EXPERT SYSTEMS CAN CONTROL FERROALLOY PRODUCTION PROCESSES

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INTRODUCTION

Knowledge based expert systems are computer programs designed to imitate human experts in activities such as decision making and problem solving. During the current decade, this powerful methodology for using computers has begun to find application in service and manufacturing industries. (1-4)

Expert systems are a technology for the 90's because, while they are already being used, the methodology is still maturing and increasing in capability. Based upon performance thus far, expert systems will become an important tool in the continual quest for improved product quality and reduced production costs.

Elkem is currently developing an expert system for application in the domain of ferroalloy smelting process control. This paper describes expert systems in general and discusses Elkem's project, the Furnace Advisor, in detail.

WHAT IS AN EXPERT SYSTEM?

An expert system is a collection of computer programs that behaves like a human expert in some useful ways.(5) Stated differently, an expert system is computer programming that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise.(6)

An expert system is comprised of several major components as shown in Figure 1.(7) The user interface is the communications link which allows the system to present results to and request data from the person using it. The working memory holds information which describes the current status of the problem being investigated. This information can be intermediate conclusions reached by the system as well as data supplied by the user. The explanation subsystem responds to user requests

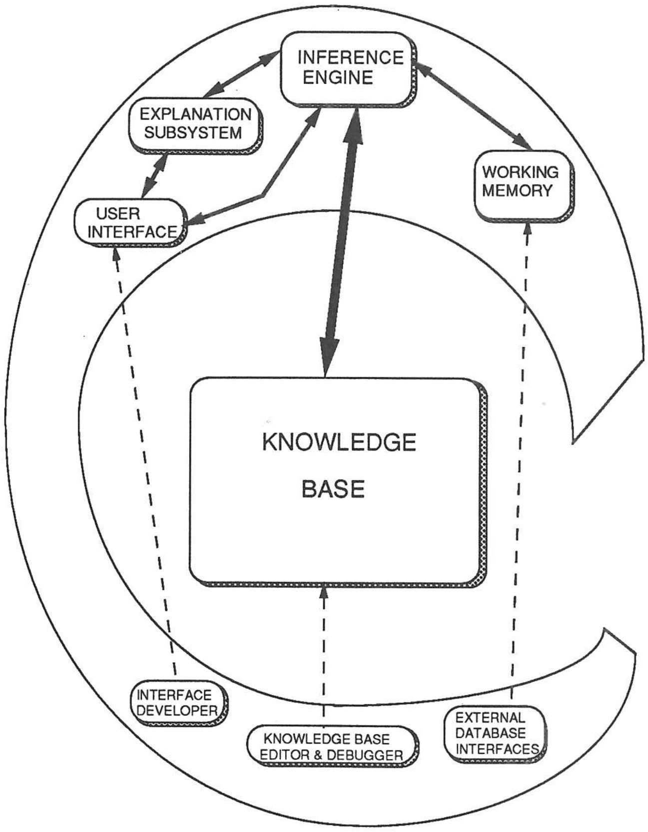

Figure 1 - Block Diagram of an Expert System
Represents Basic Relationships
Represents Additional Tools
Represents System Shell

for information about how to answer a system generated question, why a question was asked, and how a specific conclusion was reached.

The core of any expert system is its knowledge base and inference engine or interpreter. The knowledge base is that portion of the system wherein the field (i.e, domain) information is represented. One method by which information can be recorded is the If - (condition), Then - (action) or rule technique. To build a system, a knowledge engineer interviews the domain expert to gather facts and heuristics (i.e., rules of thumb) pertinent to the field. After deciding upon a particular representation method to be used, he transforms the initial interview results into the form required by that scheme. Following this, several iterations of "demonstrate system - acquire additional information - incrementally improve knowledge base" are required to bring the expert system to an acceptable level of performance.

The inference engine controls the search of the knowledge base and working memory for pieces of matching information which enable it to formulate intermediate conclusions, place additional information in the working memory, and, ultimately, draw a final conclusion. Inference engines process knowledge according to one or more paradigms or procedures. In the forward or data-driven chaining procedure, the interpreter reasons from initial status data to a goal or solution. This paradigm is often used in systems whose purpose is to act as a decision making assistant or a use advisor. The goal normally takes the form of one selection or a ranked list of selections made from many alternatives. Several inference procedures as well as knowledge representation techniques are reviewed in a paper on Expert System Building Tools. (8)

Software "tools" to build, maintain, and run an expert system consist of all the components just described with the exception that the knowledge base is empty. That is, it does not contain any domain specific information. Additional programs shown in Figure 1 are:

- o A knowledge base editor and debugger to simplify entering and correcting information in the knowledge base.
- o An interface developer to ease the programming requirements for building a user interface.
- o Interfaces to standard external database programs and to programming languages.

This combination of tools, without the domain knowledge, is often referred to as an Expert System Shell. A shell can be used to build a system for any domain as long as the knowledge representation and inferencing techniques supported by it are applicable.

ADVANTAGES OF EXPERT SYSTEMS

The methodology of expert systems does not represent a breakthrough or revolution in problem solving and decision making. Having derived from the field of Artificial Intelligence, where the goal is to enable computers to perform these tasks, expert system techniques employ today's best understanding of the processes as humans do them.

Expert system tools assist knowledge engineers in representing concepts about information and reasoning at a level of abstraction which allows them to concentrate on the domain rather than upon how to make a computer operate on the concepts. As stated in a very readable review of Artificial Intelligence, "AI is not magic; from a strictly engineering point of view, in fact, it is simply a set of programming techniques".(9) Both the methodology and goals of expert systems are compared to those of conventional programming in Table I.(10, 11)

A major portion of the life cycle of any software system is devoted to maintenance. Correcting program errors, while obviously necessary, is not the largest maintenance activity. Any significant system will need, over its lifetime, to be modified, improved, or extended. These maintenance items can be very expensive. Not the least cause of this is that often the system's data and goal (its purpose) and the control structure (its operation) are so innerconnected that any change is a major undertaking. In expert systems, the information and control structure are, by design, kept separate thereby minimizing this contributor to the maintenance problem.

A distinct advantage of expert system tools is that incremental development of the knowledge base and user interface is possible. That is, changes to an expert system can be produced rapidly, usually within a few days of a knowledge acquisition interview. This ability to quickly demonstrate the "look and feel" of a system is not available in conventional methods. Because it facilitates communication between the system's end users, the knowledge engineer, and the domain expert, incremental development has an impact upon the capability and acceptance of the system.

Conventional programming techniques have been and will continue to be used to solve many complex problems. Some tasks, however, involve so many possibilities that these methods do not suffice. The large number of possible combinations that results from problems like making a choice from multiple options can require so many conventional programming resources that such projects are economically unfeasible. Expert system techniques use heuristics or rules of good judgment to reduce the number of combinations to manageable proportions. Many formerly intractable problems can be handled by this methodology.

A full survey of expert systems currently in development or use is beyond the scope of this paper. However, the following list is a sample of systems which have been discussed in the recent literature.

- o FIS or Fault Isolation System is under development at the US Naval Research Laboratory. It assists technicians in

TABLE I

Differences Between Expert System and Conventional Programming

Expert System Programs	Conventional Programs
Use symbolic computational processes; words and lists of words are manipulated.	Use numeric processes; numbers are manipulated.
Controlled by heuristic search allowing flexibility to explore, reach dead-end, back track and explore different path.	Controlled by algorithm where all steps are defined a' priori.
Control structure (i.e., how the program works) and knowledge are separate.	Control structure and data are tightly integrated.
Interruptions of program's execution for explanations are easily done and are part of interactive use of system.	"Mid-run" explanations are meaningless except for debugging.
Satisfactory answers are often acceptable, depending upon purpose of system.	Best solution is only answer.
Incorrect responses by user are tolerable, they often lead to informative results.	Only correct responses (data) have meaning.

diagnosing faults in electronic equipment.(12)

- o Programmer's Apprentice is being developed at Massachusetts Institute of Technology. Its purpose is to automate the specification, construction, and documentation of computer programs.(13)
- o HEPAR assists in the medical diagnosis of liver and biliary diseases.(14)
- o Mudman is marketed by NL Baroid. It assists in the diagnosis and correction of deep-well drilling fluid problems.(15)
- o ASDEP is used in the design of auxiliary electrical systems in power generation facilities.(16)
- o GATES assigns passenger gates to arriving and departing flights at John F. Kennedy Airport (New York) for Trans World Airlines.(17)
- o RESRA was developed at Security Pacific Corporation to review the work of residential property appraisers for completeness and consistency.(18)

ELKEM AND EXPERT SYSTEMS

The Decision to Create an Expert System

Since 1966, a computerized process control system, SAFEPAC(tm), has been used and continually improved. This system imitates the control responses which an "ideal operator" would employ were that mythical combination of good operators manipulating a furnace. That is, its approach embodies the characteristics of a simple expert system. Conventional programming techniques were used to create and develop the system and it therefore contains disadvantages inherent in those methods. Given the investment expended in creating SAFEPAC and the fact that it controls furnaces quite well, it still is feasible to apply new programming methods (i.e., expert system techniques) to aspects of furnace control not available in the extant system.

A project for the optimization of a ferroalloy furnace's performance began in 1987 at Elkem's Ashtabula, Ohio, facility. The performance criteria for measuring progress toward that goal are furnace load, efficiency, and operating time. Given the massiveness of the operation in terms of the quantities of raw materials, energy, and alloy involved, small changes in the criteria are significant. Thus, results of any attempt to improve them can be masked by variability introduced through portions of furnace operation that are not well controlled. It followed that part of the optimization project would be to place under computer control the use of non-routine raw material combinations. This is being accomplished by building an expert system, the Furnace Advisor, and integrating it with the operation of the SAFEPAC system.

The purpose of Furnace Advisor is to significantly improve the accuracy and consistency of the use of special raw material mixtures for furnace control. Conservative expectations for its contribution to improvements in furnace load, efficiency, and operating time are 2%, 2%, and 1%, respectively. Achieving those targets will result in a project payback period of about 12 months.

The Domain of Furnace Advisor

While a submerged arc furnace is operating, direct examination of the state of reactants, products and electrode tip positions in the reaction zone is not feasible. When a unit is off, electrode tip positions can be estimated by probing for them with a measuring bar. However, disrupting the energy supply to a furnace is costly not only in terms of production lost but, when an extended period occurs, in terms of potential electrode breakage and deterioration in the efficiency of the smelting reaction itself. The 50 megawatt, 50% FeSi furnace being served by the expert system is unusual because the electrode holders are semi-stationary. That is, the vertical movement available is insufficient for raising electrode tips into a position for direct observation or for accurate measurement by probing. This same limited movement also restricts the ability to respond to tip locations which are too deep or shallow in the furnace.

Frequently, temporary changes are made to the normal amounts of reducing agents and iron source in the raw materials fed to the furnace. These special mix orders are used in response to upsets in appropriate carbon composition in the materials, so-called under- or over-coked conditions, and to deep or shallow tip positions, actually long or short electrodes, which cannot be overcome by vertical movement. Feeding special mix to the furnace was chosen as the domain of Furnace Advisor because it is not under computer control but has crucial impact upon the operation of the furnace.

Furnace operators (crew leader, supervisor, and engineer) diagnose the causes of operations problems by inferring carbon levels and electrode lengths based upon indirect indicators. While many are instrumented, several key variables are available only by human observation.

Interpreting the indications is a complex task. As a result, mistaken diagnoses and therefore inadequate or even improper corrective actions could be implemented. Thus, decisions are often temporarily postponed to allow the indicators to become more definitive or to allow consultation with the engineer who bears accountability for the furnace's operation.

Interpreting indicators is complicated by the fact that they often interact with each other. This creates uncertainty in the decision about whether a particular situation does, in fact, exist. Therefore, any diagnostic session concludes with a list of possible causes ranked in order of their certainty. If none of the possible causes have a high degree of certainty, then the furnace sometimes is shut off to collect more information, usually in the form of electrode measurements and undercover observations for water leaks. In order to improve problem diagnosis and corrective action formulation, the collective skills of all personnel involved in the furnace operation are being represented in Furnace Advisor's knowledge base.

Status of Furnace Advisor

Consultation with a Carnegie Group Incorporated systems engineer has resulted in the creation of an expert system. Modifications were made to a pre-existing system so that it would perform interpretation, accommodate some special knowledge representation, and formulate corrective action strategies in a manner appropriate for the selected domain.

Communications between computers have been established such that Furnace Advisor receives process status information from the SAFEPAC system as it monitors and controls other aspects of the furnace operation. This capability will relieve a user of Furnace Advisor from the tedium of manually entering most data. However, the expert system does not have to depend upon SAFEPAC. Its user interface allows manual data entry should that be desired.

Knowledge acquisition is continuing. While this part of building an expert system is never really complete, its progress can be described by the well known "S Curve" as shown in Figure 2. Furnace Advisor's knowledge base is still on the steeply ascending portion of the curve. However, it contains sufficient information or representations of the expert's knowledge for conducting successful prototype demonstrations of the system. Full comprehension of the complexity of the knowledge acquisition effort required could well have inhibited starting the process of building this expert system. Naivete is sometimes a useful attribute. The recent literature describes this problem which is often referred to as the acquisition bottleneck.(19-24)

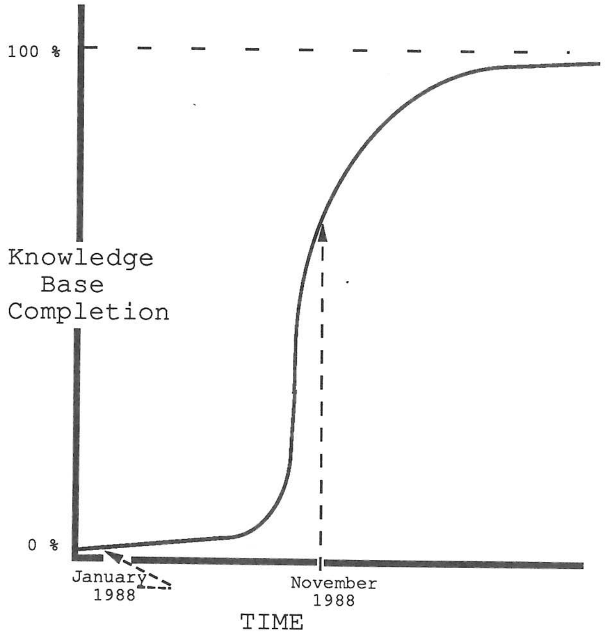

Figure 2 - Status of Furnace Advisor's Knowledge Base

The Furnace Advisor knowledge base editor and debugger tools are unable to arbitrate or resolve differences between conflicting pieces of information. The knowledge engineer must do this as the knowledge base is built. Perhaps the best way to minimize this problem is to work, at least until the base is well formed, with only one domain expert. There are cases where this presents no difficulty because there is only one acknowledged expert. In fact, the impetus for building an expert system can be to eliminate the vulnerability of that situation!

In the case of Furnace Advisor, several individuals possess domain expertise and are naturally anxious that it be represented in the knowledge base. As a practical matter, however, the production engineer responsible for technical operation of the furnace has been selected as the main domain expert. His expertise is being utilized to create a knowledge base framwork. As the performance of the expert system is reviewed by others who have been responsible for running furnaces, additions of their expertise will enhance the knowledge base's content.

During the first half of 1989 the domain expert and knowledge engineer will begin using Furnace Advisor to diagnose actual furnace conditions. In addition, shift supervisors will be interviewed to acquire their expertise for the knowledge base. Concurrently, they will be familiarized with the system's user interface; in effect, supervisors will be trained to use the system as an assistant in decision making. Testing of the system, to ensure that its decisions are as good as those of the expert, will proceed throughout most of the year.

Future Expert System Applications

Generation of the major part of Elkem's sales originates from submerged arc furnace production of ferroalloys and silicon metal. Other contributors are liquid-state, "post taphole" refining and alloying stations, aqueous electrolytic deposition cells, and solid-state vacuum refinement furnaces. Improving process control of these units offers great potential for reducing production costs and thus increasing profitability. Using expert system technology to preserve and consistently apply existing human operating expertise can contribute significantly to this effort. It is likely that diagnostic problems similar to those addressed by Furnace Advisor will be the focus of the next expert system project. However, expert systems in process control can be classified into two broad groups of which diagnosis is one.(25) The second group deals with process regulation and optimization. In this category, the selection of setpoint values (particularly the aim operating load) and the manipulation (both relaxation and restriction) of electrical constraints are potential applications.

Expert system techniques can be used in domains other than process control. Additional fields of application include:

- Production scheduling of different foundry-grade products in the liquid-state alloying facility is a tedious task. A computerized assistant would be helpful.

- Failures are infrequent in the hardware and software of the SAFEPAC process control system. When they occur, however, repair requires searching through many voluminous manuals. An expert system which could advise a user about the proper section of manual to be consulted would decrease the maintenance time required.

- Repair of electrical faults in auxiliary equipment, such as the mix delivery system, is a task requiring highly skilled technicians. An expert system running on a portable personal computer which could be taken to the job site would significantly increase their productivity.

- Foundry-grade ferroalloys are used in the production of gray and ductile iron castings. Elkem specialists in foundry practice possess expertise in analyzing the causes of casting defects. As a service to customers, an expert system which would reproduce their analysis skills would be beneficial.

FURNACE ADVISOR EXPLORED

Furnace Advisor and SAFEPAC

Users of the expert system will primarily be shift supervisors. They will initiate a session and then interact with the system by responding to queries for values of furnace operation variables which are available only by direct observation. The end of the diagnostic phase will be accompanied by a list of causes, ranked according to believability, for the furnace's substandard operation. If the diagnosis is acceptable, a list of proposed corrective actions will be displayed. These will be implemented manually. Unlike the SAFEPAC system, where control actions are performed without human intervention, the Furnace Advisor will initially be used strictly in an open-loop fashion.

As confidence in the system's accuracy is established, a series of enhancements will be implemented. First, the diagnostic list of causes will only display upon demand should the user feel it's needed. Later, corrective actions for causes whose diagnoses are independent of user observations will be communicated to the SAFEPAC computer for automatic execution. Additional corrective actions will be automated as ways are found to instrument the "observables" or as dependence upon them is diminished by more skillful diagnosis. Finally, sessions of the Furnace Advisor will be initiated by the SAFEPAC system whenever it detects that furnace performance requires them.

The goal of these improvements is to make the control of special raw material mixtures completely closed-loop. This effort obviously increases the interdependency of the two computer systems. Should either of them be inoperable, however, the other can continue to function independently. The level of control sophistication would deteriorate in such a case.

Knowledge Representation

Information about a field, that is, domain knowledge, may be represented by rules of the form If - (condition), Then - (result or action). For example, consider information about an electrode as presented in Table II. On a real furnace, of course, decisions to move an electrode or to change the mix are not so straight forward as in this simple illustration. Representing the domain knowledge for the use of special raw material mixtures would require several hundred, perhaps a few thousand, entries in the knowledge base if the rule method were the only technique available.

Any body of related facts and heuristics inherently possesses a structure that can be represented in a more understandable and maintainable way with a technique known as frames. Frames are essentially tabular data structures. As entities in a knowledge base, they have several useful features. Each frame has a unique name which is used to identify the object it represents. A frame has a list of properties which is used to describe the named object, concept, or action. Each entry of the list is a pair where the first member is the name of a property and the second is the specific value of the property for the object being described.

Frames are used in the Furnace Advisor knowledge base to represent the concept of causes responsible for substandard furnace operations. Beginning with symptoms of poor performance, the knowledge base consists of several "causal cascades". Figure 3 shows a single cascade; each decision point in the network is a frame which describes either a symptom or a cause of poor performance. Examples of symptoms are low or high single-phase resistances and low or high silicon content of alloy.

TABLE II

The Use of Rules to Represent Knowledge

Results

- If:
  - Calculated Length Maximum Desired Length
  - (And)
  - Calculated Length Minimum Desired Length
- Then :
  - Calculated Length = Normal

- If:
  - Holder Position Maximum Holder Position - 5
- Then:
  - Holder Positon = High

- If:
  - Current Maximum Current - 100
- Then:
  - Current = Acceptable

Actions

- If:
  - Calculated Length = Normal
  - (And)
  - Holder Position = High
  - (And)
  - Current = Acceptable
- Then:
  - Move Holder Down

- If:
  - Calculated Length = Normal
  - (And)
  - Holder Position = High
  - (And)
  - Current = High
- Then:
  - Decrease Coal in Mix

Intermediate causes in Figure 3 describe a model, albeit one based on a mental conceptualization rather than physically verifiable states, of the furnace's raw material overburden, reaction zone, and metal pool regions. Examples of intermediate causes are too little distance between the electrode tip and metal pool and excessive molten alloy accumulation in the furnace. Root causes cannot be further subdivided. They represent the most basic level required for proposing corrective responses such as extra electrode slipping and decreasing coal in the mix. Root causes are failures such as a long electrode and inadequate tapping practices.

Property name:value pairs in the knowledge base frames contain information about the domain. For example, the linkage between any cause and the ones below it is described by a causal frame property named Due-To. Property values are the frame names of lower level causes.

Furnace operators infer the existence of specific poor performance causes based upon indicators or evidence exhibited by the unit; for a given furnace condition, not all causes will be active (i.e., exist). The use of evidence is represented in causal frame properties called Occurs-Rules. Values of these properties are actually the names of additional frames, called rule frames, which describe how operators evaluate evidence. Examples of indicators used as evidence are hydrogen concentration in the furnace off-gas, gas temperatures in the fume hood ducts, and energy consumed between taps.

An illustration of causal and rule frames with Due-To and Occurs-Rules properties is presented in Figure 4. Evidence contributes to the believability of a cause's existence according to its type and the magnitude of its value. Thus, evidence has associated with it a certainty factor, expressed as values from -1.0 to +1.0, which describes its effect. This is represented by a rule frame property named Rule-Certainty-Factor. Rule frames employ the If, Then format where the If - (condition) portion is composed of questions about the furnace's status. The Then - (result) part of the rule is actually the value of the Rule-Certainty-Factor property.

The Interpreter

The knowledge base causal cascades form a network which starts with symptoms and ends with basic or root causes. Associated with some intermediate and all root causes are corrective actions. Paths through the network decision points are not specified. The interpreter's task is to use the furnace's status to find all paths whose causes are believable and, in traversing those paths, to collect all

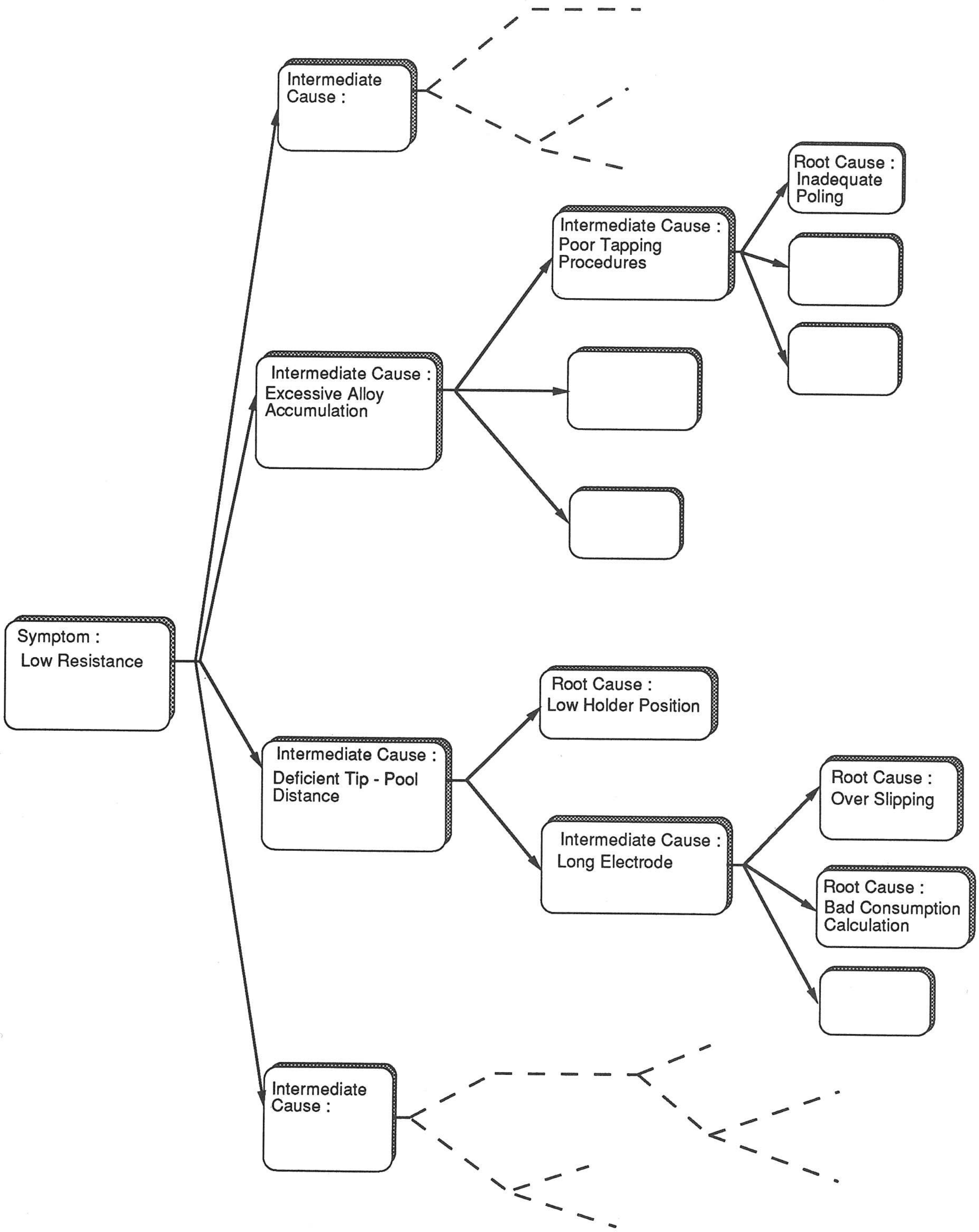

FIGURE 3 - An Example of a Causal Cascade Used to Represent Information in the Furnace Advisor Knowledge Base

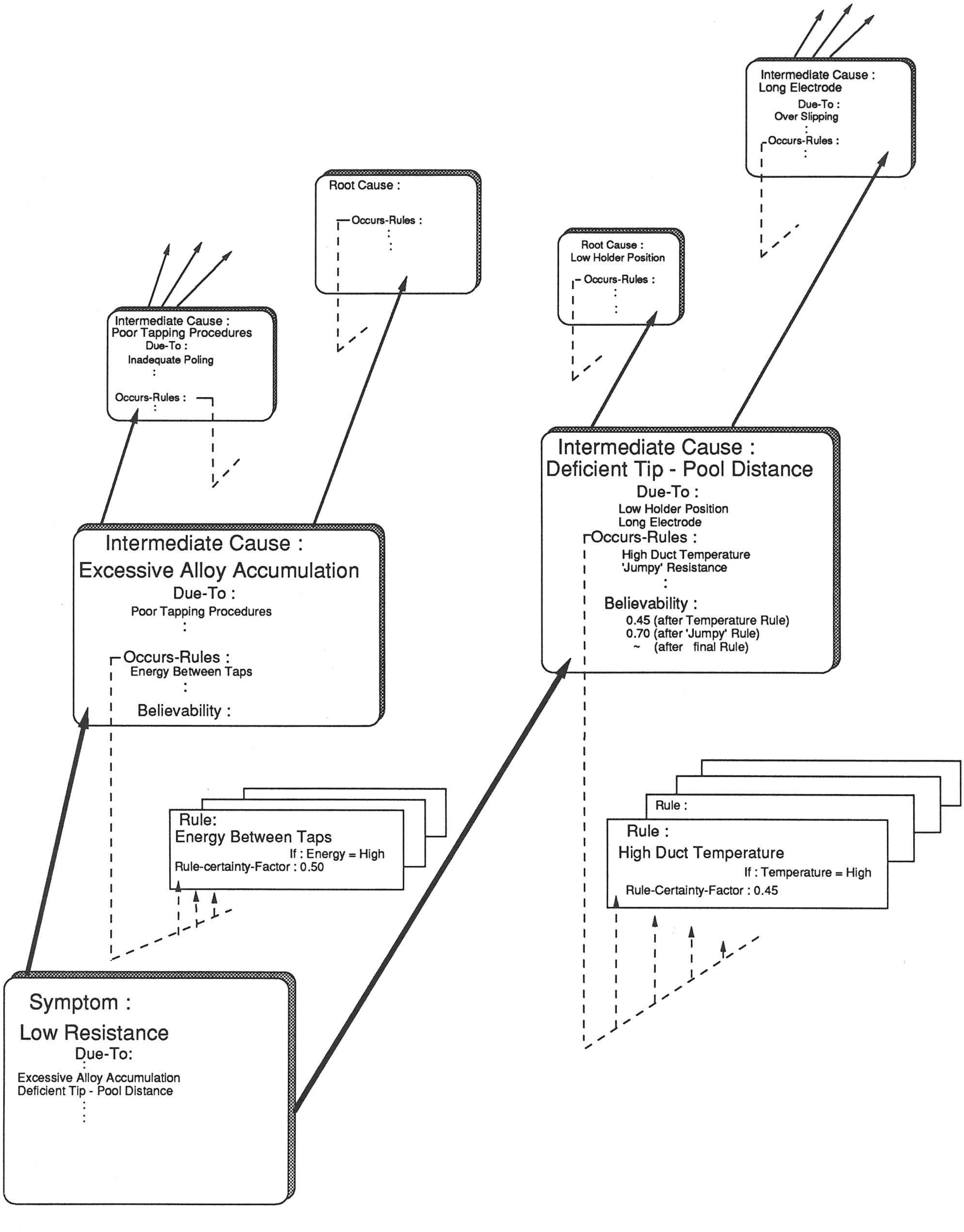

FIGURE 4 - Examples of Causal and Rule Frames
with Name:Value Property Pairs

corrective actions allowed by them. Upon completing the search of the network, the terminations or root causes of all paths are the final diagnosis. The list of corrective actions, however, has to be further refined in order to eliminate duplication and any nonsensical combinations such as slip an electrode and shutdown to measure electrode lengths.

The search for paths through the network is exhaustive. That is, the interpreter does not stop after identifying the first root cause. This approach is necessary because:

o There can actually be multiple causes of poor operation.

o There is no way to immediately confirm that a single corrective action does or does not improve the furnace. If the confirmation time required were allowed to elapse between single actions, the operation would remain substandard since new problems would occur before the old ones were all corrected.

Determining whether or not a cause is believed depends upon evaluating the rules of evidence for and against it. The interpreter compares the current values of indicators to the values required for acceptance or rejection of the cause. When the status of the furnace matches the requirements of a rule, then that rule's certainty factor is used to modify the believability of the cause. This is illustrated by the changing value for the Believability property of Intermediate Cause: Deficient Tip - Pool Distance in Figure 4. If a cause's final believability is greater than a threshold value, then it becomes part of the problem diagnosis and any causes linked to it by its Due-To property are evaluated.

In addition to the diagnostic search of the causal cascades for believable causes, there is a corrective action strategy. Each causal frame in the knowledge base carries a Has-Corrective-Responses property although many of the higher level causes have no values. If a cause is believed, its corrective actions are arbitrated by rule frames. That is, not all of the possible responses to a specific cause will be appropriate for a given furnace condition. Acceptable actions are placed upon a list. At the conclusion of diagnosis, members of this list are separated according to numerous categories. Within specific categories, further refinement of suggested actions or responses may be done to eliminate any duplications. For example, the category for special mix changes could contain more than one recommendation to add steel to the mix destined for a specific furnace bin; only one of these suggestions is retained. Also, there could be multiple recommendations for both increasing and decreasing the amount of reducing agents for the mix to a bin; these are algebraically summed. Once the final list of corrective actions has been formulated, it is presented to the user for implementation.

User Interface

A diagnostic session with Furnace Advisor involves user and system interaction which takes place through screen displays similar to the one illustrated in Figure 5. System requests for furnace operating data, shown near the top of the display, can be satisfied by using the screen pointing device to select one of the choices offered or by using the keyboard to enter a value (usually, only numerical responses are required). When a keyboard entry is appropriate, the darkened area across the center of the screen lightens, a user prompt appears, and the icons displaying choices are omitted. In cases where Furnace Advisor communicates with the SAFEPAC system, the value received is shown directly under the statement of the question. If the value is outside limits used by the data transfer function to check its accuracy, it will be rejected and the system will default to one of the other two modes of requesting input from the user.

Instead of responding with an answer to a system question, a user may select any of the utility icons shown across the bottom of the display screen. WHY generates a description of the cause responsible for invoking the question. Also displayed are the next higher cause and any other causes residing in the Due-To property of that cause's frame. HOW displays information about how to acquire the data necessary for answering the question. BACKUP allows the user to retract a previous answer and enter different data. The SUMMARY icon will generate a display showing the believabilities of all causes which have been evaluated and whether they are above or below the threshold value for being included in the diagnosis. THRESH allows this threshold value to be changed.

The area at the top of the screen can be thought of as a window upon a scroll containing every exchange which has taken place during a session with the Furnace Advisor. This window can be moved backward to allow the user to review previous exchanges not currently displayed. In addition, MENU enables the user to create

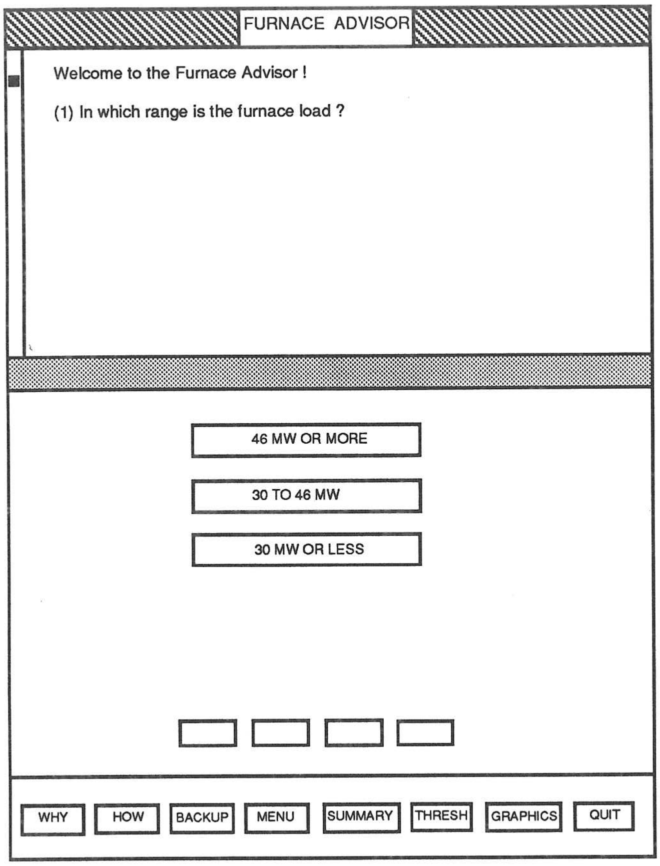

Figure 5 - An Example of the User Interface

a log of the session which can be printed out for a permanent record of all exchanges which occurred during a session.

CONCLUDING REMARKS

This paper discusses Elkem's activity in applying the technology of expert systems to computer process control. Some advantages of the technology as an improved method of instructing computers are presented. Details of knowledge representation and inferencing techniques are given.

Elkem has for some time been using a real-time process control system in the operation of ferroalloy furnaces. This system, though built with conventional programming techniques, is like an expert system in that it mimics human experts' skills. We believe the expert system methodology is an excellent choice for placing additional aspects of production processes under computer control. Several potential applications are suggested.

The rationale for selecting the domain of the Company's first expert system is given. Use of the system, to begin early in 1989, will be open-loop with control responses implemented manually. Parts of the system will be made closed-loop as development continues. It is expected that this expert system will contribute significantly to the goal of furnance optimization.

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