Field Measurement and Evaluation of Indirect-DX Air-Conditioning Systems

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Concerned with the high cost of air-conditioning (AC) to its desert climate customers, the Southern California Edison Company (SCE) has embarked on a series of demonstrations of advanced evaporative cooling techniques coupled to energy-efficient vapor compression air conditioning equipment which promise to lower AC costs. The first two demonstrations involve indirect evaporative cooling of ventilation air to reduce the energy requirements of packaged air conditioners and water source heat pumps. The demonstration sites, an automobile dealership and a resort type hotel, were selected to show the practicality and reliability of a new generation of evaporative cooling equipment in applications where comfort and trouble-free operation are paramount. This paper describes SCE's experience with the operation of these systems, the approach taken to monitor their performance, and the efforts that are contemplated to communicate the results to design professionals, developers and potential users.

Introduction

Every summer, residents of the Coachella Valley, concerned with the size of their energy bills search for ways to reduce them. SCE is committed to help its customers in this area to reduce their energy costs through demand-side management (DSM) measures.

The Coachella Valley consists of six cites; namely Palm Springs, Cathedral City, Palm Desert, Desert Hot Springs, Rancho Mirage, and Indian Wells. Palm Springs is the largest city with a population of 42,000. The summer design temperatures are 113°F DB, 73°F WB, and the annual cooling degree days are 4,216. In such a hot and dry climate, evaporative cooling should be a very effective way of reducing the cooling costs.

Albeit at considerable sacrifice in comfort, direct evaporative cooling has historically provided a highly energy efficient space cooling alternative to thousands of utility customers in dry climate. However, in extreme hot weather, direct evaporative cooling can only deliver air to the space well above the required temperature in maintaining comfort conditions in the space, further aggravated by the moisture added to the air in the cooling process. In addition, those systems impose a high maintenance burden caused by corrosion and deposition of mineral and salt on the evaporative media. Consequently, over the years evaporative cooling has become highly unpopular among the designers, developers, and potential users of new commercial buildings in climates well-suited for its use.

During the last decade, manufacturers of evaporative cooling systems have adopted new materials and fabrication techniques to reduce or eliminate some of the old drawbacks. New corrugated treated cellulose, PVC, fiberglass, and stainless steel evaporating media, along with improved water distribution and bleed-off techniques have considerably reduced salt build-up and odor problems. Corrosion is no longer a problem through the use of stainless steel and fiberglass for frame and cabinet construction. In addition to largely solving the durability and maintainability problems with the technology, the evaporative cooling industry set out to address the comfort issues by developing systems that, by means of heat exchangers, cool the air indirectly, delivering dryer air. The process, known as indirect evaporative cooling, is illustrated in Figure 1. By adding a direct evaporative stage to indirect systems, further cooling the air, indirect/direct systems are now capable of providing comfort for most residential, commercial and industrial applications.

Although improved evaporative cooling systems have now been widely available for over half a decade, their share of the air conditioning market is minute. The Evaporative Cooling Institute estimates that the annual sales for the

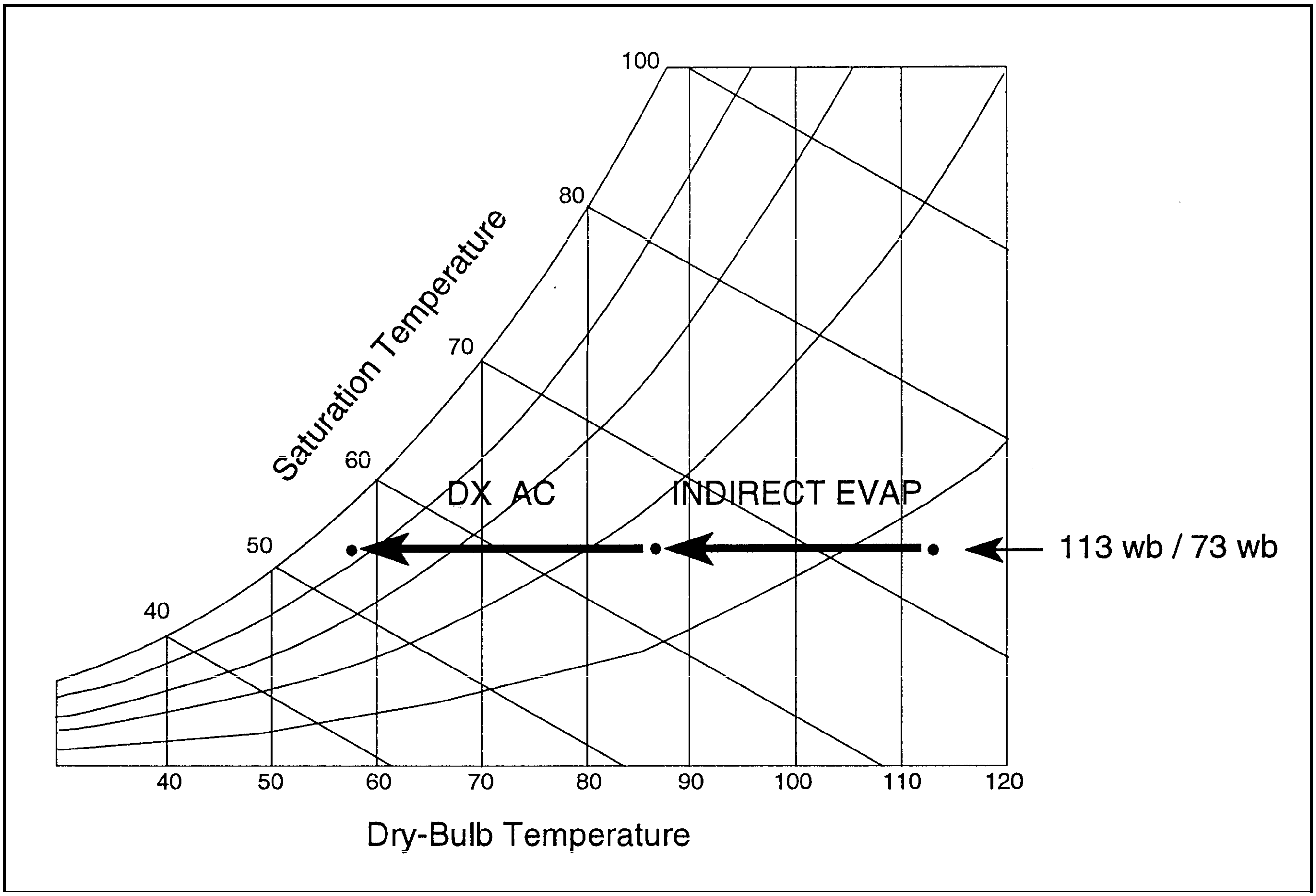

Figure 1. Indirect/DX Cooling Process

industry amount to approximately $150 million (Foster 1994); a very small fraction of the $20.8 billion in unitary air conditioning shipments reported in 1993 (Heating, Air Conditioning and Ventilating News 1993). Even if only a fraction of the unitary AC market can ever be expected to adopt evaporative cooling, a comparison of these two figures indicates that evaporative cooling hasn't yet reached its true potential. This shortfall can be attributed to a variety of factors. Perhaps the greatest factor has been the lack of standardized performance ratings and reliable design guidelines. This problem is currently being addressed by ASHRAE's development of a soon to be adopted testing standard for direct and indirect coolers. However, the lack of consideration given to the technology by HVAC engineers and cooling equipment selectors is likely to persist. Although partially attributable to the perception of the technology as maintenance intensive and not capable of providing comfort comparable to that of refrigerated AC, it also originates in insufficient promotion and marketing. It may be through the energy efficiency efforts of electric utilities that the technology will eventually be considered by more building conditioning designers. In addition to the utilities serving the traditional domain of this technology, such as those in Texas, New Mexico and Arizona, those in California are currently investigating and/or promoting evaporative cooling through their DSM programs. The research described below constitutes the first step in a knowledge transfer process which will ultimately translate what is learned into practical advice to HVAC design professionals, building owners and operators through a systematic marketing effort.

Demonstration Site Selection

As in any other technology demonstration process, site selection was a critical first step. Among the most important general characteristics for candidate sites were the willingness and commitment of the customer to work with the utility and their consultant through the unavoidably intrusive process of instrumenting the systems, and to provide occasional assistance to keep the equipment or data acquisition systems operating properly. Other desirable site characteristics included having a high visibility in the community, and being businesses types that place a high value on comfort and reliability. The local energy services representatives were asked to recruit candidate sites, which were then visited by the SCE's technical staff and their consultant. Candidate sites included a bowling alley, a mall fast food restaurant, a full service restaurant, a resort type hotel and an automobile dealership. The last two were selected for offering the most flexibility and having the potential to yield the most information. The hotel for having a system with five years of uninterrupted operation and high benefit potential by the virtue of cooling one hundred percent outside air. The automobile dealership offered the opportunity to test three new units of comparable capacity and three distinct levels of efficiency.

Wyndham Resort Hotel

The Wyndham Resort Hotel is a 550-room resort type lodging facility. The demonstration project at the Wyndham Hotel involves the monitoring and evaluation of an existing installation consisting of an indirect evaporative cooling module precooking the air for a water-source heat pump providing ventilation air to one of the guest room wings at the hotel. Five other identical units provide ventilation air to the rest of the hotel. The system tested has been in trouble-free operation since its installation in 1987.

The operation of the system can be summarized as follows. The indirect evaporative cooling module pre-cools the outside air drawn by the heat pump supply fan, thus reducing the work on the heat pump's compressor. The heat pump fan operates continuously at constant volume, drawing one hundred percent outside air for ventilation of the wing's guest rooms and hallways. The heat pump exchanges heat with a constant volume water loop. Finally, a two-cell cooling tower with two-speed fan motors rejects excess heat from the water loop into the atmosphere.

The primary objective of the Wyndham demonstration is to measure the economic benefits of indirect evaporative precooking of outside air cooled by a water source heat pump system, operating with 100% outside air. A secondary objective of the project is to document and demonstrate the durability, reliability and maintainability of the indirect evaporative cooling (IEC) module, and to ascertain and document the impact of the IC module on the cost of maintenance of the HVAC system. Historical reliability and cost data will be based on maintenance records and the recollection of the hotel's maintenance personnel and its HVAC service contractor.

In order to achieve these objectives, the Wyndharn experiment was designed to monitor and evaluate the individual and combined energy performance of (1) the indirect evaporative cooling module and (2) the water-source heat pump for a period of one year, under the unconstrained conditions found in the day-to-day operation of the hotel. The measured performance of the combined unit is to be compared to a fictitious heat pump unit of sufficient capacity to serve the total measured cooling load.

Wyndham Metering Plan. The metering plan was designed and implemented with a minimum of interference with the units' operation and with the ultimate objective of minimizing guest inconvenience and discomfort. Coolings load and energy use data for the heat pump and the indirect evaporative module are separately monitored in order to measure the cooling efficiency and operating cost of each unit. The total heat rejected at the cooling tower and the energy required by the water loop's circulation pump and evaporative cooling tower spray pump and fans are also measured, and the corresponding share allocated by the ratio of this heat pump contribution to the total heat rejection at the tower.

The cooling load served by the Indirect/DX combination unit is calculated as the change in enthalpy of the air flowing across the indirect evaporative cooling coil and the direct expansion (DX) heat pump evaporator coil. The net total energy rejected at the cooling tower is measured as the change in enthalpy of the water circulating in and out of the cooling tower. The total electric power required to maintain circulation in the water loop and to operate the loop's cooling tower is determined by continuously monitoring the circulation pump power, and a combination of one-time power measurements for each speed of the cooling tower's two cell fans and spray pump, and continuous monitoring of the fan and pump operating status. The total amount of heat rejected by the tower is continuously monitored by measuring the flow rate and arriving and leaving temperatures of the water going through the tower. Figure 2 illustrates the measurement points and the variables measured, while Table 1 lists the sensors, transducers and data acquisition systems used.

VIP Motor Cars

The second demonstration site, VIP Motors Cars Limited, a luxury car dealer, had at the time of site selection, three 5-ton rooftop packaged air conditioners near the end of their economic lives. The project involves replacing the three aging rooftop package air conditioners with three new higher efficiency package units and one indirect evaporative cooler. The dealer consists of a glass enclosed front showroom, sales people and administrative offices situated behind the showroom, and the maintenance garage located at the rear of the building. The showroom space is conditioned by two of the AC units discharging directly into the space, while the third unit serves the offices through duct work. Each unit is individually controlled by

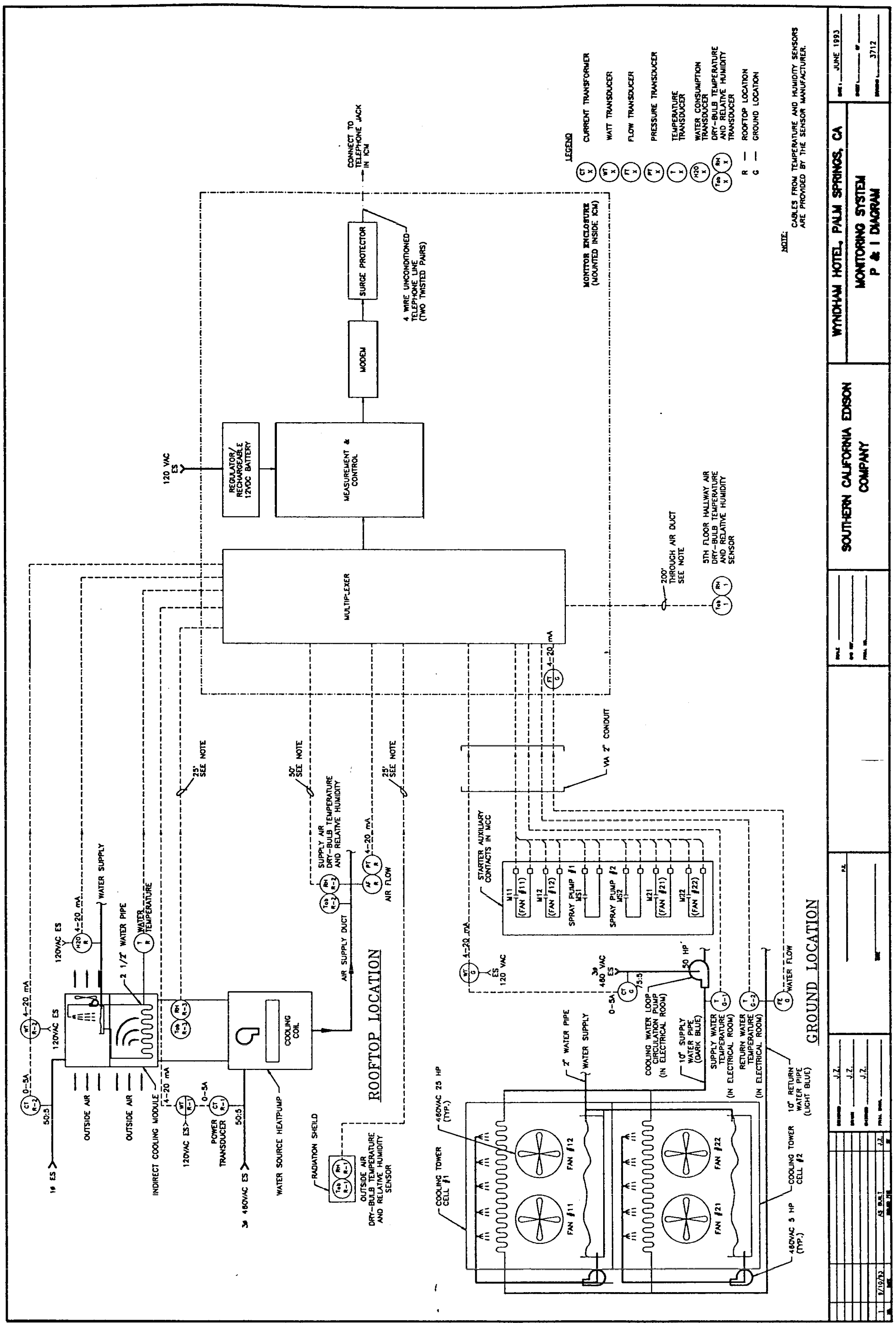

Figure 2. Wyndham Hotel Instrumentation Diagram

Table 1. Measured Variables - Wyndham Hotel

Indirect Evaporative Pre-Cooler

- Indirect Evaporative Cooler Supply Dry-Bulb and Relative Humidity
- Water Temperature at Indirect Evaporative Cooler Sump
- Indirect Evaporative Cooler Water Consumption
- Indirect Evaporative Cooler 3-phase Electric Power

Water Source Heat Pump and Auxiliaries

- Supply Air Dry-Bulb Temperature and Relative Humidity of HP Unit
- Heat Pump Unit 3-phase Electric Power
- Water Loop Circulating Pump 3-phase Electric Power;
- Water Loop Volume Flow Rate
- Supply and Return Water Loop Temperatures at Cooling Tower
- 3-phase Electric Power Requirements of Each Stage of the Loop's Cooling Tower Fans and Spray Pumps (One Time Measurements)
- On-Off Status of Electric Power to Each Stage of Loop Cooling Tower's Fans and Spray Pumps

Ambient Measurements

- Outside Air Dry-Bulb Temperature and Relative Humidity
- Hallway Dry-Bulb and Relative Humidity

its own thermostat. The mechanical garage space is not refrigerated but conditioned by direct evaporative coolers and unit heaters.

Like the units they replaced, the new units have gas heat. All three units have enthalpy controlled economizer cycle. One of the AC units, serving the office area, has an SEER of 10.0 suitable to meet but not to greatly surpass the current minimum State of California efficiency requirements of 9.9 SEER. The other two AC units, both serving the showroom floor area, have an SEER of 12.25, comfortably higher than the minimum requirements of SCE's equipment rebate program (10.4). One of the 12.25 SEER units was fitted with an indirect evaporative cooler to pre-cool the make-up outside air entering the unit, reducing the work on the unit's compressor and extending the operating range of the economizer cycle.

The primary objective of the VIP demonstration is to measure the economic benefits of high-efficiency vapor compression DX air-conditioning equipment with indirect evaporative cooling of the make-up air. A secondary objective of almost equal importance is to identify and characterize any increase in the cost of maintaining the air conditioning equipment resulting from the adoption of indirect evaporative precooking. A third objective is to measure the cost-effectiveness of surpassing the state-mandated energy efficiency to the levels required for participation in the DSM incentive program sponsored by the Southern California Edison Company.

In order to achieve these objectives, the experiment was designed to measure the energy performance of each unit for a period of one year, under the unconstrained conditions found in the day-to-day operation of the automobile dealer. Side-by-side performance comparisons of the three units are to be established at the end of the monitoring period. With differing loads and control strategies experienced by each unit during concurrent periods, this requirement has presented unique challenges, which are discussed in a subsequent section of this paper.

VIP Metering Plan. Instrumentation and remote data acquisition equipment were selected and installed to monitor the operation of the newly installed AC units and indirect evaporative pre-cooler. In order to measure the cooling efficiency and operating cost of each unit over a one-year period, the metering plan calls for the measurement of the power consumed and the cooling load served by each of the units. A complete energy balance is performed based on measurement of the change in enthalpy of the air flowing across each of the DX cooling coils and the heat exchanger in the indirect evaporative cooling unit, and the electrical energy required to operate them.

The variables measured for each unit are listed in Table 2. The instrumentation diagram in Figure 3 shows the measured variables and measurement point locations, while Table 3 lists the types of sensors, transducers and data acquisition system utilized.

The metering plan drawn for VIP Motors calls for the continuous monitoring and collection of five minute data for all 28 channels. All channels are scanned every five seconds and the readings averaged over five-minute intervals. Sensor data is converted to engineering units at the data logger, stored temporarily in RAM, and retrieved remotely on a daily basis over a standard voice grade phone line and stored for later processing.

Data Analysis

The five-minute average sensor data as received from the field is stored in ASCII comma separated value format. Data is extracted from the files in one-day segments (288 records) for all measured variables into a Microsoft Excel spreadsheet template which is used for visual data verification, data editing and filling. The spreadsheet performs psychometric calculations, calculates cooling loads as enthalpy differences, and applies one time measurement power values to on-off status readings. Tables of sensor data and 24-hour plots of all key performance parameters are printed and bound for quick visual inspection. All sensor readings and derived variables are exported as comma separated values files for further processing. All spreadsheet operations are performed by macros for unattended operation. The SAS family of statistical analysis software is used for all further data processing, analysis and plotting. All data analysis is performed on 486 PC's.

As in any field test of air conditioning equipment performed under real operating conditions, all conditions that determine the system performance can vary independent of each other. That is the outside ambient conditions, control strategies and loads vary making comparison across systems, as in VIP Motors, rather difficult. To allow comparison between systems at various conditions, all energy use measurements are normalized and plotted against the variables that determine their efficiency. Accordingly, all energy efficiency measurements are stated as energy efficiency ratios (EER), not to be confused with the American Refrigeration Institute (ARI) efficiency parameter of the same name which is determined at standard design conditions. These EERs are simply a way of visualizing and comparing the cooling effect by unit of electrical energy required to produce it [Btu/Wh]. Side-by-side comparisons can be made by simply plotting the influence of key independent variables such as outdoor temperatures and part load ratio on the EER of each unit.

Table 2. Measured Variables - VIP Motors

A/C Unit #1 and Unit #2:

- Mixed Air Dry-Bulb Temperature and Relative Humidity
- Supply Air Dry-Bulb Temperature and Relative Humidity
- Supply Air Flow Rate
- 3-phase Electric Power Requirements

A/C Unit #3:

- AC Mixed Air Dry-Bulb Temperature and Relative Humidity
- AC Supply Air Dry-Bulb Temperature and Relative Humidity
- AC Supply Air Flow Rate
- Indirect Evaporative Cooler Supply Dry-Bulb and Relative Humidity
- Indirect Evaporative Cooler Supply Air Flow
- Indirect Evaporative Cooler Water Consumption
- 3-phase Electric Power Requirements

Ambient Measurements

- Outside Air Dry-Bulb Temperature and Relative Humidity
- Showroom Dry-Bulb and Relative Humidity
- Office Dry-Bulb and Relative Humidity

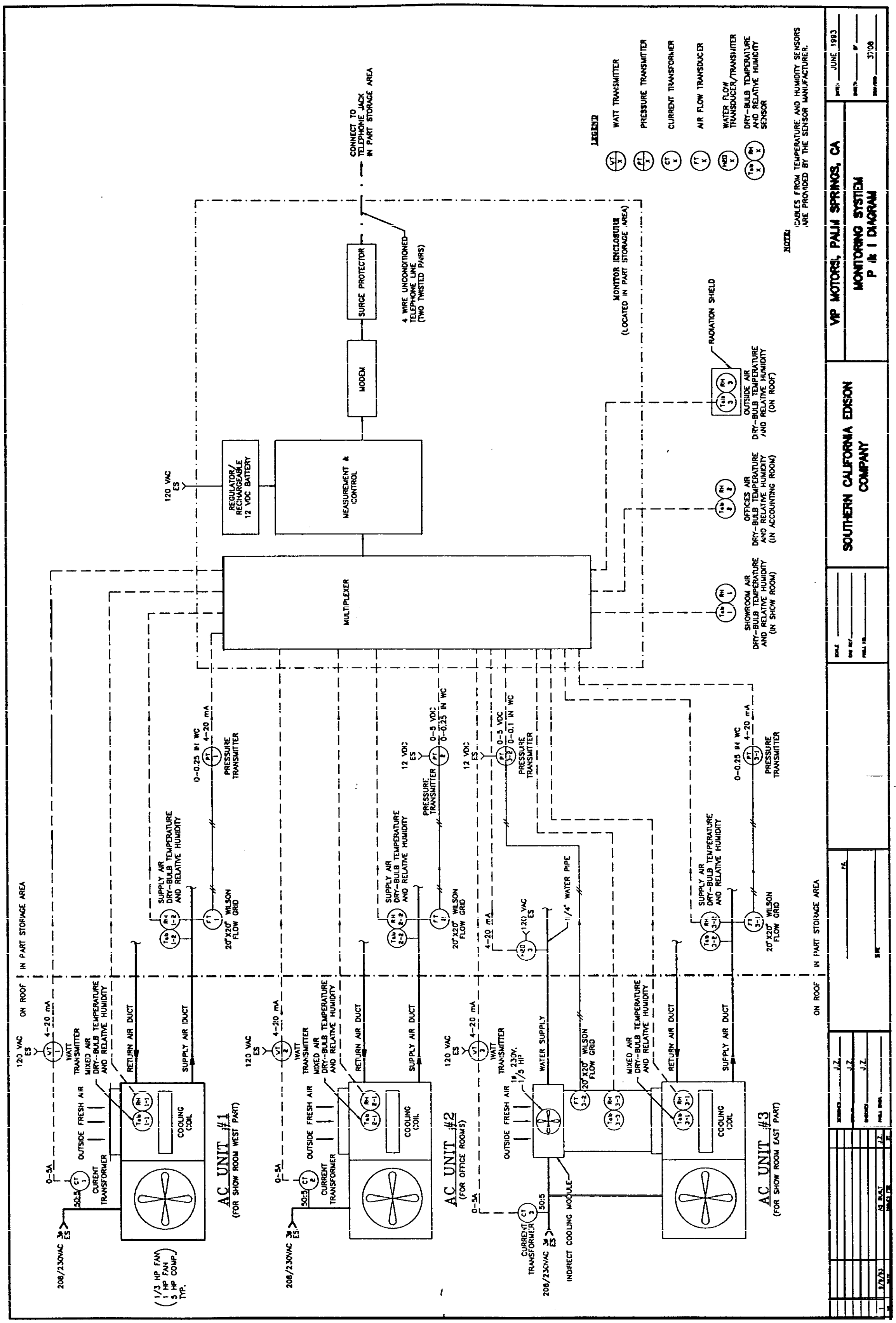

Figure 3. VIP Motors Instrumentation Diagram

Table 3. Sensors, Transducers and Data Acquisition System

Function/Variable	Sensor Type
Air Dry-Bulb Temperatures and Relative Humidity	Integrated Thermistor and Thin Film Capacitive Hygrometer
Volumetric Flow Rate	Wilson Flow Grid w/Differential Pressure Transducer
3-phase Electric Power	True RMS Watt Transducer w/AC Current Transformers
Indirect Evaporative Cooling Module Water Consumption	Rotameter w/LED Photo-Transistor Array
Water Loop Volumetric Flow Rate	Insertion type turbine flow meter (Wyndham)
On-Off Status	Electromechanical Relay (Wyndham)
Datalogger	Microprocessor Based Datalogger w/RAM Storage Capacity for 29,900 Data Points
Data Retrieval	1,200 Baud Surge Protected Modem

Status of the Projects and Preliminary Results

The design of the demonstration projects started in May of 1993. The long lead times required by instrument manufacturers delayed the start of data collection until August and September of 1993 for VIP and Wyndham respectively. Consequently, a significant portion of the summer of 1993 cooling season was missed, and data collection will continue through the summer of 1994. Both projects have proceeded with minimum data loss. October 20, 1993, the daily data verification process revealed that no cooling effect was apparent in the evaporative precooler at the VIP site and water flow was not present. A call to the site revealed that due to plugging of the drain the pan had overflown and a minor leak appeared in the showroom. A mechanic who went up to investigate turned off the valve controlling the water supply to the unit. The drain was subsequently unplugged and the roof leak repaired. Only a few days of data on the performance of the evaporative unit were lost.

The five-minute data shown in the figures is useful in visualizing the cycling of compressors and pumps and damper modulation of air flows, however, due to the thermal inertia of ducts, coils and heat exchangers, it makes the analysis of cooling energy efficiency trends difficult as it greatly increases the scatter. Consequently, the trend lines in the figures are shown for qualitative analysis purposes only, until the analysis of the data integrated over 15 minutes is complete.

The performance of the Indirect Evaporative Cooling Unit at the Wyndharn Hotel was characterized in terms of EER as a function of outdoor wet bulb depression, the difference between outdoor wet bulb and dry bulb (not shown), and outdoor dry bulb temperature. The wet bulb depression is generally a good measure of the partial vapor pressure differential that drives the evaporative cooling process. However in order to have a common basis for comparing to and combining the performance of the evaporative cooling stage to the refrigerated stage, the EER shown in Figure 4 is plotted against outdoor dry bulb temperature. The trend follows closely that of the EER when plotted against the wet bulb depression. The left-most lobes in the upper right part of the plot is likely caused by high winds and the relative proximity of the outdoor sensor to the cooling tower plume. The sensor will be relocated this summer, and the data corrected based on VIP outdoor data.

The scatter of the 5-minute data on heat pump cooling EER vs. outdoor dry bulb temperature shown in Figure 5 is exaggerated by the impact of compressor cycling. However, the data clusters around two distinct regions corresponding to the operation of one or both heat pump compressor stages. The trends in both clusters shows the characteristic reduction of compressor efficiency as outdoor temperature (and condensing temperature) increase. The same analysis of 15-minute data shows reduced scatter about the trends.

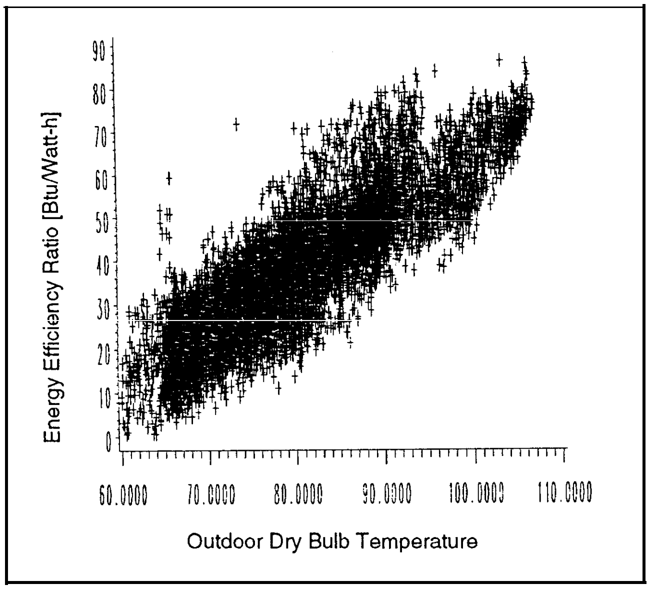

Figure 4. Wyndham, Overall Indirect/DX Cooling Efficiency

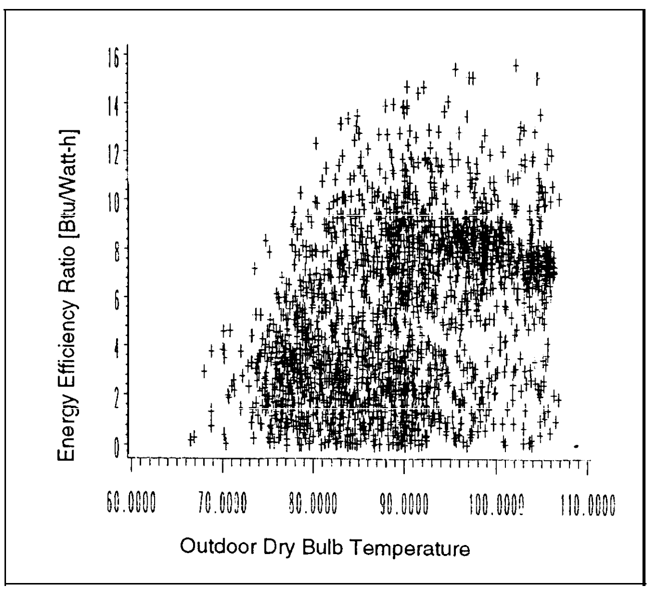

Figure 5. Wyndham, Heat Pump DX Cooling Efficiency

Figure 6 shows the combined system performance, IEC plus heat pump, against outdoor temperature. The overwhelming influence of the evaporative precooking on the overall performance of the system is apparent by the upward trend of EER with outdoor temperature. Figure 7, although again hampered by excessive scatter, shows that the load is completely carried by the indirect evaporative cooling stage a high percentage of the time at all temperatures, as demonstrated by the large number of observations with IEC partial load ratio of 1.0.

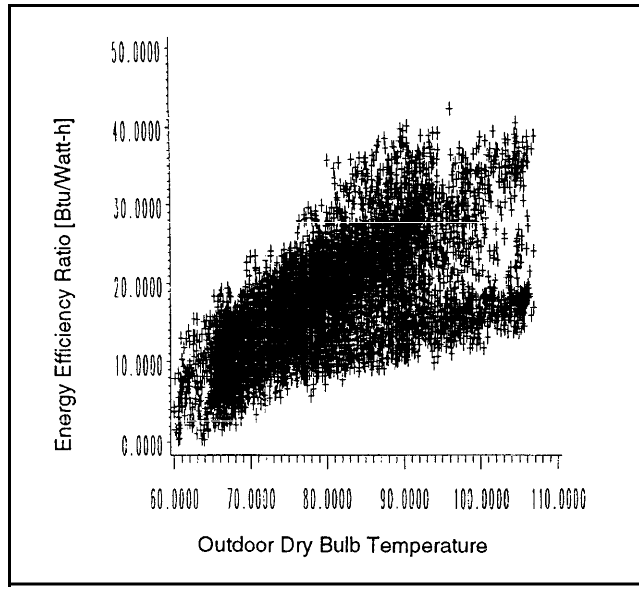

Figure 6. Wyndham, Overall Indirect/DX Cooling Efficiency

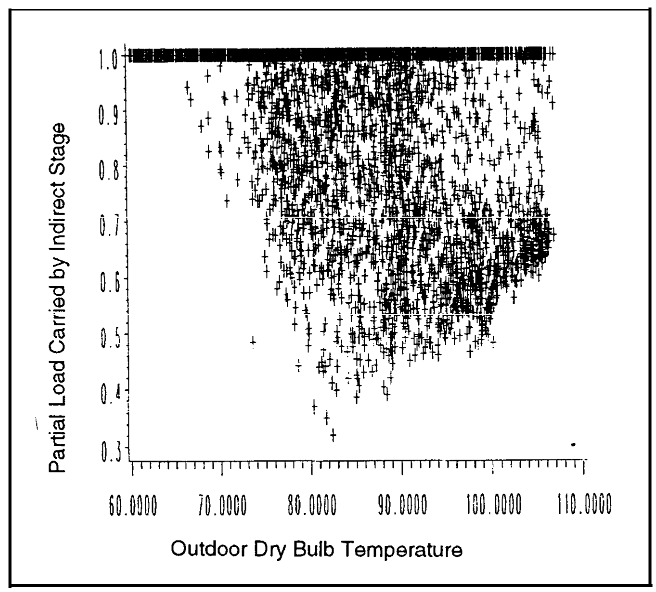

Figure 7. Wyndham, Partial Load Carried by Indirect Stage

Figures 8 through 10 show the performance of the three AC units at VIP Motors. The low efficiency unit (10.0 SEER) shows the greatest degradation of performance with increasing outdoor air temperature. This seems logical. However, the value of at the trend line at 82 “F (the value at which SEER is rated) is much higher than expected. The performance of the 12.25 SEER unit is quite what could be expected. The EER trend line at 82°F is approximately at the SEER rated value and the performance doesn’t seem to decline as sharply with temperature.

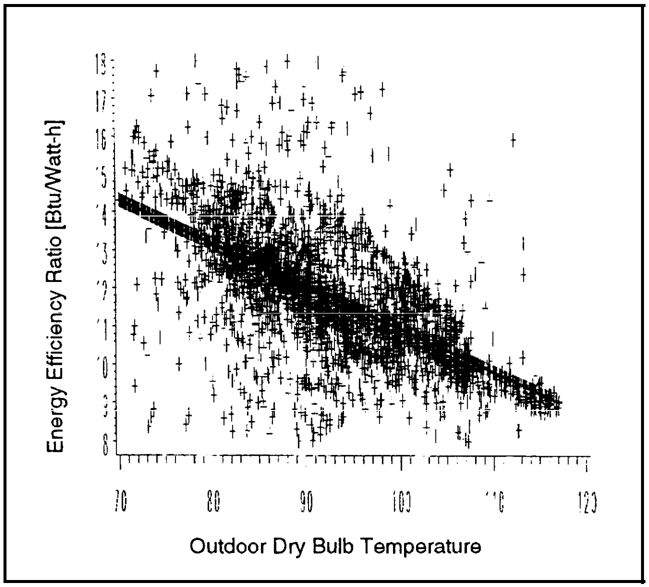

Figure 8. VIP-10.0 SEER AC Unit Cooling Efficiency

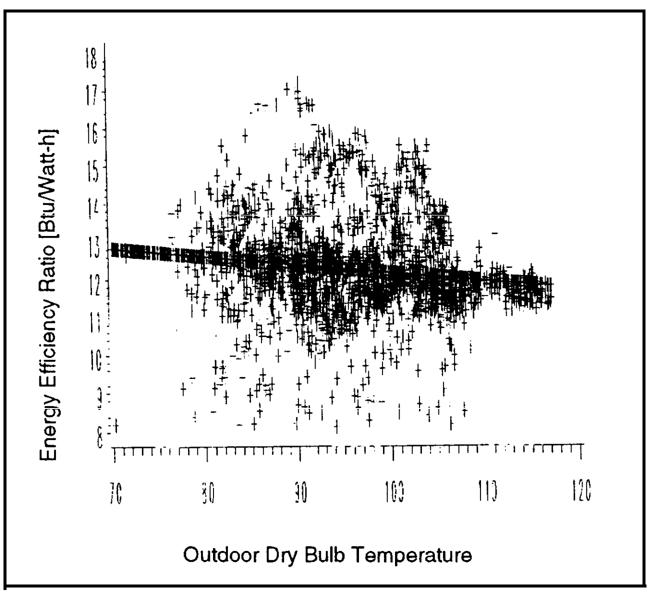

Figure 9. VIP-12.25 SEER AC Unit Cooling Efficiency

The performance of the fitted with the indirect evaporative cooling module precooking the outdoor air is illustrated in Figure 10. The performance of the combined unit shows a higher performance at the lower temperatures due to the influence of the precooler in extending economizer operation. This can be further appreciated in Figure 11 where AC Unit #3's economizer operation is seen to continue well into the 80°F's (thick solid line) while AC Units #1 and #2 are already in compressor operation mode. The performance of the Indirect/DX unit seems to degrade at high temperatures below that of the equivalent AC unit without the precooler. This can be remedied by modifying the control strategy to turn the evaporative system off whenever the its discharge temperature (enthalpy) is above

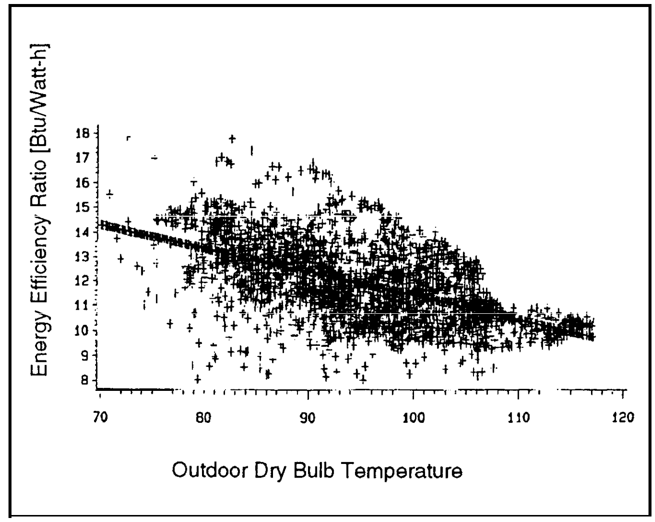

Figure 10. VIP-12.25 SEER AC Unit with Evaporative Pre-Cooling

that necessary to open the economizer damper. As currently controlled, the evaporative unit's fan and pump continue to operate when the economizer damper is closed to its minimum position. Under that condition, is more efficient to provide the same temperature drop in the ventilation air with refrigeration.

Conclusions and Further Work

The number of hours that economizers operate at VIP is very low during the summer. The cooler hours during which the economizer would operate unfortunately do not coincide with the typical summer business hours at VIP. Although the analysis is not yet complete, preliminary results indicate that a business with short business hours such as VIP Motors is not a good application of Indirect/DX systems.

By contrast, the Wyndham application with its 24-hour cooling of 100% outside air represents the optimal application of Indirect/DX cooling.

As testing is resumed this summer and the data analysis methodology is refined, sufficient data will be accumulated for the economic analysis of the systems. Data on maintenance costs for the indirect evaporative units will have to be developed from maintenance records from Wyndham.

A literature search on the long-term maintenance costs of evaporative cooling systems produced only one reference. Gallardo (1991) calculated maintenance costs for direct evaporative cooling in El Paso, Texas, that are approximately five times higher that those for conventional AC. The net present value of costs over the life of systems was still one third lower for the evaporative cooler. Once all

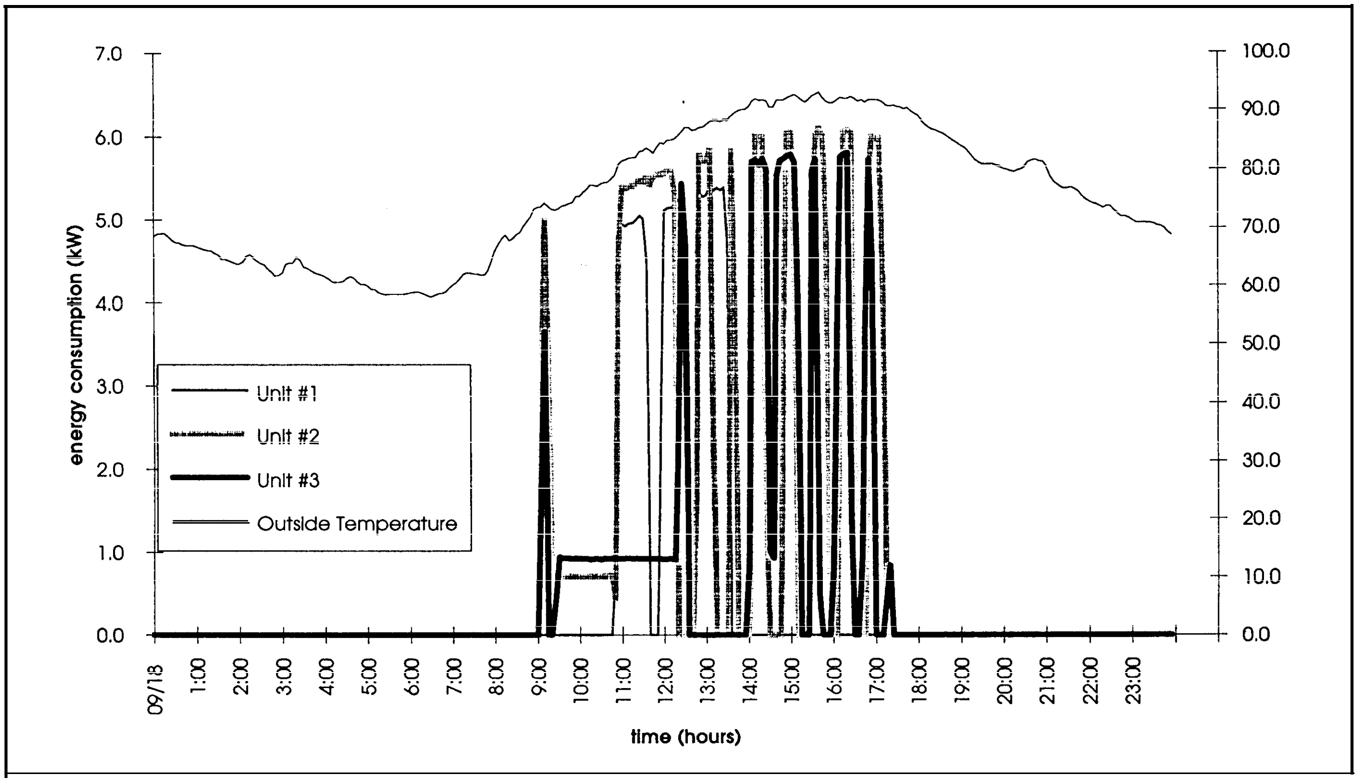

Figure 11. Energy Consumption for 3 A/C Units

annual O&M costs are established, the California Energy Commission's three-pronged test will be applied. The thresholds in the test include TRC > 1.0, no net fuel switch, and net or positive environmental impact. If Indirect/DX passes it will become one more tool in SCE's DSM tool chest.

Market Potential

There are 106,356 customers in the Coachella Valley, of which 9% of the customers (9,645 customers) are commercial, 89% (97, 171 customers) are residential, and 2% (1,917 customers) are industrial/agricultural. Total electric consumption is 1.669 billion kWh annually. Thirty-eight percent is consumed by commercial customers, 50 percent by residential, and 12 percent by industrial/agricultural. Because of the long cooling season and hot temperatures, the air conditioning units have an average life expectancy of approximately 12 years. Therefore, each year only 1/12 of the air conditioning units will be replaced. The SCE marketing group estimated that with SCE financing, 65% of the replacements will be evaporative cooler and 35% will be direct air conditioner replacements. This is equivalent to 522 commercial customers installing evaporative cooling units when their air conditioning units break down. As for residential, 40% of the homes are owner, 38% vacation homes, and 22% renter-occupied. Only owner-occupied homes are considered to be potential customers that will consider evaporative cooling. This is equivalent to 2,105 residential customers installing evaporative cooling units.

Acknowledgments

This paper was prepared with the support of the Southern California Edison Company. The opinions, findings, conclusions and recommendations expressed herein are solely those of the authors and do not necessarily reflect the view of SCE. The authors would like to recognize the participation of VIP Motors Limited and the Wyndham Resort Hotel.

References

Personal communication with Robert E. Foster, Evaporative Cooling Institute, Las Cruces, New Mexico, March 1994.

Heating, Air Conditioning and Ventilating News, March 29, 1993.

Gallardo, A. 1991. "Life Cycle Cost Analyses - Evaporative Cooling vs. Refrigerated Air Conditioning." El Paso Electric Company.