Evaporative Condensers:
The Next Generation in Residential Air Conditioning?

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ABSTRACT

Residential air conditioning is a load that many utilities love to hate since it often represents a low load factor as well as a small source of total utility revenue. Performance of typical air-cooled condensing units degrades significantly as outdoor temperatures rise, resulting in higher demand per unit of cooling delivered. Two evaporative condenser (EC) technologies offer the potential for significant performance improvements, particularly in hot, dry climates. The first technology, EC1, is an evaporative pre-cooler which significantly reduces condenser inlet air temperatures. A second generation product, EC2, offers greater efficiency improvements by immersing the condenser coil in an evaporatively cooled sump. In dry southwestern climates, the EC2 can offer a 20-35°F condensing temperature advantage over conventional equipment which translates to increased capacity, efficiency, and reduced demand.

This paper evaluates EC cooling performance from three perspectives: 1) laboratory testing of both EC technologies versus 10 and 12 SEER air conditioning, 2) EC2 field monitoring, and 3) DOE-2.2 performance projections.

Lab testing demonstrated that EC technologies consistently outperform air-cooled condensing units. At 110°F condenser inlet temperature, an EER advantage of 36% and 105% versus SEER 10 was determined for EC1 and EC2, respectively. DOE-2.2 simulations based on laboratory testing and manufacturer's data were performed using San Jose, Sacramento, and Fresno weather data. Results indicate that under typical cooling use assumptions and current technology costs, both EC technologies are cost-effective in Fresno, but not in San Jose or Sacramento. This is not discouraging given that 1) EC costs will come down with increased production, 2) high-use customers will have more favorable economics, and 3) California builders value technologies which offer energy compliance credits. Extrapolating DOE-2.2 performance projections to the potential 120,000 annual new and retrofit EC sites in Northern California results in projected annual energy and demand savings of 86.3 GWH and 167 MW.

Introduction

Conventional air conditioning has become commonplace in much of the country over the last 30-40 years and is well suited for efficient operation in warm moist climates like those found in the eastern and southeastern U.S. The performance of conventional condensing units, however, is significantly impacted by the high dry bulb temperatures experienced in the western portion of the United States due to their air-cooled, fin tube heat exchanger design. As condensing temperatures rise with increasing outdoor temperature, cooling system electrical demand increases and overall cooling capacity and operating efficiency falls. In humid areas of the country where outdoor temperatures rarely exceed 95°F, capacity and efficiency degradation due to outdoor temperature is less pronounced than in the hot, dry regions of the West.

Although the intent of the Seasonal Energy Efficiency Rating (SEER) procedure is to represent full-season cooling performance, SEER does not adequately reflect air conditioning system operation under high temperature conditions. The SEER rating for single speed equipment is based on two aspects of performance. The first measure is the unit steady-state efficiency at an ambient temperature of 82^0F and the second accounts for performance under part load or cycling operations. Using SEER as a yardstick for cooling system performance in areas of the country where temperatures exceed 100°F is questionable at best.

What is needed in hot, dry regions is a condenser technology that is not adversely effected by high ambient temperatures. This paper presents laboratory and field test data of EC performance, as well as full-year computer simulation performance projections based on test data results.

Technology Description

Two commercially available, residential-scale evaporative condensers are evaluated in this paper. The first generation unit ("EC1"), an evaporative condenser pre-cooler, utilizes wrap-around evaporative media supported by a fiberglass frame to pre-cool air prior to entering a conventional condensing unit. A pump located in the water sump at the base of the unit continually distributes water to the evaporative media. By pulling outdoor air through the wetted media, the condenser inlet temperature is reduced, improving cooling system capacity and efficiency, and reducing electrical demand. The EC1 was previously installed and monitored in two utility-sponsored residential integrated design projects. As part of Pacific Gas and Electric Company's (PG&E) Advanced Customer Technology Test, EC1 was monitored at sites in Stockton, CA (PG&E, 1994) and in Walnut Creek, CA from 1993 to 1996. For Southern California Edison (SCE), two sites in the Palm Springs area were monitored. The EC1 indicated favorable performance with Palm Springs data demonstrating a 21% efficiency improvement relative to the same condensing unit without EC1 at an outdoor dry bulb temperature of 100°F (SCE, 1995).

The second generation "EC2" unit, introduced in 1997, is a true evaporative condenser. The EC2 replaces the fin-tube air-cooled condenser coil with an immersed refrigerant-to-water spiraled copper heat exchanger. As shown in the exploded view in Figure 1, water is circulated through a counterflow heat exchange path in the sump containing the condenser coil, then over the evaporative media, and back to the sump. A fan draws outdoor air through the wetted evaporative media evaporatively cooling sump water to within $5\text{-}10^0$F of the outdoor wet bulb temperature. The immersed heat exchanger offers significant performance benefits due both to improved refrigerant-to-water heat transfer and to lower condensing temperatures than typically experienced by air-cooled condensing units.

Both of these EC technologies perform best in relation to air-cooled condensing units when operated in climates with large outdoor wet bulb depressions. For example, EC performance would be suprior in California's Central Valley, where typical summer conditions may be 100°F dry bulb and 70°F wet bulb, relative to Atlanta, where summer conditions of 90°F dry bulb and 75°F wet bulb are more typical.

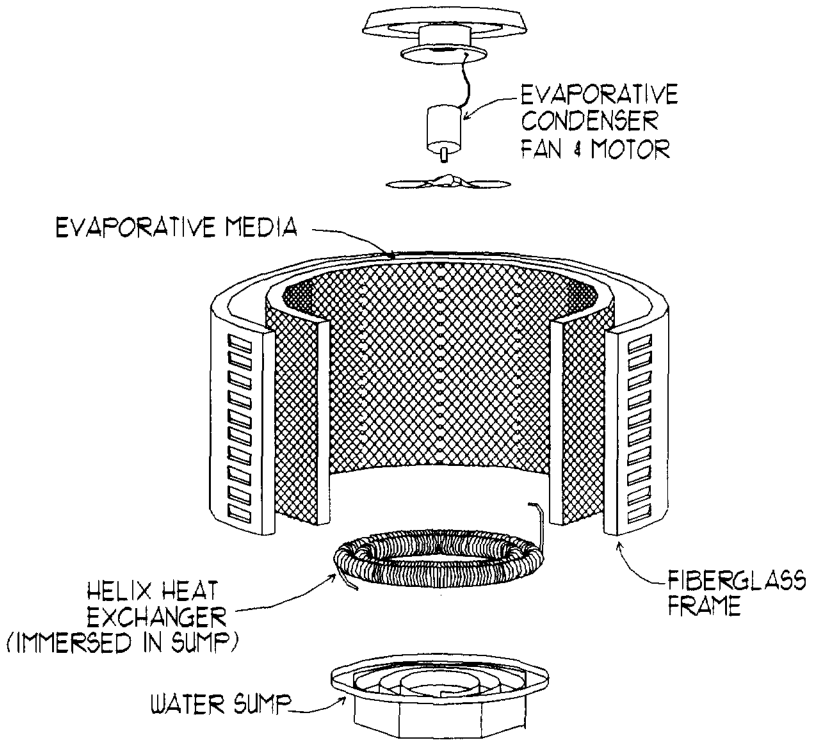

Figure 1. Exploded View of EC2 Evaporative Components

Methodology

Laboratory Testing

Laboratory testing was conducted by PG&E over a two-year period. In 1996, a nominal 3 ton EC1 unit was tested to compare performance to a conventional 3 ton SEER 10 air conditioner under high temperature conditions. In 1997, the two previously tested units, and a SEER 12 unit and an EC2 unit, were tested to compare capacity, demand, and efficiency characteristics relative to the SEER 10 unit. All four units were rated at 3 ton capacity, although the EC1 had a 2 ton compressor and the EC2 a 2.5 ton compressor. (The EC manufacturer assumes 3 ton equivalence with air-cooled condensers based on derating of air-cooled equipment at high outdoor temperatures.)

Performance testing was conducted by placing the condensing units in a 10' x 20' x 8' environmental chamber located at PG&E's Technical and Ecological Services center in San Ramon, California. A supply fan, heater and humidifier were used to control the condition of air supplied to the test chamber. Chamber temperature was increased in 10° increments from 85°F to 115°F and relative humidity was maintained in the 30-40% range. The variation in relative humidity due to difficulties in maintaining chamber moisture levels typically resulted in less than 2°F fluctuations in wet bulb temperature during any one test, however during one of the high temperature tests a variation of up to 5°F was observed. Additional testing was performed on both EC units to determine the impact of varying chamber relative humidity from 10% to 40% over the 85^0F to 115^0F range of dry bulb temperatures. All four units were operated at full load conditions and under part load conditions of 20%, 50% and 75% operation for cycle intervals of 10, 20, and 30 minutes. A total of 53 tests were performed.

The environmental chamber supply air wet and dry bulb temperatures were monitored at four positions around the condensing units. Total condensing unit electrical demand was also monitored for all four units as was water consumption for the two evaporative technologies. Indoor fan power was not monitored, therefore reported demand and efficiencies do not include indoor fan energy.

The tested unit's indoor coil was connected to a once-through load duct located outside the test chamber which heated outdoor air to the 80°F return air condition. Difficulties in obtaining reliable latent cooling measurements resulted in reporting of sensible capacities only, however since much of the testing was done in the Fall, necessary heating of the return (outdoor) air resulted in very dry conditions, and therefore little latent cooling. Some of the early SEER 10 and EvapCon unit testing was performed during late-summer periods when the 80°F return (outdoor) temperature could not be maintained due to high inlet air temperatures. Results from these tests were mathematically "adjusted" using an empirically derived heat exchanger calculation to be consistent with the 80°F return temperature. Only the adjusted results are presented in this paper.

Field Testing

An EC2 Model 10K2C31, with a listed capacity of 32,300 Btuh, was installed at a small office building in Davis, CA in late August 1997, replacing an existing 3.5 ton condensing unit originally installed on the building in 1985. Davis Energy Group independently began measuring outdoor unit power consumption a few weeks after installation of the unit. PG&E soon expressed interest in detailed field monitoring of this unit to provide field results for comparison with the ongoing laboratory testing. A detailed monitoring plan was developed which included monitoring of the following key parameters:

- Sensible and total AC2 cooling capacity
- AC2 compressor and fan electrical energy use
- Indoor air temperature and outdoor dry bulb temperature and relative humidity
- Make-up water use

A monitoring plan was developed and monitoring equipment including datalogger, duct temperature/relative humidity sensors, power monitor, immersion thermocouple probe (sump temperature), and make-up water flow meter was installed in late October 1997. Sensors are scanned by the datalogger every 15 seconds, and summed or averaged data are stored every 15 minutes. Cooling energy delivered to the building is computed on 15 second intervals. One week of data was collected at the end of the 1997 cooling season. Monitoring will continue through the 1998 summer.

Development of Cooling Performance Algorithms

PG&E laboratory data and manufacturer's performance data were used to develop performance relationships for the four cooling systems in the hourly DOE-2.2 building energy simulation program.

DOE-2.2 characterizes residential cooling system capacity and electric input ratio (condensing unit energy input per unit of delivered cooling) with bi-quadratic functions of outdoor dry bulb temperature and return air wet bulb temperature according to the following equations:

$$CAP = a + b*Tci + c*Tci^2 + d*Tiwb + e*Tiwb^2 + f*Tci*Tiwb \qquad \text{(Eqn 1)}$$

$$EIR = g + h*Tci + i*Tci^2 + j*Tiwb + k*Tiwb^2 + l*Tci*Tiwb \qquad \text{(Eqn 2)}$$

where, a-l = constants, Tci = condenser inlet temperature, Tiwb = indoor wet bulb temperature

Since the PG&E laboratory dataset did not have the range needed for development of the curves, manufacturer's data were also used. The process involved developing bi-quadratic curves using a least-squares fit of the manufacturer's test data and then adjusting the intercept (e.g. "a" in Equation 1) to minimize the Chi-squared difference between manufacturer's data curve and the datapoints calculated using the laboratory results. This approach maintains the same curve "shape", while minimizing differences between the two datasets.

The two EC technologies utilized the DOE-2.2 evaporative pre-cooler model to allow characterization of performance relative to outdoor wet bulb. Efficiency and capacity curves based on outdoor wet bulb and a pre-cooler effectiveness of 100% were used to model the EC units.

Development of Prototype Building and Market Evaluation Inputs

The prototype building used to develop performance projections was a 1665 ft^2 single-story, new construction house complying with the California Residential Building Energy Standards (CEC, 1995). The prototype building was run with the four cooling system types in three California climate zones. Zones 4 (San Jose), 12 (Sacramento), and 13 (Fresno) represent climates ranging from the mild coastal-transitional (4) to the hot, inland Central Valley (13). San Jose has a 1% summer design temperature of 85°F (66°F coincident wet bulb), Sacramento 101°F (70°F), and Fresno 102°F (70°F) (ASHRAE, 1993). Although, the difference between Sacramento and Fresno design conditions is small, the duration of heat spells in Fresno is much longer. Assumed cooling thermostat setpoints ranged from 78°F (6 PM to 10 AM) to 80°F the remainder of the day.

In today's deregulated utility environment, promising technologies must demonstrate cost-effectiveness without significant long-term utility support. Overall customer cost-effectiveness was evaluated to determine where, under current market conditions, the EC technologies are cost-effective, and also under what conditions short-term utility incentives could be used to increase volume so that the technologies could become cost-effective without utility intervention. Installed cooling system equipment costs were based on information provided by RTI and a local HVAC equipment distributor which carries both the EC2 and conventional cooling equipment. For volume production builders, the incremental cost estimates for a nominal 3 ton system are $630 for SEER 12, $568 for EC1, and $1071 for EC2. (Note that EC1 and EC2 systems are assumed to have 2.5 ton compressors.) Typical PG&E utility rates of $.12/kWh were assumed in the analysis.

The California Energy Commission (CEC, 1991) estimates that there are approximately four million housing units (single and multi-family) in the PG&E service territory. Of these, approximately 27% have central air conditioning systems, 8% have evaporative cooling systems, another 8% have room air conditioners, with the remaining 57% having no cooling system. With a growth rate in the housing stock averaging about 1.6% per year, approximately 64,000 housing units are being constructed annually in Northern and Central California. Since most of California's residential growth is occurring in inland regions of California and the perceived need for air conditioning is increasing in transitional climate areas, a 75% new construction EC market potential (48,000 units per year) was estimated in this study. Assuming an average residential HVAC equipment lifetime of 15 years, the potential EC retrofit market is estimated at 72,000 units per year, making the total market approximately 120,000 units per year.

Table 1. Estimated AC2 Market Within PG&E Service Territory

Existing Housing Stock	**4,000,000**	**Annual Market Size**
Central air conditioning	1,080,000	72,000 (6.7%)
Evaporative cooling	320,000	0
Room air conditioning	320,000	0
No cooling system	2,280,000	0
New construction	64,000	48,000
Total Target Market- Units/Year		**120,000**

RESULTS

Laboratory Results

1997 testing demonstrated significant EC potential for improving cooling system energy efficiency. Table 2 below summarizes laboratory results at 85°F and 110°F condenser inlet temperatures, which roughly represent the range of outdoor temperature conditions during which cooling occurs in California. Following Table 2 are a series of graphs depicting the resulting linear regression curves for cooling capacity, condensing unit demand, and condensing unit EER as a function of condenser inlet temperature.

Capacity vs. Temperature. The capacity of all four technologies declined with increasing condenser inlet temperature (Tci), as shown in Figure 2. At 85°F, the SEER 10 and 12 units and the EC2 provided 3 tons of cooling; the EC1, with a 2 ton compressor, provided about 2.5 tons of cooling. At 110°F, the SEER 10 demonstrated the greatest degradation, losing nearly 16%. The reduction for the other systems was less than half of the SEER 10, with the EC2 losing only 3.8% (1.3 kBtu/hr) over the 25°F range.

Table 2. Summary of PG&E Laboratory Results

	Cooling Capacity (kBtu/hr)			**Condensing Unit Demand (kW)**			**Condensing Unit EER (Btu/Wh)**		
	85°	110°	Δ%	85°	110°	Δ%	85°	110°	Δ%
SEER 10	36.7	30.8	**-15.9**	3.08	3.59	**+16.6**	11.8	8.7	**-26.3**
SEER 12	37.5	35.9	**-4.3**	2.92	3.80	**+30.2**	12.5	9.5	**-24.0**
EC1	29.3	27.2	**-7.3**	2.08	2.32	**+11.3**	14.0	11.8	**-15.7**
EC2	35.5	34.2	**-3.8**	1.64	1.94	**+18.1**	20.8	17.8	**-14.4**

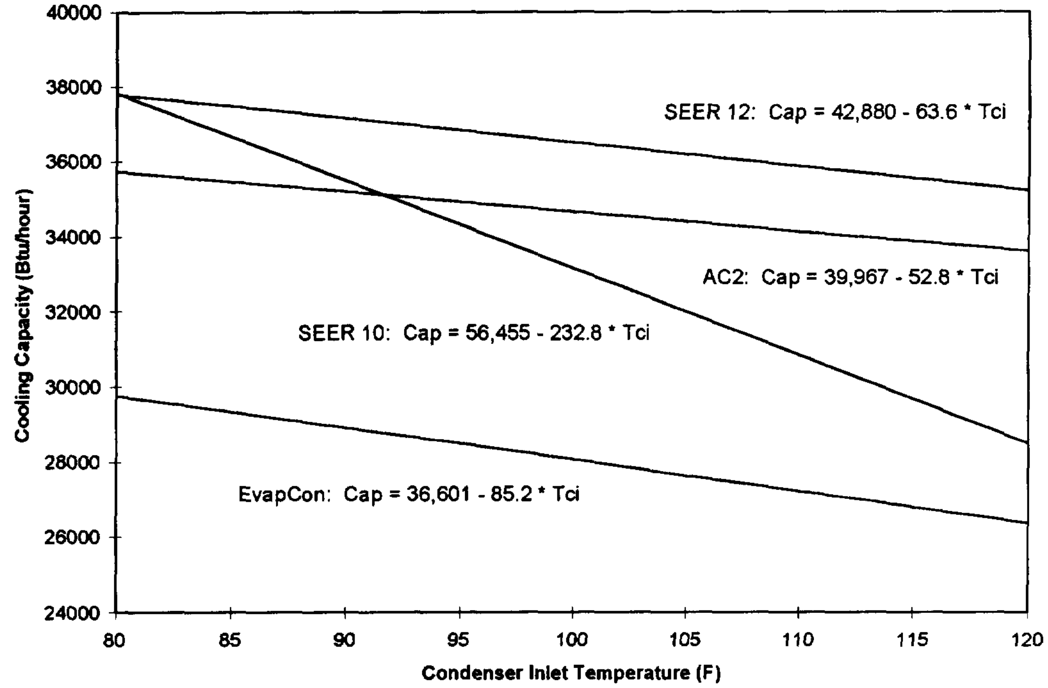

Figure 2: Comparison of Steady-State Cooling Capacity

Condenser kW vs. Temperature. Condensing unit demand of all four technologies increased with temperature as shown in Figure 3. However, the conventional unit's demand increased more than either of the EC units with the SEER 10 and 12 increasing 0.51 and 0.88 kW, respectively, versus 0.24 and 0.30 kW for EC1 and EC2, respectively. Curiously, at temperatures above 96^{0}F the SEER 12 unit had a greater demand than the SEER 10 unit. At 110°F, the EC2 had a demand roughly half of the SEER 12 unit (1.94 vs. 3.80 kW).

Condenser EER vs. Temperature. While the SEER 12 technology was shown to be more efficient than the SEER 10 technology (6% at 85°F and 9% at 110°F), the overall EC efficiency advantages were significantly higher than the conventional technologies. At 85°F, the data indicate a 19% and 36% EER advantage versus SEER 10 for EC1 and EC2, respectively. At 110°F, the efficiency advantage increases to a staggering 36% and 105% for EC1 and EC2, respectively. The combined effects of reduced capacity degradation and "flatter" demand profiles contribute to this huge efficiency advantage. Figure 4 plots EER versus condenser inlet temperature for the four systems.

Water Consumption. EC's consume water both to provide evaporative cooling and to "bleed off" water to minimize problems with mineral deposits on the evaporative media. Full-load testing showed that water consumption for the EC2 was 7.01 gallons per hour and the EC1 was 4.45 gallons per hour at 115^{0}F outdoor temperatures at an average relative humidity of 35%.

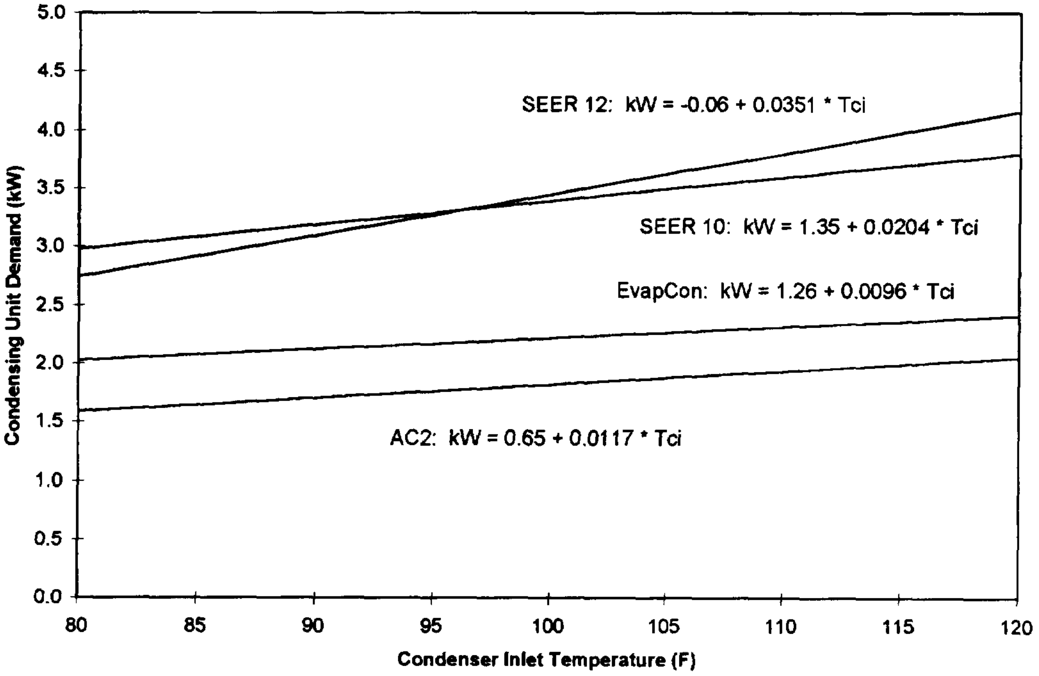

Figure 3. Comparison of Condensing Unit Steady-State Demand

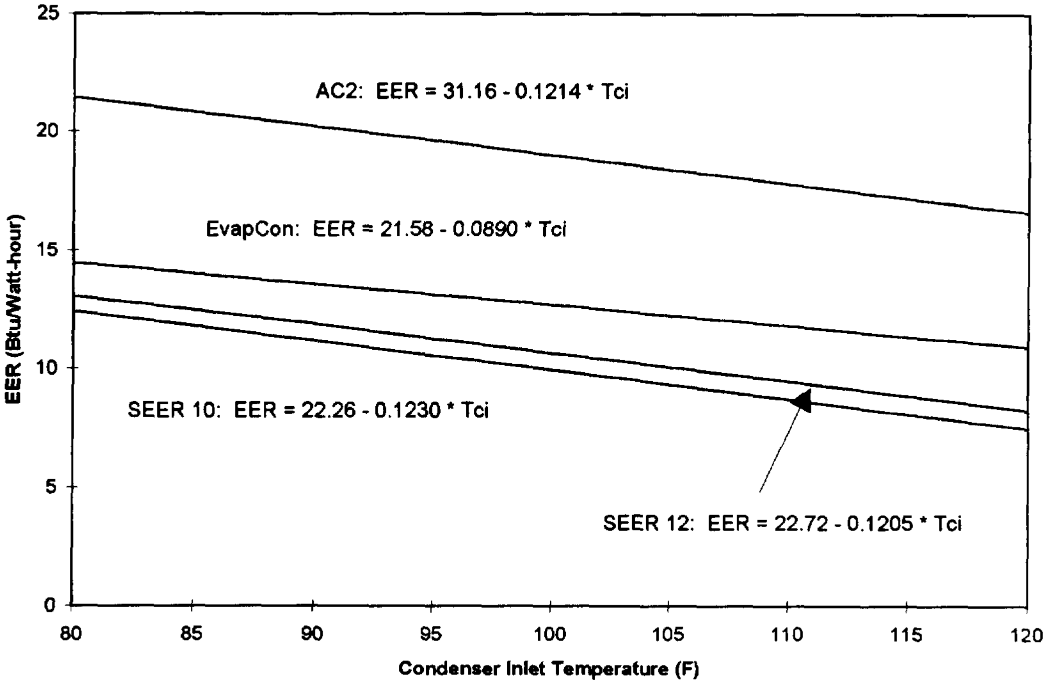

Figure 4. Comparison of Steady-State EER's (Condensing Unit Only)

Field Results

Following installation and commissioning of the detailed monitoring system at the Davis office building, seven days of data for the period October 27 - November 2, 1997 were collected and analyzed. Data are summarized in Table 3 below.

Table 3. EC2 Field Monitoring Data (October 27 - November 2, 1997)

Monitoring Point	Average	Sum	Comments
Outdoor Temperature (°F)	61.2	n/a	peak of 82.1
Total Cooling (kBtu)	n/a	702	peak of 42.4 kBtu/hr
Outdoor Unit Energy Use (kWh)	n/a	34.4	peak of 1.62 kW
Operating Hours	n/a	22.3	
Make Up Water Use (gallons)	11.9 gals/hr	265	
Calculated EER (Btu/Watt-hr)	15.6	n/a	peak of 19.2

Mild weather during this week resulted in peak outdoor temperatures ranging from the mid-60's to the low 80's. Total cooling delivered by the indoor unit was 702 kBtu, or an average of 31,480 Btu per operating hour. Make-up water use averaged 11.9 gallons/hour, which is high when compared to the PG&E lab test results. The average measured EER for the week, including indoor fan power, was calculated to be 15.6 (20.4 for the condensing unit EER).

Figure 5 plots outdoor temperature, water temperature entering the sump (Tmedia), indoor temperature, and EC2 EER and demand. The data indicate that the EC2 supplied water to the sump at a fairly constant 70-75°F during the two days. Monitored EER's ranged from a low of 11 to close to 19 with the highest values consistently occurring during full-load operation. A peak outdoor unit demand of 1.62 kW was monitored for the nominal 2.7 ton unit with outdoor conditions of 80.2°F and 49.4% relative humidity (wet bulb of 66.5°F).

Performance and Market Projections

Table 4 summarizes DOE-2.2 performance projections for the four cases and three climate regions. Savings are smallest in the mild San Jose climate with EC1 and EC2 kWh savings relative to SEER 10 projected at 6% and 28%, respectively. For Sacramento and Fresno, EC1 and EC2 kWh savings average about 16% and 35%, respectively. Higher loads in Fresno result in projected EC1 and EC2 annual savings of $65 and $141, respectively. Project EC1 demand savings range from 0.5 to 1.1 kW; EC2 savings range from 1.1 to 1.7 kW. Table 4 demonstrates a key EC benefit of increasing demand reduction as the outdoor design temperature increases.

Assuming the incremental system cost is amortized over 30 years (at 8% interest), the increase in annual mortgage cost amounts to $55 for SEER 12, $50 for EC1, and $94 for EC2. Only EC1 and EC2 applications in Fresno are expected to generate savings exceeding this level. Homeowner cost savings for targeted "high-use" retrofit sites would be higher than results presented in Table 4 due both to the lower thermal quality of the building envelope and to the lower cooling system efficiency than the 10 SEER assumed in the new construction case.

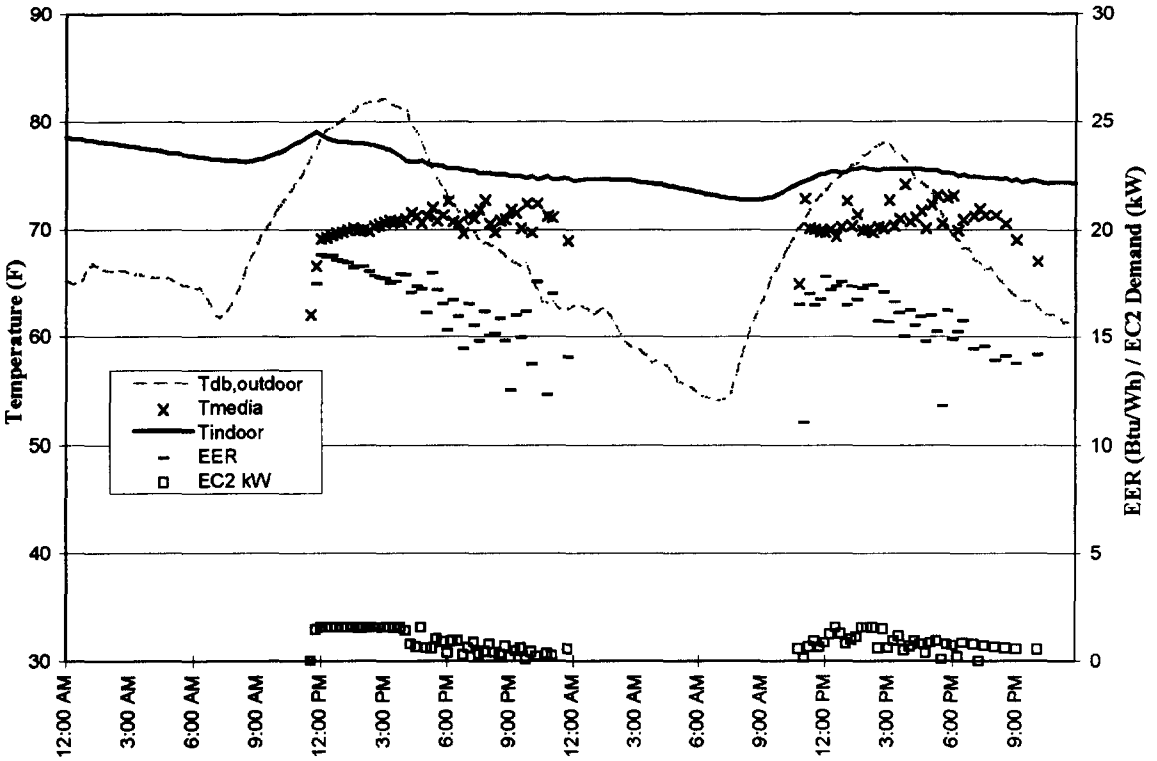

Figure 5. EC2 Operating Data (November 1-2, 1997)

Table 4. Simulation Results Summary

	Climate Zone 4 (San Jose)			Climate Zone 12 (Sacramento)			Climate Zone 13 (Fresno)		
	kWh	kW	savings	kWh	kW	savings	kWh	kW	savings
SEER 10	996	3.1	n/a	1431	3.4	n/a	3241	3.7	n/a
SEER 12	926	2.9	$8	1332	3.2	$12	3008	3.5	$28
EC1	935	2.6	$7	1223	2.6	$25	2698	2.6	$65
EC2	720	2.0	$33	934	2.0	$60	2063	2.0	$141

Given the potential EC market size shown in Table 1, PG&E systemwide energy and demand impacts were developed based on the simulation results. Assuming that 100,000 of the 120,000 annual installations were EC2 (the remainder EC1) and that the installations would be distributed 50% Fresno, 30% Sacramento, and 20% San Jose, an annual potential energy savings of 86.3 GWH is projected with corresponding demand savings of 167 MW.

CONCLUSIONS

EC technology may well become the next generation in residential air conditioning as the technology can provide significant operating cost savings in hot, dry climates where much of the U.S. population growth is occurring. Utilities can also benefit from significant reductions in systemwide demand, since peak load weather sequences in California and the southwestern U.S usually have high outdoor temperatures coincident with low relative humidity. Laboratory testing at 110°F condenser inlet temperatures demonstrated that the EC1 and EC2 can generate EER improvements of 36% to 105%, respectively. Field testing of the technology demonstrated demand and efficiency results consistent with the laboratory testing.

Other specific project conclusions include:

1. Economic projections indicate current EC viability in only the hottest Fresno climate. This is not discouraging since if EC production volume increases, costs will come down. In addition, targeted high-use retrofit sites will have more favorable economics. Also, no builder "credit" was assumed with implementation of the EC technologies. In the California Building Energy Standards process, builders can take credit for efficiency features allowing for trade-offs with other features desired by homebuyers, such as increased glazing area.

2. Although EC system water consumption is an issue, the cost of added water use is small. Assuming 1030 EC2 operating hours per year in Fresno (2063 kWh divided by 2.0 kW), a high water use estimate of 11.9 gallons per hour, and conservative water rates of $.50 per 100 ft^3, annual water costs amount to only $8.

3. EC system maintenance costs are a potential issue, however limited information to date makes conclusions difficult. The evaporative media and circulating pump will need to be replaced at roughly 5 year intervals, depending upon system use and water quality.

4. Targeted utility involvement to help spur the EC technology is a valuable step in educating homeowners, builders, and contractors. A program sponsored by California public goods funds is currently underway in PG&E territory. Program goals include contractor education, system commissioning, and incentive money for up to 200 installations.

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