunctioning . ")

RULE359
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 7)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is higher than normal
and the level of excess oxygen is also above normal ." :LINE "
INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
There is excessive scale on the water side of the fire tubes .
" :LINE "(2) There is too much mud around the morrison tube ."
:LINE "(3) If your boiler has four or more passes then there
may be a leak in the baffles that seperate the passes . "
:LINE "(4) The fireside of the fire tubes are coated with soot
. " :LINE "(5) The linkages connecting the mod motor shaft to
the air damper are not functioning properly and this is letting
in too much air .")

RULE360
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 8)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is higher than normal ,
the level of excess oxygen is also above normal level and the
level of combustibles is below normal ." :LINE "INEFFICIENCY IS
PROBABLY BECAUSE OF THE FOLLOWING ;" :LINE "(1) There is
excessive scale on the waterside of the fire tubes ." :LINE "
(2) There is too much mud around the morrison tube . " :LINE "
(3) If your boiler has four or more passes then there could be
a leak in the baffles seperating the passes ." :LINE "(4) The
air damper is letting in too much air . The linkages connecting
the modulating motor shaft to the air damper are not
functioning properly . ")

RULE361
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 9)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is higher than normal ,
the level of excess oxygen is below normal and the level of
combustibles is above normal ." :LINE "INEFFICIENCY IS PROBABLY
DUE TO THE FOLLOWING ;" :LINE "(1) There is excessive soot on
the fireside of the firetubes . " :LINE "(2) The flame is
excessively fuel rich ." :LINE "(3) There is too much mud
around the morrison tube ." :LINE "(4) If your boiler has four
or more passes then there may be a leak in the baffles
seperating the passes .")

RULE362
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 10)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the level of excess oxygen is below normal and
the level of combustibles is above normal ." :LINE "
INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1) The
air damper could be letting in too little air ." :LINE "(2) The
excess oxygen sensor could be malfunctioning . ")

RULE363
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 11)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is lower than normal ,
the level of excess oxygen is also below normal and the level
of combustibles is above normal ." :LINE "INEFFICIENCY IS
PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1) The air damper is
letting in too little air ." :LINE "(2) The temperature sensor
is malfunctioning . ")

RULE364
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 12)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
inefficiently as the stack temperature is higher than normal .
" :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING :"
:LINE "(1) There is excessive scale on the water side of the
fire tubes ." :LINE "(2) There is too much mud around the
morrison tube ." :LINE "(3) If your boiler has four or more
passes then there may be a leak in the baffles between the
passes . ")

DIAGNOSIS FRAME RULES: ABBREVIATED RULE LANGUAGE (ARL) VERSION

RULE365
=======
```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 13)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
    inefficiently as the stack temperature is higher than normal
    and the level of excess oxygen is below normal ." :LINE "
    INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
    There is excessive scale on the waterside of the fire tubes ."
    :LINE "(2) There is a lot of mud around the morrison tube ."
    :LINE "(3) If your boiler has four or more passes then there
    may be a leak in the baffles which seperate the passes ."
    :LINE "(4) You may have underestimated load ." )
```

RULE366
=======
```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 15)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
    inefficiently as the stack temperature is lower than normal ."
    :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "
    (1) The temperature sensor is malfunctioning " :LINE "(2) You
    overestimated boiler load . " )
```

RULE367
=======
```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 16)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
    inefficiently as the level of excess oxygen is above normal ."
    :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "
    (1) The air damper is not moving freely . The linkages between
    the modulating motor shaft and the air damper is either too
    tight or too loose . " )
```

RULE368
=======
```
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 17)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
    inefficiently as the stack temperature is lower than normal and
    the level of excess oxygen is above normal ." :LINE "
    INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING" :LINE "(1)
    Outside air is mixing with the flue gases before it reaches the
    sensors . " )
```

```
RULE369
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 IF  :: (SET = 18)
 THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the level of combustibles is below normal ."
        :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "
        (1) The combustibles measuring device is faulty . " )

RULE370
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 IF  :: (SET = 19)
 THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently though the stack temperature is normal because
        the level of excess oxygen is above normal and the level of
        combustibles is below normal ." :LINE "INEFFICIENCY IS PROBABLY
        DUE TO THE FOLLOWING " :LINE "(1) Outside air is mixing with
        the flue gases before it reaches the sensors . " )

RULE371
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 IF  :: (SET = 20)
 THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is lower than normal ,
        the level of excess oxygen is above normal and the level of
        combustibles is below normal ." :LINE "INEFFICIENCY IS PROBABLY
        DUE TO THE FOLLOWING ;" :LINE "(1) Outside air is mixing with
        the flue gases before it reaches the sensors ." )

RULE372
=======
 SUBJECT :: DIAGNOSIS-RULES
 ANTECEDENT :: YES
 IF  :: (SET = 21)
 THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating
        inefficiently as the stack temperature is higher than normal
        and the level of combustibles is below normal ." :LINE "
        INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1)
        There is excessive scale on the waterside of the firetubes "
        :LINE "(2) There is too much mud around the morrison tube"
        :LINE "(3) If your boiler has four or more passes then there
        may be a leak in the baffles . " :LINE "(4) You underestimated
        boiler load ." )
```

RULE373
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 22)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating inefficiently as the stack temperature is lower than normal and the level of combustibles is also below normal ." :LINE " INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING ;" :LINE "(1) The combustibles meter is faulty ." :LINE "(2) You have overestimated boiler load or your temperature reading is incorrect ")

RULE374
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 23)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating inefficiently as the stack temperature is higher than normal , the level of excess oxygen is below normal and the level of combustibles is also below normal ." :LINE "INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING" :LINE "(1) There is excessive scale on the water-side of the fire tubes ." :LINE "(2) There is too much mud around the morrison tube " :LINE "(3) If your boiler has four or more passes then there could be a leak in the baffles . " :LINE "(4) The combustibles meter is faulty " :LINE "(5) The air damper or the linkage connecting it to the modulating motor's shaft is faulty . " :LINE "(6) You have underestimated boiler load ")

RULE375
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 24)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 "The boiler is operating inefficiently as the level of excess oxygen is below normal and the level of combustibles is also below normal ." :LINE " INEFFICIENCY IS PROBABLY DUE TO THE FOLLOWING" :LINE "(1) Both the excess oxygen metering device and the combustibles metering device are faulty ")

RULE376
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 25)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 " The boiler is operating inefficiently as the stack temperature is lower than normal , the level of excess oxygen is below normal and the level of combustibles is also below normal ." :LINE "INEFFICIENCY IS PROBABLY DUE THE FOLLOWING" :LINE "(1) Air from outside is mixing with the flue gase before its temperature is measured or

its composition analysed and the oxygen metering device is
faulty ." :LINE "(2) The temperature measuring device is faulty
and the flue gas analysers are also faulty . ")

RULE377
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 26)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 "The boiler is operating
inefficiently as the level of excess oxygen is below normal ."
:LINE "THE FOLLOWING COULD BE CAUSES OF INEFFICIENCY " :LINE "
(1) Your excess oxygen metering device is faulty . ")

RULE378
=======
SUBJECT :: DIAGNOSIS-RULES
ANTECEDENT :: YES
IF :: (SET = 27)
THEN :: (PRINT :LEFT 10 :RIGHT 70 :LINE 3 "The boiler is operating
inefficiently as the stack temperature is lower than normal and
the level of excess oxygen is also below normal ." :LINE "THE
FOLLOWING COULD BE THE CAUSE OF INEFFICIENCY ; " :LINE "(1) You
overestimated boiler load " :LINE "(2) The flue gas temperature
measuring device is faulty or its positioning is faulty . "
:LINE "(3) The excess oxgen reading is incorrect . ")

APPENDIX C:

Sample Program Session

Assume sensor feedback from the boiler output has shown the amount of combustibles present to be at an acceptable level, as is the temperature of the flue gas exiting the boiler. Assume, however, that the amount of oxygen found at the boiler output is 4.0percent. Assume the optimal amount of excess oxygen for this particular boiler, given the type of fuel and its firing rate, is 2.5 percent. The following dialogue might take place.

MAD: Are the sensors that gather flue gas data intrusive to the stack?
USER: Yes, with a certainty factor (CF) of 100 percent

MAD: Are the sensors that gather flue gas data located at the boiler outlet?
USER: Yes, CF 90

MAD: Is the sensor located at the center of the stack's cross-section?
USER: Yes, CF 80

MAD: Are the sensors that gather flue gas data located BEFORE a stack junction coming from another boiler?
USER: Yes, CF 70

MAD: Is the stack draft positive?
USER: Yes, CF 60

MAD: Is the stack sensor clean from dirt?
USER: Yes, CF 50

MAD: Are the sensors calibrated?
USER: Yes, CF 40

MAD: Is the grade of fuel the same as it was the last time the boiler was known to be running efficiently?
USER: Yes

MAD: Which type of air/fuel controller do you have?
USER: Mechanical

MAD: Does the boiler have some sort of oxygen trim system?
USER: Yes

MAD: Use the arrow keys to select the type of trim assembly on the boiler, then press 'Enter'.
USER: O_2 probe with variable link

MAD: Are the linkages connected to the jackshaft tight, with no slippage?
USER: No, CF 10

MAD: The conclusions are as follows. The fact that there is a little bit of looseness in the linkages associated with the jackshaft indicates that there may be too much oxygen entering through the air damper in proportion to the amount of fuel being fed for combustion. Tighten up the looseness. Also check the adjustment cam assembly (where the jackshaft linkages meet the fuel valves) for deformations in the roller plate or for loose screws which shape that plate.

The following might also need adjustment in order to achieve optimal excess oxygen: burner gun position, furnace pressure, and the swirl at burner inlet. There may be looseness or sloppiness in the variable link of the oxygen trim assembly, causing it to allow too much oxygen to enter. Tighten it up if there is any sloppiness.

This opinion on the cause of the boiler's inefficiency is only APPROXIMATELY 60 percent reliable.

Associated with each ~~of the~~ questions above is a help key which instructs the user on how to use the arrow keys to indicate his desired input, and explains why it is important to collect data in a certain manner. Consider the following example.

MAD: Are the sensors which gather flue gas data intrusive to the stack?
USER: Yes, with a certainty factor (CF) of 100 percent

MADHELP: The sensors should be intrusive. If they are extrusive, this means that flue gas is being removed from the stack and circulated through piping to an external sensor. Extrusion is less accurate because this external piping allows for a greater chance that tramp air (the ambient room air surrounding the piping) will infiltrate the piping and falsely increase the oxygen reading. Also, the temperature of the flue gas will definitely, and sometimes drastically, be lowered as a result of the gas being extracted from the stack and allowed to cool in the extrusive piping before being monitored by the probe.

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US Army Engr District
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US Army Engr Division
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US Army Europe
ATTN: AEAEN-EH 09014
ATTN: AEAEN-ODCS 09014
29th Area Support Group
ATTN: AERAS-FA 09054
100th Support Group
ATTN: AETT-EN-DPW 09114
222d Base Battalion
ATTN: AETV-BHR-E 09034
235th Base Support Battalion
ATTN: Unit 28614 Ansbach 09177
293d Base Support Battalion
ATTN: AEUSG-MA-AST-WO-E 09086
409th Support Battalion (Base)
ATTN: AETTG-DPW 09114
412th Base Support Battalion 09630
ATTN: Unit 31401
Frankfurt Base Support Battalion
ATTN: Unit 25727 09242
CMTC Hohenfels 09173
ATTN: AETTH-DPW
Mainz Germany 09185
ATTN: BSB-MZ-E
21st Support Command
ATTN: DPW (10)
US Army Berlin
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ATTN: AEBA-EN 09235
SETAF
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ATTN: AESE-EN 09630
Supreme Allied Command
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HQ XVIII Airborne Corps 28307
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4th Infantry Div (MECH)
ATTN: AFZC-FE

US Army Materiel Command (AMC)
Alexandria, VA 22333-0001
ATTN: AMCEN-F
Installations:
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FORSCOM
Forts Gillem & McPherson 30330
ATTN: FCEN
Installations:
ATTN: DPW (23)

6th Infantry Division (Light)
ATTN: APVR-DE 99505
ATTN: APVR-WF-DE 99703

National Guard Bureau 20310
ATTN: Installations Division

TRADOC
Fort Monroe 23651
ATTN: ATBO-G
Installations:
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USA Natick RD&E Center 01760
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USARPAC 96858
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SHAPE 09705
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Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

HQ USEUCOM 09128
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AMMRC 02172
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ATTN: Facilities Engr (3) 85613

USAARMC 40121
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Military Traffic Mgmt Command
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Fort Leonard Wood 65473
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ATTN: ATZA-TE-SW
ATTN: ATSE-CFLO
ATTN: ATSE-DAC-FL

Military Dist of WASH
Fort McNair
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USA Engr Activity, Capital Area
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Defense Logistics Agency
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Walter Reed Army Medical Ctr 20307

National Guard Bureau 20310
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US Military Academy 10996
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ATTN: Geography & Envr Engrg

Naval Facilities Engr Command
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ATTN: Division Offices (11)
ATTN: Public Works Center (8)
ATTN: Naval Constr Battalion Ctr 93043
ATTN: Naval Civil Engr Service Center (3) 93043

8th US Army Korea
ATTN: DPW (12)

USA Japan (USARJ)
ATTN: APAJ-EN-ES 96343
ATTN: HONSHU 96343
ATTN: DPW-Okinawa 96376

416th Engineer Command 60623
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US Army HSC
Fort Sam Houston 78234
ATTN: HSLO-F
Fitzsimons Army Medical Ctr
ATTN: HSHG-DPW 80045

Tyndall AFB 32403
ATTN: HQAFCESA Program Ofc
ATTN: Engrg & Srvc Lab

USA TSARCOM 63120
ATTN: STSAS-F

American Public Works Assoc. 64104-1806

US Army Envr Hygiene Agency
ATTN: HSHB-ME 21010

US Gov't Printing Office 20401
ATTN: Rec Sec/Deposit Sec (2)

Nat'l Institute of Standards & Tech
ATTN: Library 20899

Defense Tech Info Center 22304
ATTN: DTIC-FAB (2)

295
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