PG&E *Research and Development*

AC2 Evaporative Condenser

Monitoring Report:

1998 Cooling Season

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EXECUTIVE SUMMARY

California statistics show that residential air conditioners consume 9% of total residential energy use, but air conditioners contribute about 58% to the peak load. To address this load factor and peak load problem, PG&E initiated several projects to investigate emerging technologies that apply principals of evaporative cooling to reduce air conditioner energy demand. A major focus of PG&E's efforts is to determine the performance of the "AC2" evaporative condenser in laboratory and field situations, and to use those results to generate performance projections with a full-year hourly simulation model. This report summarizes one of the AC2 field monitoring efforts.

The AC2 is an evolutionary improvement in split-system condenser technology, since it replaces the finned-tube air-cooled refrigerant condenser coil with an immersed refrigerant-to-water copper heat exchanger. The condenser coil sump is evaporatively cooled whenever the compressor operates. This novel approach to condenser heat rejection offers significant performance benefits, resulting in peak condensing temperatures roughly 30-40°F lower than conventional air-cooled equipment.

A detailed monitoring system was installed in October 1997 to monitor the nominal 2.5 ton unit installed at Davis Energy Group's office, which replaced an existing 3.5 ton air-cooled unit. Limited data were taken in 1997; however the unit was extensively monitored from June through mid-October 1998. Data recorded on 15 minute intervals included condensing unit energy and water consumption, outdoor temperature and relative humidity, indoor temperature, supply and return air temperature and relative humidity, and indoor fan status.

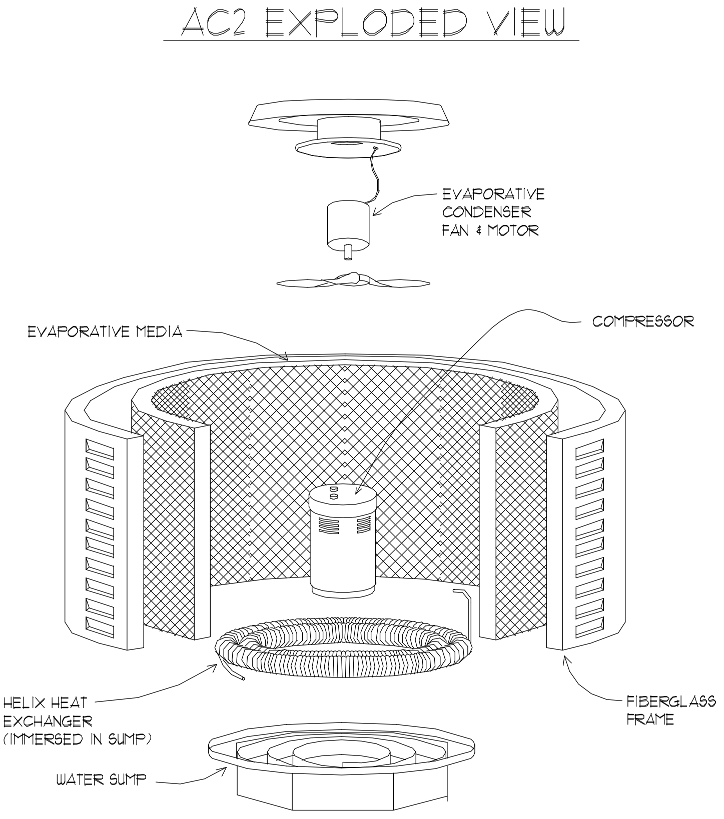
Results indicate very favorable performance with an average 1998 full-season EER of 12.8. The average water temperature leaving the evaporative media (entering the condenser sump) was 73.8°F, or about 8°F higher than the corresponding wet bulb temperature. Monitoring indicated steady-state EERs averaging 14.1, or a full 10% higher than the full-season average value. This high efficiency under continuous operation was most evident on the 109°F peak day, when the AC2 provided relatively constant demand at an average 13.8 EER. Data also indicate that under extreme outdoor temperature conditions, a nominal 2.5 ton AC2 has greater cooling capacity than a conventional 3 ton air-cooled unit with half the condensing unit power consumption, resulting in condensing unit EERs double that of a standard 10 SEER unit. Simulations were performed with DOE2.2 to assess AC2 performance relative to a conventional 10 SEER cooling system. Results for a prototype 2000 ft^2 house in Sacramento project full-season EERs 57-69% higher than a 10 SEER unit.

Favorable field monitoring results validate prior PG&E laboratory test results and confirm that the AC2 technology offers significant potential for energy and demand savings in California. Continuing market transformation efforts including marketing, contractor training, and short-term targeted incentives would play a critical role in getting AC2 established in California.

1. BACKGROUND & OBJECTIVES

RTI introduced the AC2, their second-generation evaporative condenser, to the market in 1997. The AC2 is an evolutionary improvement over the first generation "Evapcon" evaporative pre-cooler, which uses wrap-around evaporative media to precool air entering a conventional condenser coil. The AC2, a true evaporative condenser, replaces the finned-tube air-refrigerant condenser coil and uses an immersed refrigerant-to-water copper heat exchanger. 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 pump. A fan draws outdoor air through the wetted media to evaporatively cool the sump water. The immersed heat exchanger offers significant performance benefits relative to air-cooled due both to improved refrigerant-to-water heat transfer and to reductions in condensing temperatures of up to 30-40°F versus air-cooled condensing units. Figure 1 shows the key components of the AC2.

Figure 1: AC2 Schematic



An AC2 Model 10K2C31 was installed at Davis Energy Group (DEG) offices on August 18, 1997, replacing a nominal 3.5 ton condensing unit (Carrier 38ED042) originally installed in 1985. The AC2 has a listed capacity of 32,300 Btuh, compared to the 42,000 Btuh capacity of the system it replaced. DEG independently began measuring outdoor unit power consumption a few weeks after installation. A monitoring system was installed on

October 23, 1997 as part of this PG&E contract. Data was collected for two weeks in 1997 and then for the full 1998 summer.

This evaluation project includes the following tasks:

1. Development of a monitoring plan (included as Appendix A)
2. Procurement and installation of monitoring hardware
3. Collection of data and comparison to laboratory test data developed by PG&E
4. Development of monitoring-based performance curves and estimation of energy and demand savings using DOE-2 for a typical residential buildings
5. Comparison of AC2 field performance to measurements completed at PG&E's Technical and Ecological Services (TES) test facility in San Ramon
6. Reporting at the end of the 1997 and 1998 cooling seasons

The work presented here is part of a comprehensive effort by PG&E to assess the performance of evaporative condensers relative to conventional air-cooled condensing units. Other aspects of the work include the testing performed by PG&E at their TES facility, and field monitoring of five AC2 residential sites by Proctor Engineering. Based on testing results, a detailed DOE2 modeling study was undertaken to develop full-season projections of customer savings for a range of California climates.

2.0. METHODOLOGY

2.1. Monitoring

The monitoring plan was developed to collect data characterizing AC2 performance as a function of indoor and outdoor conditions. (Appendix A includes the monitoring plan which contains a thorough discussion of sensor types, installation, and commissioning procedures.) These data were then used to develop performance algorithms for incorporation in the POWERDOE hourly simulation.

Key monitoring parameters include:

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

The small office space where the AC2 was monitored is the second floor of a 3600 ft^2 office building located in downtown Davis, CA. The total floor area served by the 2.5 ton unit is approximately 1190 ft^2. Due to the energy conscious nature of the building inhabitants, summer cooling setpoints are typically in the upper 70's. Typical occupancy for the building is 7 AM to 7 PM weekdays, with occasional weekend or extended hours operation.

The monitoring system installed at the Davis site included the following equipment:

- Programmable dataloggers for recording temperature, power, flow, and relative humidity
- Solid state or RTD temperature sensors for indoor, outdoor, and duct temperatures
- Immersion thermocouple probe for measuring fluid temperature entering the sump
- Solid state relative humidity sensors for supply and return air RH
- Power monitors generating pulsed output proportional to energy use
- Flow meter for measuring AC2 makeup water use
- Flow hood for one-time supply air flow measurement

All sensors are scanned every 15 seconds, and data are stored in datalogger memory every 15 minutes. The datalogger computed cooling energy transfers at 15 second intervals, as defined in Equations 1 and 2, based on measured air flow rates and supply to return air temperature differences. Enthalpy was calculated based on 15 second supply and return air temperature and relative humidity.

Eqn. 1: *Sensible Cooling* (Btu/hr) = 1.08 * cfm * (return – supply air temperature)

Eqn. 2: *Total Cooling* (Btu/hr) = 1.08 * cfm * (return – supply air enthalpy)

Data, in comma-delimited ASCII format, were regularly downloaded, stored, and screened using software to review system operation. Reports summarizing key data in both graphical and tabular form were sent to the PG&E project manager on a weekly basis, with a sample included in Appendix B.

2.2. Data Analysis

Upon completion of the 1998 monitoring, all data were compiled and tabulated to generate full-season summaries of system performance including energy use. Key parameters presented in Section 3 include total cooling delivered, AC2 and total cooling system energy use, EER (as defined in Equation 3), AC2 water use, and indoor and outdoor conditions.

Eqn 3: *Cooling EER* (Btu/Watt-hr) = $\dfrac{DeliveredCooling(Btu/hour)}{Power(Watts)}$

Full-load 15 minute data were used to develop steady-state performance relationships for use in the hourly DOE-2.2 building energy simulation. DOE-2.2 characterizes residential cooling system capacity and electric input ratio (EIR, defined as 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:

Eqn 4: *Cooling Capacity* $= a + b*T_{ci} + c*T_{ci}^2 + d*T_{iwb} + e*T_{iwb}^2 + f*T_{ci}*T_{iwb}$

Eqn. 5: $EIR = g + h*T_{ci} + i*T_{ci}^2 + j*T_{iwb} + k*T_{iwb}^2 + m*T_{ci}*T_{iwb}$

where, a-m = constants, T_{ci} = condenser inlet temperature, T_{iwb} = indoor wet bulb temperature.

Performance curves generated from these field data were compared to curves based on laboratory and manufacturer's test data (DEG, 1998) to assess if field performance is consistent with the measured laboratory performance. DOE2 simulations were performed with both sets of curves to assess full-season impact on overall AC2 energy use and efficiency.

3. RESULTS

Monitoring results from the 1998 cooling season are summarized in Section 5. More detailed graphical presentation of the results can be found in Appendix C.

3.1. 1998 Monitoring Results

The original plan for 1998 AC2 monitoring was to initiate monitoring in March, but a very cool spring resulted in no cooling operation until June. Monitoring began on June 2 and continued through October 19. The 1998 summer was characterized by a very hot July through early September period with August 1998 being the hottest August on record in nearby Sacramento. The unit performed well the entire season with no maintenance required other than the manufacturer's recommended pre-season cleaning of the evaporative media and water sump. Data were continually available during the 1998 season with the exception of an 8 day period during mid-July.

Table 1 summarizes key monitoring results for 1998. "AC2 kWh" represents total condensing unit energy use and "total kWh" adds indoor fan energy use. (Fan power was measured at 0.66 kW for 1621 cfm of supply air.) Peak condensing unit demand was measured at 1.80 kW, or 0.72 kW per nominal ton of cooling capacity. Total cooling capacity ("Qclg") was calculated based on enthalpy calculations derived from supply and return air temperature and humidity measurements. Total EER was calculated based on monthly total "Qclg" and "Total kWh". Average "Twb" and "Tmedia" represent the average outdoor wet bulb temperature and water temperature entering the AC2's sump during system operation.

The bulk of cooling operation occurred from July to mid-September. Monitored full-summer usage was 1544 kWh. After correcting for missing July data, total summer usage is projected to be 1687 kWh, or 1.42 kWh/ft^2-year. Average total EER for the season (defined as total cooling delivered divided by total energy use) was 12.8. Water use averaged 13.2 gallons per full-load hour for the continuous bleed system installed on the monitored AC2. Newer AC2 versions have a solid state water purge control which reduces water use by roughly 50% vs. the continuous bleed system.

Average monitored outdoor wet bulb temperatures during AC2 operation was 65.9° F, with a peak reading of 77.3° F, over 5° F above the ASHRAE 1% design wet bulb temperature. For the 1998 summer, 84 hours exceeded the Sacramento 72°F design wet bulb. The average water temperature entering the sump was eight degrees higher than the average outdoor wet bulb temperature during system operation, resulting in an average seasonal effectiveness of 75%, based on the approach of *Tmedia* to the outdoor wet bulb temperature. Peak recorded water temperature leaving the evaporative media was 82.3°F. Total water use, after accounting for missing July data, amounted to 9711 gallons for the year, equivalent to $7 at the current Davis water rate of $.49/hundred ft^3. (The solid state water purging control system would reduce usage by roughly 50%.)

Table 1: Monthly Monitoring Data Summary

Month	AC2 kWh	Total kWh	Qclg (kBtu)	Total EER	Water Use (gal)	Average Twb	Average Tmedia
June	130	185	2387	12.9	1090	63.8°F	70.3°F
July(1)	251	353	4716	13.4	2066	67.1°	73.9°
August	411	579	7246	12.5	3399	66.4°	75.3°
September	286	401	4938	12.3	2264	65.5°	73.4°
October	18	26	403	13.9	185	57.3°	n/a
Totals	1096	1544	19690	12.8	9004	65.9°	73.8°

Notes: (1) ~8 days of data missing

Figure 2 plots AC2 operation on a peak August day. The graph plots indoor and outdoor temperature, outdoor wet bulb, AC2 demand (including indoor fan), and total EER. On this 109°F day, the AC2 ran nearly continuously from 6 AM to 6 PM. Early morning operation pulled the office down from over 80° to the mid 70's. After the building reached setpoint, the unit cycled from roughly 7 to 10 AM. During this period, EERs fell from roughly 14 to around 12. From 10 AM to 6 PM, the AC2 ran constantly in an effort to maintain indoor temperatures. Given the slight system undersizing and outdoor temperatures 8°F above design, the AC2 performed well by allowing indoor temperatures to rise only to 80°F by the end of the work day. During this 8 hour operating cycle, total system EER was a consistent 14. Peak demand (condensing unit and indoor fan) of 2.46 kW was measured with almost no variation with outdoor temperature.

Figure 3 plots AC2 operation on a more typical summer day where outdoor temperatures peaked at 95°F. The AC2 cycled from 6 AM to 6 PM with peak measured demand of 2.34 kW. The impact of cycling is clearly evident in Figure 3. The two data points where the AC2 did not cycle demonstrate EERs of nearly 14, comparable to the values shown in Figure 2. At lower loads, AC2 EERs fall to about 9 due to cycling degradation.

Figure 2: Peak Day AC2 Operating Plot - August 5, 1998

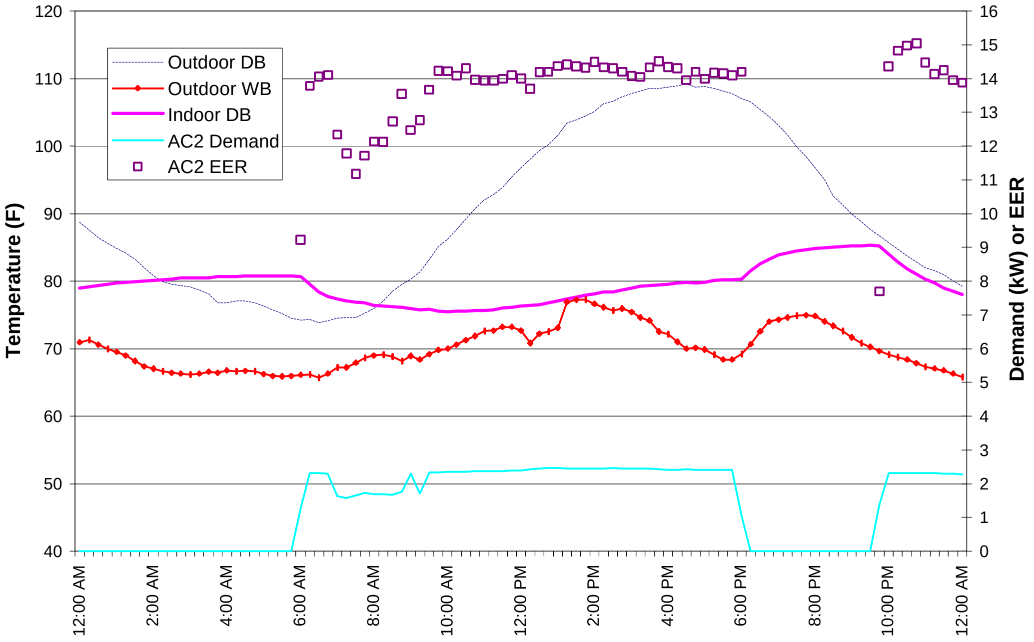


Figure 3 : Typical Day AC2 Operating Plot - August 7, 1998

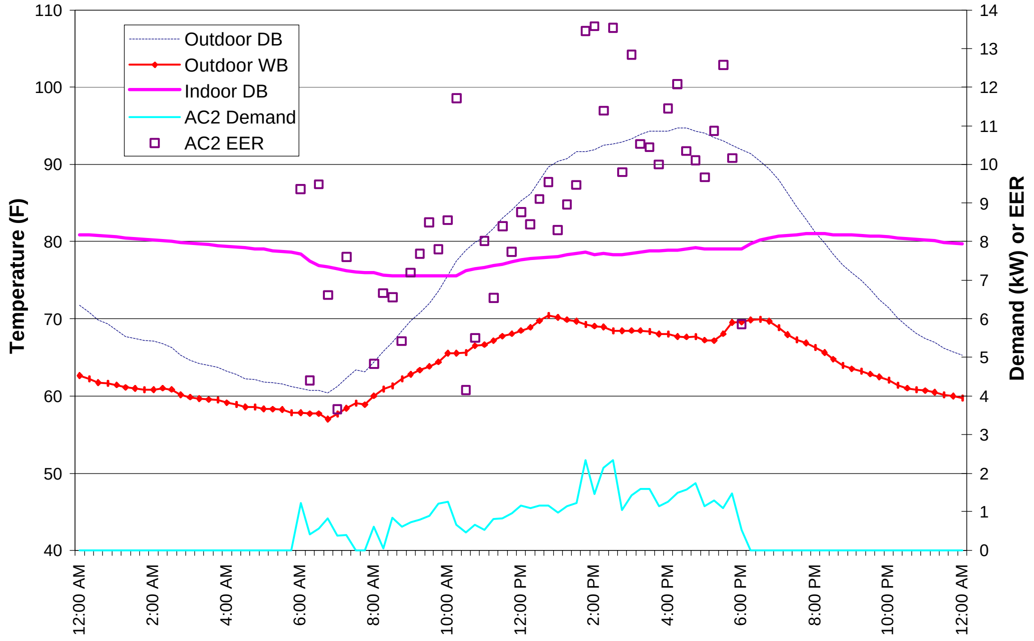


Figure 4 plots monitored condensing unit demand as a function of outdoor dry bulb temperature. Although AC2 performance is dictated primarily by outdoor wet bulb temperature, dry bulb temperature is a more widely recognized performance descriptor and is a better indicator of utility peak demand conditions. (The labels shown above the bars indicates the average wet bulb temperature for that dry bulb range.) Also shown in the graph is the linear regression of condensing unit demand as a function of outdoor temperature for a 3 ton SEER 10 unit, as measured at the PG&E Technical and Ecological Services laboratory (PG&E, 1998).

Figure 5 shows a similar plot of cooling capacity binned as a function of outdoor dry bulb temperature for both the AC2 and a linear fit to the 3 ton SEER 10 unit performance monitored at PG&E's TES facility. The SEER 10 unit is projected to have a 25.8% capacity reduction in the 65 to 110°F range, while the AC2 shows fairly constant cooling capacity with outdoor temperature. It is important to note that at higher outdoor temperatures, the monitored indoor temperature (average value shown above bar) rose above the thermostat setpoint, increasing the calculated total cooling capacity. A half ton larger AC2 system would likely have not demonstrated this trend.

Figure 6 plots monitored condensing unit EER for both the AC2 unit and the linear fit from the PG&E monitored SEER 10 unit. DEG AC2 results demonstrate a nearly flat relationship with outdoor temperature, partly due to the increase in cooling capacity at high temperatures. The SEER 10 unit shows a significant degradation at higher temperatures, with EERs approximately half that of the AC2 at 110°F.

Figure 4: Monitored AC2 and "Typical" SEER 10 Demand

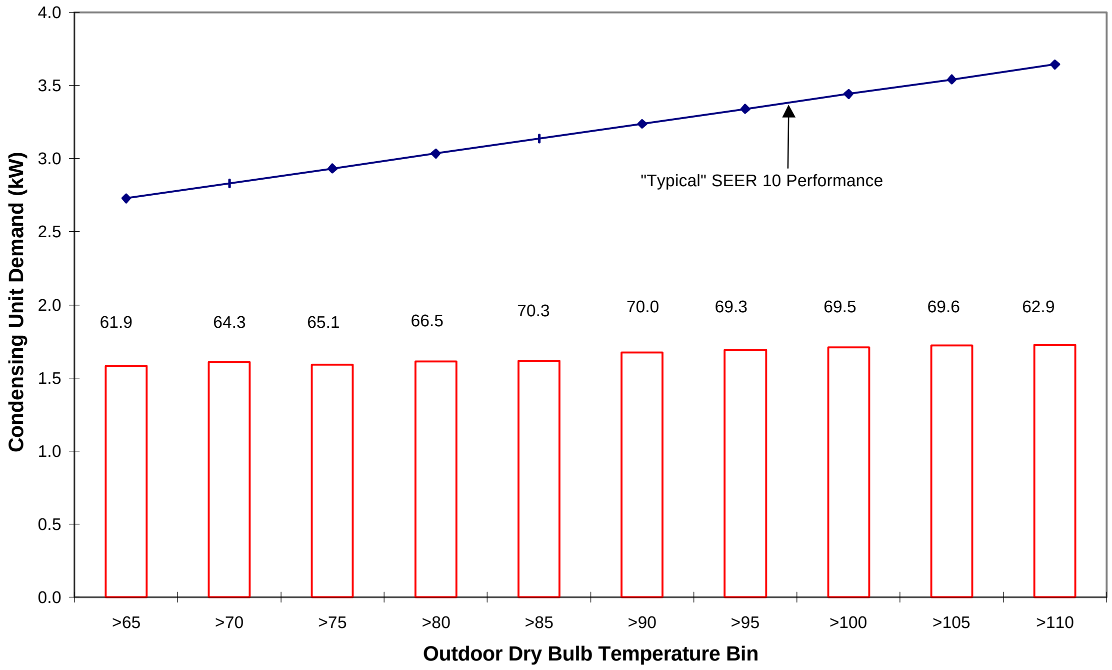


Figure 5: Monitored AC2 and "Typical" SEER 10 Cooling Capacity

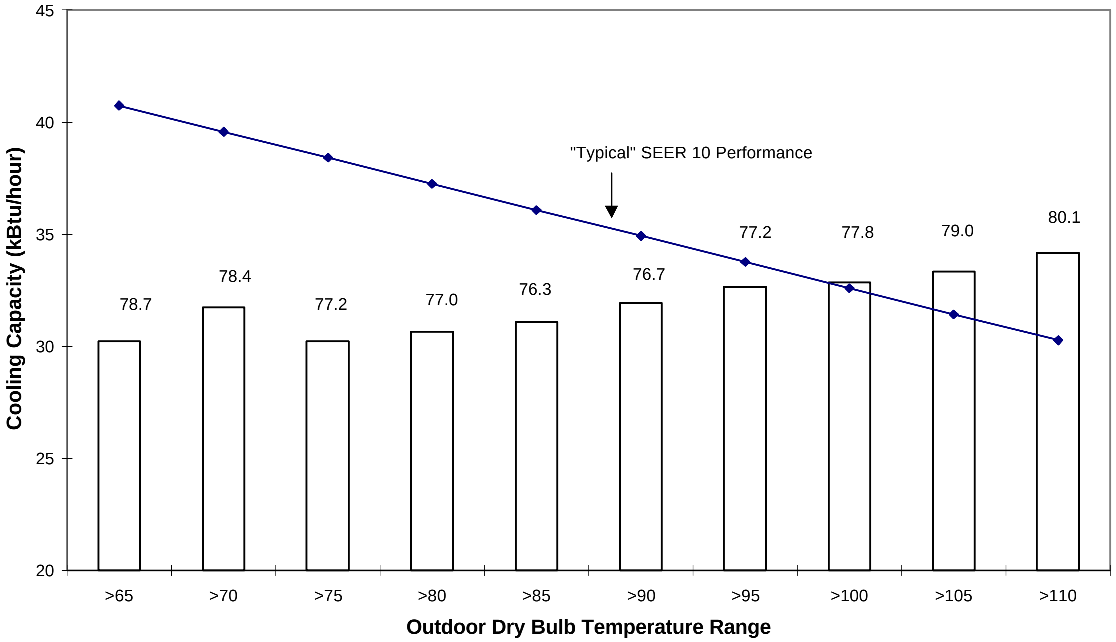


Figure 6: Monitored AC2 & "Typical" SEER 10 Condensing Unit EER

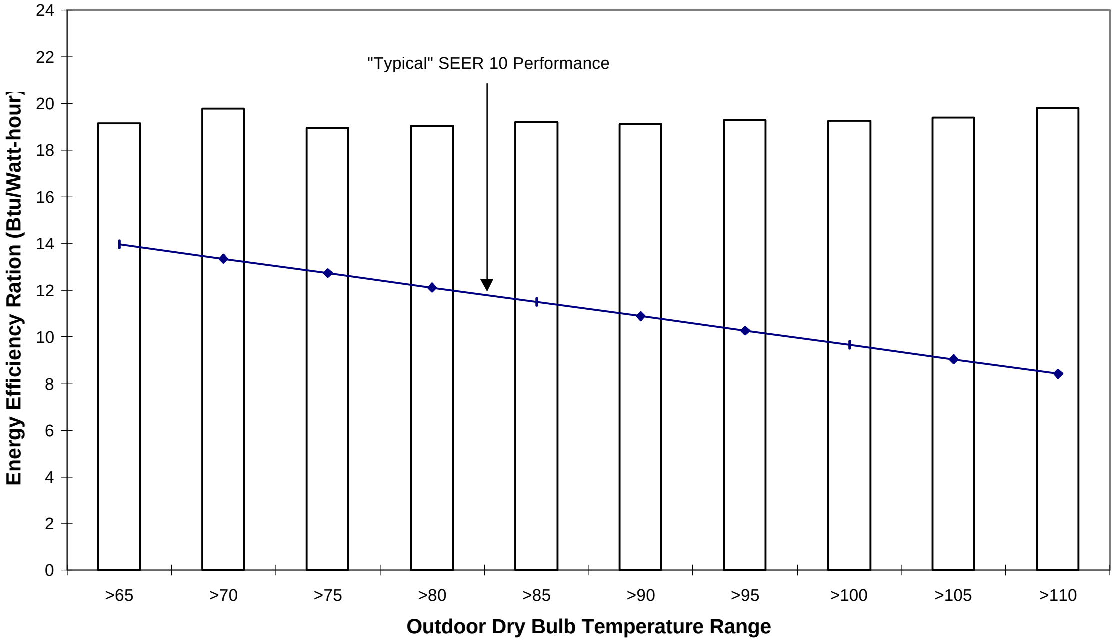


Table 2 summarizes monitored AC2 and SEER 10 performance as a function of outdoor dry bulb temperature. Cooling capacity, condensing unit demand, and condensing unit EER are shown at 80° and 110°F dry bulb temperature based on linear fits to both the DEG and the PG&E laboratory test data. The SEER 10 unit tested by PG&E was a nominal 3 ton unit and the AC2 was a 2.5 ton. Although it is somewhat simplistic to characterize AC2 performance as a function of dry bulb temperature, it is the standard by which conventional cooling system performance is judged.

There are two caveats regarding the AC2 data in Table 2. PG&E testing includes many AC2 tests at very high wet bulb temperatures which would tend to make the results more conservative. The average wet bulb of the high outdoor dry bulb tests (>105°F) is 78.3°F, which is higher than the peak outdoor wet bulb monitored during the 1998 season. The second issue is related to the slight undersizing of the AC2 system at the DEG office. Since the system is unable to maintain indoor temperature under the hottest conditions, the monitored capacity at high temperatures is higher than if the setpoint were maintained.

Results indicate relatively stable AC2 capacity with outdoor temperature in contrast to the 18% degradation for the 10 SEER unit. At 110°F, the nominal 2.5 ton AC2 is projected to have ¼ ton additional cooling capacity than the nominal 3 ton air-cooled unit. Condensing unit capacity and EER indicate a rough factor of two advantage for the AC2 unit relative to the 10 SEER. The PG&E AC2 data appears conservative due to the high wet bulb temperatures during the high ambient testing, while the DEG data is slightly optimistic due to the higher measured capacity, and therefore EER, when indoor setpoint could not be maintained.

Table 2: Summary of Monitored Performance with Outdoor Temperature

	Cooling Capacity (kBtu/hr)			Condensing Unit Demand (kW)			Condensing Unit EER (Btu/Wh)		
	80°	110°	**Δ%**	80°	110°	**Δ%**	80°	110°	**Δ%**
DEG									
AC2	31.1	33.5	**+7.8**	1.62	1.73	**+6.8**	19.2	19.4	**+1.0**
PG&E									
SEER 10	37.8	30.8	**-18.5**	2.98	3.59	**+20.5**	12.4	8.7	**-29.8**
AC2	35.7	34.2	**-4.2**	1.59	1.94	**+22.0**	21.4	17.8	**-16.8**

3.2. Simulation Projections

DOE2 performance runs were completed for a 2000 ft^2 new construction house located in Sacramento for both 10 SEER and AC2 systems. AC2 runs were completed based on two sets of capacity and efficiency curves. The first AC2 run used the relationships developed based on PG&E laboratory testing and manufacturer's test data. The second run was based on the data collected in the 1998 DEG office monitoring. Results, summarized for both typical and high use customers, are presented in Table 3. Full-season EERs shown include indoor fan energy consistent with ARI testing standards (365 Watts/1000 cfm of supply air).

Projected AC2 energy savings range from 36-40%, with slightly higher savings projected for the runs with the DEG-based performance curves, since these curves demonstrate higher EERs than the PG&E curves at typical outdoor wet bulb conditions. AC2 full-season EERs are projected to be 57-69% higher than a standard SEER 10 unit.

Table 3: DOE2 Projected SEER 10 and AC2 Performance

System Type	Load	Performance Curve	Annual Cooling Energy (kWh)	Full-season EER
SEER 10	Typical	PG&E	1303	8.9
AC2	“	PG&E	833	14.0
AC2	“	DEG	776	15.0
SEER 10	High	PG&E	2097	8.6
AC2	“	PG&E	1341	13.6
AC2	“	DEG	1274	14.3

4. CONCLUSIONS

Key conclusions from this study are:

1. Monitoring results from this study, in conjunction with PG&E laboratory testing, indicate that at 110°F outdoor dry bulb temperature, a nominal 2.5 ton AC2 provides approximately ¼ ton more capacity that a nominal 3 ton SEER 10 condensing unit. Equally as significant AC2 condensing unit demand is roughly half of the SEER 10, and EER double that, of the SEER 10 unit at this operating condition.

2. Monitored full-season EER for the system, including indoor fan energy, was measured at 12.8. Steady-state operation, defined as continuous operation for a 15 minute period, demonstrated an average EER of 14.1, 21.5% higher than the 11.6 EER for the periods when the AC2 unit cycled. These results point to the value of proper system sizing to maximize operating efficiency.

3. In dry climates characteristic of most of PG&E’s service territory, the AC2 can provide exceptional performance due to favorable operating conditions in the form of low wet bulb temperatures. In a summer where peak outdoor temperatures of 112°F were monitored, a maximum water temperature entering the condenser of 82.3°F was measured.

4. Performance curves based on the DEG monitoring results indicate slightly better performance than that projected with the PG&E curves. DOE2 projected AC2 full-season EERs are 57-69% higher than a 10 SEER unit for a 2000 ft^2 house in Sacramento.

5. During the 1998 cooling season, the AC2 unit installed at the DEG office delivered reliable and consistent performance. Other than routine "start of season" cleaning, no maintenance was performed on the system.

5. RECOMMENDATIONS

The AC2 offers significant promise as a technology that provides both utility value through peak load reduction and improved load factor, and customer value through reduced cooling costs. However, before the AC2 can achieve a significant share of the market, the technology must demonstrate the following:

- consistent operational reliability and minimal maintenance
- reduced installation costs
- increased contractor familiarity and confidence in EC technologies

Emerging technologies require greater marketing efforts to build product confidence, and investments in the infrastructure needed to support installation and service than mature technologies. The following actions are recommended to advance the market for EC technologies:

1. Continue market transformation programs, such as the Home Cooling Program, as a vehicle to market the AC2 technology to developers and builders in PG&E territory. Securing multi-family or subdivision projects throughout Northern California is an important step in developing a critical mass that could spur the industry.
2. Maintain contact with existing EC installations and installing HVAC contractors over the next several years to develop a base of information on maintenance requirements and costs, and to identify product improvements that could reduce maintenance.
3. Evaluate the merit of manufacturer or distributor incentives as a means to reduce system first cost.
4. Consider targeting high cooling load areas where shorter paybacks are likely and also growth areas which are capacity limited by transmission and distribution system limitations.

6. REFERENCES

1. Davis Energy Group. 1998. *Evaluation of Residential Evaporative Condensers in PG&E Service Territory.*
2. Pacific Gas & Electric Company. 1998. Evaluation of Evaporatively Cooled Residential Air Conditioners - Final Report. Report # 500-98.3.