TEACHING A COMPLEX INDUSTRIAL PROCESS

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COINS Technical Report 86-~~24~~ 66

A slightly condensed version of this paper has appeared in the National Conference for Artificial Intelligence (AAAI-86), Philadelphia, PA., 1986.

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ABSTRACT

Computer training for industry is often not capable of providing advice custom-tailored for a specific student and a specific learning situation. In this paper we describe an intelligent computer-aided system that provides multiple explanations and tutoring facilities tempered to the individual student in an industrial setting. The tutor is based on a mathematically accurate formulation of the kraft recovery boiler and provides an interactive simulation complete with help, hints, explanations, and tutoring. The approach is extensible to a wide variety of engineering and industrial problems in which the goal is to train an operator to control a complex system and to solve difficult "real time" emergencies.

This work was supported by The American Paper Institute, Inc. a non-profit trade institution for the pulp, paper, and paperboard industry in the United States, Energy and Materials Department, 260 Madison Ave., New York, NY, 10016. Preparation of this paper was supported by the Air Force Systems Command, Rome Air Develpoment Center, Griffiss AFB, New York, 13441 and the Air Force Office of Scientific Research, Bolling AFB, DC 20332 under contract No. F30602-85-C-0008

1. Tutoring Complex Processes

Learning how to control a complex industrial process takes years of practice and training; an operator must comprehend the physical and mathematical formulation of the process and must be skilled in handling a number of unforeseen operating problems and emergencies. Even experienced operators need continuous training. A potentially significant way to train both experienced and student operators for such work is through a "reactive computer environment" [Brown et al., 1982] that simulates the process and allows the learner to propose hypothetical solutions that can be evaluated in "real time". However, a simulation without a tutoring component will not test whether a student has actually improved in his ability to handle the situation. In addition, a simulation alone might not provide the conceptual fidelity [Hollan, 1984] necessary for an operator to learn how to use the concepts and trends of the process or how to reason about the simulation. For instance, evaluating the rate of change of process variables and comparing their relative values over time is an important pedagogical skill supporting expert reasoning; yet rate of change is a difficult concept to represent solely with the gauges in a traditional simulation.

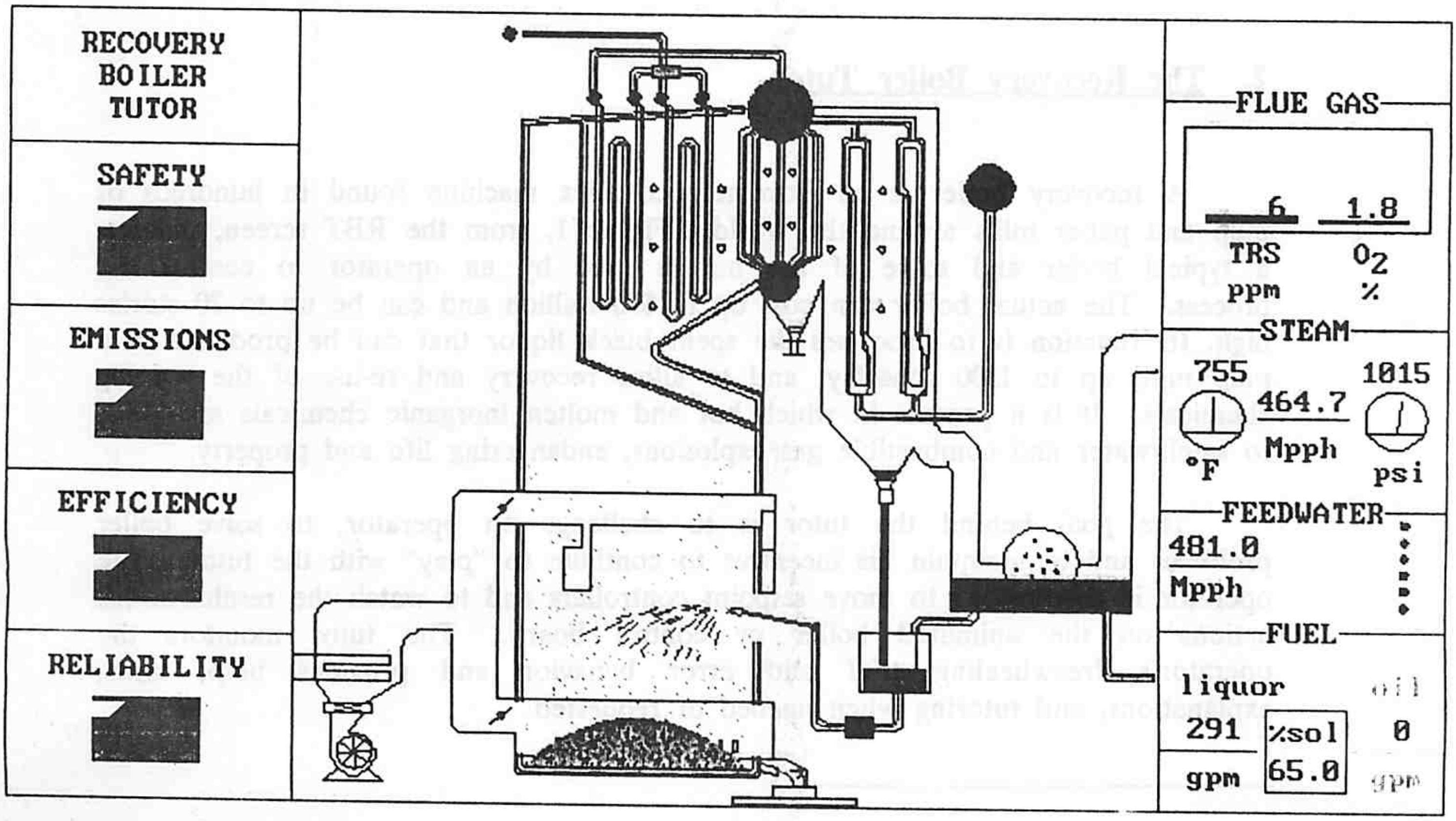

Figure 1: Sectional View of the Recovery Boiler.

We have built a Recovery Boiler Tutor, RBT, that provides tools for developing abstract models of a complex process. The system does not actually represent the mental models that a learner might develop; rather, it provides tools for reasoning about that complex process. These tools include graphs to demonstrate the relationship of process parameters over time, meters to measure safety, emissions, efficiency, reliability, and safety, and interactive dialogues to tutor the operator about the on-going process. The system renders a mathematically and physically accurate simulation of a kraft boiler and interacts with the student about those concepts needed for his exploration of the boiler. Our goal has been to couple the motivational appeal of an interactive simulation with the tutoring and modeling ability of an artificial intelligence system to direct the student in his experimentation.

The tutor was built in direct response to a serious industrial situation. Many industrial accidents, caused in part by human errors, have lead to dangerous and costly explosions of recovery boilers in pulp and paper mills. The American Paper Institute* built the interactive tutor to provide on-site training in the control room of recovery boilers. The tutor is now being beta tested in pulp and paper mills across the United States and is being prepared for nationwide distribution.

2. The Recovery Boiler Tutor

A recovery boiler is an extremely complex machine found in hundreds of pulp and paper mills around the world. Figure 1, from the RBT screen, pictures a typical boiler and some of the meters used by an operator to control the process. The actual boiler can cost up to $70 million and can be up to 20 stories high. Its function is to processes the spent black liquor that can be produced in a pulp mill, up to 1500 tons/day, and to allow recovery and re-use of the pulping chemicals. It is a process in which hot and molten inorganic chemicals may lead to smelt/water and combustible gas explosions, endangering life and property.

The goal behind the tutor is to challenge an operator, to solve boiler problems and to maintain his incentive to continue to "play" with the tutor. The operator is encouraged to move setpoint controllers and to watch the results of his actions on the animated boiler or control board. The tutor monitors the operator's freewheeling trial and error behavior and provides help, hints, explanations, and tutoring when needed or requested.

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*The American Paper Institute is a non-profit trade institution for the pulp, paper, and paperboard industry in the United States.

[Note: A partial blackout is in progress and it will lead to deterioration of the combustion process if no action is taken. Meters indicate that CO, SO_2, and O_2 readings are abnormally high.]

[An alarm buzzer sounds.]
Tutor: What action are you going to take?
Student: Check smelt spout cooling water. [Student's action does not result in a change in the boiler.]
Tutor: It looks as though the liquor isn't burning . . .
Student: Help. What is going on? [Student requests help.]
Tutor: A partial blackout is occurring and this causes TRS, CO, SO_2, and O_2 to increase. Steam flow and steam temperature are dropping. I think part of the bed is not burning.
Student: Rod the primary air ports. [A small improvement in the boiler readings can be observed.]
Tutor: Your action is correct; however, at this time rodding alone is not effective . . .
Student: Raise the liquor temperature. [Student's action does not reverse the emergency and a new alarm buzzer sounds]
Tutor: Rodding the air port apparently was not enough to undo the blackout.
Student: Increase the oil fuel supply. [Student's action reverses the emergency.]
Tutor: That solved the problem alright. Good thinking.

Analysis of the problem: You had a partial blackout caused by plugged primary air ports and a cold bed. Partial blackout can be effectively treated through a combination of rodding the primary air ports and adding more heat. The problem can be avoided by keeping the air ports clean.

Figure 2: Dialogue Between Tutor and Operator.

An example interaction* between the student and tutor is shown in Figure 2. As the operator changes setpoint controllers and requests information about the boiler, the tutor selectively discusses the optimality of his actions (we show how in Section 3) and suggests how he might better focus his action or better utilize his data. An important feature to note about this dialogue is that at any point during the simulated emergency there are a large number of actions an operator might take and, as the problem worsens, an increasing number of actions that he *should* take to correct the operating conditions. Thus, an immediate and correct response might require only one action, such as rodding the primary air ports, but

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*The dialogue of Figure 2 was not actually produced in natural language; student input was handled through menus (Figure 3) and tutor output produced by cutting text from emergency-specific text files loaded when the emergency was invoked.

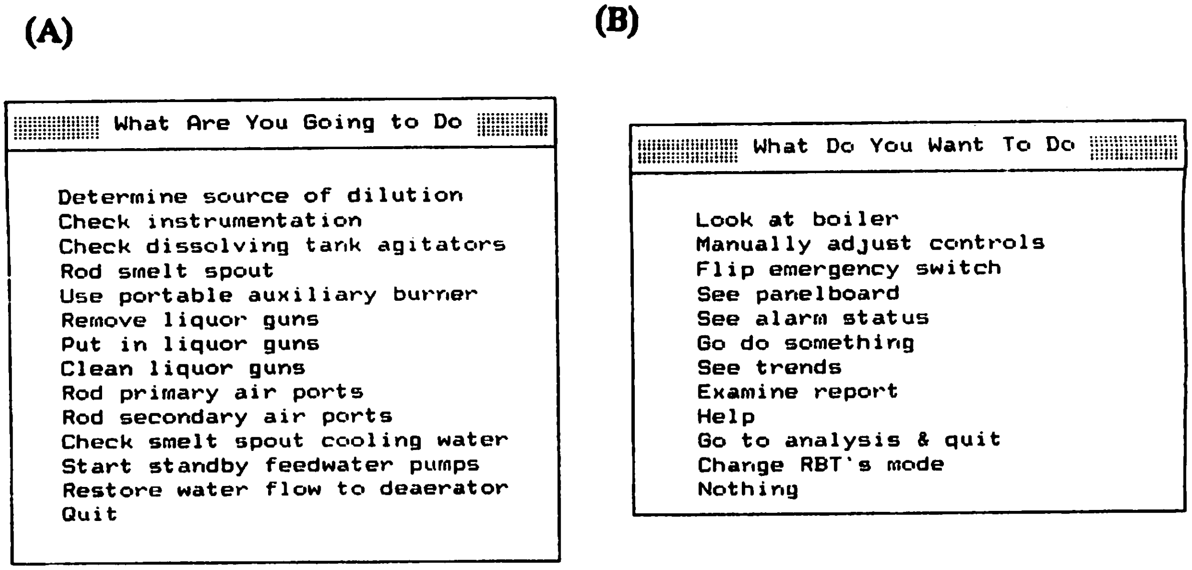

Figure 3: Menus to Select Tasks to be Performed on the Boiler..

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a delayed response causes the situation to worsen and requires the addition of auxiliary fuel.

The operator interacts with the tutor through a hierarchy of menus, one of which is shown in Figure 3. The first menu, (A), allows an operator to select a physical activity to be performed on the boiler, such as checking for a tube leak or rodding the smelt spout. The second menu, (B), allows the operator to select a particular computer screen, such as the alarm board or control panel board.

The student can initiate any of 20 training situations, emergencies, or operating conditions (see Appendix 1). He can also ask that an emergency be chosen for him or he might accidently trigger an emergency as a result of his actions on the boiler. Once an emergency has been initiated, the student should adjust meters and perform actions on the simulated boiler to solve the emergency.

For example, if the system has simulated a TRS reading of greater than 15 ppm and if the amount of oxygen is less than 2%, then the student is expected to increase the oxygen until it is 2.5%. If he does this, the level of TRS will automatically be reduced to less than 5 ppm and the boiler will return to a normal state. However, if he does not perform this action, a critical situation will develop accompanied possibly by a blackout and, if the situation is allowed to continue, a dangerous explosion.

While the simulation is running, the operator can view the boiler from many directions and can focus in on several components, such as the fire bed in Figure 4. The tutor provides assistance through visual clues, such as a darkened smelt bed; acoustic clues, ringing alarm buzzers, textual help, explanations, and dialogues, such as that illustrated in Figure 2. The operator can request up to 30 process parameters on the complete panel board, Figure 5 or can view an alarm board (not shown). The tutor allows the student to change 20 setpoints and to ask

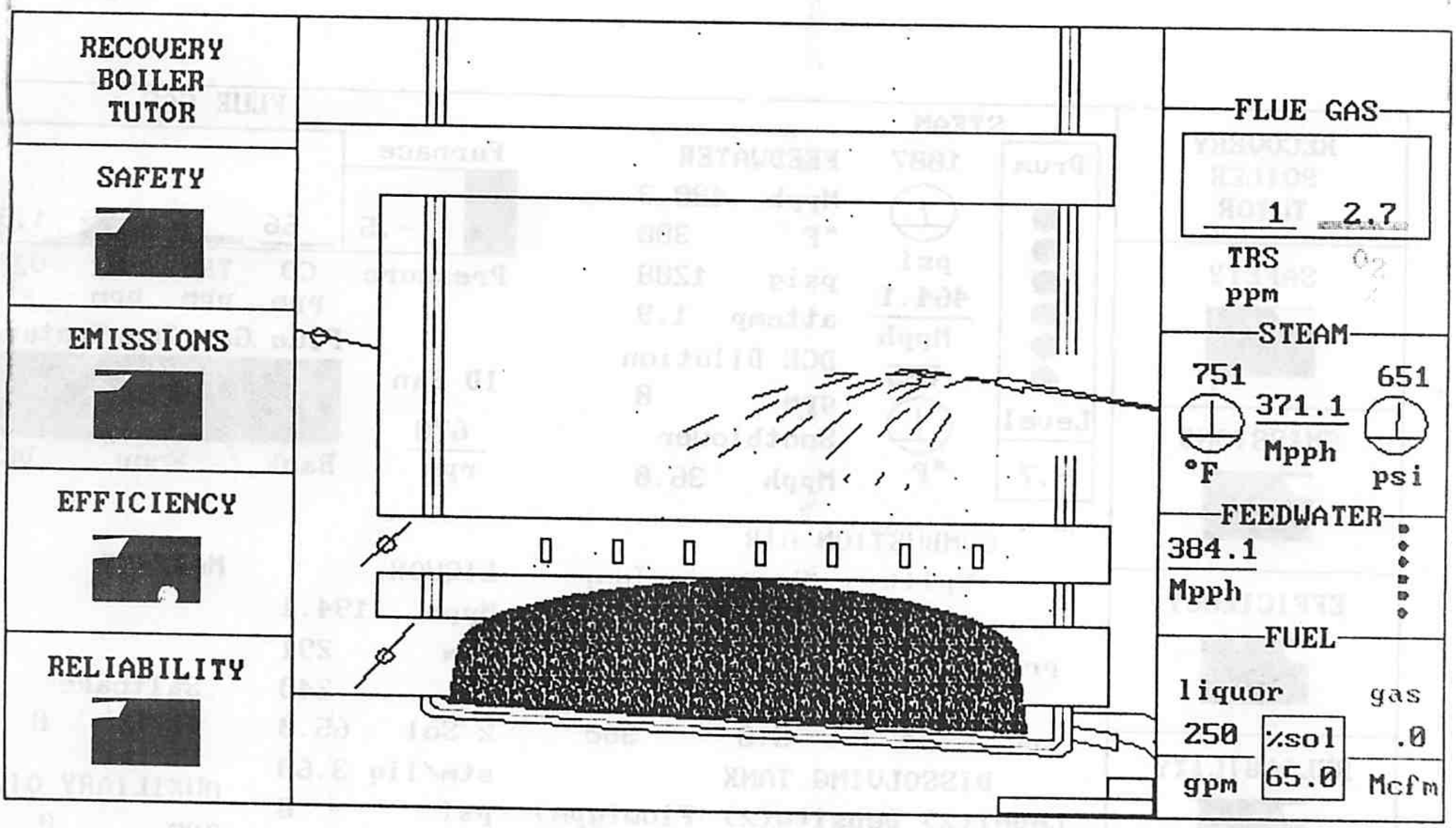

Figure 4: Focused View of the Fire Bed.

menued questions such as "What is the problem?", "How do I get out of it?", "What caused it?", and "What can I do to prevent it?."* The operator can request meter readings, physical and chemical reports, dynamic trends of variables. All variables are updated in real time (every 1 or 2 seconds).

In addition to providing information about the explicit variables in the boiler, RBT provides information about implicit processes through *reasoning* tools, with which an operator can understand and reason about the complex processes. One such tools is composite meters (left side of Figures 1 and 5). These meters record the state of the boiler using synthetic measures for safety, emissions, efficiency, and reliability of the boiler. The meter readings are calculated from complex mathematical formulae that would rarely, if ever, be used by an operator to evaluate the same characteristics of their boiler. For instance, the safety meter is a composition of seven independent parameters, including steam pressure, steam flow, steam temperature, feedwater flow, drum water level, firing liquor solids, and combustibles in the flue gas. Meter readings allow a student to make

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*These four questions are answered by cutting text from a file which was loaded with the specific emergency. These questions do not provide the basis of the tutor's knowledge representation, which will be discussed in Section 3.2

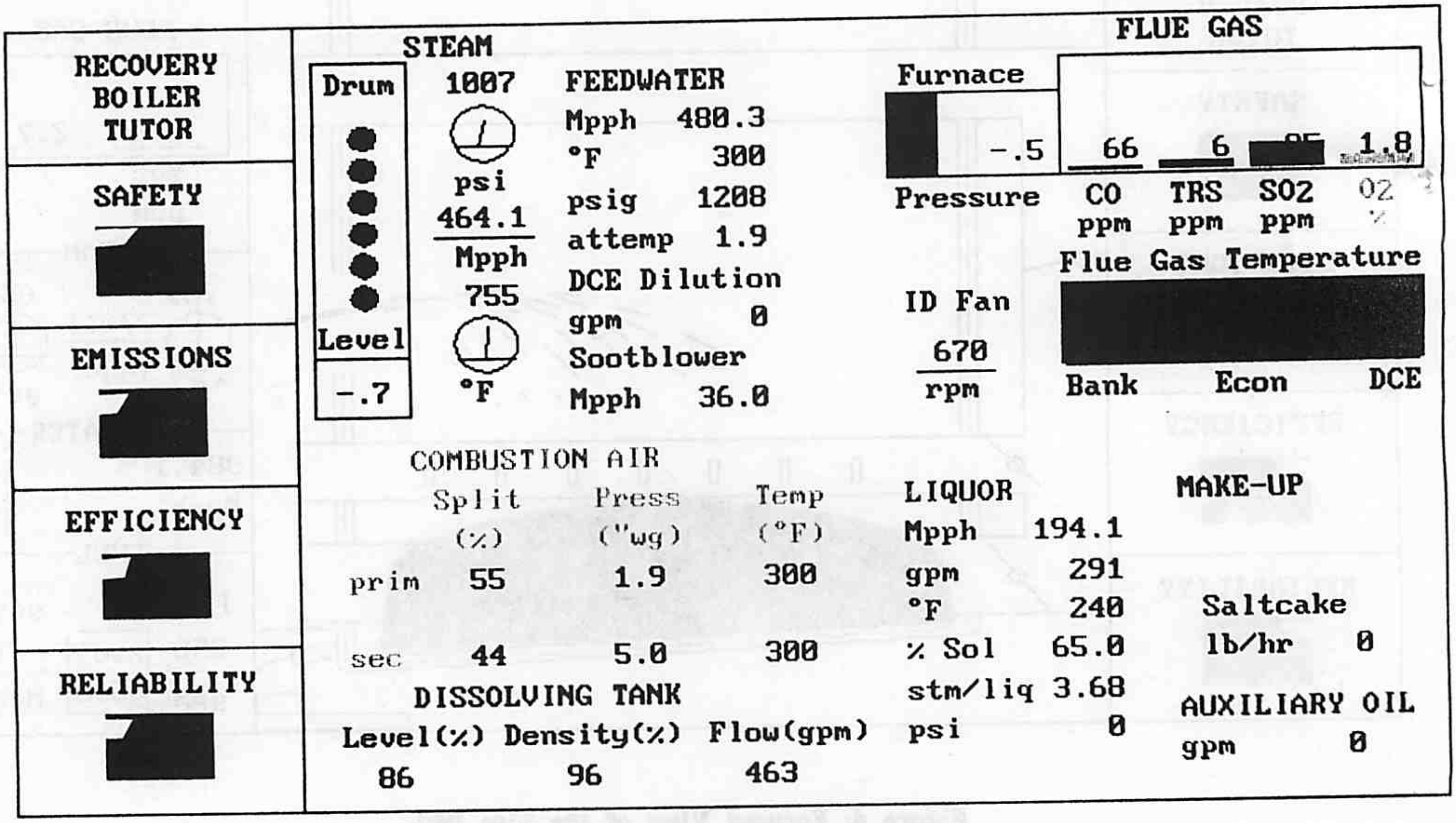

Figure 5: The Complete Control Panel.

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inferences about the effect of his actions on the boiler using characteristics of the running boiler. These meters are not presently available on existing pulp and paper mill control panels; however, if they prove effective as training aids, they could be incorporated into actual control panels.

Other reasoning tools include trend analyses, Figure 6, and animated graphics, such as shown in Figures 1 and 4. Trend analyses show an operator how essential process variables interact in real time by allowing him to select up to 10 variables, including liquor flow, oil flow, and air flow, etc, and to plot each against the others and time. Animated graphics are provided as a part of every view of the boiler and include realistic and changing drawings of dynamic components of the boiler, such as steam, fire, smoke, black liquor, and fuel.

Each student action, be it a setpoint adjustment or proposed solution, is recorded in an accumulated response value. This value reflects an operator's overall score and how successful, or unsuccessful, his actions have been and whether the actions were performed in sequence with other relevant or irrelevant actions. This accumulated value is not presently used by the tutor, but the notation might be used to sensitize the tutor's future responses to the student's record. For instance, if the operator has successfully solved a number of boiler emergencies, the accumulated value might be used to temper subsequent tutoring

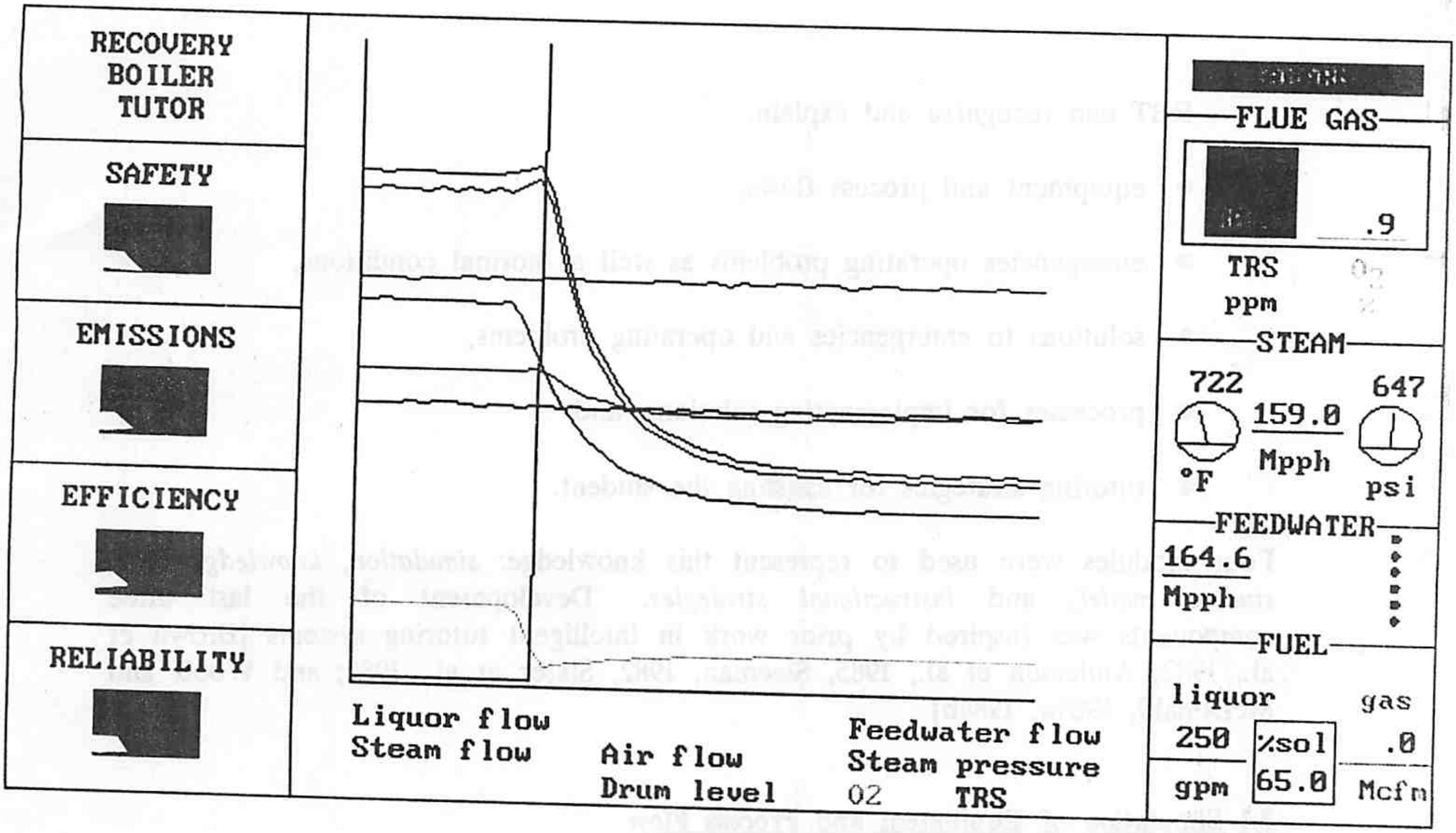

Figure 6: Trends Selected by the Operator.

so that it is less intrusive. Similarly, if a student´s past performance has been poor, the accumulated value could be used to activate more aggressive responses from the tutor.

3. Multiple Representations of Knowledge

Multiple concepts and processes were represented in RBT, some procedurally, some declaratively, and some in both ways. For example, emergencies in the steam boiler were first represented as a set of mathematical formulae so that process parameters and meter values could be produced accurately in the simulation. Then these same emergencies were encoded within the tutor´s knowledge base as a frame-like data structure with slots for preconditions, optimal actions, and conditions for solution satisfaction so that the tutor could evaluate and comment upon the student´s solution.

RBT can recognize and explain:

- equipment and process flows,
- emergencies operating problems as well as normal conditions,
- solutions to emergencies and operating problems,
- processes for implementing solutions, and
- tutoring strategies for assisting the student.

Four modules were used to represent this knowledge: *simulation*, *knowledge base*, *student model*, and *instructional strategies*. Development of the last three components was inspired by prior work in intelligent tutoring systems [Brown et al., 1982; Anderson et al., 1985, Sleeman, 1982, Slater et al., 1985; and Woolf and McDonald, 1984a, 1984b]

3.1 Simulation of Equipment and Process Flow

The *simulation* uses a mathematical foundation to depict processes in a boiler through meter readings and four animated views of the boiler. It reacts to more than 35 process parameters and generates dynamically accurate reports of the thermal, chemical, and environmental performance of the boiler (not shown) upon request. An alarm board (not shown) represents 25 variables whose button will turn red and alarm sounded when an abnormal condition exists for that parameter.* The simulation is interactive and inspectable in that it displays a "real time" model of its process, yet allows the student to "stop" the process at anytime to engage in activities needed to develop his mental models [Hollan et al., 1984]. The operators who tested RBT mentioned that they like being able to stop the process to ask questions or to explore boiler characteristics.

If a student working on a problem inadvertently triggers a second problem, the least serious problem will be placed on a stack and held in abeyance while the student is coached to solve the more serious problem. After the more serious problem is solved, the student is coached to solve the remaining one. Thus, the simulation provides facilities for handling multiple instantiations of emergencies.

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*Engineering details about the steam and chemical parameters in RBT and the boiler simulation capabilities can be found in [Jansen et al., 1986].

One advantage of a formal representation of the process is the availability of a "database" of possible worlds into which information based on typical or previous moves can be fed into the simulation at anytime [Brown et al., 1982] and a solution found. In this way, a student's hypothetical cases can be proposed, verified, and integrated into his mental model of the boiler.

3.2 Knowledge Base of Emergencies and Operating Conditions

The *knowledge base* contains preconditions, postconditions, and solutions for emergencies or operating conditions, described as scenarios. Scenarios are represented in frame-like text files containing preconditions, postconditions, and acceptable solutions for each scenario. For example, in Lisp notation, a true blackout would be described as:

```
preconditions:
      (or (<= blackout_factor 1)
            (< heat_input 5000))
postconditions:
      (or (increasing O2)
            (decreasing steamflow)
            (increasing TRS)
            (increasing CO)
            (increasing SO2))
solution_satisfaction:
      (and (= blackout_factor 1)
             (> heat_input 5200))
```

Scenarios in RBT have been teased apart to represent successively more serious problems. For instance, a smelt spout pluggage is represented as separate scenarios depending on whether the solution requires rodding the spout, applying a portable auxiliary burner, removing the liquor, or a combination of all three. Again, formalized knowledge of the domain made it easy to represent and evaluate graduated scenarios, as well as multiple operator actions.

The efficiency of the student's action is evaluated both through the type of action performed, such as increasing O_2 or increasing steamflow for a true blackout, and the effect of that action on the boiler. Thus, if an inappropriate action nevertheless resulted in a safe boiler, the student would be told that his action worked, but that it was not optimal. For example, a partial furnace blackout requiring manual rodding of the air delivery system can be alleviated by shutting down the boiler. However, this is an expensive and unwarrented action and the student will be advised to use an alternative approach.

3.3 Student Model to Monitor the Operator s Solution

The *student model* records actions carried out by the student in solving the emergency or operating problem. It recognizes correct as well as incorrect actions and identifies each as relevant, relevant but not optimal, or irrelevant.

The tutor compares the student's actions with those specified by the knowledge base and uses a simplified differential model to recognize and comment about the difference between the two. For instance, if a partial blackout has been simulated, the black liquor solids are less than 58%, and the operator adjusts the primary air pressure, the tutor might interrupt with a message such as:

"Primary air pressure is one factor that might contribute to blackout, but there is another more crucial factor -- try again."

or

"You have overlooked a major contributing factor to blackouts."

The student model is currently the weakest component of the tutor. We intend to incorpoarate inferences about patterns of student errors and possible misconceptions[*] as a way to increase the tutor's ability to reason about what the operator has accomplished so far and what possible misconception he has. For example, we would like to test presumed misconceptions and use future operator actions to verify the existence of those misconceptions. To do so, the student model would have to link misconceptions with scenarios and to record all common errors and evidence for possible misconceptions.

3.4 Instructional Strategies to Assist the Student

The *instructional strategies* contain decision logic and rules to guide the tutor's intervention of the operator's actions. In RBT, the intent has been to "subordinate teaching to learning" and to allow the student to experiment while developing his own criteria about boiler emergencies. The tutor guides the student, but does not provide a solution as long as the student's performance appears to be moving closer to a precise goal.

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[*] Misconceptions will be compiled by J. H. Jansen Co., Inc. Steam and Power Engineers, who, in addition to being the authors of RBT, have extensive operating experience with boilers in the U.S.A. and Canada.

Represented as if/then rules based on a specific emergency and a specific student action, the instructional rules are designed to verify that the student has "asked" the right questions and has made the correct inferences about the saliency of his data. Responses are divided into three categories:

Redirect student: "Have you considered the rate of increase of O_2?"
"If what you suggest is true, then how would you explain the low emissions reading?"

Synthesize data: "Both O_2 and TRS have abnormal trends."
"Did you notice the relation between steam flow and liquor flow?"

Confirm action: "Yes, It looks like rodding the ports worked this time".

The tutor selects from within each category a response that address both the operator's action and his apparent ability to solve the problem. Special precautionary messages are added to the most specific tutor responses to alert an operator when a full scale disaster is imminent.

The instructional strategies are designed to encourage an operator's generation of hypotheses. Evidence from other problem solving domains, such as medicine [Barrows and Tamblyn, 1980], suggests that students generate multiple (usually 3-5) hypotheses rapidly and make correct diagnoses with only 2/3 of the available data.* The RBT tutor was designed to be a partner and co-solver of problems with the operator, who is encouraged to recognize the effect (or lack of same) of his hypotheses and to experiment with multiple explanations of an emergency. No penalty is exacted for slow response or for long periods of trial and error problem solving.

This approach is distinct from that of Anderson et al., [1985] and Reiser et al., [1985] whose geometry and Lisp tutors immediately acknowledge a incorrect student answers and provide hints. These authors argue that erroneous solution paths in geometry and Lisp are often so ambiguous and delayed that they might not be recognized for a long time, if at all, and then the source of the original error might be forgotten. Therefore, immediate computer tutor feedback is needed to avoid fruitless effort.

However, in industrial training, the trainee must learn to evaluate his own performance from its effect on the industrial process. He should trust the process itself to provide the feedback, as much as is possible. In RBT we provide this

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*Medical students have been found to ask 60% of their questions while searching for new data and obtain 75% of their significant information within the first 10 minutes after a problem is stated [Barrows and Tamblyn, 1980].

feedback through animated simulations, trend analyses, and "real-time" dynamically updated meters. The textual dialogue from the tutor provides added assurance that the operator has extracted as much information as possible from the data and it establishes a mechanism to redirect him if he has not [Burton and Brown, 1982; Goldstein, 1982].

4. Developmental Issues

RBT was developed on an IBM PC AT (512 KB RAM) with enhanced graphics and a 20 MB hard disk. It uses a math co-processor, two display screens (one color), and a two key mouse. The simulation was implemented in Fortran and took 321 KB; the tutor was implemented in C and took 100 KB.

Although we tried to implement the tutor in Lisp, we found extensive interfacing and memory problems, including segment size restrictions (64k), incompatibility with the existing Fortran simulator, and addressable RAM restrictions (640K). To circumvent these problems the tutor was developed in C with many Lisp features implemented in C, such as functional calls within the parameters of C functions. Meter readings and student actions were transferred from the simulation, in Fortran, to the tutor, in C, through vectors passed between the two programs.

The approach taken here can be extended to other engineering and industrial training problems. Factors that are likely to be considered in building a training system are availability, cost, and appropriateness of software and hardware for the scope of the task. In our case, decisions were made to ensure swift production of a simulation and tutor, given approximately 18 months development time.

5. Evaluations

The tutor has been well-received thus far. It is presently used in actual training in the control rooms of several pulp and paper mills throughout the U.S. Formal evaluation will be available soon. However, informal evaluation suggests that working operators enjoy the simulation and handle it with extreme care. They behave as they might at the actual control panel of the pulp mill, slowly changing parameters, adjusting meters through small intervals, and checking each action and examining several meter readings before moving on to the next action.

Both experienced and novice operators engage in lively use of the system after about a half hour introduction. When several operators interact with the tutor, they sometimes trade "war stories" advising each other about rarely seen situations. In this way, experienced operators frequently become partners with novice operators as they work together to simulate and solve unusual problems.

6. Conclusions

Several fundamental lessons about building an intelligent tutor were learned from this project. The first and foremost was the need for "in-house" expertise; in our case the programmer, project manager, and director of the project were themselves chemical engineers. More than 30 years of theoretical and practical knowledge about boiler design and teaching was incorporated into the system. Had these experts not previously identified the chemical, physical, and thermodynamic characteristics of the boiler and collected examples of sucessful teaching activities, development time for this project would have been much longer.

A second critical lesson was the need to clarify and implement the components of a teaching philosophy early in the development process in order to ensure full realization of a tutor in the completed system. For example, in order to manifest a philosophy of subordinating teaching to learning, we had to build up the system's ability to recognize partially correct as well as irrelevant actions, (in the knowledge base), to custom-tailor its responses to each type of answer (in the instructional strategies), and to quietly monitor the operator while judiciously reasoning about when to interrupt him (in the student model). The need to limit authoritarian responses from the system and to restrict it to giving only as much help as absolutely needed, meant that tutoring was not tacked onto the end of an expert system, but rather was developed as a part of components of the expert system. We suggest that silence (inactivity) on the part of a computer system is in itself a recognition of the learner's role in the training process and provides an expression of our confidence in his progress.

A third and most surprising lesson learnt from this project was that a teaching system can be designed for multiple students. The system is now being used with groups of operators who work with each other and with the computer to solve problems; pedagogically wholesome things are beginning to happen among them. For example, novice and experienced operators, who might otherwise not be comparable in training and ability, can share their problem solving knowledge and experience; each teaching and learning in a non-evaluative environment.

Several issues remain unresolved in our work to improve the compter tutor's ability to respond to the student. We need to to sort out those skills or processes that a student has learned from those that he is still trying to learn and to sort out those concepts he has from those he still has problems with; we also need to recognize which techniques have been effective in helping him. Currently, the tutor can not do this and we have suggested how we might extend the student model to incorporate inferences made about the student's knowledge, his errors and potential misconceptions to make progress along these lines.

7. Acknowledgements

The authors thank Jeremy Metz, Bradford Leach, and the A.P.I. Recovery Boiler Committee for their encouragement and support.

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9. Appendix 1: Emergencies and Operating Problems Simulated by the Tutor

Emergency Situations:

Smelt/Water Explosion
Combustible Gas Explosion
Tube Rupture (various locations)

Operating Problems:

High Drum Water Level
Low Drum Water Level
Loss of Steam Header Pressure
Nozzle Pluggage
Liquor Supply Loss
Smelt Spout Pluggage
Heavy Smelt Run-off
ID Fan Failure
FD Fan Failure
Carryover and Pluggage
Depleted Weak Wash Flow

Low Liquor Firing Solids
Partial Blackout
Complete Blackout
Instrument Air Failure
Electrical Power Failure