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APPLICATION OF ARTIFICIAL INTELLIGENCE TO MELTER CONTROL: REALTIME PROCESS ADVISOR FOR THE SCALE MELTER FACILITY

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ABSTRACT

The Defense Waste Processing Facility (DWPF) at the Savannah River Plant (SRP) is currently under construction and when completed will process high-level radioactive waste into a borosilicate glass waste-form. This facility will consist of numerous batch chemical processing steps as well as the continuous operation of a joule-heated melter and its off-gas treatment system. A realtime process advisor system based on Artificial Intelligence (AI) techniques has been developed and is currently in use at the semiworks facility, which is operating a 2/3 scale of the DWPF joule-heated melter.

The melter advisor system interfaces to the existing data collection and control system and monitors current operations of this facility. The advisor then provides advice to operators and engineers when it identifies process problems. The current system is capable of identifying process problems such as feed system pluggages and thermocouple failures and providing recommended actions. The system also provides facilities normally found with distributed control systems. These include the ability to display process flowsheets, monitor alarm conditions, and check the status of process interlocks.

Additional features are being added to the melter advisor to provide the ability to perform online material and energy balances and to provide advice based on these balances. The ability to provide recommendations for process controller settings based on the current operation of the melter system is also being investigated.

The melter advisor has been developed on a Symbolics™ LISP computer and uses Inference Corporation's Automated Reasoning Tool (ART™). The use of these high-end AI tools permitted the development and deployment of this system in 6 man-months and the ability to add to the system incrementally without affecting prior functionality.

INTRODUCTION

One of the recent outgrowths from the efforts of the artificial intelligence community is the field of expert systems or knowledge-based computer systems as they have recently come to be known. Expert systems are attracting a great deal of interest from the industrial sector since they represent a practical application of artificial intelligence useful in everyday business activities. In many cases the use of an expert system is analogous to the use of a spreadsheet; it is another tool at our disposal to use as we see fit in performing our business.

What is an expert system or knowledge-based computer system? An expert system is a computer program that utilizes the organized expertise of one or a number of human experts to provide advice or to solve a problem within the domain of the expertise. For the case of the melter advisor and many other expert systems, this expertise is coded in the form of rules that are applied to a specially structured knowledge base containing information about the domain of the expertise and the problem currently being examined. When confronted with a problem, the expert system takes actions specified by rules based on the human experts knowledge, and in so doing simulates the behavior of the human experts had they confronted the problem.

The thrust of this work is the use of expert systems to provide advice, on a realtime basis, to engineers and operators running a chemical process -- in this case a melter system for the production of glass. The development of an expert system to monitor a chemical process requires the coding of the knowledge base, a description of the components of the process, and the rules for interpreting the state of the process and recognizing when problems have developed. The ultimate objective of this study is to provide the following expert systems capabilities:

- Process Operating Advice
- Fault Diagnosis
- Process Control Advice
- Multiple Alarm Analysis

Examples illustrating each of the above capabilities is provided in Table I.

The philosophy behind the development of the melter advisor has been to consider it an experiment. Given the current state of AI computer systems and software, we want to determine whether an online process advisor is feasible or indeed worthwhile. With this in mind, the near-term experimental objectives behind the project are twofold: first, to provide expert systems capability in the form of an online advisor; and second, to use the power of AI tools to provide additional capabilities not present with the current control and data monitoring system. With the second objective, we also are determining how much time is required compared to conventional hardware and software systems.

SCALE MELTER DESCRIPTION

The scale melter is a 2/3 linear scale of the actual DWPF joule-heated melter. It has been used to demonstrate many of the design and operational concepts of the DWPF melter. The scale melter facility includes the melter, two separate feed systems for the melter, and an extensive off-gas scrubbing system.

A cross-sectional view of the melter interior is shown in Figure 1. The melter vessel is lined with K-3 refractory to provide containment of the molten glass. Two pairs of diametrically opposed electrodes provide around 90 kW of power into the glass pool to maintain the glass temperature between 1,050 and 1,100°C. Each pair of electrodes is controlled separately to provide different amounts of power to the upper and lower portions of the melt pool. Lid heaters located in the vapor space of the melter provide an additional 120 kW of power to the pool surface to vaporize the water in the melter feed. Glass is poured from the melter through the heated riser and pour spout sections of the melter.

The process control system for the scale melter facility consists of a panelboard containing controllers, chart recorders, and a graphic alarm panel at the top. Each controlled variable is typically handled by an individual controller. The facility does not have a programmable logic controller (PLC) or a distributed control system (DCS) typically found in many newer facilities. The melter facility has 275 process variables (temperatures, pressures, flowrates, voltages, etc.), which are monitored by a Kaye™ Datalogger system. The Datalogger system updates current values of the process variables every 7 seconds. Data collection software running on a DEC VAX™ computer collects data from the Datalogger every minute for long-time storage, data analysis, and reporting. This control and data monitoring system has been quite reliable.

SCALE MELTER PROCESS ADVISOR

Hardware and Software Considerations

The problem of providing a realtime process advisor for an operating chemical process is a large one. To provide the expert systems capabilities desired and also to provide the speed required to work in realtime, it was decided to use a high-end AI expert systems tool on a Symbolics™ LISP machine. The expert systems tool chosen was the Automated Reasoning Tool (ART™) from Inference Corporation. ART™ provided the expert systems capabilities and was perceived as being one of the fastest expert system tools available at the time. The Symbolics™ LISP machine served as an excellent hardware and software

Table I: Examples of Potential Expert Systems Capabilities

Process Operating Advice

- "The cold cap coverage is 100%, the melter is being overfed. The suggested action is to reduce the feed rate to 0.25 gpm."
- "Instrument readings indicate the riser heater is operating at 3.6 kW. Based on the four thermocouples monitoring its temperature, the operating mode of the melter, and previous operating history, this appears high by 1 kW. Please investigate the ..."

Fault Diagnosis

- "The power being supplied to the pour spout heater has been steady for the last 10 hours. Over this time period, one of the two thermocouples monitoring its temperature has been drifting steadily up at a rate of 10° C/hr. This thermocouple is probably failing."
- "The feed system pump will not start. Let's go through the diagnostic program..."

Process Control Advice

- "The flow controller for the condenser cooling water is overshooting badly. It needs adjustment. I recommend ..."
- "The feed composition to the melter has changed significantly with this new batch of feed. This will change the dynamics of the melter pool (glass resistivity, viscosity, etc.). The control parameters for the electrode controllers should be changed to ..."

Multiple Alarm Analysis

- "High pressure alarms in numerous melter off-gas locations occurred in the last 2 minutes. The problem appears to be ... because ..."

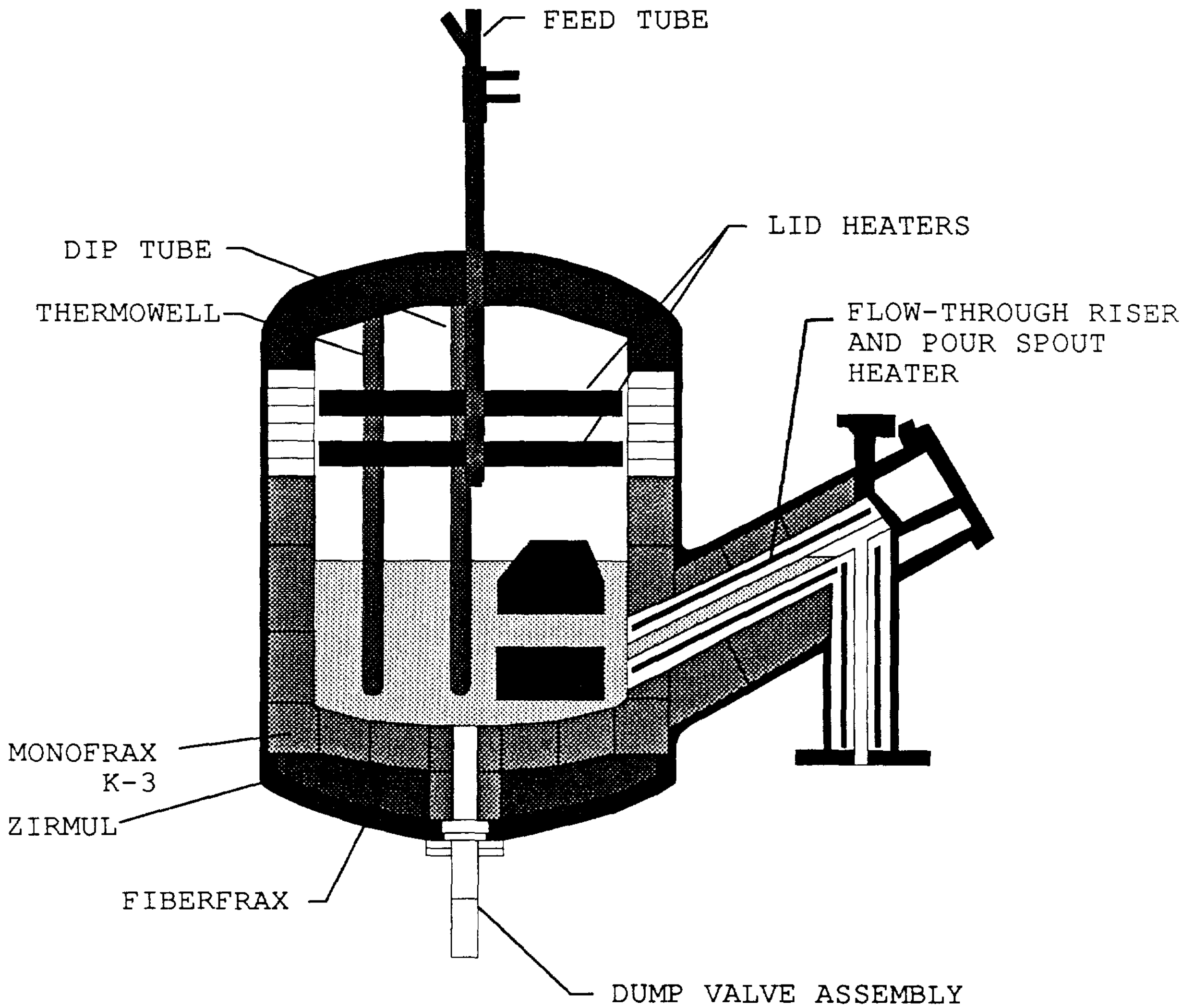

Figure 1: DWPF Scale Glass Melter.

Cross-sectional view of the DWPF scale glass melter.

platform by providing a mouse-driven user interface, a complete windowing system, a full screen editor, networking capabilities, and excellent debugging features. The Symbolics™ LISP machine also supports object-oriented programming and incremental compilation of source code. This latter feature provides the ability to modify a small section of code (or to add new code to the advisor) while the advisor is running. This feature greatly increases the productivity of the developer.

Advisory Capabilities

The current version of the scale melter advisor is capable of providing process operating advice for the melter feed system and for some areas of melter operation. This advice includes recommendations covering feed system pluggages, melter thermocouple failures, and melter riser and pour spout heat load and thermocouple inconsistencies. In the feed system, for instance, the advisor will watch the pressure drop across the strainer in the feed line to the melter. If the pressure drop across the strainer is increasing with time, and this increase exceeds a threshold value, then the advisor warns that the strainer is probably plugged and provides the recommended action to remedy the situation. There are a number of places in the feed system where pluggages could occur, and these locations are monitored by the advisor. In the melter a number of thermocouples are redundant (in the same location), and the advisor will watch for discrepancies between these thermocouples. It is particularly important for melter control to recognize that a thermocouple is failing. If a thermocouple in the melter electrode control loop fails, and this event goes undetected, it could lead to improper operation of the melter. This situation happened during the operation of the scale melter and resulted in lower pool temperatures and the formation of foam in the melter. The advisor will now warn operators of this problem should it occur in the future.

The melter advisor also contains many features that are not related to expert systems, but that were easily incorporated because of the power of the hardware and software tools being used. These include graphic displays of the process showing current values of process variables, recognition and logging of alarms, and the ability to check the interlock status of process equipment based on current process conditions. These features are normally found in distributed control systems.

Future capabilities of the advisor system include energy and material balance calculations for the melter system and the ability to reason from these balances. Also, the capability to provide recommendations for electrode controller settings based on the current operation of the melter is being investigated.

Functional Description

The melter process advisor is built around the user interface inherent with the Symbolics™ LISP machine and as supported by the Automated Reasoning Tool (ART™). Navigation through the system is completely done through mouse selections with very little need for typed input from the user. Screen displays of the melter process advisor are shown in Figures 2 through 7. As shown in these figures, the advisor consists of a number of smaller windows (or panes in LISP machine terminology) arranged on a larger window (or frame), which covers the full size of the screen.

The upper left-hand corner of the screen contains the window labelled "Notifications." This is a log by date and time of all significant events and advice that has been provided since the advisor has been running. This window primarily contains notifications of process variables entering or leaving alarm condition. The window is scrollable, so one can easily go back in time to view past notifications.

The upper right-hand corner of the screen contains the window labelled "Selections." This window provides menu selections that allow the user to determine current melter conditions. The energy balance and material balance selections are not functional yet. An example of choosing "Check Interlocks" from this menu is shown in Figure 7. This selection brought up another menu, which is the listing of all interlocked devices. In this case, the "Primary Feed Pump" was selected, and a description of this interlock and its current status are displayed. It is also possible to check all of the interlocks and display a listing of the ones that have a status of "Tripped." Because of the structured nature of the knowledge base of the advisor (discussed later), the addition of the interlock functionality to the advisor only took 3 man-days to accomplish. It is also worth noting from examination of Figure 7, that any one of 11 process variable could prevent or stop the primary feed pump from operating. The advisor can report the status of this interlock in less than 2 seconds; it takes an operator or engineer somewhat longer. The interlock knowledge is an example of an addition to the present control system, which is arguably not expert systems technology, but which could be done much quicker using the power of the AI tools than by using more conventional software.

The narrow middle section of the screen contains the window labelled "Flowsheet Selections." This is a menu window that controls the display of the main process graphic, which is located in the bottom window of the screen. This graphic shows the current conditions for a major section of the process. Figures 2, 4, and 6 show the major graphic displays for the melter system, the off-gas system, and the alternate feed system respectively. This process graphic display capability is very similar to those found with distributed control systems.

Each major process graphic displayed at the bottom of the screen contains current values for process variables. Each of the process variables are mouse-sensitive. Selecting a particular variable, for instance the riser heat amperage shown in Figure 3, will provide a description of the variable displayed in the upper left-hand corner of the screen. This contains information about the process variable including the current, maximum and minimum values, as well as the alarm settings and alarm condition for each variable. This display can change depending on the attributes of the particular variable selected. For instance, a number of variables will also display information about their rate of change over a certain period of time.

It is also noteworthy that the alarm limits to be applied to a process variable may be different for run and extended idle conditions (Figure 3) of the melter. The advisor contains rules based on melter and feed conditions, which determine the transition from run to extended idle or vice versa. It then applies the correct alarm limits. In the case of the Datalogger monitoring and alarm system, an operator must load a tape in order to switch the alarm settings.

The major process graphic displays also contain mouse-sensitive regions of particular portions of the display. When one of these regions is selected, a detailed displayed of this area is presented. For instance, the display produced by selecting the riser/pour spout section of the melter in Figure 2 produced the more detailed graphic of this area shown in Figure 3. Likewise, the selection of the area highlighted in Figure 4 produced the more detailed graphic of the steam atomized scrubbers shown in Figure 5. This way of moving through the graphic displays appears quite intuitive. Most of the detailed graphic images, the melter and the riser/pour spout for instance, were drawings created by members of the melter team using the Macintosh™ personal computer. These images were directly imported to the Symbolics™ LISP machine. This saved considerable time in creating the advisor screen displays and also gave the members of the melter team a feeling of ownership in the advisor system.

The most time-consuming task during the development of the advisor system was the interface of the process data with the Symbolics™ machine. This task took approximately 50% of the development time of the advisor (about 3 man-months), and improvements in this area can still be made. The method used was task-to-task communication of the Symbolics™ and the DEC VAX™ (running the data collection software) using Decnet software over an ethernet connection. This provides the melter process advisor with new values for the 275 monitored process variables once per minute. It is limited to once per minute because the data collection software on the VAX™ only updates values once per minute. The advisor is capable of updating all the variables once every 15 seconds. Because of the dynamics of the melter process, it turns out that once per minute is more than adequate. Also, the use of the ethernet for a "data highway" allows for more freedom in the location of the Symbolics™ computer during development.

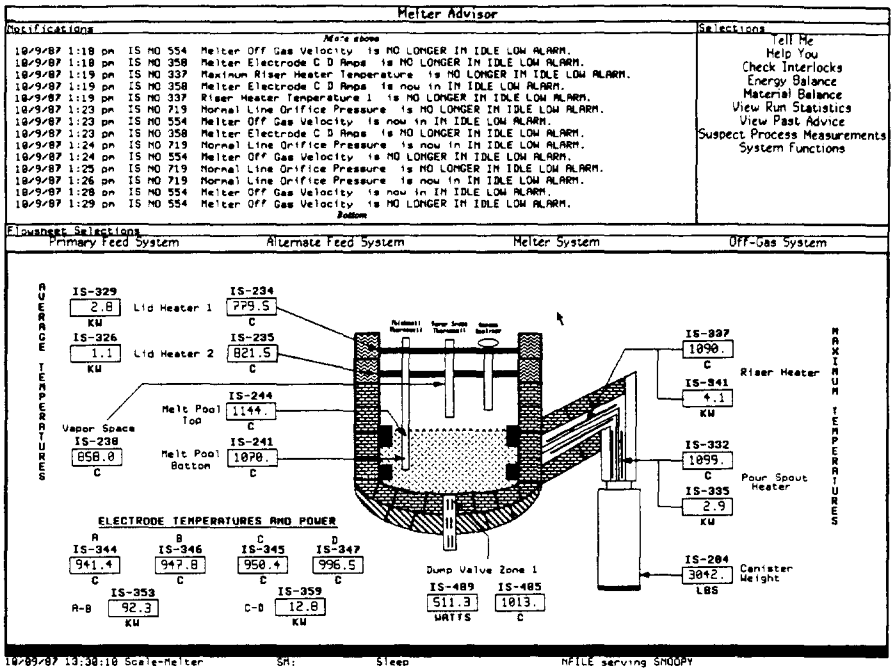

Figure 2: Melter Advisor Screen Display 1.

This screen illustrates the window layout of the advisor and shows the major process graphic display of the scale melter.

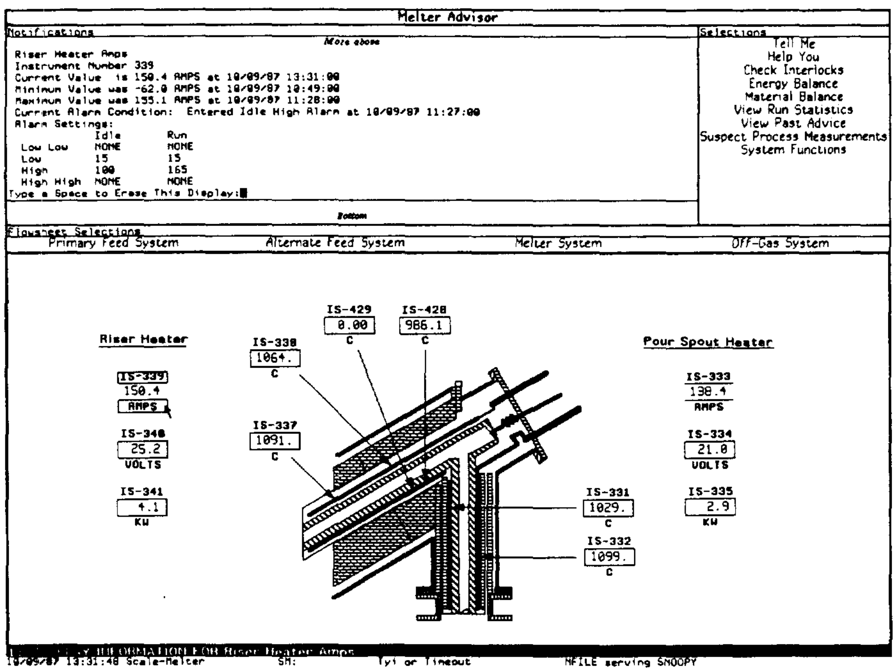

Figure 3: Melter Advisory Screen Display 2.

This screen illustrates the detailed graphic for the riser/pour spout section of the scale melter obtained by selection of the area of the melter shown in Figure 2. This screen also illustrates the selection and description of the process variable "Riser Heater Amps."

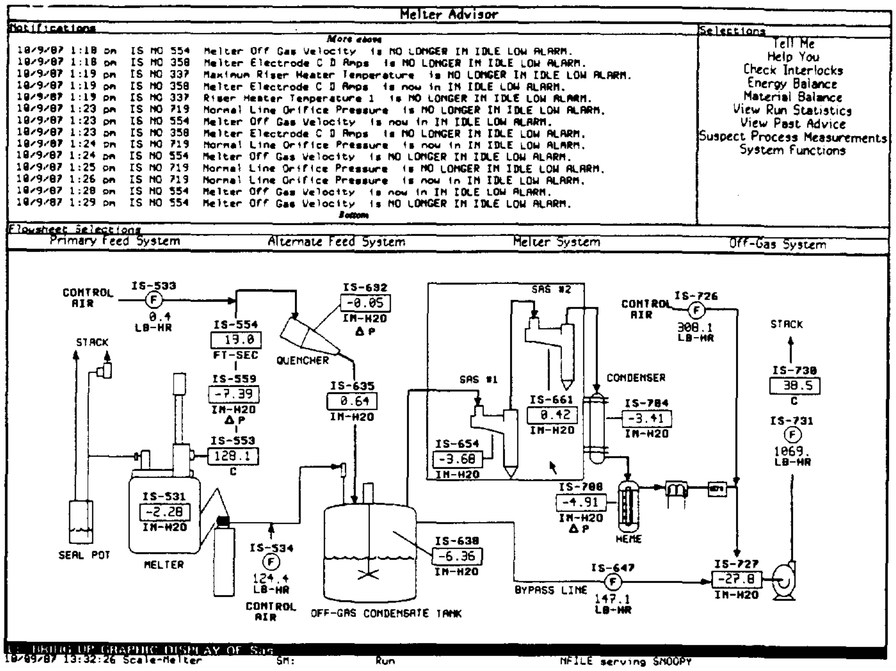

Figure 4: Melter Advisor Screen Display 3.

This screen illustrates the major process graphic display of the scale melter off-gas system and shows an area of the screen highlighted for selection.

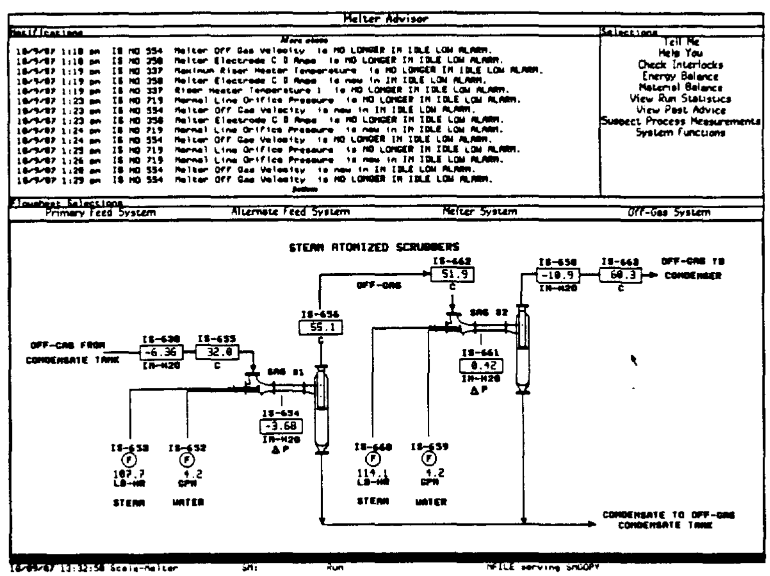

Figure 5: Melter Advisor Screen Display 4.

This screen illustrates the detailed graphic for the steam atomized scrubbers obtained by selecting the area of the screen highlighted in Figure 4.

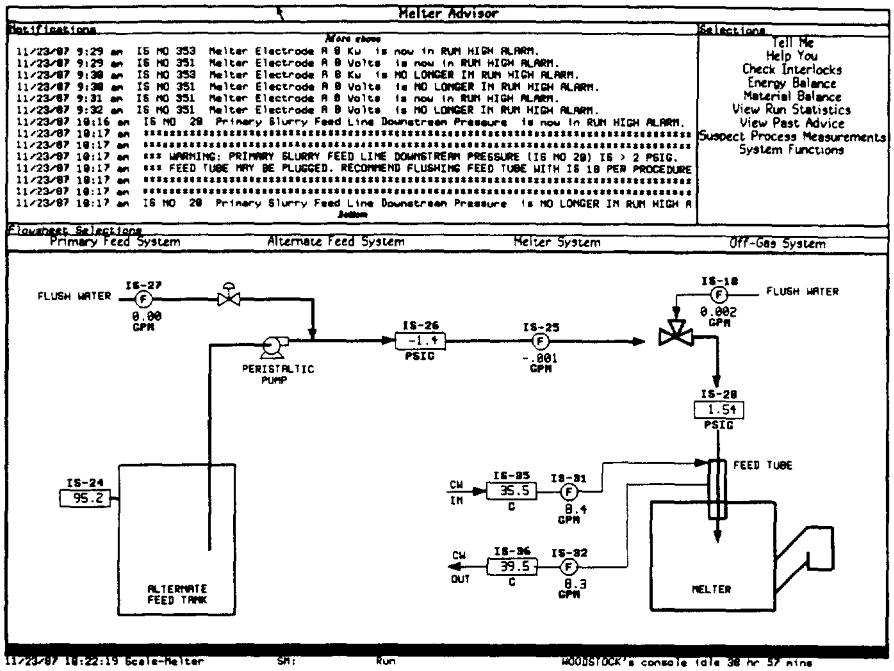

Figure 6: Melter Advisor Screen Display 5.

This screen shows the alternate feed system of the scale melter minutes after a pluggage of the melter feed tube. The notification provided by the advisor concerning the problem is illustrated.

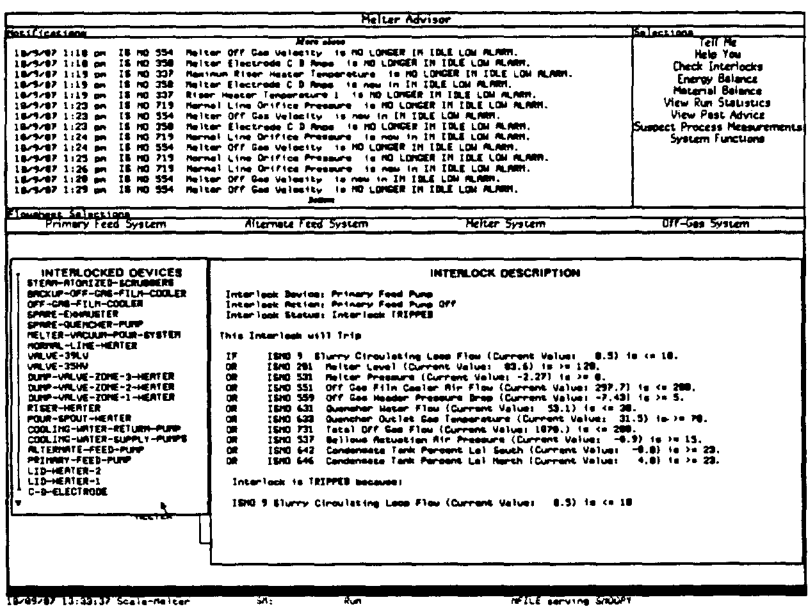

Figure 7: Melter Advisor Screen Display 6.

This screen illustrates the interlock devices menu and the interlock description for the primary feed pump.

Knowledge Base

The knowledge base for the advisor consists of an object-oriented description of the process components of the scale melter facility and the relations among the components. The knowledge base also utilizes the attachment of procedural LISP code to an object and the inheritance of object attributes and procedural code by related objects. In these ways, the knowledge base utilizes the complete object-oriented programming facilities provided by the Automated Reasoning Tool (ART™) by Inference Corporation. Object-oriented programming is a very powerful way to describe the objects (pumps, temperature sensors, heaters, electrodes, etc.) found in the scale melter process, and the relations between the objects, and at the same time provide coding that is applicable to related objects.

The best means to describe the knowledge base is through the use of an example. Figure 8 contains a description of the object electrical-resistance-heater. The attributes of an electrical-resistance-heater are defined as length, width, thickness, material, temperature, amperage, voltage, and wattage. Following this description is the object pour-spout-heater, which is an instance of an electrical-resistance-heater. The pour-spout-heater has values filled in for the attributes associated with it being an electrical-resistance-heater. The attribute values in this case are either numbers or the names of other objects. For instance, one of the temperatures of the pour-spout-heater is the object pour-spout-temperature-1, which has its own attributes and values. Pour-spout-temperature-1 is an actual process-measured temperature for one location along the pour-spout-heater. Another attribute of pour-spout-heater is the material of which it is made -- in this case, the object Inconel-690, which has attributes of its own including its melting point. This object-oriented description continues on to describe the entire melter system, its components, and the relations among the components. The excerpt shown in Figure 8 is a simple example, but it should convey the basic idea.

Also, associated with objects is the attachment of procedural code. The object electrical-resistance-heater may have "actions" associated with it. The actions are procedural code that would be common to all objects that are electrical-resistance-heaters. For example, this object could have an action that will calculate the current density of the heater from the current value for the amperage of the heater and the heater cross-sectional area. This action would be inherited by all objects that are electrical-resistance-heaters -- the pour-spout-heater being one example. The attachment of procedural code to objects is an extremely powerful programming capability. It also illustrates the modular or "building block" nature of this programming environment. Each object and its code are complete unto themselves. They can be reused in other applications, modified, or added to without affecting the coding of the rest of the system.

Rulebase

The rulebase provides the ability to reason, based on the state of the melter process and the knowledge-based description of the process. This is done in the form of "If-Then" rules. If a condition becomes true, then assert a new fact into the knowledge base concerning the state of the process or issue a warning to an operator. Asserting a new fact into the knowledge base may cause additional rules to activate (called firing), which may assert a new fact into the knowledge base or possibly withdraw facts from the knowledge base. One example of a rule that uses the knowledge base excerpt of Figure 8 would be as follows:

> "IF the temperature of an electrical-resistance-heater is within 150°C of the melting point of the heater material and the temperature has a high belief value,
> THEN warn the operator."

This rule will activate and warn the operator whenever any electrical-resistance-heater is within 150°C of the melting point of the material of which it is made. The rule is very general and very powerful. It doesn't matter how many electrical-resistance-heaters are in the process or of what material they are made as long as they have been included in the knowledge base. Likewise, a heater could be deleted from the knowledge base, and this has no affect on the rule. Other general rules have been easily incorporated into the advisor. For example, in the area of sensor validity, if the power (wattage) of an electrical-resistance-heater is a negative value, then don't believe the value; it is probably zero. Or, if a temperature reading has a negative value on an absolute temperature scale, then don't believe the value. The rulebase provides the same building block concept as the knowledge base. It can be added to incrementally without altering the previous rules in the system or the knowledge base.

```
(defschema ELECTRICAL-RESISTANCE-HEATER
  (LENGTH)
  (WIDTH)
  (THICKNESS)
  (MATERIAL)
  (TEMPERATURE)
  (AMPERAGE)
  (VOLTAGE)
  (WATTAGE))


(defschema POUR-SPOUT-HEATER
 (instance-of ELECTRICAL-RESISTANCE-HEATER)
  (LENGTH  200")
  (WIDTH    1.00")
  (THICKNESS  0.25")
  (MATERIAL  Inconel-690)
  (TEMPERATURE POUR-SPOUT-TEMPERATURE-1
           POUR-SPOUT-TEMPERATURE-2)
  (AMPERAGE POUR-SPOUT-HEATER-AMPERAGE)
  (VOLTAGE  POUR-SPOUT-HEATER-VOLTAGE)
  (WATTAGE  POUT-SPOUT-HEATER-WATTS)
 (instance-of MELTER-COMPONENT))


(defschema POUR-SPOUT-TEMPERATURE-1
 (instance-of MEASURED-VARIABLE)
  (INSTRUMENT-NUMBER 331)
  (INPUT-DEVICE ROCHESTER-B)
  (TRANSMITTER-RANGE 0 TO 1300 DEGREES C)
  (DATALOGGER-RANGE 300 TO 1300 DEGREES C)
     .
     .
     .
     )

(defschema INCONEL-690
 (instance-of  METAL-ALLOY)
 (melting-point 1350 DEGREES C)
    .
    .
    .
    )
```

Figure 8: Knowledge Base Structure

This provides a simple example of the object-oriented structure of the knowledge base. The object pour-spout-heater is defined along with its related objects, Inconel-690 of which it is made, pour-spout-temperature-1, which is one of its monitoring temperatures, and electrical-resistance-heater of which it is an instance.

CONCLUSION

The experiment has been a success. The advisor demonstrates the feasibility of an online advisor and the power of the AI tools being used. It contains many features that are not completely related to expert system technology. Although the expert systems capabilities of the advisor are limited at present, the added expertise is only a few rules away. Because of the building block structure of the advisor, rules or other features can be added without changing any of the prior coding or functionality of the advisor. As the melter facility is operated and more expertise is acquired, this expertise is translated into rules and added to the advisor.

Future work in this area will involve additions to the present advisor system and the transfer of this technology to the actual production facility (DWPF). Work is also underway to provide batching advice to control the feed composition to the melter in view of upstream process uncertainty.

ACKNOWLEDGMENTS

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