SIMULATION AND OPTIMIZATION ON POWER PLANT OPERATION USING SEGA'S EOP PROGRAM

ESL-HH-00-05-45

Jijun Zhou
Research Assistant
Energy System Laboratory
Texas A&M University

Song Deng
Senior Research Associate
Energy System Laboratory
Texas A&M University

Dan Turner, Ph.D., P.E.
Professor
Energy System Laboratory
Texas A&M University

Mingsheng Liu, Ph.D., P.E.
Associate Professor
Architecture Engineering Dept.
University of Nebraska

ABSTRACT

The operation of a cogeneration power plant is complicated. The Energy Optimization Program (EOP, software made by SEGA, Inc.) was designed to simulate and optimize the operation of TAMU power plant. All major plant components were represented by appropriate models and then structured to establish a system model. A better understanding of the complicated interaction among all energy components within the plant was achieved through systematic simulation using EOP. Overall performance of the plant operation under different conditions was investigated. Further more, (online) operational optimization is made possible by load re-assignment according to EOP's calculation. Other researches on plant operation, such as the impact of utility rates on operational decision making, were also carried out with the help of this program. This paper shows how a well-designed commercial software is exploited in engineering research.

INTRODUCTION

Texas A&M University central power plant is a combined heat and power (CHP) plant with a total steam net rating of 750,000 Lb/h at 600 psig, 750F superheated steam and a total electricity generation capacity of 36.5 MW. There are four steam boilers (including a heat recovery boiler) using natural gas as fuel. Electricity is generated by three steam turbine generators and a gas turbine generator, and is supplied to campus electricity users as well as to the plant itself for station service use. There are four centrifugal chillers, six absorption chillers in the main plant and another six centrifugal chillers in the west plant. Three main steam distribution headers collect and distribute steam at pressure of 600 psig, 150 psig and 20 psig respectively. The 600-psig steam is the heat source for the two steam extraction turbine generators (steam extracted at 20 psig), the back pressure steam turbine generator (exhaust steam at 150 psig) and three steam-turbine-driven centrifugal chillers. Part of 600-psig steam is supplied to the west plant directly. The processed steam (at 150 psig and 20 psig respectively) supplies heat for the absorption chillers, hot water exchangers, hot water pumps, boiler feed water pumps, steam evaporators, boiler feed water deaerators, and other auxiliary plant devices. Figure 1 shows the plant's main steam flow diagram [1].

In general, the overall guidelines for operating the plant are straightforward: supply the campus with uninterrupted heating, cooling and electricity by using the most efficient load combination of boilers, turbines, chillers, and purchased electricity. Simple as the guideline is, the operation of such a large, complicated power plant is anything but an easy task. This complication is mostly due to the dynamic nature of the plant itself, which is caused by dynamic campus load, dynamic utility rates, equipment downtime, equipment replacement, and other uncontrollable special requirements [2].

ENERGY OPTIMIZATION PROGRAM (EOP)

In 1985, Texas A&M University retained Sega to perform an energy study of the main campus power plant and the original west campus chiller plants. The study included performance testing of the boilers, gas turbines, steam turbine generators, steam absorption chillers, steam turbine and electric motor powered centrifugal chillers, and the major auxiliaries including the water evaporators.

Using the study test results, Sega created mathematical models to represent energy production and consumption for each piece of power plant equipment. These models were connected to build a computer program that replicated entire power plant

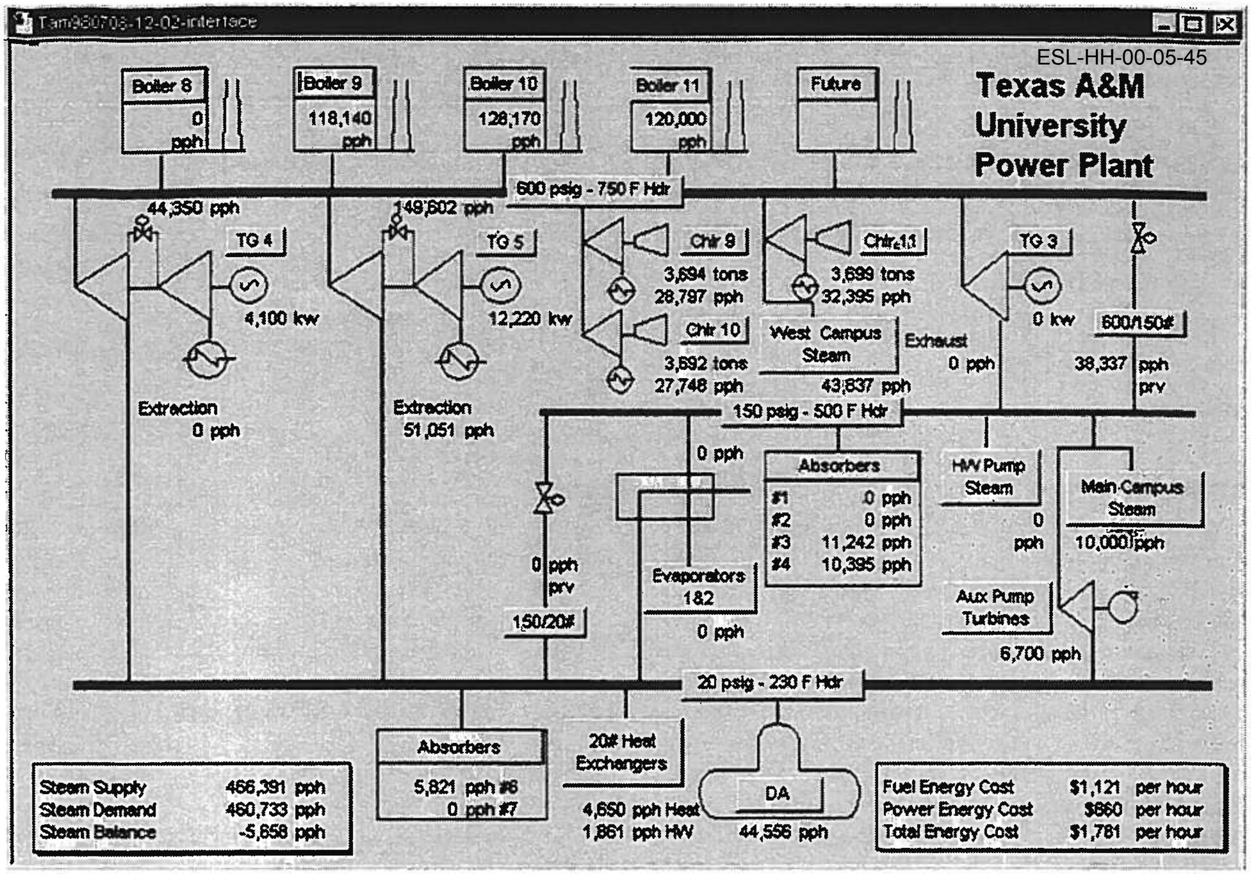

Figure 1. Central plant main steam flow diagram

operations. In 1988, the program was given the capability to automatically optimize the loading of available power plant equipment and power company tie lines to produce the lowest operating cost possible for a given campus load scenario.

In subsequent years the program was updated to reflect changes in power plant operations. In 1997, Texas A&M retained Sega again to convert the program to a spreadsheet-based software and update the model to incorporate recent changes to the power plant. This was accomplished using Sega's EndResult® Power Plant Performance Monitoring and Information System software and Microsoft Excel®. The result is an easily maintainable and expandable spreadsheet-based Power Plant Energy Optimization Program (EOP).

In the future, EOP can be connected directly to the power plant information and control system. This will give management and operations immediate and continuous dynamic information about the most efficient power plant equipment loading distribution for the current steam, chilled water, and electric power energy demand [3].

SYSTEM SIMULATION

In EOP, each major equipment in the power plant has its own model. All models were constructed separately and then connected to each other to replicate the operation of entire power plant. The input data (equipment load and other operational data) for all the models are given through the program's user interface. A set of all the input data is called an operating scenario, which gives a general description of a specific operational condition for the entire plant. In each model, calculations can be done according to certain thermodynamic equations or mathematical regression equations. Both energy (e.g., natural gas consumption) and cost (e.g., hourly operating cost) related results can be achieved. In some cases, the input and output of the models are interconnected to each other as they do in the real world. Once calculations have been done for all the models, a total energy consumption and operating cost can also be computed.

As we mentioned before, the operation of a CHP plant is rather complicated due the complex and the dynamic nature of the system itself. Plant operation related studies through experiments in such a sensitive facility are usually quite limited and expensive. With the help of plant simulation tools like EOP, a better understanding of the complicated interaction among all energy components within the plant can be achieved through systematic simulation. Overall performance of the plant operation under different conditions can also be investigated.

SYSTEM OPTIMIZATION

Under a certain total load (heating, cooling, and electricity power) requirements, the plant can be operated in a variety of loading combinations for boilers, turbines, chillers and utility tie lines. Each of such a loading combination is a feasible operating scenario as long as all load requirements can be satisfied. However, the total operating cost varies from one scenario to another mainly due to the performance difference among individual equipment even their functions are all same (e.g., all boilers supply steam for the plant itself as well as for the campus).

The ultimate objective of EOP program is to find the optimal loading scenario so that the plant is operated in a most economic way (i.e., the total operating cost is minimum). The decision variables of the optimization program are loads of all operating equipment and the main restrictions are equipment capacities and other specified requirements. Not all equipment loads in the plant can be continuously controlled, some of them might not be able to be changed at all. Most of the thermodynamic and mathematical equations in each model are highly nonlinear. Generally speaking, the optimization problem involved here is a large scale, nonlinear problem with implicit objective function. The dynamic nature of plant equipment's performance profiles adds to the complication of the problem.

The basic idea of the optimization approach adopted by EOP is to redistribute loads for plant equipment within each of all energy supply groups (e.g., all boilers is a group, all main campus chillers is another group, etc.)according to each equipment's incremental cost (the marginal operating cost of adding unit load to the equipment). That is to say, the equipment with higher incremental cost will be loaded down and the equipment with lower incremental cost will be loaded up, while the total load requirement is still satisfied. Since the incremental cost continuously changes as load changes, equipment with highest and lowest incremental cost within a group also changes, this load redistribution process is therefore also a dynamic process.

Case Study One - Determine Energy and Cost Saving of an Optimized operating Scenario

To illustrate the optimization approach EOP can make, one can compare EOP's calculation results for an original operating scenario and its optimized operating scenario. A series of such simulations has been done for this purpose, and some of the results can be seen in Appendix 1. Calculation results for one of these scenarios will be discussed in detail in the following text as an example.

In this case study, the original scenario data was extracted from the power plant control system, which represents the plant's actual operating condtion at a certain time. Simulation was first done for this original scenario and a total operating cost is calculated. With all total load requirements (heating, cooling and electricity power) unchanged, optimization routine can be executed and an optimized loading scenario can be found. Total operating cost corresponding to the optimized scenario can also be calculated.

Main equipment load distributions and total operating costs are listed for both the original and optimized scenarios in Table 1. The table shows that almost all major equipment's load changed by the optimization routine and a 10.4% total operating cost saving is obtained (from $1821.49 per hour before optimization to $1632.87 per hour). Figure 2 shows partial load ratio (load over capacity) for each of the plant's major equipment before and after optimization. From this figure, we can clearly see how the equipment is loaded up or down to achieve an optimum loading scenario. Figure 3, 4, 5 are original and optimized load distribution within each of the three major energy groups - steam generation, power generation and main campus chilled water production.

All these table and figures provide us with crucial information for plant operation optimization. In this specific case, Figure 3 indicates that for an optimum operating scenario, all turbine generators should be loaded up and the amount of purchased power should be decreased. In other words, the plant should produce as much electricty as possible by itself instead of purchasing electricity from utility company, which is an indication of a relatively high electricty rate and a relatively low natural gas price.

Table 1. Equipment load assignment before and after optimization

Group	Equipment	Unit	Maximum Load	Minimum Load	Original Load	Optimized Load
Total load requirements	Total main campus chiller load	tons	15,468			
	Total west campus chiller load	ton	4,444			
	Total campus electricity load	kW	36,171			
Boiler Steam Production	Boiler 9 Steam	pph	175,000	17,500	118,110	80,506
	Boiler 10 Steam	pph	175,000	0	90,091	174,837
	Boiler 11 Steam	pph	300,000	120,000	165,235	120,000
Generated and Purchased power	Turbine 4 power	kW	6,000	1,000	4,100	5,526
	Turbine 5 power	kW	13,000	5,000	12,220	13,000
	(Gas)Turbine 6 power	kW	13,000	7,700	12,150	13,000
	Purchased power	kW	50,000	0	22,011	16,198
Main Campus Chiller Load	Chiller 9 load	ton	1,000	1,000	2,947	3,700
	Chiller 10 load	ton	3,700	1,000	3,000	3,700
	Chiller 11 load	ton	3,700	1,000	3,000	3,700
	Chiller 12 load	ton	3,700	1,000	3,087	1,014
	Absorber 3 load	ton	1,500	500	1,000	1,376
	Absorber 4 load	ton	1,500	500	1,000	1,460
	Absorber 6 load	ton	1,000	250	734	258
	Absorber 7 load	ton	1,000	250	700	260
West Campus Chiller Load	Carrier 1 load	ton	1,000	100	982	998
	York 3 load	ton	2,200	600	1,673	2,194
	Trane 1 load	ton	1,334	150	875	626
	Trane 3 load	ton	1,334	150	914	626
Total Costs	Total purchased gas cost	$/hr			1,157.73	1,119.49
	Total purchased power cost	$/hr			663.77	513.38
	Total operating cost	$/hr			1,821.49	1,632.87

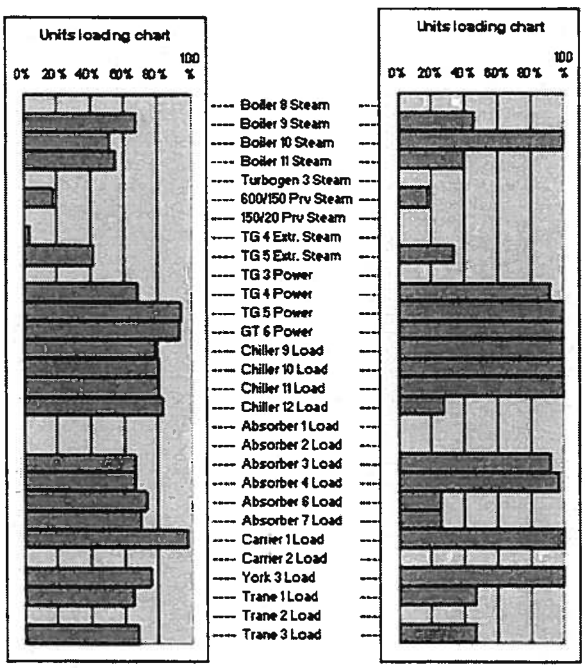

Figure 2. Equipment partial load ratios before and after optimization

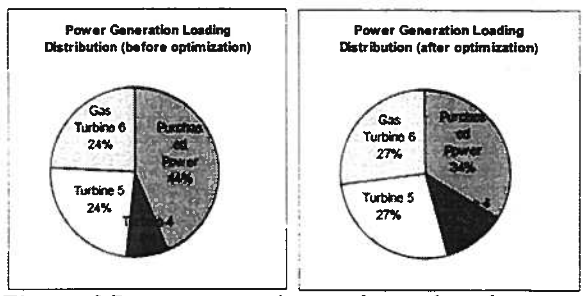

Figure 3.Power generation and purchased power loading distribution (before and after optimization)

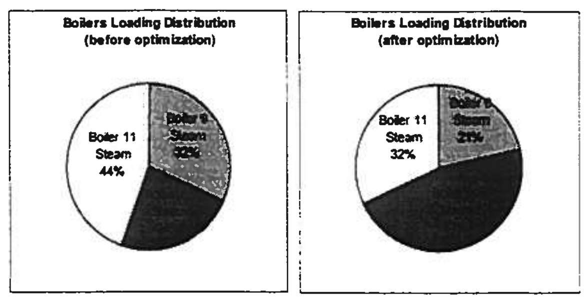

Figure 4.Boilers steam generation loading distribution (before and after optimization)

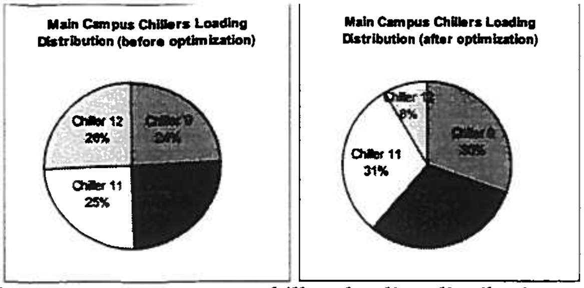

Figure 5. Main campus chillers loading distribution (before and after optimization)

Figure 4 indicates boiler 10 should be loaded up while other boilers should be loaded down, mainly because boiler 10's overall efficiency is higher than other boilers. A closer look at Table 1 and Figure 2 shows that the optimized solution suggests boiler 10 should be fully loaded while boiler 11 should be loaded down to minmum load possible. Since boiler 10 is a heat recovery steam boiler heated by exhaust flue gas from gas turbine 6, this particular case reflects a relative high efficiency of a combined cycle subsystem (gas turbine and heat recovery boiler) in the plant.

As for the main campus chiller load distribution, Figure 5 doesn't include all chillers in the main plant. Since the total chiller production contributed by chiller 9, chiller 10, chiller 11 and chiller 12 roughly remains the same before and after the optimization, only load distribution among these four chillers are displayed for the sake of discussion. Among these four chillers, chiller 12 is an electrical motor powered centrifugal chiller, while all other three are driven by steam turbines powered by 600 psig steam. For this reason, the load reassignment suggested by the optimization solution also reflects the relative price between natural gas and electricity. According to Figure 2, all three steam turbine driven chillers are loaded up to maximum and chiller 12 is loaded down, indicating a relative high electricity price and a relative low natural gas price, which is consitant with the induction from Figure 3.

Case Study 2 - "Impact of Basic Utility Rates On Power Plant's Decision Making"

As a CHP plant, Texas A&M university power plant generates both heat and power, while the basic utility supply are natural gas and purchased electricity. It's of the interest of power plant operators and managers to investigate how the plant operation should respond to a change in basic utility rates in order to save the operating cost. The EOP program can be used to help plant operators in making such decisions.

In this study, experiments had been done for 6 electricity prices and 6 gas prices (totally 36 scenarios). All other conditions remain the same except the utility rates. Optimized load distributions calculated by EOP under all scenarios were collected and analyzed. Some interesting results were observed. Figure 6 (and Figure 7) shows the optimized load for chiller 12 as a function of electricity price and gas price. The figures indicate this chiller should increase its load when the price of natural gas rises and decrease its load when the price of electricity rises. Since this is then only electrical motor driven chiller in all main campus chillers, it does makes sense that it's load is negatively related to the electricity price and positively related to the gas price.

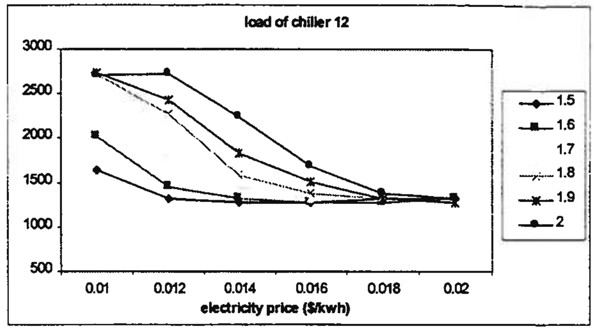

Figure 6. Chiller 12 load as function of electricity price and gas price (The legend on the right of the figure represents different gas prices, in $/MMBtu)

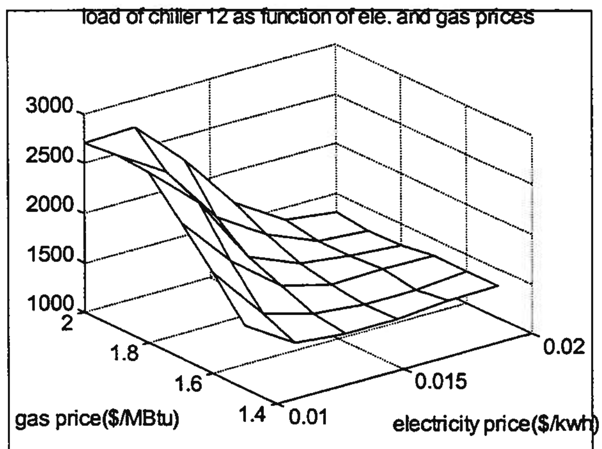

Figure 7. Chiller 12 load as function of electricity price and gas price

CONCLUSIONS

The Energy Optimization Program (EOP) establishes a sophisticated model for the operation of Texas A&M university power plant. A better understanding of the complicated interactions among all plant equipment can be achieved through system simulations. Combined with the utility rate models, the total operating cost of the plant can be calculated for a certain operating scenario. The optimization model gives suggestions on more economic loading assignments. An overall operating cost saving can be expected through such load reassignments. This computer program is quite helpful to power plant engineers and operators in various aspects. Further research on plant operation can be done with the help of this program.

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Appendix 1. Scenario simulation and optimization results

		scenario 1		scenario 2		scenario 3		scenario 4		scenario 5		scenario 6		scena
		before	after	before	after	before	after	before	after	before	after	before	after	before
Total Steam Generation	pph	386,650	383,628	291,835	291,591	374,028	376,769	231,560	213,433	373,440	375,876	274,374	269,307	260,415
Total Power Generation	kWh	29,625	29,625	26,690	26,690	28,470	28,470	18,281	18,281	30,318	30,318	25,540	25,540	25,500
Total Purchased Power	kWh	25,744	25,597	14,000	12,788	22,012	20,473	28,168	28,860	18,850	18,683	20,476	19,918	25,373
Total Purchased Gas Cost	$/hr	$1,213.64	$1,158.32	$918.69	$917.75	$1,159.14	$1,142.65	$799.63	$751.27	$1,153.16	$1,136.60	$881.02	$870.64	$847.98
Total Purchased Power Cost	$/hr	$760.33	$756.54	$456.53	$425.21	$663.80	$623.97	$823.04	$828.00	$581.99	$577.16	$624.06	$609.63	$750.74
Total Purchased Utility Cost	$/hr	$1,973.97	$1,914.86	$1,375.22	$1,342.96	$1,822.94	$1,766.62	$1,622.67	$1,579.26	$1,735.15	$1,712.76	$1,505.08	$1,480.27	$1,598.71
Boiler 8 Steam	pph	0	0	0	0	0	0	0	0	0	0	0	0	0
Boiler 9 Steam	pph	127,160	127,160	132,490	132,490	118,140	118,140	0	0	115,260	115,260	161,340	161,340	113,140
Boiler 10 Steam	pph	90,190	136,466	159,345	159,101	90,091	138,218	90,690	93,423	92,360	140,326	113,034	107,967	147,275
Boiler 11 Steam	pph	179,300	120,000	0	0	165,797	120,410	140,870	120,010	165,820	120,286	0	0	0
Turbogen 3 Steam	pph	0	0	0	0	0	0	0	0	0	0	0	0	0
600/150 Prv Steam	pph	49,521	49,518	28,096	28,972	36,800	38,426	52,500	53,414	18,590	18,590	29,971	30,714	19,150
150/20 Prv Steam	pph	0	0	0	0	0	0	0	0	0	0	0	0	0
Turbogen 4 Extraction Steam	pph	3,160	388	0	0	2,718	46	52,290	27,882	13,970	316	0	0	0
Turbogen 5 Extraction Steam	pph	71,970	78,095	60,915	70,390	66,854	72,919	0	0	89,880	107,716	65,018	70,766	91,792
Turbogen 3 Power	kWh	0	0	0	0	0	0	0	0	0	0	0	0	0
Turbogen 4 Power	kWh	5,065	5,065	1,000	1,000	4,100	4,100	5,281	5,281	5,058	5,058	0	0	0
Turbogen 5 Power	kWh	12,020	12,020	12,690	12,690	12,220	12,220	0	0	12,260	12,260	12,540	12,540	12,500
Gas Turbine 6 Power	kWh	12,520	12,520	13,000	13,000	12,150	12,150	13,000	13,000	13,000	13,000	13,000	13,000	13,000
Chiller 9 Load	tons	3,180	3,699	0	0	2,947	2,960	3,558	3,682	0	0	0	0	0
Chiller 10 Load	tons	3,500	3,699	3,700	3,699	3,000	3,650	0	0	3,700	3,694	3,500	3,698	3,640
Chiller 11 Load	tons	3,460	3,699	3,182	3,699	3,000	3,020	1,000	1,609	3,700	3,694	3,354	3,698	1,277
Chiller 12 Load	tons	2,870	1,692	2,786	1,368	3,087	1,383	0	0	2,440	2,269	2,717	1,409	2,346
Absorber 1 Load	tons	0	0	0	0	0	0	0	0	0	0	0	0	0
Absorber 2 Load	tons	1,500	1,499	0	0	0	0	1,000	1,482	0	0	0	0	0
Absorber 3 Load	tons	1,500	1,499	0	0	1,000	1,500	1,500	1,482	0	0	0	0	0
Absorber 4 Load	tons	1,500	1,499	1,000	1,499	1,000	1,500	1,500	1,482	0	0	1,000	1,498	0
Absorber 6 Load	tons	778	999	697	811	734	564	890	405	810	994	726	996	735
Absorber 7 Load	tons	1,000	999	700	999	700	1,000	1,000	305	0	0	1,000	998	0
Carrier 1 Load	tons	0	0	0	0	982	991	371	103	0	0	0	0	0
Carrier 2 Load	tons	0	0	901	996	0	0	890	994	0	0	0	0	0
York 3 Load	tons	1,146	800	1,855	2,186	1,673	2,196	0	0	0	0	0	0	0
Trane 1 Load	tons	989	1,260	855	682	875	630	816	734	0	0	937	682	622
Trane 2 Load	tons	0	0	0	0	0	0	852	721	895	1,077	0	0	0
Trane 3 Load	tons	1,035	1,321	900	666	914	629	866	1,262	869	687	977	1,332	0

* Within each scenario, the shaded column represents load assignment after optimization.

**For each scenario, operational cost saving from optimization can be seen by comparing "Total Purchased Utility Cost" data for the original load assignment and the optimized load assignment.

Proceedings of the Twelfth Symposium on Improving Building Systems in Hot and Humid Climates, San Antonio, TX, May 15-17, 2000