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Authors

Huang, Y.J.
Hanford, J.W.
Wu, H.F.

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PRELIMINARY EVALUATION OF THE PERFORMANCE, WATER USE, AND CURRENT APPLICATION TRENDS OF EVAPORATIVE COOLERS IN CALIFORNIA CLIMATES

Y. J. Huang, J. W. Hanford, and H. F. Wu

Energy & Environment Division
Lawrence Berkeley Laboratory
Berkeley, California 94720

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ABSTRACT

This paper describes the latest results of an ongoing analysis investigating the potential for evaporative cooling as an energy-efficient alternative to standard air-conditioning in California residences. In particular, the study uses detailed numerical models of evaporative coolers linked with the DOE-2 building energy simulation program to study the issues of indoor comfort, energy and peak demand savings with and without supplemental air-conditioning, and consumptive water use. In addition, limited surveys are used to assess the current market availability of evaporative cooling in California, typical contractor practices and costs, and general acceptance of the technology among engineers, contractors, and manufacturers.

The results show that evaporative coolers can provide significant energy and peak demand savings in California residences, but the impact of the increased indoor humidity on human comfort remains an unanswered question that requires further research and clarification. Evaluated against ASHRAE comfort standards developed primarily for air-conditioning, both direct and two-stage evaporative coolers would not maintain comfort at peak cooling conditions due to excessive humidity. However, using bioclimatic charts that place human comfort at the 80% relative humidity line, the study suggests that direct evaporative coolers will work in mild coastal climates, while two-stage models should provide adequate comfort in Title 24 houses throughout California, except in the Imperial Valley.

The study also shows that evaporative coolers will increase household water consumption by less than 6% on an annual basis, and as much as 23% during peak cooling months, and that the increases in water cost are minimal compared to the electricity savings. Lastly, a survey of engineers and contractors revealed generally positive experiences with evaporative coolers, with operational cost savings, improved comfort, improved air quality as the primary benefits in their use. On the other hand, the survey respondents felt the primary barriers to public acceptance of evaporative coolers to be the poor image of earlier swamp coolers, and unfamiliarity about evaporative coolers among engineers and building owners.

LBL-32828

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INTRODUCTION

The use of evaporative coolers is an energy-conserving alternative to air-conditioning that is particularly suited to the dry and relatively mild cooling season found in most of California. Previous studies by the authors using hourly computer simulations of various evaporative cooler designs in prototypical pre-1973 and Title 24 houses have indicated that simple direct evaporative coolers are able to maintain indoor conditions at a set temperature of 78 F for mild cooling loads, such as those of new houses in the coastal climates, while more sophisticated two-stage evaporative coolers can maintain this indoor temperature throughout the state except in the Imperial Valley or in poorly-insulated houses in the Central Valley on peak cooling days (Huang et al. 1991).* These studies, however, did not address whether the increased humidity levels were also acceptable in terms of human comfort.

Since evaporative coolers require power only to drive fans and pumps, it is not altogether surprising that both monitored data and simulation results show evaporative coolers consuming from 1/3 to 1/5 of the electricity used by compressive air-conditioners (Wu et al. 1989, Huang et al. 1991). In spite of these apparently large energy savings, there is still much public hesitancy about the use of evaporative coolers due to a number of unanswered questions and various institutional factors. The objective of this paper is to concentrate on more detailed issues for evaporative coolers, specifically indoor comfort, water consumption, and system operation strategies, and to begin looking at actual user experiences and the market situation.

Evaporative coolers can be classified as either direct, indirect, or two-stage (typically indirect followed by direct) systems. In its simplest form, a Direct Evaporative Cooler (DEC) is simply a fan supplying moistened air into a living space (see Figure 1). Although this moisture can be injected using sprays, current DEC models invariably do this by drawing air through pads made of aspen wood or synthetic materials that are

† Joe Huang is a staff scientist and Jim Hanford a research associate with the Energy Analysis Program, Energy and Environment Division, Lawrence Berkeley Laboratory; Hofu Wu is a professor in the College of Architecture at California State Polytechnical University, Pomona, CA. This work was sponsored by the California Institute of Energy Efficiency (CIEE), and done at Lawrence Berkeley Laboratory (LBL).

* See Huang et al. 1991 for details on the physical and operational characteristics of the pre-1973 and Title 24 prototypical houses modeled. These prototypical houses will be referred to as simply *Old* and *Current* houses throughout this paper.

Figure 1. Simple Roof-mounted Direct Evaporative Cooler

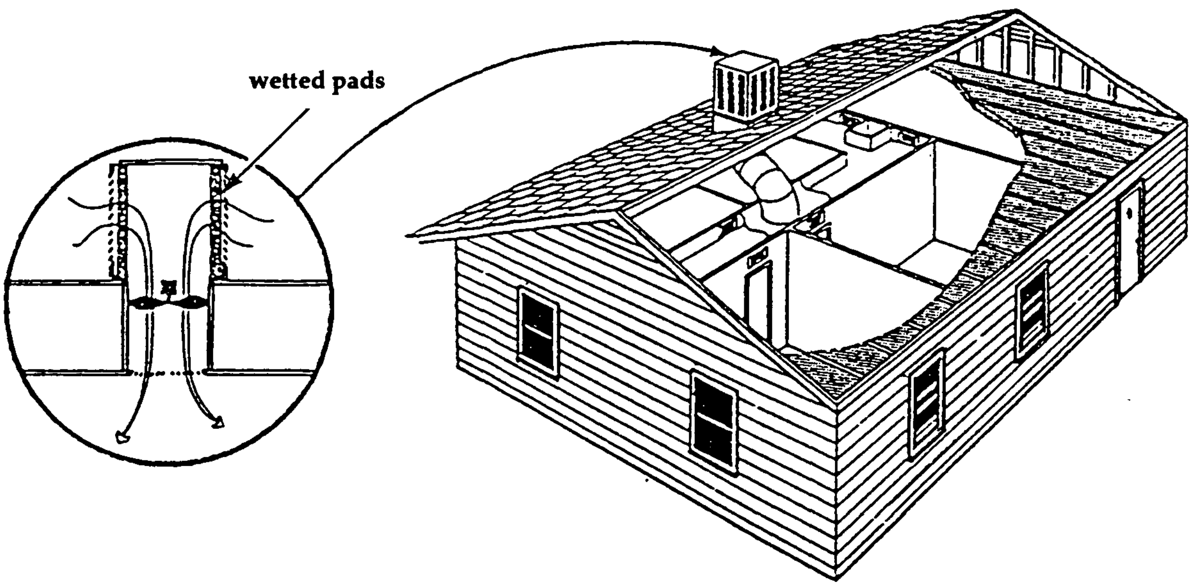
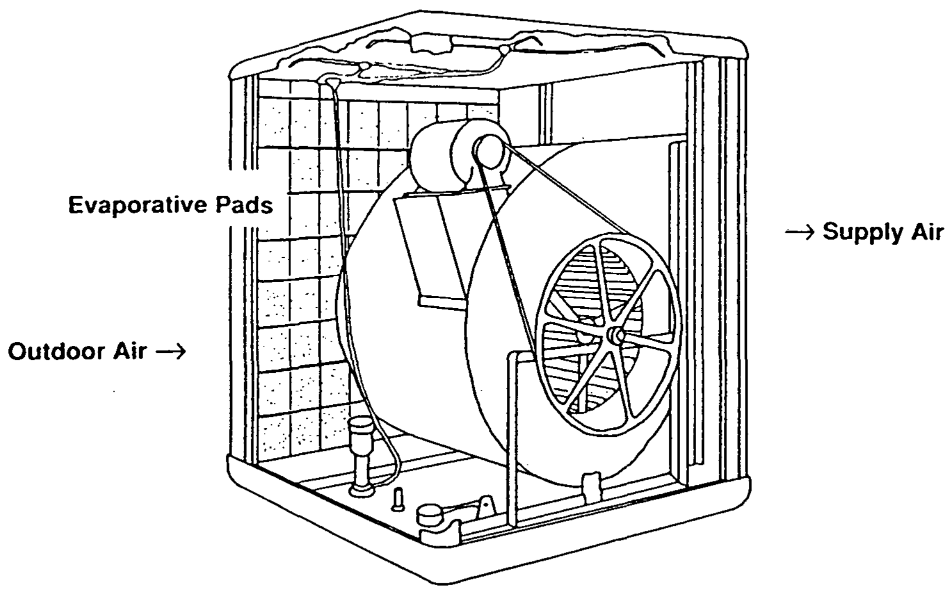


Figure 2. Direct Evaporative Cooler



kept wet by water pumps (see Figure 2). The added moisture produces a cooling effect as the air is adiabatically humidified, i.e., the wet bulb temperature and enthalpy of the air stay constant, while the dry bulb temperature drops and the humidity ratio, i.e., the absolute amount of moisture in the air, as well as the relative humidity, both rise. This process is indicated schematically on Figure 3 by Line A along a constant enthalpy path. After the evaporatively cooled air leaves the supply duct, its temperature rises because of mixing with the warmer room air. It is apparent from Figure 3 that evaporative coolers are most effective in hot arid locations with large potentials for "dry-bulb depression" from this adiabatic process. In humid locations, a DEC will produce little change in the dry-bulb temperatures, while in the worst case, raising the indoor humidity to uncomfortable levels.

An Indirect Evaporative Cooler (IEC) can be regarded as a DEC coupled with a heat-exchanger. Such a system has two separate air streams, each served by its own fan. The secondary air stream is evaporatively cooled as in a simple DEC, but instead of being supplied to the living space, it passes through a heat exchanger with the primary air and is then exhausted (in reality, the humidification and heat exchange occurs simultaneously). The primary, or supply, air is driven by a fan through the heat-exchanger, where it undergoes sensible cooling with no change in its humidity ratio, i.e, no moisture is added to the air, although its relative humidity will change due to the drop in temperature. Because of the inefficiencies of the heat-exchanger, the dual air streams, and the increased fan energy to overcome resistance in the heat-exchanger, an IEC produces less cooling while consuming more electricity than a DEC. As a consequence, IEC are seldom used by themselves. However, because of its ability to cool the primary air without humidification, the IEC works well in two-stage applications as a precooler followed by a direct evaporative cooling stage (see Figure 4).

Compared to DECs, two-stage Indirect/Direct Evaporative Coolers (IDEC) have better humidity control and significantly increased cooling capacities. This two-stage evaporative cooling process is shown schematically on Figure 3 by Line B, with first sensible cooling, then adiabatic cooling, and finally warming after mixing with the room air. Huang et al. 1991 show that IDECs are able to maintain indoor temperatures in *Current* houses for all but one California climate, while in *Old* houses, there will be a few days of undercooling in Central Valley locations (34 hours above 79 F in Sacramento). This "undercooling" refers only to the inability of the evaporative cooler to maintain the indoor temperature at the thermostat setting, and not to uncomfortable indoor conditions due to excessive humidity. As comparison, a one-stage DEC in Sacramento produces more than a week of undercooling in *Current* houses (66 hours above 79 F), and more than a month of undercooling in the *Old* houses (269 hours above 79 F). *

* These numbers are slightly higher than in the original paper (Huang et al. 1991) due to using a temperature (hours above 79 F), rather than a unmet cooling load (over 1,000 Btu/hr), criteria in determining the number of "undercooled hours". For reference, the revised electricity consumption tables for the earlier paper are included in Appendix A, along with a table of building characteristics.

Figure 3. Schematic Drawing of Evaporative Cooling Processes on a Psychrometric Chart

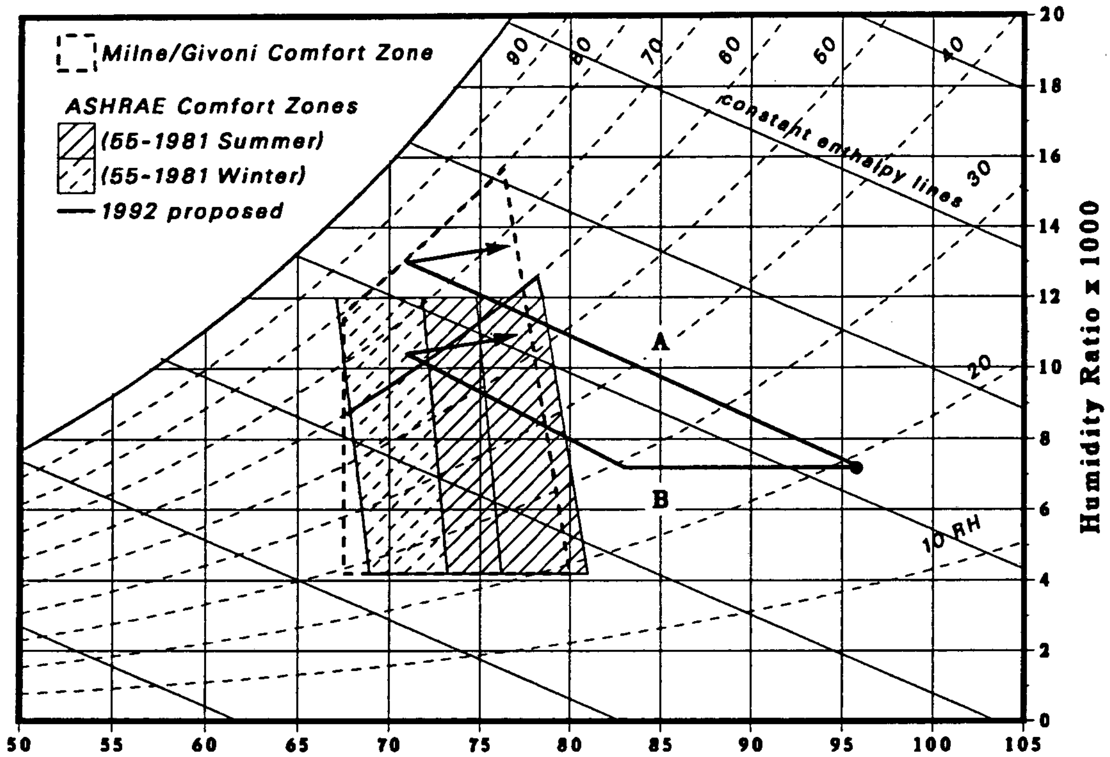
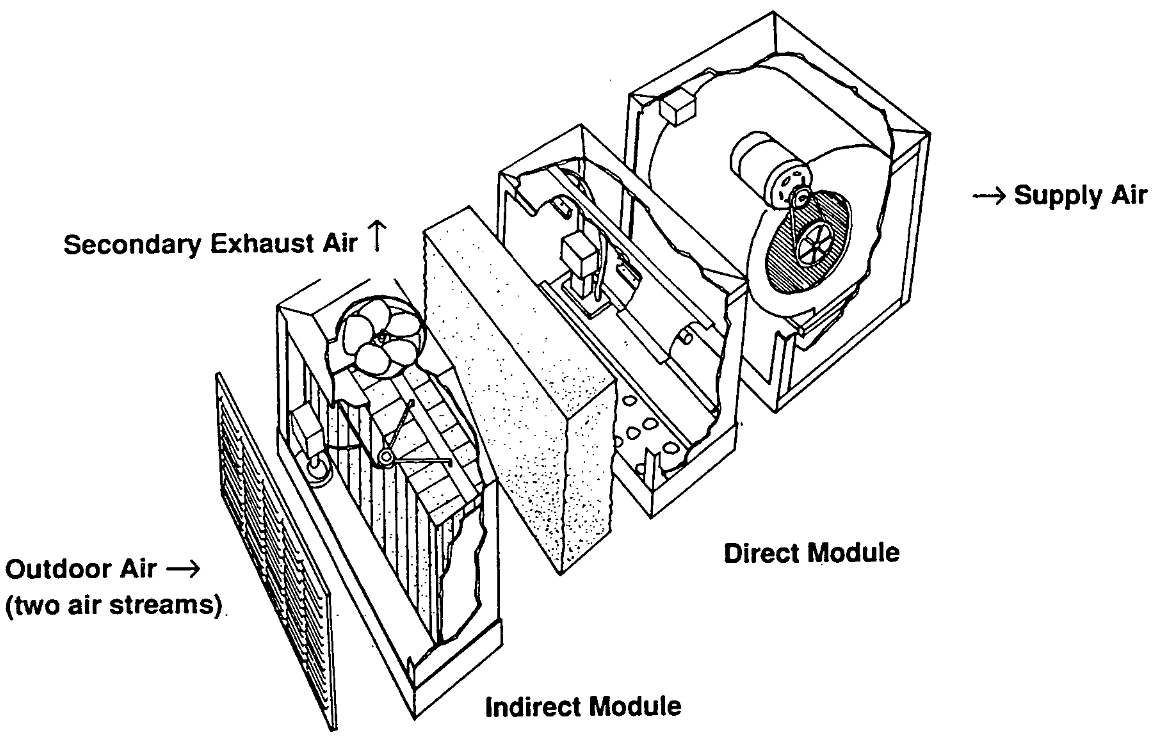


Figure 4. Two-stage Indirect/Direct Evaporative Cooler



BACKGROUND

This paper describes some of the research results from an ongoing LBL project to investigate evaporative cooling systems as a low-energy cooling strategy suited to California climates. The first phase of the project was completed in 1990 and involved the development of numerical models for simulating different evaporative cooler systems and to couple these models with the DOE-2 building energy simulation program. A technical description of the model is given in Chen et al. 1990, while the results of the DOE-2 simulations are given in Huang et al. 1991.

In the current second phase of the project, the DOE-2 simulation tool was enhanced and used to investigate in more detail the indoor conditions produced and the amount of water consumed by different evaporative cooling systems. The project also studied various control strategies such as using a back-up air-conditioner (AC) during peak cooling hours, and innovative designs to improve the performance and extend the applicability of evaporative coolers (Chen et al. 1991a, 1991b). Lastly, the project conducted a survey of engineers and contractors and did a limited sampling of evaporative cooler availability and costs in Northern California.

The LBL project team on evaporative cooling does not regard their research as completed, nor do they feel that they have answered all the questions. The four papers completed to date are essentially evaluations of evaporative cooler performance using computer simulations. We hope in the future to work with other researchers and interested organizations in gathering measured data through pilot projects, and investigating the institutional barriers that may hamper the proliferation of evaporative coolers.

INDOOR COMFORT CONDITIONS USING EVAPORATIVE COOLERS

Because an evaporative cooler "cools" by adding moisture into air, a frequently asked question is how comfortable are the resultant indoor conditions with these increased humidity levels? We have used the modified DOE-2 program with the evaporative cooling algorithms to simulate the hourly indoor temperature and humidity ratio in typical *Old* and *Current* California houses when equipped with various evaporative cooling and air-conditioning systems. In all cases, we assume that the equipment is controlled by a thermostat set to 78 F at all hours. The EC model calculates first the supply air conditions, which are then used in DOE-2 to compute the room air temperature. The model, therefore, checks for saturation of the supply air stream, but is not able to detect temperature variations inside the house, since the room calculation assumes uniform conditions throughout the zone. We do not consider such temperature variations to be a major problem in our modeling because the high EC air flow rates tend to keep such variations to a minimum.

To visualize better the temperature and humidity histories within the house, the hourly values have been plotted on standard psychrometric charts. Figures 5 through 10 show the simulated indoor conditions for various prototypical houses during the summer in four very different cooling climates - Pasadena, Fresno, Miami, and Phoenix. Pasadena has mild warm summers typical of the inland locations in southern California; Fresno has hot and dry summers and the most severe cooling requirement of major California population centers; Miami and Phoenix are shown as prototypical hot/humid and hot/arid climates.

The original intent in this study was to evaluate these indoor conditions by comparing them to the human comfort zone as defined by ASHRAE and others. This task, however, has proven to be inconclusive because the upper limits of the comfort zone, particularly the interactions between temperature and humidity, is not well understood and still under considerable debate.

Figure 3 shows three differing comfort zones from two sources. The first, indicated by the shaded box in the figure, is the current ASHRAE Comfort Zone defined by ASHRAE Standard 55 in 1981. It is bounded in temperature by 73 F and 79 F Effective Temperature (ET*) during the summer, 68 F and 74.5 ET* during the winter, and in humidity by Humidity Ratios of 0.0042 and 0.012.* The second zone, indicated by the curved solid line, is the proposed 1992 modification of the ASHRAE Comfort Zone whereby the upper humidity boundary has been changed from 0.012 Humidity Ratio to 60% Relative Humidity. Except at the highest temperature bounds, this modification will impose more stringent limits on indoor humidity levels.

According to a member of the ASHRAE Comfort Committee, neither the current 0.012 Humidity Ratio nor the proposed 60% Relative Humidity boundaries were based on thermal comfort, but rather on other environmental concerns such as mold growth and condensation in the supply air duct of compressive air-conditioners.* Several researchers have stated that such concerns are not relevant to evaporatively or ventilatively cooled buildings with high air flow rates, no recirculated air, and higher supply temperatures (Watt 1986, Givoni 1991). In an environmental chamber study with human subjects, one researcher found no sensation of discomfort at relative humidity levels up to 80% (Scheatzle et al. 1989).

The third zone, indicated by the dashed line, is based on work by Milne and Givoni (Watson and Labs 1983). This zone differs from the ASHRAE zones in using a one degree lower temperature boundary (78 F ET*) and a humidity limit of 80% Relative Humidity rather than 0.012 Humidity Ratio or 60% Relative Humidity. Other reesearchers have proposed increasing the upper temperature boundaries when there is air

* "Effective Temperature (ET*) is the uniform temperature of a radiantly black enclosure at 50% relative humidity, in which an occupant would experience the same comfort, physiological strain and heat exchange as in the actual environment with the same air motion" (ASHRAE 1981).
* Personal communication with Ed Arens, Department of Architecture, U.C. Berkeley, June 1992.

movement (Arens 1984), but these effects will not be considered here.

For this study, the major discrepancy is between either the 0.012 Humidity Ratio or 60% Relative Humidity lines used in the ASHRAE and the 80% Relative Humidity line used in Milne/Givoni comfort zones. Since the determination of human comfort is beyond the scope of this project, we can only note the different interpretations and opinions, and encourage further research to determine and distinguish the comfort and non-comfort criteria for the upper temperature and humidity boundaries of the human comfort zone. The following discussion of the psychrometric charts will refer chiefly to the existing ASHRAE and the Milne/Givoni comfort zones.

Figures 5 to 10 superimpose the outlines of the three comfort zones onto five sequential plots showing the hourly a) ambient air conditions, b) floating indoor conditions with no cooling, and indoor conditions with c) a simple DEC, d) a two-stage IDEC, and finally, e) a standard air-conditioner for a summer month. Natural ventilation through open windows is assumed down to 70 F during the day and 60 F at night.

In interpreting these figures, it should be noted that the simulations assumed both the ECs and air-conditioner were controlled by thermostats set at 78 F. With the air-conditioner, the lower indoor humidity levels kept the indoor conditions always within the Milne/Givoni comfort zone, but not necessarily within the ASHRAE comfort zones. With the ECs, however, the higher indoor humidity levels on occasion pushed the indoor conditions outside even the Milne/Givoni comfort zone due to the slope of the ET* boundary. This does not reflect the cooling capacity of the ECs, but rather the limitations of the thermostatic control. Although EC control systems is the topic of another CIEE exploratory study (Wu 1992), Appendix C shows the results for the Pasadena and Fresno simulations repeated with a lower thermostat setting of 76 F to compensate for the increased humidity.

Figure 5 shows that, for the mild and relatively dry cooling climate in Pasadena, a simple DEC in a *Current* house in July can maintain indoor conditions within the Milne/Givoni Comfort Zone for almost all hours, but with humidty levels outside the current ASHRAE Comfort Zone. The indoor relative humidities while the DEC is running will average 65%, with a maximum of 75%. If an IDEC is used, the average relative humidity when the machine is operating drops to 55%, but there will be still a few hours outside the current ASHRAE Comfort Zone. To compare, the air-conditioner produced an average indoor relative humidity of 40%, with all hours falling within the ASHRAE Comfort Zone. Figure 6 shows that during the more humid month of August, a DEC in the same house and location will result in several days when the afternoon temperatures and humidity indoor are clearly outside the human comfort range (see arrow on figure).

Figure 7 shows that in the hotter Central Valley climate of Fresno, a DEC in a *Current* house in July will fail to maintain indoor conditions within the Milne/Givoni comfort zone for nearly 40 hours in the month, or roughly 1/3 of the afternoons. During those hours, the indoor temperature will be as high as 83 F and the relative humidity

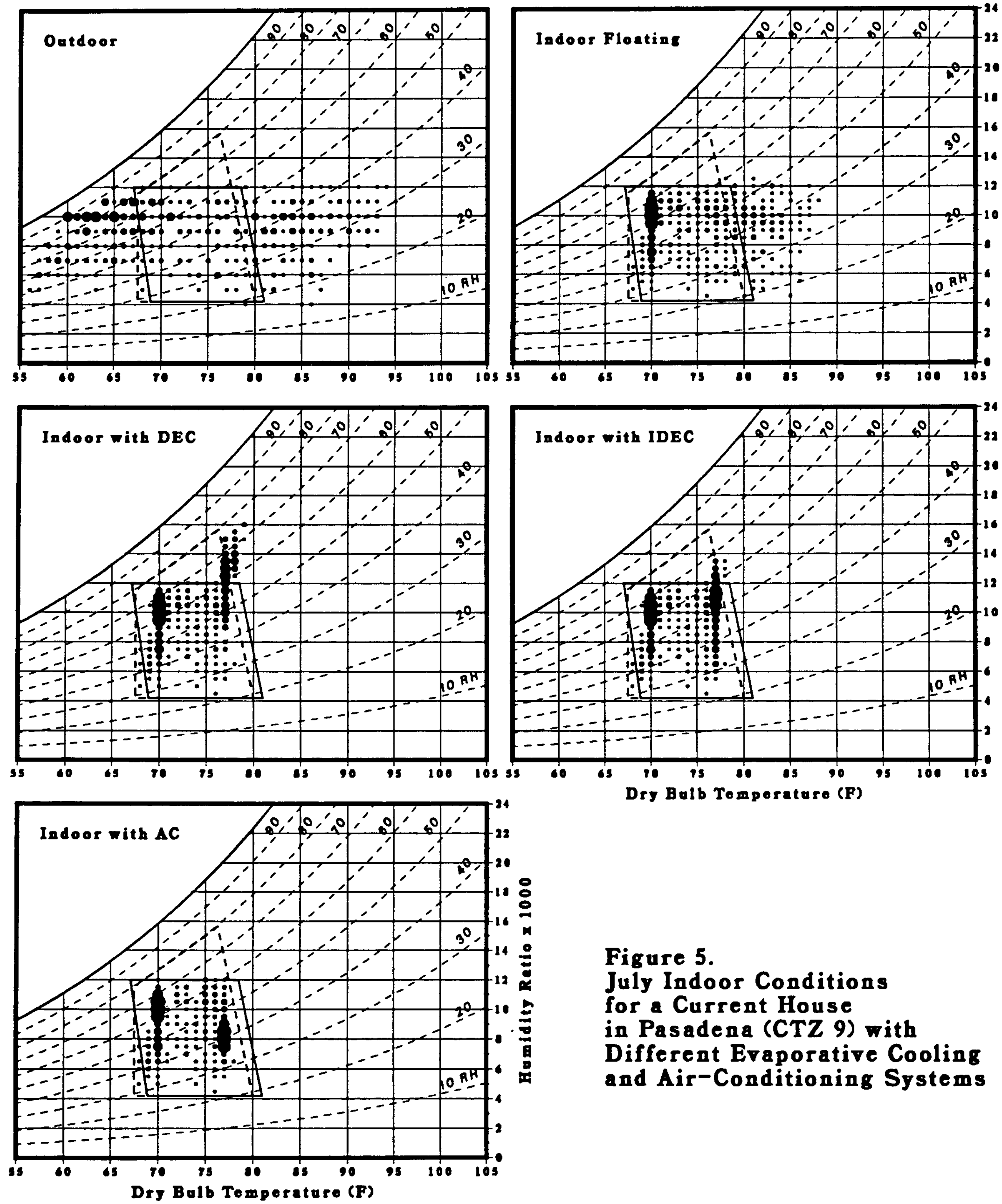


Figure 5.
July Indoor Conditions for a Current House in Pasadena (CTZ 9) with Different Evaporative Cooling and Air-Conditioning Systems

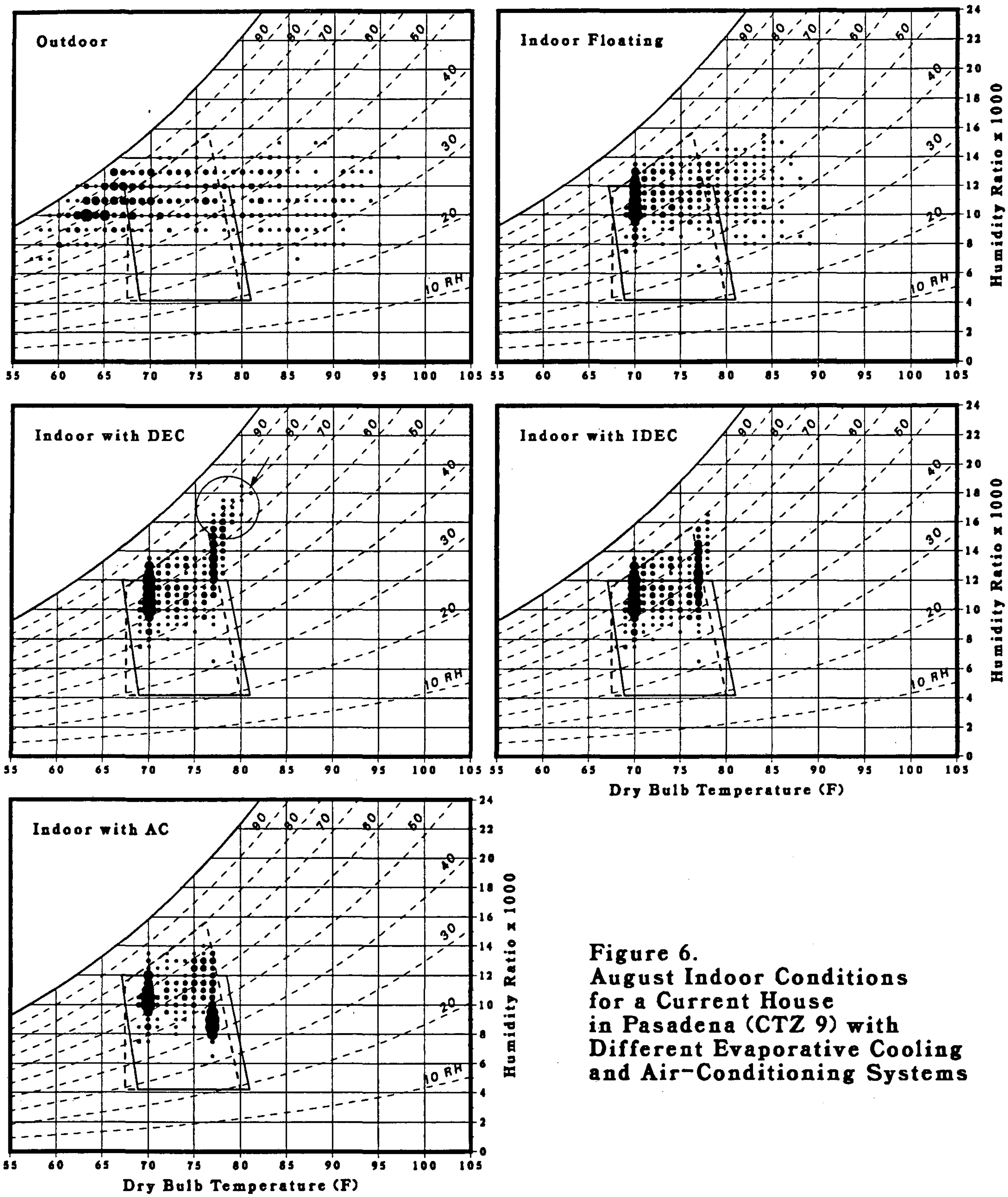


Figure 6.
August Indoor Conditions for a Current House in Pasadena (CTZ 9) with Different Evaporative Cooling and Air-Conditioning Systems

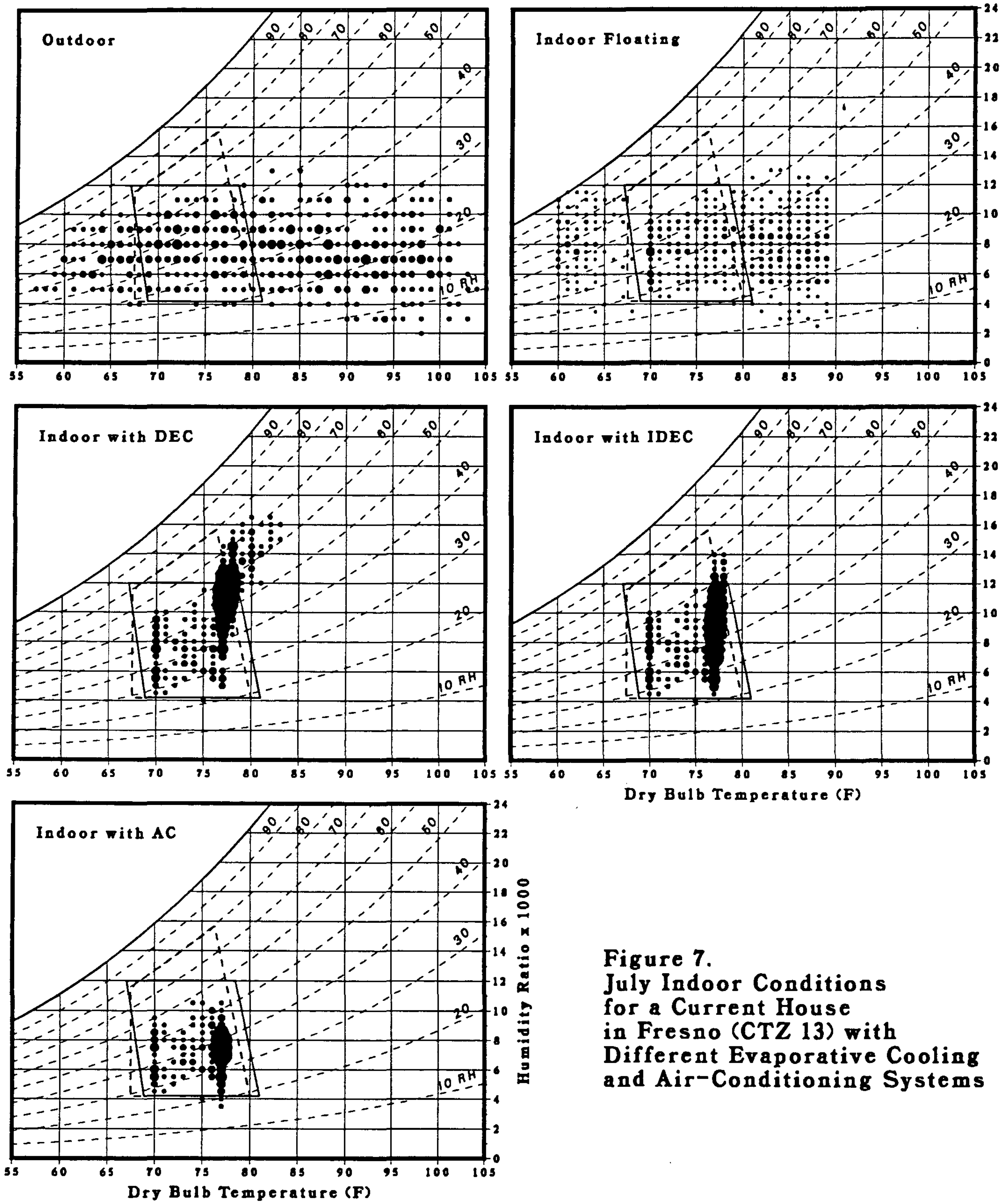


Figure 7.
July Indoor Conditions for a Current House in Fresno (CTZ 13) with Different Evaporative Cooling and Air-Conditioning Systems

will be from 60 to 75%. An IDEC under the same conditions, however, can still maintain indoor conditions within the Milne/Givoni comfort zone, with the temperature never higher than 78 F, and the humidity averaging 45% and never more than 70%. If evaluated against the current ASHRAE comfort zone, the IDEC will produce 47 unacceptable hours with humidity ratios above 0.012. In contrast, Figure 8 shows that even an IDEC will not work at all hours in an *Old* house in Fresno. Due to its higher cooling loads, the uninsulated *Old* house will experience a few hours when the temperature is as high as 83 F, although humidity does not seem to be a problem (see arrow on figure).

Figures 9 and 10 show what happens when evaporative coolers are used in extremely hot-humid and hot-arid climates. Figure 9 shows that neither the DEC or IDEC work well in Miami, where there is little potential for dry-bulb depression. Figure 10 shows that in Phoenix, where it is very hot but quite dry, evaporative coolers can greatly reduce the indoor temperature, but at the penalty of pushing the indoor humidity periodically to unacceptable levels. A DEC clearly does not have the capacity to maintain indoor comfort, with the temperature rising to as high as 86 F and the relative humidity to 85%, whereas an IDEC keeps the indoor temperature at below 83 F, but with occasional periods when the relative humidity rises as high as 85%.

The evaluation of comfort conditions indicates that evaporative coolers must be used with some discretion, since unlike air-conditioners, they cannot work at all times and under all conditions. Evaporative coolers, however, seem well-suited to the relatively mild cooling demands in California, if evaluated with the more lax humidity limits of the Milne/Givoni comfort zone. For houses built to 24 standards, a DEC should be adequate in the coastal climates, and an IDEC in the inland Valley areas. For older houses with minimal insulation, an IDEC would be required even in the coastal climates, while in the Valley areas they would produce unsatisfactory indoor conditions during peak cooling periods.

If ASHRAE comfort zones, particularly the proposed 1992 modification, are used in evaluating indoor conditions, then it would be difficult for evaporative coolers to maintain comfort conditions for all hours in most California locations. Paradoxically, using the proposed 1992 modification, an IDEC would be more satisfactory in Fresno than in Pasadena due to its lower relative humidity (compare Figures 6 and 7). The primary conclusion from this investigation, however, is that a clearer definition is needed of human comfort requirements under elevated temperatures and humidity levels.

EVAPORATIVE COOLERS WITH A BACK-UP AIR-CONDITIONER

Since an evaporative cooler might not always meet the cooling demand, a seemingly prudent strategy would be to install an air-conditioner as a back-up cooling system. Although such a configuration would save energy and still provide comfort at all

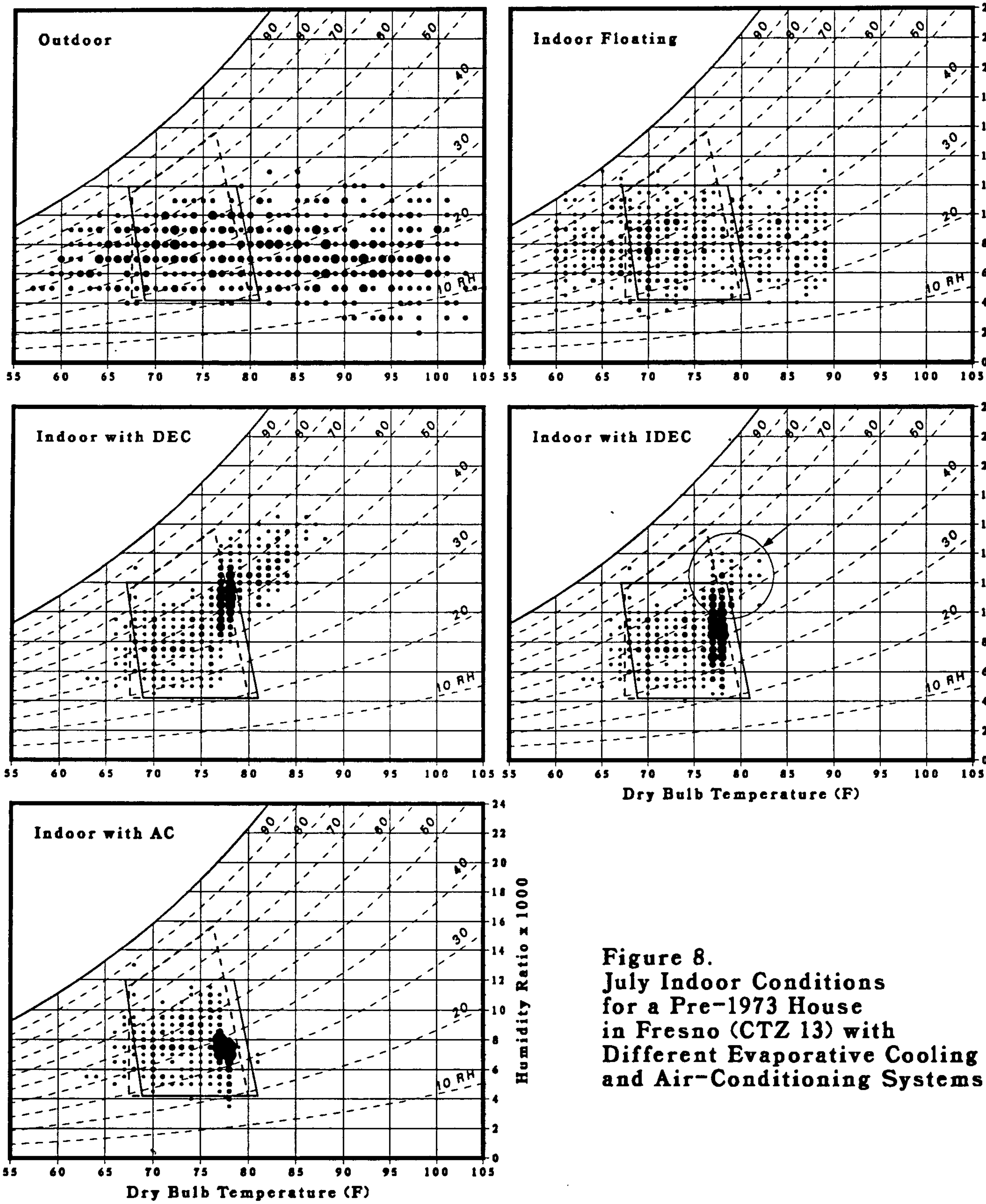


Figure 8.
July Indoor Conditions for a Pre-1973 House in Fresno (CTZ 13) with Different Evaporative Cooling and Air-Conditioning Systems

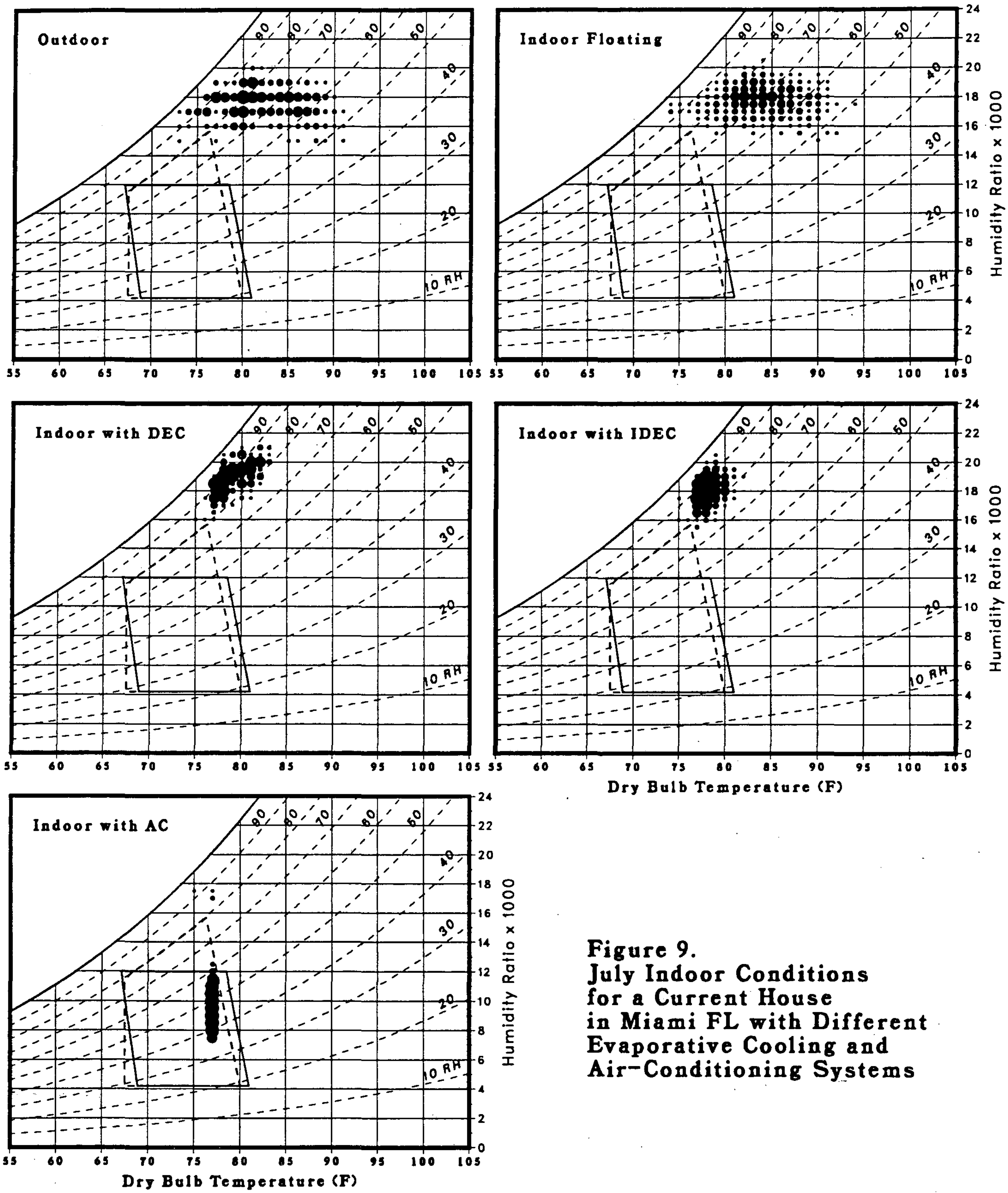


**Figure 9.
July Indoor Conditions
for a Current House
in Miami FL with Different
Evaporative Cooling and
Air-Conditioning Systems**

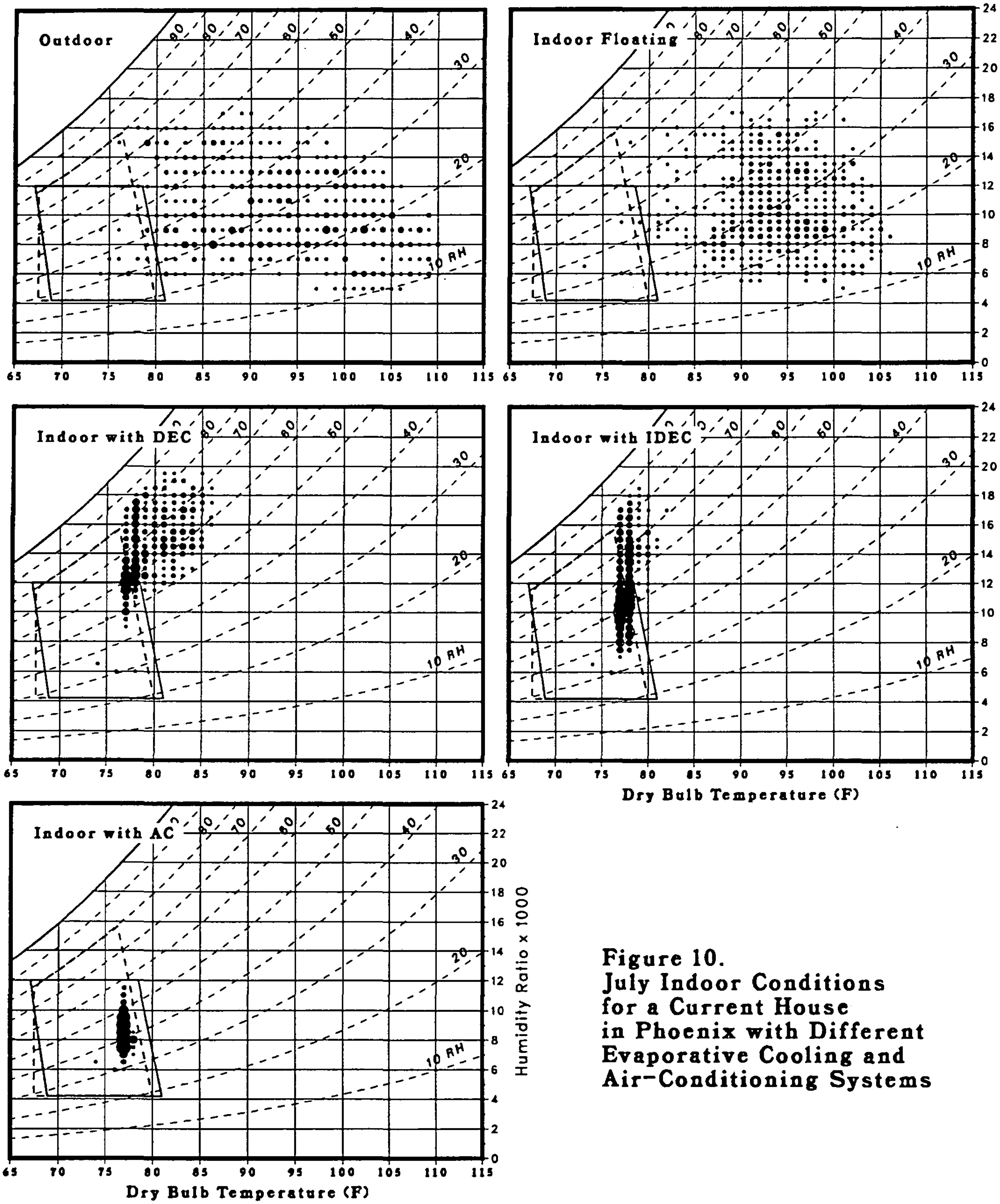


Figure 10.
July Indoor Conditions for a Current House in Phoenix with Different Evaporative Cooling and Air-Conditioning Systems

hours, it has two serious drawbacks : (1) the increased first costs of installing two cooling systems, each of which requires its own duct system, and (2) from a utility district's point of view, it would not improve the residential load shape since the back-up air-conditioner would be running during the peak hours. If the evaporative cooler and air-conditioner were installed with separate controls, as typically done, the peak energy use might even increase if both systems were used at the same time. There are potential savings in peak demand if the back-up air-conditioner were down-sized, but this would require careful engineering study to insure that the down-sized air-conditioner could still perform its intended function of providing comfort during peak conditions. Despite these unresolved questions, our phone survey indicated that builders installing evaporative coolers in California are, in fact, putting in DECs in conjunction with air-conditioners.

To investigate the energy implications of this configuration, we repeated the simulations described in Huang et al. 1991 for prototypical *Old* and *Current* California houses, but adding a back-up air-conditioner to either the DEC or IDEC. As in the previous simulations, we assume that natural ventilation is used whenever possible during the day and up until 11 at night. If natural ventilation fails to hold the indoor temperature at 78 F, then the evaporative cooler is turned on. If the evaporative cooler also fails to maintain the thermostat set point, the air-conditioner is turned as the equipment of "last resort" (The use of 78 F is conservative in respect to the comfort zone, but warranted since the previous evaporative cooling stage might result in higher humidity levels). We are not aware of any controls currently available that can do this switching, so the simulations mimic what an occupant should do for maximum cooling performance if both systems are available. The simulated annual electricity consumptions are shown in Table 1. * Some of the same data are plotted in Figure 11.

The results show that using a back-up air-conditioner can still lower annual cooling electricity bills by nearly half in the *Old* and more than a half in the *Current* homes. With higher cooling loads, such as for an *Old* house in Sacramento or a *Current* house in Fresno, an IDEC with an back-up air-conditioner will actually use less electricity than will a DEC, because of the fewer hours that the air-conditioner must be turned on.

Table 2 compares the peak electricity demand of the various evaporative cooler configurations to that of a standard air-conditioner. The air-conditioner has been modeled with a rated capacity of 36,000 Btu/h, a full-load COP of 2.18 (EER=7.42), and a fan capacity of 1,050 cfm for all vintages and locations, except for *Old* houses in Climate Zone 11 (Red Bluff) and Phoenix, where a capacity of 48,000 Btu/h has been used

* The simulation results differ from those given in the earlier paper (Huang et al. 1991) because of the following modeling changes: (1) the crankcase heater for the air-conditioner was eliminated, (2) the water consumption calculation in the IDEC model was improved, resulting in somewhat higher electricity consumptions, and (3) the definition of "undercooled hours" was changed from an unmet cooling load to those hours where the temperature rose more than one degree above the setpoint. For reference, the revised electricity consumption tables for the earlier paper are included in this paper as Appendix A.

Table 1. Annual electricity consumption of stand-alone evaporative coolers compared to those with a back-up air-conditioner for California Climate Zones and other locations

Climate Zone or Location	Current houses					Old houses				
		Stand-alone		w/AC backup			Stand-alone		w/AC backup	
	AC (kWh)	DEC (kWh)	IDEC (kWh)	DEC (kWh)	IDEC (kWh)	AC (kWh)	DEC (kWh)	IDEC (kWh)	DEC (kWh)	IDEC (kWh)
1 (Arcata) *	0	0	0	0	0	0	0	0	0	0
2 (Santa Rosa)	1122	229	354	406	412	2457	425	689	1213	866
3 (Oakland)	42	2	4	8	9	141	12	19	18	25
4 (Sunnyvale)	275	30	47	52	58	595	72	114	130	140
5 (Santa Maria)	98	10	16	31	35	252	32	49	65	68
6 (Long Beach)	840	108	163	127	168	1486	227	347	329	366
7 (San Diego)	541	35	54	41	55	797	84	128	109	134
8 (El Toro)	680	95	145	113	147	1658	270	422	506	444
9 (Pasadena)	965	157	240	195	245	2123	363	571	704	626
10 (Riverside)	1569	286	439	446	470	3315	553	889	1455	1081
11 (Red Bluff)	2236	452	707	858	763	4213	778	1305	2238	1722
12 (Sacramento)	1013	224	349	369	377	2537	454	742	1304	879
13 (Fresno)	2179	450	697	788	739	4167	703	1171	2271	1563
14 (China Lake)	3085	592	900	1021	942	4822	812	1278	2203	1350
15 (El Centro)	4904	1177	2002	2653	2232	7409	1367	2416	4738	3479
16 (Mt. Shasta)	729	94	139	229	270	861	121	179	280	311
Fort Worth TX	3309	973	1802	2230	2156	4776	1063	2054	3738	3565
Miami FL	5624	1742	3230	3391	3501	7033	1815	3467	5028	4869
Phoenix AZ	4515	1134	1945	2627	2200	8568	1687	3114	5893	5050

* No cooling required in Climate Zone 1 (Arcata).

because of the higher cooling loads. The evaporative coolers have been modeled with a 3,500 cfm primary fan and a 100W water pump (see Huang et al. 1991 for details on the system modeling). The peak electricity demand for evaporative coolers with AC back-up are not shown since these are basically identical to those for the standard AC.

Table 2 shows that the peak electricity demand varies by location for the AC, as do those for the IDEC in the *Current* houses. However, the peak consumptions for DEC in most houses and the IDEC in the *Old* houses are constant, another indication that they are running at full capacity and not meeting all the cooling load. Disregarding those situations where evaporative coolers are obviously not maintaining adequate indoor

Figure 11
Comparison of Annual Electricity Use for Different Evaporative Cooling Controls

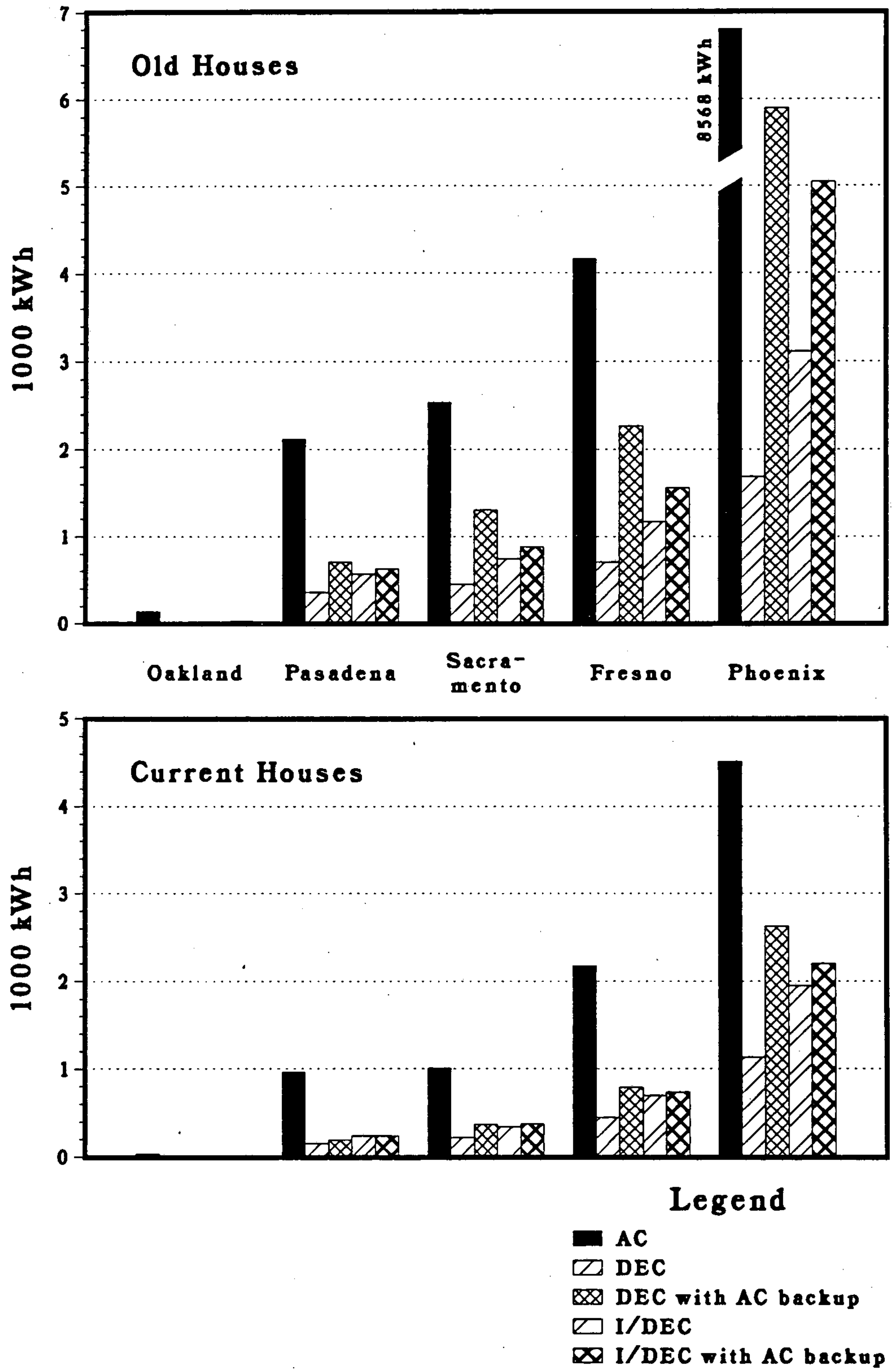


Table 2. Peak electricity consumption of various evaporative coolers compared to standard A/C for California Climate Zones and other locations

Climate Zone or Location	Current houses AC (kW)	Current houses DEC (kW)	Current houses IDEC (kW)	Old houses AC (kW)	Old houses DEC (kW)	Old houses IDEC (kW)
1 (Arcata) *	0.00	0.00	0.00	0.00	0.00	0.00
2 (Santa Rosa)	2.21	0.55	1.25	4.15	0.55	1.25
3 (Oakland)	1.21	0.19	0.28	1.85	0.32	0.47
4 (Sunnyvale)	2.14	0.55	1.07	3.97	0.55	1.25
5 (Santa Maria)	1.52	0.55	0.83	3.02	0.55	1.01
6 (Long Beach)	1.77	0.55	1.25	2.98	0.55	1.25
7 (San Diego)	2.01	0.55	1.25	3.49	0.55	1.25
8 (El Toro)	1.54	0.55	1.04	3.19	0.55	1.25
9 (Pasadena)	1.67	0.55	1.25	3.32	0.55	1.25
10 (Riverside)	2.24	0.55	1.25	4.32	0.55	1.25
11 (Red Bluff)	3.11	0.55	1.25	6.05	0.69	1.58
12 (Sacramento)	2.33	0.55	1.25	4.41	0.55	1.25
13 (Fresno)	2.31	0.55	1.24	4.37	0.55	1.25
14 (China Lake)	2.43	0.55	1.08	4.29	0.55	1.25
15 (El Centro)	2.77	0.55	1.25	4.59	0.55	1.25
16 (Mt. Shasta)	1.86	0.55	0.88	2.68	0.55	0.98
Fort Worth TX	2.66	0.55	1.25	4.57	0.55	1.25
Miami FL	2.16	0.55	1.25	3.51	0.55	1.25
Phoenix AZ	3.48	0.55	1.25	6.08	0.69	1.58

* No cooling required in Climate Zone 1 (Arcata).

comfort, a comparison of the IDEC to AC in *Current* houses shows reductions in electricity demand ranging from 20% in Pasadena (1.57 to 1.25 kW) to 77% in Oakland (1.21 to 0.28 kW). As already mentioned, these reductions must be regarded with caution, since the evaporative cooler might be "peaking" during the extreme cooling periods.

WATER CONSUMPTION OF EVAPORATIVE COOLERS

Evaporative coolers perform best in arid climates, where water is typically scarce. Water systems in the western United States, particularly California with its expanding urban population and water-intensive agriculture, are straining to meet growing water demands for municipal and agricultural uses while maintaining environmental quality. This section will discuss the potential impact on water demand which may result from increased use of residential evaporative cooling in California and the West.

Water Consumption Model

Water consumption by direct, indirect, and two-stage evaporative cooling systems in the prototype building is calculated within the DOE-2 model by multiplying the difference in humidity ratio (lb H_2O/lb air) between ambient and supply air (exhaust air for IEC) by the supply air flowrate. These values are calculated hourly and summed daily, monthly, and annually. Water consumption for DECs and two-stage IDECs in the *Old* and *Current* residential prototypes is given in Table 3. Some of the same data are also plotted in Figure 12.

The values presented here include only the amount of water evaporated into the air streams. In practice, some water must be wasted in "bleed-off" or "blowdown" to drain minerals that build up in the recirculated sump water because of the evaporation which occurs. The required bleed-off rate is highly dependent on the hardness of the supply water, which varies between locations. Rules of thumb for areas of moderate water hardness range from bleed-off rates equal to one-half the evaporation rate to one-tenth of the peak evaporation rate (Watt 1986). For the California climates and buildings used in the simulations, these rules of thumb would suggest that total water use may be anywhere between 10% to 50% greater than the minimums presented here. However, because the required blowdown rate depends so greatly on the local water supply, no attempt has been made to adjust the values calculated by the model.

For the *Old* house (1384 ft^2), DEC water consumption is 4000 gallons per year in the mild Pasadena climate and 9500 gallons per year in the hotter Fresno climate. Water consumption by two-stage IDEC units in these climates is 10 to 20 percent greater. A thermally improved building, while significantly reducing the cooling load, also leads to reduced water consumption by evaporative coolers. Annual water consumption in *Current* houses in Pasadena and Fresno is 1800 gallons and 6200 gallons, respectively, for DEC and 1900 and 6700 gallons for two-stage IDEC units.

When air-conditioning is used instead of evaporative cooling during periods of extreme high loads, water consumption drops considerably, particularly in the climates where evaporative coolers would otherwise run continuously while still not meeting the cooling load. This reduction in water consumption is illustrated in Figure 13. For example, the *Old* house in Fresno with a DEC uses 9500 gallons per year while still not meeting the load in 361 hours. Air conditioning backup meets the period of extreme load and reduces water consumption to 4700 gallons. Alternatively, AC backup has little effect on water consumption, as well as energy consumption, in the *Current* house in Pasadena with a two-stage IDEC where evaporative cooling meets the load in all hours.

Table 3. Annual water consumption by different evaporative cooling systems for California Climate Zones and other locations†

Climate Zone or Location	Current houses					Old houses				
	Cool Load (MBtu)	Stand-alone DEC (gal/yr)	Stand-alone IDEC (gal/yr)	w/AC backup DEC (gal/yr)	w/AC backup IDEC (gal/yr)	Cool Load (MBtu)	Stand-alone DEC (gal/yr)	Stand-alone IDEC (gal/yr)	w/AC backup DEC (gal/yr)	w/AC backup IDEC (gal/yr)
1 (Arcata) *	0.01	0	0	0	0	0.06	0	0	0	0
2 (Santa Rosa)	6.50	3107	3370	2127	3310	19.20	5510	6418	3019	5640
3 (Oakland)	0.18	27	28	27	28	0.99	114	119	114	119
4 (Sunnyvale)	1.59	298	323	221	323	4.56	645	722	509	634
5 (Santa Maria)	0.40	154	160	143	160	1.69	414	430	353	430
6 (Long Beach)	5.16	1065	1103	973	1095	11.84	2145	2259	1857	2168
7 (San Diego)	3.20	307	332	266	317	6.17	644	686	570	646
8 (El Toro)	3.76	1010	1056	861	1056	13.17	2589	2844	1835	2702
9 (Pasadena)	5.53	1784	1885	1464	1873	16.88	3993	4394	2874	4048
10 (Riverside)	9.05	3847	4117	2809	4107	26.13	7301	8377	4467	7391
11 (Red Bluff)	13.22	6652	7431	4042	7227	30.07	11411	13517	5829	10869
12 (Sacramento)	5.87	2957	3235	1942	3102	20.16	5577	6612	2857	5947
13 (Fresno)	12.94	6199	6744	3934	6700	32.82	9476	11458	4724	9406
14 (China Lake)	17.25	10548	11165	7064	11165	33.44	14260	15931	8094	15719
15 (El Centro)	29.43	18467	22652	7645	17912	52.40	21586	27976	8135	19695
16 (Mt. Shasta)	3.55	1159	1178	1118	1178	4.94	1502	1534	1340	1534
Fort Worth TX	21.42	7446	10607	1646	4733	37.37	8205	12182	1686	3532
Miami FL	37.18	7967	10733	2531	4818	55.68	8719	12104	2385	4572
Phoenix AZ	28.02	15616	19640	5840	15306	61.67	23673	31056	8192	17252

† Water evaporated into the airstream(s) only.

* No cooling required in Climate Zone 1 (Arcata).

Peak monthly cooling typically occurs in July for the California climates and the cooling season is typically 4 to 6 months in duration. Thus, water consumption will peak in the summer. Table 4 shows annual average and peak month water use for current construction houses in selected climates with two different evaporative cooling configurations. These configurations were chosen because they are able to meet the load in all climates, except for Phoenix.

Figure 12
Annual Water Consumption of Evaporative Coolers for Prototypical Houses in Different Climates

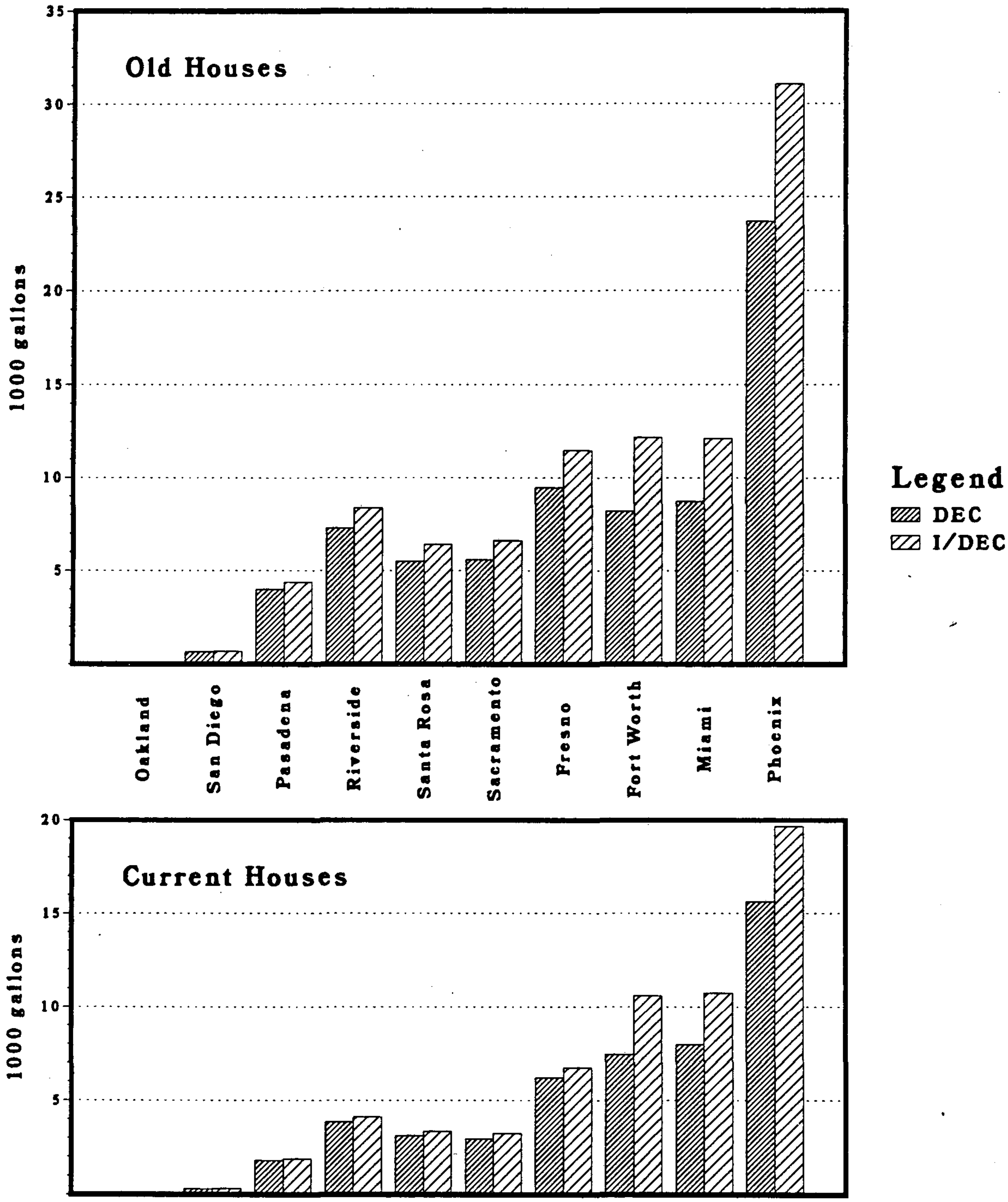


Figure 13
Comparison of Annual Water Usage for Different Evaporative Cooling Controls

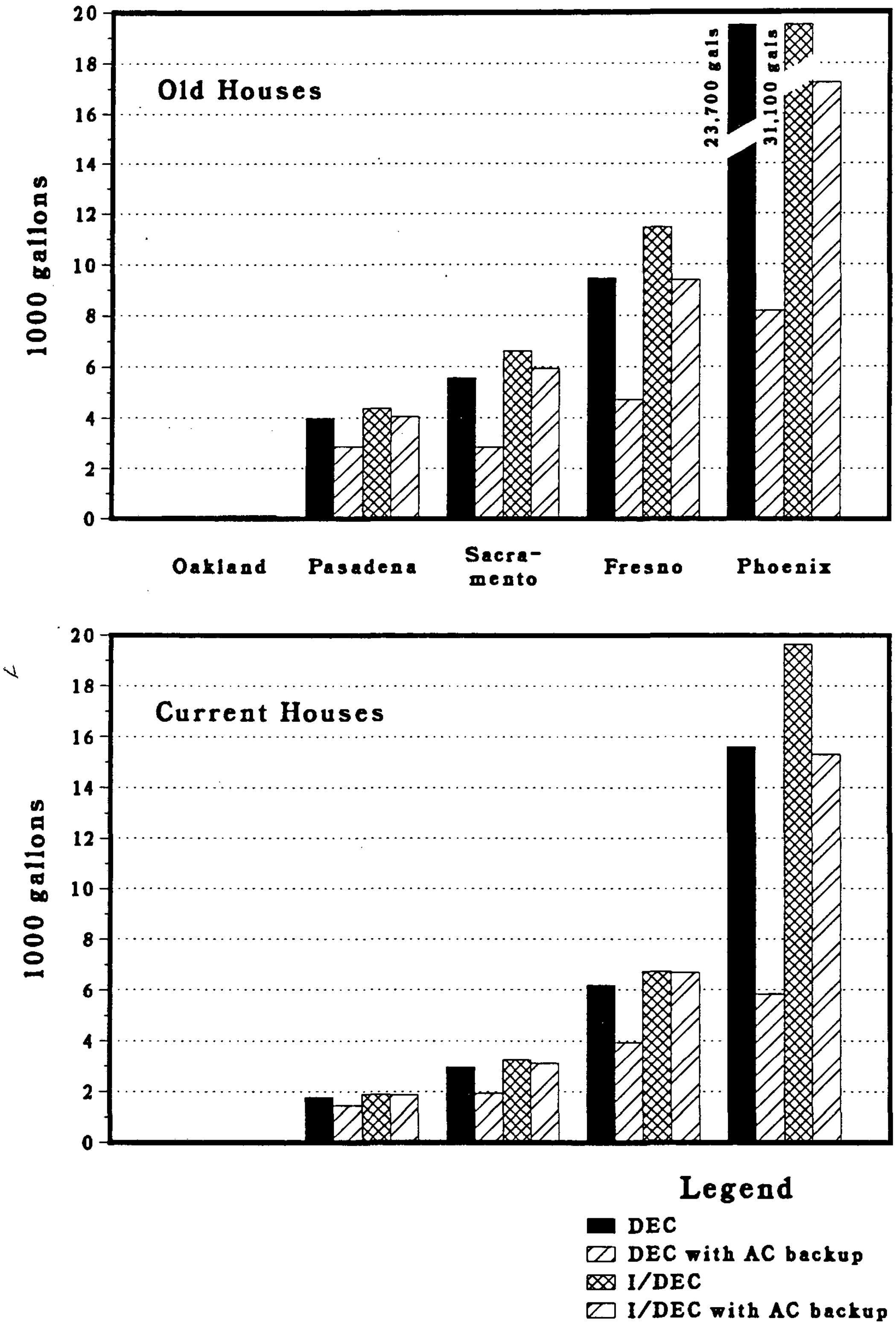


Table 4. Annual and peak month average daily water use in Current houses for two evaporative cooling system types*

Climate Zone or City	DEC w/AC Backup Annual (gal/day)	DEC w/AC Backup Peak Month (gal/day)	Stand-alone IDEC Annual (gal/day)	Stand-alone IDEC Peak Month (gal/day)
2 (Santa Rosa)	6	20	9	41
7 (San Diego)	1	7	1	7
9 (Pasadena)	3	12	4	15
10 (Riverside)	8	42	11	62
12 (Sacramento)	5	18	9	38
13 (Fresno)	10	36	17	69
Phoenix	16	41	53	192

* Water evaporated into the airstream(s) only.

Comparison with Measured Data

The only source of measured water consumption data for evaporative coolers is a study of a single-family house in the Phoenix area (Wu 1990). During one day of this field test, the DEC water use totaled 80 gallons, with a peak hourly demand of 7.9 gal/hr. On a different day, a two-stage IDEC used 86 gallons, with a peak hourly demand of 8.2 gal/hr. The values for DEC compare favorably with the simulated peak demands, which range between 6 and 8 gallons per hour depending on location. The comparison for the IDEC is less in agreement, where simulated daily summer use for Phoenix is over twice the monitored level. These peak days and peak months may be more severe than the single day in which the home in Phoenix was measured. Further model testing using measured data as a baseline is desirable.

Impact on Household Water Consumption

The calculated water consumption shown in Table 4 suggests that using evaporative cooling could significantly increase household water demand in California. The highly varied nature of water supply and demand in California precludes an in-depth evaluation of potential impacts on local water supply systems. However, a simple comparison is outlined below.

While detailed data is not presently collected, estimates from various parts of the state suggest that typical residential water consumption is between 100 and 140 gallons/capita-day, or 300 to 420 gallons/day for a family of three. Of this total, approximately 60% is for indoor usage such as toilets, showers, and cooking and 40% is for outdoor landscaping and swimming pools (EBMUD 1988, NYT 1991). Assuming household water consumption is approximately 300 gallons per day (180 indoors, 120 outdoors), IDEC in a *Current* construction house in Pasadena would increase annual household use by 2%, while in Fresno it would increase household use by 6%. Peak month evaporative cooling usage is more significant, and would increase monthly water consumption by 5% (8% if considering only indoor water use) and 23% (40% of indoor use) in the same climates, which may severely impact households under water rationing in time of drought.

Tradeoff Between Electricity and Water Consumption

Neglecting the issue of comfort, evaporative cooling represents substitution of one resource, water, for another, electricity. Following this reasoning, we calculated the cost, in water, for electricity savings by the evaporative cooler compared to conventional air-conditioning. Some typical results, given in Table 5, are calculated by dividing the evaporative cooling water consumption in Table 3 by the difference between air-conditioner electricity use and evaporative cooling electricity use given in Table 1. This figure varies by location as the relative evaporative cooler effectiveness and air-conditioner efficiency change with the changes in ambient air conditions. In general, the simulations show the water cost per electricity saving to be lower in the mild climates and higher in the more extreme climates.

Table 5. Water consumption per energy saved by different evaporative cooling systems

Climate Zone or Location	*Current* Houses DEC w/AC backup (gal/kWh)	*Current* Houses IDEC stand-alone (gal/kWh)	*Old* Houses DEC w/AC backup (gal/kWh)	*Old* Houses IDEC stand-alone (gal/kWh)
2 (Santa Rosa)	3.0	4.4	2.4	3.6
7 (San Diego)	0.5	0.7	0.8	1.0
9 (Pasadena)	1.9	2.6	2.0	2.8
10 (Riverside)	2.5	3.6	2.4	3.5
12 (Sacramento)	3.0	4.9	2.3	3.7
13 (Fresno)	2.8	4.6	2.5	3.8
Phoenix	3.1	7.6	3.1	5.7

Thermal electricity generating power plants also consume water for cooling. Thus, depending on the source of the electricity, evaporative cooling has the potential to reduce water consumption at the source, thereby reducing net water demand. Fossil fuel power plants consume water at the rate of 0.25 to 1.00 gal/kWh produced, while nuclear plants use 0.85 to 1.33 gal/kWh (Ottinger et al. 1990). Thus, it appears that evaporative cooling water consumption varies between one and five times the potential savings at the power plant.

The Cost of Water

A full analysis of the costs and benefits of evaporative cooling would need to include the average cost of water and the marginal cost of new water supply. This analysis is beyond the scope of this report. Water pricing and allocation decisions in California are highly localized and extremely political. For some areas such as Santa Barbara, the new water supply may be desalination plants, with costs up to $2,000/acre-foot ($0.0061/gallon). With the recent drought however, the State of California has initiated a water bank, whereby agricultural users can sell water rights to the State which then sells it to municipal users. The cost of this water is $175/acre-foot plus transportation charges, or approximately $200/acre-foot ($0.00061/gallon) *.

Compared against the cost savings in electricity use, the cost of water used by evaporative coolers is quite small. Table 5 shows that the water consumption rates per kWh saved in different California locations vary from a low of 0.5 gal/kWh in San Diego to a high of 4.9 gal/kWh in Sacramento. Even using a high water cost of $0.0061/gallon, these translate to avoided electricity costs of $0.003/kWh to $.030/kWh, much lower than the typical electricity cost of $0.10/kWh. Table 6 shows the annual cost savings for various evaporative cooling strategies in different California locations derived by taking the savings in electricity based on Table 1, and subtracting the costs for water based on Table 3. Because of their wide variation, two water costs differing by a factor of ten have been used, while an average electricity price of $0.10/kW has been assumed for all locations.

AVAILABILITY AND COSTS OF EVAPORATIVE COOLERS IN CALIFORNIA

To develop a picture of the evaporative cooling market in California, we surveyed a small number of cooling distributors and contractors in the central valley and southern California. The intent was to determine the availability of evaporative cooling systems in the state, to gather estimates of module and system costs, and to get an indication of the relative market penetration of evaporative cooling compared to standard air-

* Personal communication Jim Hanford with Sami Yassa, Natural Resources Defense Council, Nov. 12, 1991.

Table 6. Annual cost savings by different evaporative cooling systems for California Climate Zones and other locations
(cost of electricity assumed at $0.10/kWh in all locations)

California Climate Zone and Location	Current houses Stand-alone DEC ($)	Current houses Stand-alone IDEC ($)	Current houses w/AC backup DEC ($)	Current houses w/AC backup IDEC ($)	Old houses Stand-alone DEC ($)	Old houses Stand-alone IDEC ($)	Old houses w/AC backup DEC ($)	Old houses w/AC backup IDEC ($)
(cost of water assumed at $200/acre-feet or $0.00061/gallon)								
1 (Arcata) *	0	0	0	0	0	0	0	0
2 (Santa Rosa)	87	74	70	68	203	173	120	157
3 (Oakland)	3	3	3	3	12	12	12	11
4 (Sunnyvale)	24	22	22	21	52	47	46	45
5 (Santa Maria)	8	8	6	6	21	20	18	18
6 (Long Beach)	72	67	70	66	125	112	114	110
7 (San Diego)	50	48	49	48	71	66	68	65
8 (El Toro)	57	52	56	52	138	122	113	120
9 (Pasadena)	79	71	76	70	175	152	139	147
10 (Riverside)	125	110	110	107	276	238	180	220
11 (Red Bluff)	174	148	135	142	343	283	189	245
12 (Sacramento)	77	64	63	61	208	176	119	164
13 (Fresno)	169	144	136	139	346	293	182	257
14 (China Lake)	242	211	202	207	400	345	252	342
15 (El Centro)	361	276	220	256	604	486	250	388
16 (Mt. Shasta)	62	58	49	45	73	67	57	54
(cost of water assumed at $2,000/acre-feet or $0.0061/gallon)								
1 (Arcata) *	0	0	0	0	0	0	0	0
2 (Santa Rosa)	70	56	58	50	203	143	85	140
3 (Oakland)	3	3	3	3	12	11	11	10
4 (Sunnyvale)	22	20	20	19	52	44	42	42
5 (Santa Maria)	7	7	5	5	21	17	16	16
6 (Long Beach)	66	60	65	60	125	100	101	100
7 (San Diego)	48	46	48	46	71	62	64	62
8 (El Toro)	52	47	51	46	138	107	97	110
9 (Pasadena)	69	61	68	60	175	130	115	132
10 (Riverside)	104	87	95	84	276	198	134	196
11 (Red Bluff)	137	107	113	103	343	221	115	213
12 (Sacramento)	60	46	52	44	208	145	82	148
13 (Fresno)	135	107	115	103	346	241	119	231
14 (China Lake)	184	150	163	146	400	267	164	297
15 (El Centro)	260	152	178	157	603	367	96	343
16 (Mt. Shasta)	56	51	43	38	73	59	48	46

* no cooling needed in Climate Zone 1 (Arcata)

conditioning. The results are summarized below, followed by a more detailed discussion.

- The market is characterized by small manufacturing volume and sales. The survey identified five brands which are available in California.
- Evaporative coolers represent a small part of cooling distributor and contractor business.
- 90% of evaporative cooling unit sales are for residential use.
- 90% of evaporative cooling sales are direct evaporative coolers.
- In new houses, evaporative cooling is installed as a supplementary system to standard AC.
- In existing houses without AC, evaporative cooling is installed as a stand-alone system.

For the businesses contacted, it appears that about 90% of the business in evaporative cooling sales is for residential buildings. This does not include window evaporative coolers which can be purchased in building supply stores and installed by the homeowner. The majority of evaporative coolers sold by distributors and cooling contractors are direct units between 4500 and 6500 cfm capacity. Of the five evaporative cooler brands we identified, only one of the manufacturers makes a two-stage IDEC evaporative cooler, which is a direct unit with an indirect module add-on. According to the contractors and distributors, IDEC units are rarely used because of the added costs.

Evaporative cooling represents a small part of cooling distributor and contractor business compared to conventional air-conditioning. From this survey, it was impossible to estimate the market shares of evaporative coolers versus AC either for stock or existing buildings. Depending on the location and the business, the portion of evaporative coolers going to new construction versus retrofit installations is quite variable. However, the contractors we surveyed who work solely in new construction noted that evaporative cooling in new houses is always used in combination with conventional air-conditioning. For retrofit situations, evaporative coolers may be a first-time cooling system, an addition to an existing AC system, or a replacement for an existing evaporative cooling system.

Based on our inquiries in 1991, the costs for evaporative coolers appear to vary little between contractors and distributors. A typical 4600 cfm direct unit costs about $350 wholesale. A plastic unit, which reportedly reduces maintenance costs, is sold for $450. Two-speed switches and roof mounts are extra. The two-stage unit costs about 50% more. A fully ducted direct evaporative cooler with upducts for venting typically costs $1500 installed, although there is debate about the need to duct every room in the house and the benefits of upducts. All respondents noted that the evaporative cooling system should be separate from the AC system, if it exists, because of the need for larger ducting. The costs for evaporative coolers and AC are summarized in Table 7.

Table 7. Evaporative cooler and air-conditioner costs *

Equipment	Wholesale	Installed
Standard air-conditioning	$900-1200	$2500-2800
Direct evaporative coolers (DEC)	360-400	1500
Two-stage evaporative coolers (IDEC)	700-800	1800-2000

* based on 1991 information

Since they have lower first costs than air-conditioners, as well as much lower operating costs, evaporative coolers from a strictly economic point of view would more than pay for themselves from the moment they are installed. Therefore, it is clear that their slow market penetration is caused by other factors than economics, namely, concerns about their performance, indoor humidity levels, and general unfamiliarity about the technology.

SURVEY OF ENGINEERS AND CONTRACTORS

To balance the computer studies of evaporative cooler performance, the project also conducted a survey of engineers and contractors familiar with this technology to assess their personal experiences and evaluation of evaporative coolers. A three-page questionnaire (see Appendix B) was sent to over fifty people who are either members of ASHRAE Evaporative Cooling committees or are known to the authors as having worked with evaporative coolers. Because of the self-selected nature of the respondents, the survey results cannot be regarded as statistically representative of HVAC engineers or the residential buildings market as a whole. Nevertheless, the survey is very useful in pointing out potential problem areas and unexpected benefits related to the use of evaporative coolers.

The project received back 26 completed surveys, made up of 15 engineers, 2 contractors, 11 HVAC manufacturers or industry representative, and 1 building owner. Of these respondents, 24 were experienced in design, 15 in installation, 16 in operating, and 1 in research of evaporative coolers.

Table 8 shows the types of evaporative cooler used by the respondents and their applications. In contrast to the market study mentioned earlier, most of those surveyed used evaporative coolers in custom commercial applications, sometimes in tandem with standard compressive cooling. This preponderance of larger commercial applications is not unusual because of the high percentage of engineers among the respondents.

Table 8. Types of Evaporative Cooler Used

Types of EC Used		Applications	
Direct	22	Residential	8
Indirect	20	Commercial	21
Two-stage	18	Stand-alone units	10
Three-stage (IDEC/Refrig)	2	Attached units	6
Desiccant-boosted Refrigeration	1		
Roof Spray	1		
Indirect/DX	1		

Table 9 lists the reasons given by the respondents for using evaporative coolers. Although lower operating costs received the largest number of responses, there were significant numbers that expected improved comfort and air quality from the use of evaporative coolers.

Table 9. Reasons for Using Evaporative Cooling

Influenced by		Benefits in EC use	
First costs	6	First cost savings	9
Operating costs	16	Improved comfort	14
Health	4	Operating cost savings	24
Previous experience	13	Improved air quality	13
Exploring new technology	8		

Table 10 gives the responses for the comfort conditions maintained by their evaporative cooling systems. The responses were overwhelmingly positive, with only two cases of humidity and one case of noise level being unsatisfactory.

The survey asked the respondents to describe any problems that they encountered in either installing or operating their evaporative cooling systems. In terms of installation, the following were cited as problems that were encountered:

- Must pay attention to maximum rated air velocity. Water carry-over will result.

Table 10. Comfort Conditions Maintained by Evaporative Coolers

	Satisfactory	Unsatisfactory
Noise	23	1
Air Movement	24	0
Temperatures	19	0
Humidity	17	2

- Physical dimensions of equipment and ducting are sometimes objectionable. Poor ducting designs do not support good air movement.
- Proper maintenance plus understanding limits of application. For example, effective water treatment will minimize maintenance and water use.
- Installers not familiar with EC's. Problems with communication to plumbing trades and controls contractors.
- Some problems with unjustified customer expectations.

In terms of operating evaporative coolers, the following were cited as problems that were encountered:

- Large pumping costs, losses due to water make-up and bleed-off, incomplete wetting, and blow through in aspen pads at high velocity.
- Educating end users in proper maintenance of their equipment, i.e., water treatment. System should be designed with enough controls and features like automatic flush and freeze protection.
- Manufacturer's exaggeration of performance, in general an industry-wide problem. Not all applications in all geographic locations will be successful.
- Humidity control is sometimes needed.
- Problems with temperature control system.

Since evaporative cooling is still a unfamiliar technology to many, the survey asked the respondents to list any hidden problems as well as unexpected benefits that they encountered with their evaporative cooling equipment. Of the six cases described, five were unexpected benefits, while the remainder could be regarded an instance of information dissemination.

- Evap coolers will remove dust from the air, keeping secondary filters clean.
- Can be used as humidifier in winter.
- Smaller mechanical equipment, chiller, cooling towers, pumps.
- Occupants of EC buildings start to feel physically better and comment to that effect due to 100% outside air cooling.
- Using up-ducts with the EC keeps the attic cooler and reduces heat damage to stored items.
- Need for "certified performance" equipment and public education.

Lastly, the respondents were asked to rank the reasons why evaporative cooling still has not caught on with the general public. Table 11 is a tabulation of their responses. Of the eleven possible barriers listed on the survey, the three that were given the greatest weights were (1) the poor public image from earlier "swamp coolers", (2) unfamiliarity of engineers about the technology, and (3) lack of design guidelines and rules that they can use.

Table 11. Respondent's Perception of the Significant Barriers to Widespread Usage of Evaporative Cooling
(1 = most significant, 5 = least significant)

	1	2	3	4	5
Poor public image of earlier swamp coolers	11	3	2	5	2
Unfamiliarity about EC among engineers	8	5	4	4	1
Unfamiliarity about EC among building owners	6	5	6	2	2
Unfamiliarity about EC among the general public	7	3	6	3	3
Lack of design info for engineers and contractors	3	11	2	3	1
Unreliable or poor performance	2	2	6	3	4
High first costs	5	5	3	4	2
High installation costs due to unfamiliarity	1	2	7	4	4
High installation costs due to required changes in building shell	1	3	6	3	3
Poor comfort conditions due to higher temperatures and humidity	2	5	3	1	3
Noise and air movement	2	1	3	5	4

CONCLUSIONS

The computer analyses indicate that evaporative coolers are a viable cooling technology for the warm but dry California climates, provided that the increased humidity levels are still within human comfort zone. In terms of electricity use, evaporative coolers are clearly very energy efficient. In the coastal areas DECs will use only one-sixth of the energy of standard air-conditioning, but the absolute savings will be small due to small cooling loads. In the inland zones, IDECs will use one-fourth to one-third the energy of standard AC, depending on the building thermal integrity, and give significant energy and peak demand savings.

The investigation of indoor conditions disclosed unresolved questions about the appropriateness of using the current and proposed ASHRAE comfort zones to evaluate evaporatively cooled buildings. Because of their increasingly stringent limits on indoor humidity, it would be difficult for even IDECs to provide ASHRAE-defined comfort at all hours. If the Milne/Givoni comfort zone is used as a more appropriate measure of human comfort, the following observations can be made : (1) DECs will produce some undercooling, i.e., elevated temperatures, and objectionable humidity levels during peak cooling conditions even in a coastal climate such as Pasadena. (2) In a Central Valley, e.g. Fresno, a DEC will fail to maintain indoor comfort for a substantial number of hours, but an IDEC will do so for all hours in Title 24 houses. (3) In pre-1973 houses in the Central Valley, even an IDEC will produce some undercooling, but without problems with excessive indoor humidity. In El Centro, California's most severe cooling climate, neither EC system is able to meet peak cooling loads even in a thermally efficient Title 24 house.

Backup air-conditioning is one way to solve the problems of undercooling. Energy savings are still significant with this configuration, but there would be little change in the peak demand since the air-conditioner would be operating during the hottest periods. Considering that IDECs provide adequate comfort in new houses in most climates, a prudent strategy for both homeowners and utilities would be to promote greater use of IDECs without air-conditioning.

The analysis of water consumption by evaporative coolers shows that, on an annual basis, it is relatively small compared to typical residential water usage, around 1% in the coast climates (Pasadena or Long Beach) and 4-7% in the Central Valley (Sacramento or Fresno), although during the peak months, it might increase total *indoor* water use by 40%. On the other hand, if we consider water usage by the energy supply as well as the energy use side, between one-half and one-fifth of the water used by evaporative coolers is balanced by the avoided water use at the power plant. Because water supply and price issues are extremely localized in California, decisions about the seriousness of evaporative cooler water consumption should be made at the local level.

The market and engineer surveys indicate that the biggest barriers to the adoption of evaporative coolers are the lack of knowledge of the technology, the instability of the industry, and the absence of design guidelines. Although our analyses have shown that IDECs are much more reliable in meeting California cooling loads, particularly in Central Valley locations, the market survey indicates that primarily DECs are being installed to date. Because of their lower performance and cooling capacities, it is not surprising that builders have invariably installed them in conjunction with standard air-conditioners. The smallness of the manufacturers results in frequent changes or unavailability of models, absence of product improvement, and poor information dissemination. The survey of engineers showed overwhelmingly positive experiences with evaporative coolers, but listed the major problems as the poor public image of "swamp coolers" and the the lack of design information for engineers and contractors.

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DISCLAIMER

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APPENDIX A: REVISED ELECTRICITY CONSUMPTION TABLES

(see Huang et al. 1991 for explanation of earlier versions)

Table A.1 Comparison of Air-Conditioning and Evaporative Cooler Consumption for Current Construction Houses in California Climate Zones and Other Locations

(Stand-alone Evaporative Cooling Systems)

		A/C				Direct (DEC)				2-stage (IDEC)			
Location	Cool. Load (MBtu)	Cool (kWh)	Fan (kWh)	Total (kWh)	Cool. Hrs	Pump (kWh)	Fan (kWh)	Total (kWh)	Under Cooled Hrs	Pump (kWh)	Fan (kWh)	Total (kWh)	Under Cooled Hrs
1 (Arcata) *	0.01	0	0	**0**	1	0	0	**0**	0	0	0	**0**	0
2 (Santa Rosa)	6.50	1096	25	**1122**	991	41	187	**229**	69	45	308	**354**	0
3 (Oakland)	0.18	41	0	**42**	49	0	2	**2**	0	0	3	**4**	0
4 (Sunnyvale)	1.59	269	5	**275**	300	5	24	**30**	6	6	41	**47**	0
5 (Santa Maria)	0.40	96	1	**98**	95	1	8	**10**	0	2	14	**16**	0
6 (Long Beach)	5.16	821	18	**840**	903	19	88	**108**	8	20	143	**163**	0
7 (San Diego)	3.20	530	11	**541**	652	6	28	**35**	5	6	47	**54**	0
8 (El Toro)	3.76	666	13	**680**	800	17	78	**95**	5	18	127	**145**	0
9 (Pasadena)	5.53	945	20	**965**	1063	28	128	**157**	22	30	210	**240**	0
10 (Riverside)	9.05	1533	35	**1569**	1539	52	234	**286**	74	56	382	**439**	0
11 (Red Bluff)	13.22	2183	53	**2236**	1978	82	370	**452**	192	92	614	**707**	0
12 (Sacramento)	5.87	991	22	**1013**	954	40	183	**224**	66	45	304	**349**	1
13 (Fresno)	12.94	2128	51	**2179**	1999	82	368	**450**	155	90	607	**697**	0
14 (China Lake)	17.25	3013	72	**3085**	2826	108	484	**592**	192	115	785	**900**	0
15 (El Centro)	29.43	4783	121	**4904**	3934	214	962	**1177**	1004	278	1723	**2002**	186
16 (Mt. Shasta)	3.55	716	13	**729**	639	17	77	**94**	1	17	121	**139**	0
Fort Worth TX	21.42	3238	70	**3309**	2873	177	796	**973**	949	263	1539	**1802**	343
Miami FL	37.18	5506	117	**5624**	5454	318	1424	**1742**	1469	469	2761	**3230**	767
Phoenix AZ	28.02	4408	107	**4515**	3634	207	927	**1134**	977	272	1673	**1945**	162

* No cooling required in Climate Zone 1 (Arcata).

APPENDIX A: REVISED ELECTRICITY CONSUMPTION TABLES (cont.)

(see Huang et al. 1991 for explanation of earlier versions)

Table A.2 Comparison of Air-Conditioning and Evaporative Cooler Consumption for Pre-1973 Construction Houses in California Climate Zones and Other Locations (Stand-alone Evaporative Cooling Systems)

Location	Cool. Load (MBtu)	A/C Cool (kWh)	A/C Fan (kWh)	A/C Total (kWh)	A/C Cool. Hrs	Direct (DEC) Pump (kWh)	Direct (DEC) Fan (kWh)	Direct (DEC) Total (kWh)	Direct (DEC) Under Cooled Hrs	2-stage (IDEC) Pump (kWh)	2-stage (IDEC) Fan (kWh)	2-stage (IDEC) Total (kWh)	2-stage (IDEC) Under Cooled Hrs
1 (Arcata) *	0.06	0	0	**0**	0	0	0	**0**	0	0	1	**0**	0
2 (Santa Rosa)	19.20	2378	78	**2457**	1264	77	347	**425**	222	92	596	**689**	28
3 (Oakland)	0.99	138	3	**141**	124	2	10	**12**	0	2	16	**19**	0
4 (Sunnyvale)	4.56	578	16	**595**	451	13	59	**72**	17	14	99	**114**	2
5 (Santa Maria)	1.69	245	6	**252**	185	6	26	**32**	3	6	42	**49**	0
6 (Long Beach)	11.84	1441	45	**1486**	1028	41	186	**227**	32	44	302	**347**	5
7 (San Diego)	6.17	775	22	**797**	654	15	69	**84**	8	16	112	**128**	1
8 (El Toro)	13.17	1608	50	**1658**	1130	49	221	**270**	77	55	367	**422**	4
9 (Pasadena)	16.88	2057	65	**2123**	1344	66	297	**363**	108	74	496	**571**	15
10 (Riverside)	26.13	3207	107	**3315**	1774	101	452	**553**	252	118	770	**889**	43
11 (Red Bluff)	30.07	4089	124	**4213**	1912	113	665	**778**	383	140	1165	**1305**	84
12 (Sacramento)	20.16	2457	80	**2537**	1324	82	371	**454**	269	100	642	**742**	34
13 (Fresno)	32.82	4033	134	**4167**	2054	128	575	**703**	464	160	1011	**1171**	80
14 (China Lake)	33.44	4679	143	**4822**	2893	148	664	**812**	426	168	1109	**1278**	3
15 (El Centro)	52.40	7191	217	**7409**	3947	249	1118	**1367**	1269	343	2072	**2416**	422
16 (Mt. Shasta)	4.94	842	19	**861**	642	22	99	**121**	6	22	157	**179**	0
Fort Worth TX	37.37	4647	129	**4776**	2692	194	869	**1063**	1148	306	1748	**2054**	773
Miami FL	55.68	6851	182	**7033**	4807	331	1484	**1815**	1719	512	2955	**3467**	1172
Phoenix AZ	61.67	8320	247	**8568**	3600	245	1442	**1687**	1295	355	2758	**3114**	616

* No cooling required in Climate Zone 1 (Arcata).

Table A.3 Prototypical Building Characteristics

Location	R-values Ceiling	Wall	Found.	Windows Panes	Area *	S.C. *	Infiltration ELF *
Old Houses							
CTZ 1 through 13	0	0	0	1	14%	.66	.007
CTZ 14,15, and 16	19	0	0	1	14%	.66	.007
Phoenix	0	0	0	1	12%	.66	.007
Fort Worth	11	0	0	1	14%	.66	.007
Miami	0	0	0	1	12%	.66	.007
Current Houses							
CTZ 1	30	19	5 2 ft.	2	14%	.66	.003
CTZ 2,3,4,5,6	30	19	5 2 ft.	2	14%	.66	.005
CTZ 7	30	11	5 2 ft.	2	14%	.66	.005
CTZ 8,9,10,11,12,13	30	19	5 2 ft.	2	14%	.36	.005
CTZ 14,15	38	19	5 2 ft.	2	14%	.15	.003
CTZ 16	38	19	5 2 ft.	2	14%	.66	.003
Phoenix	22	11	5 2 ft.	2	12%	.15	.005
Fort Worth	30	11	0	1	12%	.36	.005
Miami	19	7	0	1	12%	.36	.005

* Window area is in percent of floor area; S.C. = Shading coefficient; ELF = Effective-Leakage-Fraction used in the Sherman-Grimsrud model to describe the tightness of a house to infiltration (Sherman and Grimsrud 1980).

APPENDIX B: SURVEY ON THE CURRENT STATUS OF EVAPORATIVE COOLER TECHNOLOGY

What is your occupation ?

- ☐ Engineer
- ☐ Contractor
- ☐ Builder
- ☐ HVAC manufacturer
- ☐ Building owner or operator
- ☐ Utility representative

What kinds of experience have you had with Evaporative Coolers (EC) ?

- ☐ Design
- ☐ Installation
- ☐ Operations

What kinds of EC did you use ?

- ☐ Direct (swamp-coolers)
- ☐ Indirect
- ☐ Two-stage (indirect-direct)
- ☐ Others (please describe)

What kinds of HVAC applications were these EC units used in ?

- ☐ Residential
- ☐ Commercial
- ☐ Stand-alone units
- ☐ Attached units, i.e., pre-coolers to conventional HVAC systems

What factors influenced your decision to use EC ?

- ☐ First costs
- ☐ Operating costs
- ☐ Health
- ☐ Previous experience
- ☐ Exploring new technologies

How were the comfort conditions maintained by the EC unit ?

Noise	☐ Satisfactory	☐ Unsatisfactory
Air movement	☐ Satisfactory	☐ Unsatisfactory
Temperatures	☐ Satisfactory	☐ Unsatisfactory
Humidity	☐ Satisfactory	☐ Unsatisfactory

Other comments (please describe)

What benefits did you find in the use of EC ?

- ☐ Savings in first costs
- ☐ Improved indoor comfort
- ☐ Savings in operating costs
- ☐ Improved indoor air quality

What problems were encountered in installation EC's (please ignore if not applicable).

What problems were encountered in using EC's (please ignore if not applicable).

Please describe briefly any additional unexpected problems or benefits that you encountered in either installing or operating EC's :

What is your overall assessment of your experience with EC ?

- ☐ Extremely favorable
- ☐ Favorable
- ☐ Neutral
- ☐ Problematic
- ☐ Disastrous

Please rank from 1 to 5 (with 1 being most significant) those factors that, in your estimation, are the most important barriers against the widespread usage of EC.

_____ poor public image due to earlier swamp cooler technology
_____ unfamiliarity of EC technology among engineers
_____ unfamiliarity of EC technology among building owners
_____ unfamiliarity of EC technology among general public
_____ lack of design information on EC's for engineers and contractors
_____ unreliable or poor performance
_____ high first costs
_____ high installation costs due to unfamiliarity with technology
_____ high installation costs due to needed changes in building shell
_____ poor comfort conditions (higher temperatures and humidity levels)
_____ noise and air movement

APPENDIX C: SIMULATION RESULTS FOR EVAPORATIVE COOLERS OPERATED AT A LOWER THERMOSTAT SETTING

The upper temperature boundary of the human comfort zone follows a sloped Effective Temperature (ET*) line that results in dry bulb temperatures that are several degrees lower at higher humidity levels. Because evaporative coolers introduce moisture into the air, a typical thermostat setting of 78 F can result in indoor conditions that fall outside any of the comfort zones referenced in this study. It should be clear that these conditions are the result of the theromstatic control, and not the cooling capacity of the evaporative cooler.

The following plots and table show the results when the DEC and IDEC are operated at a two degrees cooler setting (76 F) to compensate for the increased humidity. The plots should be compared to Figures 8 and 9, and the table to the numbers for Pasadena and Fresno in Table A.1.

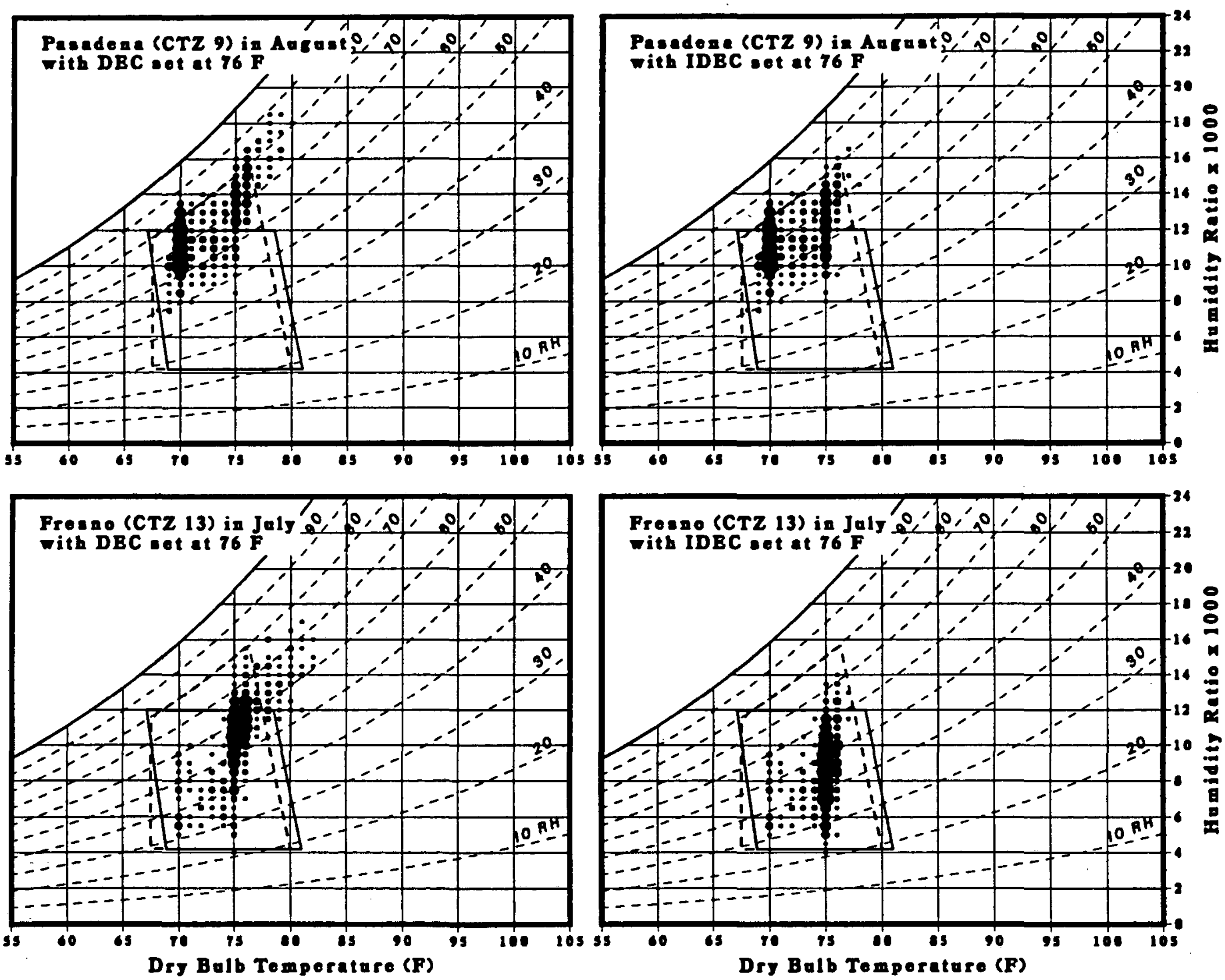

Table C.1 Evaporative Cooler Electricity Consumption for Current Construction Houses Operated at 76 F

Location	Cool. Load (MBtu)	Direct (DEC) Pump (kWh)	Direct (DEC) Fan (kWh)	Direct (DEC) Total (kWh)	2-stage (IDEC) Pump (kWh)	2-stage (IDEC) Fan (kWh)	2-stage (IDEC) Total (kWh)
9 (Pasadena)	5.53	44	197	**240**	49	329	**378**
13 (Fresno)	12.94	105	471	**577**	123	798	**920**

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