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Computerized Control and On-Line Performance Monitoring of an Instructional Mini-Steam Cycle Power Plant

HALIL M. GUVEN
Department of Mechanical Engineering, San Diego State University, San Diego, CA 92182, USA

An NSF-ILI award enabled the San Diego State University to upgrade a 10 kW mini-steam cycle power plant and greatly enhance its instructional value. A computer-operated control system for automatic control and data acquisition; temperature, flow and pressure instruments around all major equipment units for heat balance and efficiency analysis; and a computerized on-line performance monitoring system for real-time cycle efficiency calculations were installed. The mini-plant is put to use as an effective and modern teaching tool in thermodynamics instruction and in an Engineering Systems Laboratory course. The plant laboratory experiments demonstrate to students the principles of thermodynamics, data acquisition, computerized control functions, performance engineering, and also acquaint them with the state-of-the-art in instrumented plant operations.

AUTHOR QUESTIONNAIRE

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in:
   Teaching of the principles of thermodynamics and power plant engineering. As well as demonstration of instrumentation and control functions.
2. The paper describes new equipment useful in the following courses
   Elements of thermal and mechanical systems, thermodynamics, engineering systems laboratory, and power plant engineering.
3. Level of students involved in the use of equipment
   Both undergraduate (sophomore, junior, senior) and graduate (technical elective course).
4. What aspects of your contribution are new?
   Fully instrumental power generation equipment with on-line performance monitoring capability.
5. How is the material presented to be incorported in engineering teaching?
   Laboratory notes or handout.
6. Which texts or other documentation accompany the presented materials?
   None.
7. Have the concepts presented been tested in the classroom? What conclusions have been drawn from the experience?
   Yes, they have been in use for three years. The students responded very positively and with a lot of excitement.
8. Other comments on benefits of your presented work for engineering education
   The presented work can be used as a guide to help other schools initiate similar laboratory improvement projects. We truly believe that our facility brings back the systems approach and engineering synthesis concepts to the engineering education.

INTRODUCTION

MOST ENGINEERING schools in the United States are having to contend with aging laboratory equipment [1]. This is particularly true for thermal engineering related instructional labs where lab equipment, such as boiler-turbine-generator sets and internal combustion engines, are generally in poor condition. Most facilities have not been replaced or updated for over 25 years. To become effective and modern teaching tools, these facilities are in desperate need of repair and update.

The San Diego State University (SDSU) Mechanical Engineering (ME) Department has approximately 600 students, about 100 of which are graduate students. The goals of the department include creating continually evolving undergraduate curricula, to educate present and future students in state-of-the-art theory and applications of mechanical engineering.

Like many other engineering schools, the SDSU ME Department lagged behind in modernizing its thermal engineering laboratory equipment. In the mid-1970s, the department did away with its quite old boiler–turbine generator set and did not replace it with new equipment. Having increasingly felt the need for meaningful, modern thermodynamic experiments, both in the thermal engineering laboratory and in the instruction of thermodynamics, the department decided to build an instructional mini-steam cycle power plant in 1987.

The bulk of the major equipment for the project were purchased, for manual operation only, with the available funds through the benefit of large vendor discounts and outright gifts. The plant was originally constructed for manual operation and manual data collection only. Provisions, however, were made to incorporate a computerized data acquisition and control system at a future date. The plant was completed for manual operation in early 1989. In the same year, the department received a National Science Foundation Instrumentation and Laboratory Improvement (NSF-ILI) award to incorporate state-of-the-art controls and on-line performance monitoring capabilities to the power plant. The installation was completed in 1992. In its present form, the plant serves as a multi-purpose facility. Its main purpose is to teach SDSU engineering students principles of thermodynamic, and to provide practical education and training as related to power plant performance, efficiency improvements and controls. However, the facility can also be used:

1. to teach advanced courses in powerplant design, operation and maintenance engineering, power plant controls, instrumentation, and performance engineering;
2. to conduct power generation and control research experiments; and
3. to carry out training courses for power plant operators.

MINI-STEAM CYCLE POWER PLANT

The plant has all the components found in a utility thermal-electric powerplant. It is fully instrumented with temperature, flow and pressure instruments around all the major equipment units. A photograph of the plant is shown in Fig. 1.

SDSU students were involved in all stages of plant design, construction and instrumentation. The plant's basic design consists of a steam generator package with ancillary equipment, and a 10 kW turbine generator set. The electric power generated is dissipated as heat through resistance load banks. (The generated power cannot be fed into the building power supply, due to the expensive tie-in protective equipment needed for phase and voltage regulation. Moreover, the generated power is too little and intermittent in nature.) The plant process flow diagram is shown in Fig. 2, and Table 1 presents the state-point summary of the plant at selected reference points.

The boiler unit (steam generator package) was a Clayton E-60 [2,3], provided by Clayton Industries, and included the steam generator with the boiler feedwater pump, hotwell (DEA tank), three chemical feed pumps for boiler water treatment, zeolite water softening equipment with brine tank (model 60–A [4]) and flash tank.

The turbine was an overhauled Coppus Murray synchronous 10 kW turbine generator set [5]. A condensate system consisting of a primary condenser (ITT SU-6 3–2 [6]), a secondary heat exchanger (CHX-2 8–15), and a return pump were provided by Dawson Company at 50% cost.

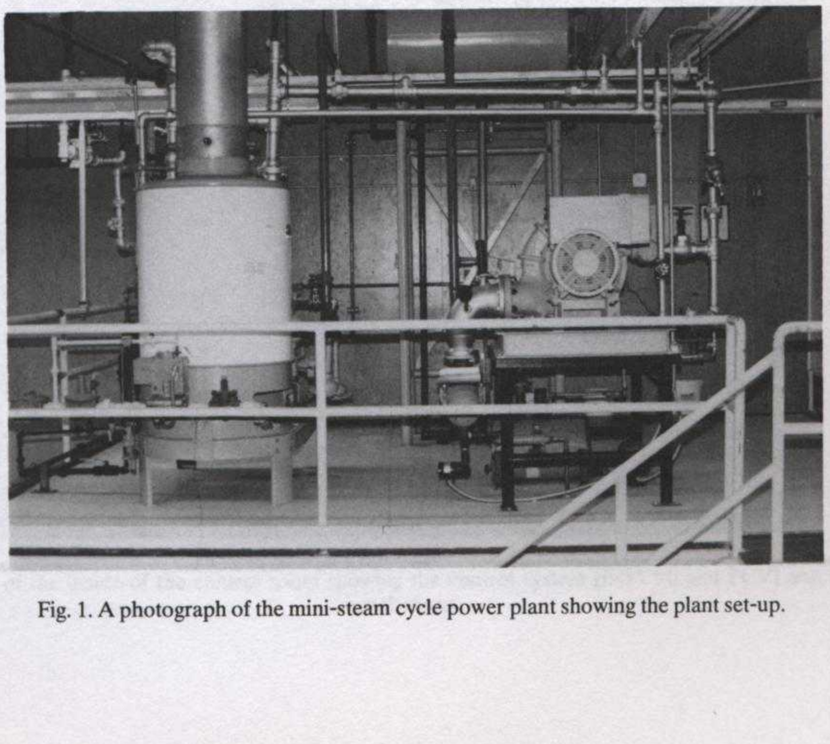

Fig. 1. A photograph of the mini-steam cycle power plant showing the plant set-up.

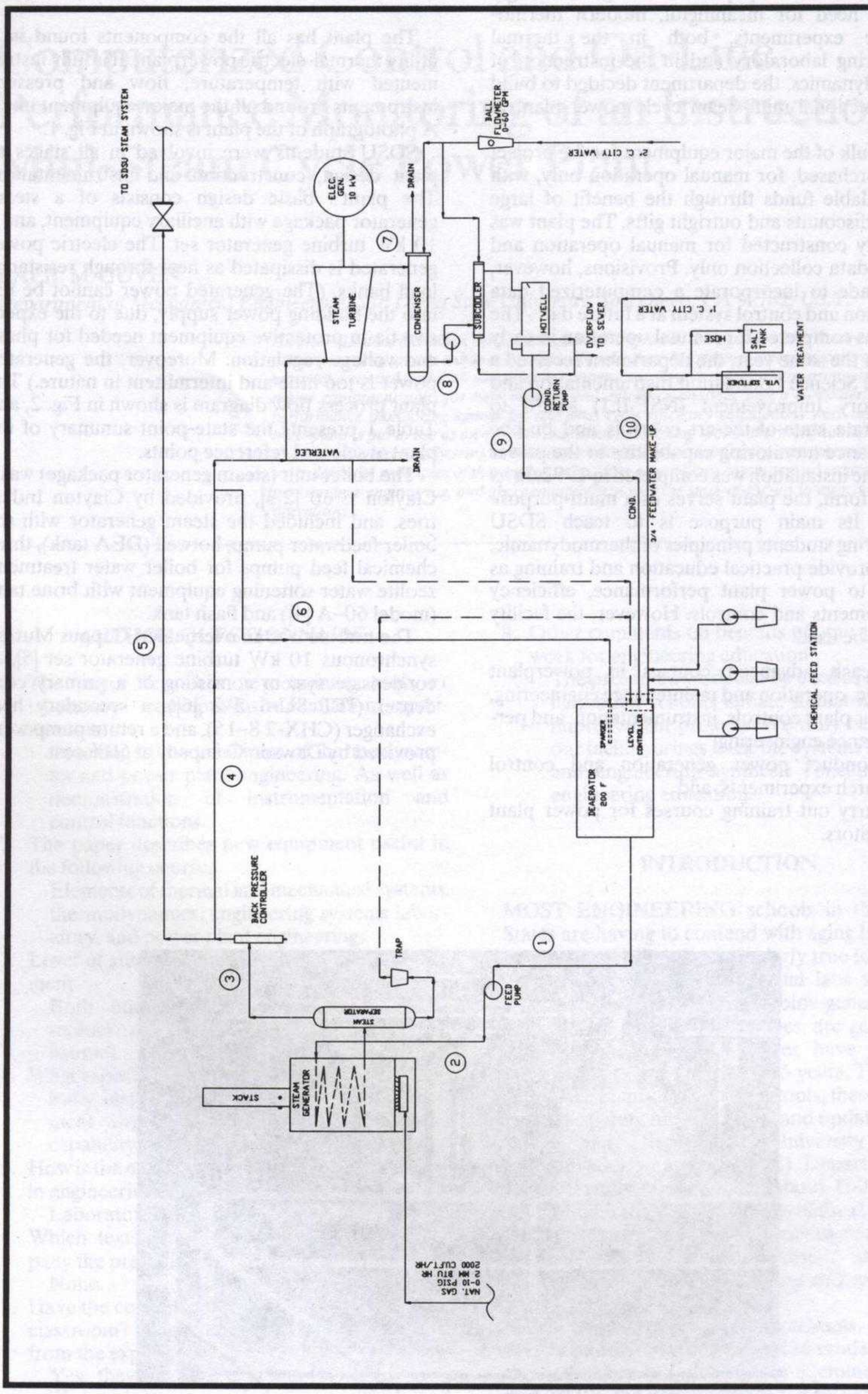

Fig. 2. Power plant design layout and process flow diagram.

Table 1. Mini-steam cycle state points

	Temp.	Press.	h	Flow
	°C	MPa_g	kJ/kg	kg/hr
1	96.1	0.069	402.4	469.5
2	97.2	2.517	--	469.5
3	207.8	1.724	2793.5	469.5
4	207.8	1.724	2793.5	318.9
5	207.8	1.724	2793.5	150.6
6	98.9	0.103	2677.2	3.2
7	100.0	0	2674.9	315.7
8	93.3	0	390.8	315.7
9	93.3	0.034	390.8	315.7
10	21.1	0.034	--	157.9

DESCRIPTION OF INSTRUMENTATION AND EQUIPMENT OBTAINED THROUGH NSF-ILI

The NSF-ILI award enabled the purchase of instrumentation, the automated control system, and the performance monitoring system. This equipment was installed in the plant control room adjacent to the plant installation. A photograph of the plant control room is shown in Fig. 3.

Instrumentation and control system

The control system consisted of a Bailey Network INFI 90 with Process Control View (a 386 PC connected to INFI 90 configured for screen displays with built-in control functions for warnings, alarms, etc.) [7]. Figure 4 shows the sensor/probe locations, and Table 2 lists all the instruments interfaced with the Bailey control system. The controls logic diagram for the plant is shown in Figure 5.

The Bailey INFI 90 is a state-of-the-art industrial standard control system. Briefly, the Bailey INFI 90 is a scalable, microprocessor-based system capable of addressing a wide variety of process control strategies. The mini-steam cycle plant has 25 I/O points. These I/O signals to and from the control system will gather data from various parts of the plant, open and close control valves, and issue appropriate alarms (e.g. low/high water level in the deaerator tank, loss of boiler feedwater, turbine vibration). There are 13 vendor-developed computer screens which can be pulled up on the screen from a menu. The 'Steam System Graphics' and the 'Steam System Control' screens are shown here in Figures 6 and 7, respectively, as samples of available control operations. Plant control and operation can be done by changing the set points on the PCV screens.

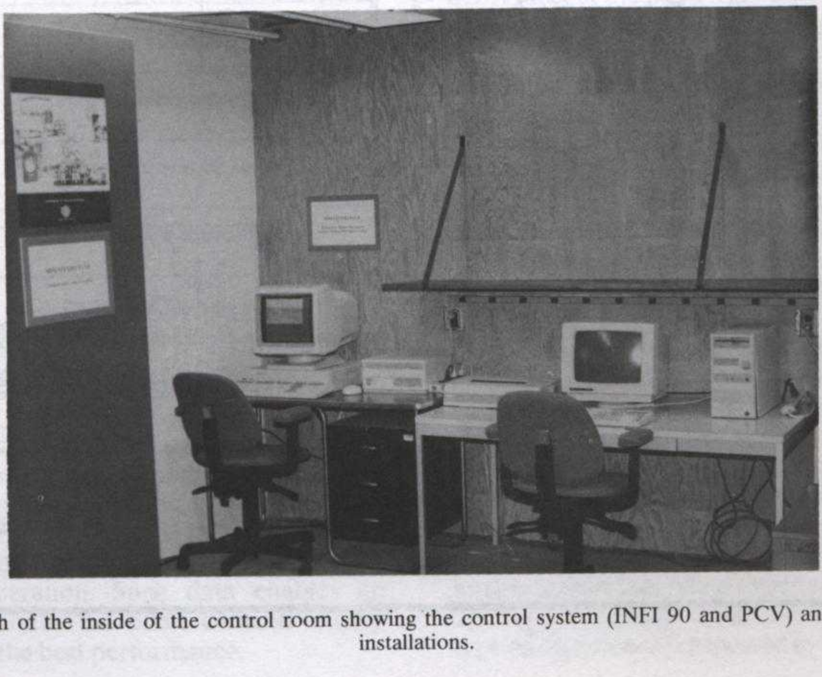

Fig. 3. A photograph of the inside of the control room showing the control system (INFI 90 and PCV) and OTIS VAX-station installations.

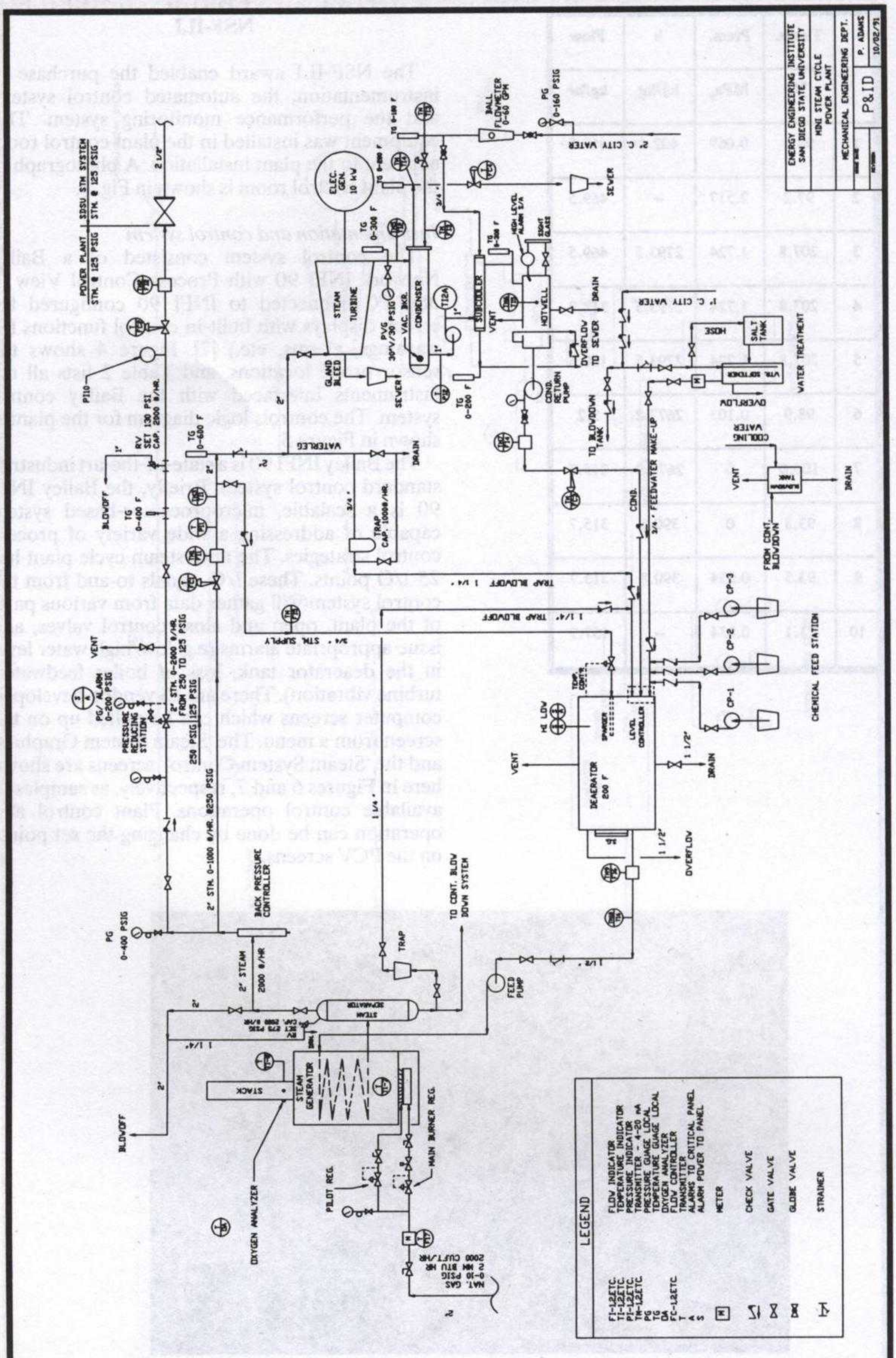

Fig. 4. Sensor/probe locations of 10 kW mini-steam cycle power plant.

Table 2. Bailey control logic diagram legend (see Fig. 5)

PI1	Turbine steam pressure
FI1	Turbine steam flow
TI1	Turbine steam temperature
FC1	Turbine steam control valve
FI2	SDSU Steam system flow
TI2	Turbine to cndnsr inlet T
FI3	City water to condenser flow
PI10	SDSU Steam system pressure
TI3	Cooling wtr to cndnsr. inlet T
FC3	Hotwell to DEA control valve
FI4	Hotwell to DEA flow
TI4	Condenser to sewer temp.
FI5	DEA extraction steam flow
TI5	Hotwell temperature
FC4	Cndnsr to sewer control valve
FI6	DEA to steam generator flow
FI7	N. Gas to steam generator flow
TI7	Steam generator temperature
TI6	Feedwater temperature
TI8	Steam generator stack temp.
FC2	SDSU Steam sys control valve
TI2A	Condenser to subcooler temp.

On-line performance and diagnostic monitoring

The on-line performance monitoring is a new idea based on the needs of the utilities to make plant performance data (heat rate, component efficiency trends, etc.) available to the operators during plant operation. Such data enables an operator to optimize the plant controls during operation to get the best performance.

In the mini-steam cycle plant, ABB Power Plant Controls supplied their On-line Thermal Information System (OTIS) for the SDSU power plant efficiency and diagnostic calculations [8]. The platform used for this system is a VAX 3100 workstation. The data inputs for the calculations are extracted directly from the control system using a standard RS232 data communications protocol. The extracted operational data are brought to the VAX-station in real-time. Heat rate and component efficiency calculations are performed by OTIS and results are presented on the screen (or printed). The effect of changes made to the controllable parameters can be viewed on the VAX-station when a new heat rate is computed.

OTIS was selected for this system as it provides an innovative approach to block-style configuration for all types of calculations. The students are able to configure performance and other diagnostic type calculations through an easy-to-use form style data entry input, relational database. Student-defined calculations and graphics are easily implemented with a minimal amount of training. The block calculation format eliminates potential confusion and allows each students to direct their focus on the subject at hand.

CLASSROOM EDUCATION

The plant serves a very unique role in the SDSU ME Department's undergraduate and graduate education. First of all, the plant exposes students to real-world engineering application hardware in a system setting. This enables students to visualize engineering at work.

Students' first exposure to the plant comes in this setting as part of a sophomore-level energy engineering synthesis course, 'Elements of Thermal and Mechanical Systems'. In this course, students meet at the plant once a week with a member of faculty to develop an appreciation of system component functions, piping color codes, instrumentation calibration, an overview of the power industry, etc. These lab sessions are highlighted in the classroom lectures.

During the junior year, students get a significant exposure to and a chance to experiment with the plant. Exposure comes mainly in the regular ME thermodynamics class. In this setting, the plant serves as an excellent tool to make the blackboard cycle drawings come alive.

At the junior level, students also perform experiments. In the SDSU ME Department, thermal engineering laboratory instruction is carried out as part of the Engineering Systems Laboratory (ME 390/395) course sequence. The emphasis in this course is on how to do experimental work; how to formulate the problem at hand; and how to obtain and interpret data. Students are then required to integrate their individual experiences into a report. The report emphasizes technical writing skills. This type of experience is repeated in the context of 15–

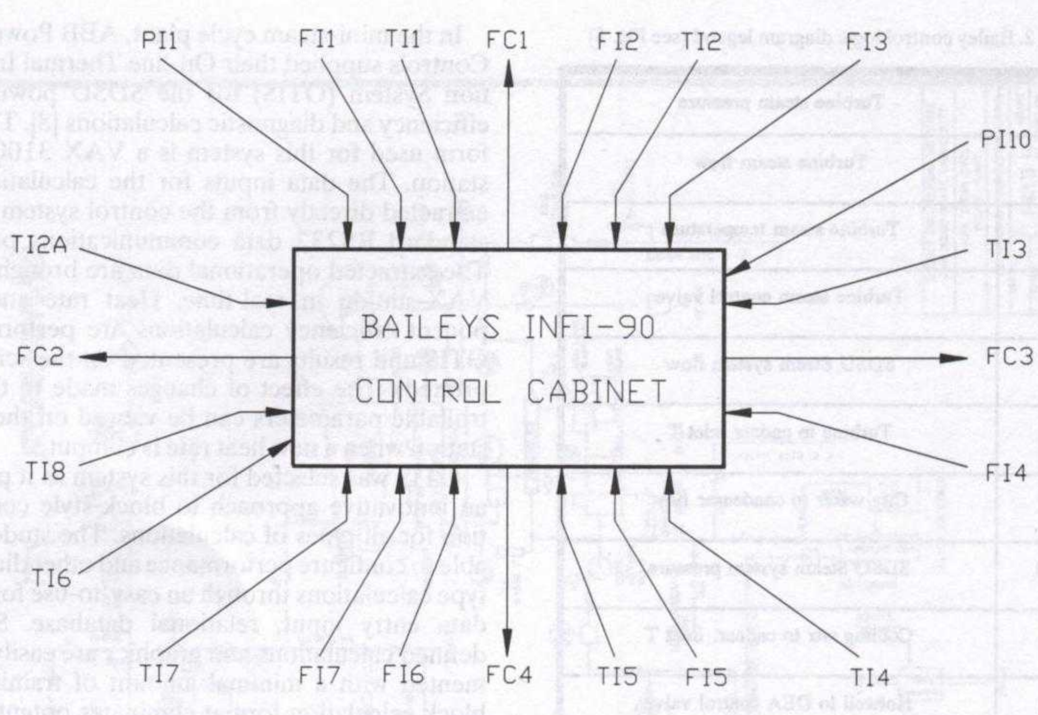

Fig. 5. Control logic diagram of the plant

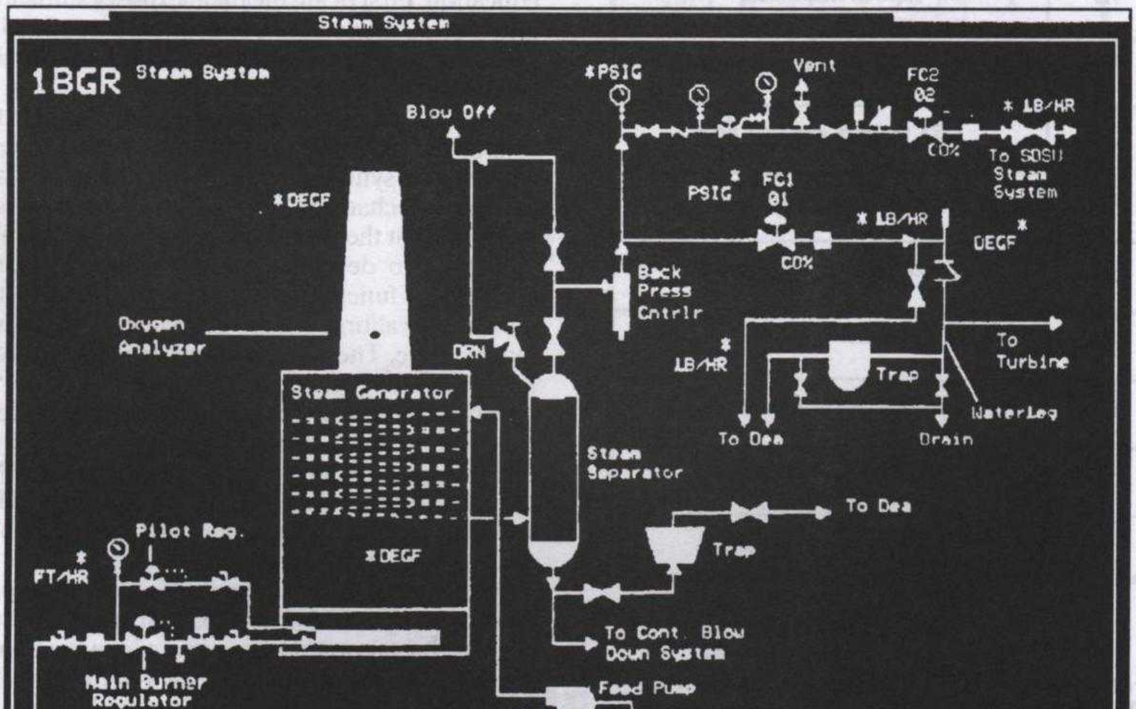

Fig. 6. Bailey INFI-90 process control view steam system graphics screen (showing the steam generator and ancillary equipment, and current temperature, pressure and flow rate values at various parts of the steam system).

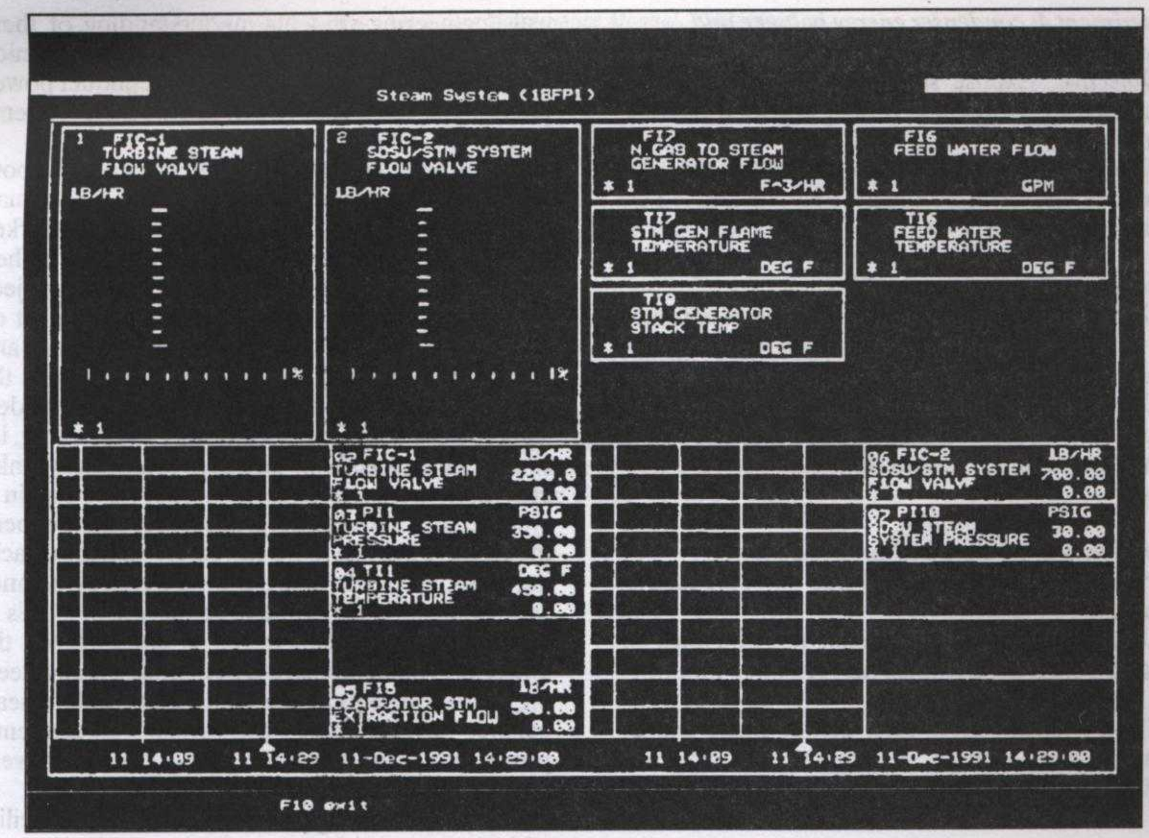

Fig. 7. Steam system control screen (showing the set points for controllable parameters).

20 experiments covering vibration analysis, electronics laboratory work, materials testing and thermal engineering. In the thermal engineering portion, students conduct three or four experiments. The mini-steam cycle plant added six experiments to the ME 390/395 'operational experiment pool' bringing the total to 11. The six power plant experiments are described in some detail in the section below.

Lastly, the plant is heavily used in teaching an upper division technical elective course called 'Power Plant Engineering'. In this course every aspect of the plant is discussed at some length and students are assigned homeworks and projects related to the plant.

HANDS ON TRAINING

Students get to do hands-on training during the junior-level engineering systems laboratory course, where they are assigned experiment/projects on the plant. As part of this assignment, students run the steam generator and measure such cycle parameters as temperature, pressure and flow around all the major pieces of the equipment. Then they use these values in establishing the energy balance for the component under consideration or for the entire plant. The six specific experiments set up for this purpose are described below:

Experiment 1: boiler energy balance and efficiency

Objective: Explain operating principles of a boiler, expose students to instrumentation related to boiler heat balance.

Theory taught: Conservation of mass/conservation of energy, fuel heating value, boiler efficiency, losses.

Experiment 2: turbine generator energy balance and efficiency

Objective: Explain operating principles of a steam turbine. Introduce turbine efficiency, shaft power, electrical power and irreversibility. Expose students to turbine instrumentation and controls.

Theory taught: Conservation of mass/conservation of energy, adiabatic turbine efficiency, power cycle and turbine generator irreversibility.

Experiment 3: pump efficiency and parasitic loads in a cycle

Objective: Introduce pump efficiency. Demonstrate efficiency of different size pumps used in thermal processes and systems. Introduce parasitic loads in a power cycle.

Theory taught: Conservation of mass/conservation of energy, isentropic pump efficiency, power cycle and parasitic loads.

Experiment 4: condenser energy balance and effectiveness

Objective: Expose students to heat exchanger principles. Pressure drop, fouling and instrumentation.

Theory taught: Conservation of mass/conservation of energy. Heat exchanger analysis and NTU-effectiveness.

Experiment 5: combustion efficiency

Objective: Expose students to high-temperature gas measurement instruments. Flue (exhaust) gas measurements and analysis.

Theory taught: Chemical reactions—stoichiometric and non-stoichiometric reactions, adiabatic flame temperature, excess air, combustion efficiency.

Experiment 6: power plant controls: plant efficiency and heat rate at full-load and part-load operation

Objective: Exposing students to principles of controls, control functions, performance monitoring, part-load efficiencies.

Theory taught: Heat-rate, power plant energy balance and thermal efficiency. Performance engineering, controls engineering.

COSTS

The costs incurred in the construction of the power plant were mainly funds expended towards the purchase of equipment, supplies, and instrumentation. As mentioned previously, design, electrical works, mechanical works, installations and all other construction was done in-house, mostly by students and the department's technicians.
The costs breakdown as follows:

Equipment, materials and supplies:		$162,500
Labor:	Faculty	1000 man-hours
	Students	7800 man-hours
	Technicians	50 man-hours

CONCLUSIONS

Engineering students feel that they are saturated by theory in classroom curriculum. An understanding can become somewhat difficult if there are no visual or 'hands-on' stimuli to complete comprehension of the subject being studied [9,10]. This project was conceived to further develop mechanical engineering students' understanding of thermodynamic principles, and to allow junior mechanical engineering students to conduct power plant experiments in their engineering systems laboratory course.

The project has been received favorably by both the students and the faculty. A total of 40 graduating senior mechanical engineering students worked on the mini-steam cycle power plant as part of their senior engineering design capstone course/project. The program provided a very positive impact on our curriculum, both at the undergraduate and graduate levels. At the undergraduate level, the mini-plant helped students synthesize and understand the 'systems' point of view in engineering, i.e. to see the locations of pumps, valves, flash tanks, etc., and to understand how they interact in a system. Also at the undergraduate level, the experiments have proven to be extremely valuable teaching tools. In particular, the boiler energy balance and efficiency experiment (experiment 1) is a favorite of students. At the graduate level, the efficiency calculations, and performance-engineering-related aspects of the mini-plant (on-line heat-balance calculations, excess air adjustments, production cost tracking, etc.) have been very effective teaching tools.

The author strongly believes that such a facility adds an extremely powerful 'real-world' component to the thermal sciences portion of a mechanical engineering curriculum. It supplements and strengthens thermodynamics course lectures, facilitates student understanding of abstract concepts, and provides for an invaluable hands-on training in modern instrumentation and controls. Moreover, exposing students to these new technologies, on-line data acquisition/data analysis and decision making and the real-life demonstration of the marriage between the old (heat engine) and the new (computers) is found to be an excellent way to capturing a student's interest and hence making instruction of thermodynamics a truly enjoyable experience.

Acknowledgements—The author and the ME Department are in debt to the late Donald Lark who contributed enormously to the design and construction of the plant. His fine memory will always live with the plant. This project was funded by the NSF-ILI program, San Diego Gas & Electric (SDG&E), SDSU College of Engineering, SDSU Department of Mechanical Engineering, and SDSU Energy Engineering Institute. The author is grateful for the assistance and cooperation he received from his university and the industrial colleagues. Special thanks are due to all the student who worked on the project and, in particular, the efforts and professionalism of Peter Adams and Terry Fredlund are greatly appreciated.

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Dr Halil Guven has taught mechanical engineering at San Diego State University since 1984. He is the founder and director of SDSU's Energy Engineering Institute, which conducts applied energy R&D for industrial sponsors, and is the director of the university-affiliated and US Department of Energy-funded Energy Analysis and Diagnostic Center, which conducts energy audits for small manufacturers. A native of Cyprus and a Fulbright Scholar, he earned his Ph.D. in mechanical engineering from the University of Houston.