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POTENTIAL OF SOLAR COOLING SYSTEMS FOR PEAK DEMAND REDUCTION

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ABSTRACT

We investigated the technical feasibility of solar cooling for peak demand reduction using a building energy simulation program (DOE2.1D). The system studied was an absorption cooling system with a thermal coefficient of performance of 0.8 driven by a solar collector system with an efficiency of 50% with no thermal storage. The analysis for three different climates showed that, on the day with peak cooling load, about 17% of the peak load could be met satisfactorily with the solar-assisted cooling system without any thermal storage. A performance availability analysis indicated that the solar cooling system should be designed for lower amounts of available solar resources that coincide with the hours during which peak demand reduction is required. The analysis indicated that in dry climates, direct-normal concentrating collectors work well for solar cooling; however, in humid climates, collectors that absorb diffuse radiation work better.

INTRODUCTION

The concept of using solar energy to cool buildings is appealing because the cooling load is roughly in phase with solar energy availability. In addition, when solar cooling is combined with solar heating and hot water, the year-round usage is increased, which could decrease the amortization cost and improve the cost effectiveness of the solar systems (Löf and Tybout, 1974). In a solar cooling system, solar collectors (such as flat plates, parabolic troughs, evacuated tubes, etc.) provide thermal energy to drive cooling equipment (such as a desiccant air conditioner, absorption chiller, or Rankine vapor-compression chiller). In solar hybrid systems, gas-fired cooling systems or electricity-driven equipment is used in addition to solar cooling systems. A large potential market exists for solar cooling in most parts of the United States, but because of their high first-costs, existing solar cooling systems cannot compete with electricity-driven or gas-fired air conditioning systems. Payback periods for solar cooling equipment are more than 20 years (Warren, 1993; Pesaran and Wipke, 1994) because of low fossil fuel prices.

In the early 1980s, there were several field tests of solar absorption and Rankine-vapor compression refrigeration systems (Wahlig, 1993). These tests identified shortcomings of the early systems and indicated the need for further research and development (R&D), particularly in improving the integration of the solar subsystem and cooling equipment. American Solar King introduced and field-tested a solar desiccant cooling system during 1984–1985; however, because of high first-costs, the solar feature was not offered in later years. An excellent overview of the early research and development in solar cooling is provided in Löf (1993). Currently, there are no suppliers of integrated solar cooling systems. Instead, cooling equipment and solar collector subsystems must be acquired separately and then integrated. In the last few years, there have been only two solar cooling field applications in the United States. In Florida, a hybrid solar desiccant cooling system was installed in a fast-food restaurant to provide supplemental cooling (West and Iver, 1995). The system used a solid-desiccant dehumidifier wheel containing lithium chloride, which was regenerated with heat supplied by an array of evacuated-tube solar collectors and waste heat from condensers of a conventional air-conditioning system. The hybrid system improved the comfort in the restaurant because of lower humidity achieved by adding the desiccant dehumidifier. The second application is in California, where an absorption refrigeration system integrated with solar collectors provide cooling to a small office building (Bergquam, 1993). Initially, flat-plate collectors were used to provide heat for driving the lithium bromide absorption chiller; now, parabolic troughs are used for this purpose.

Until recently, most of the solar cooling projects funded by government agencies focused on systems for broad long-term market applications such as residential air conditioning. Although these efforts resulted in improved performance and reliability, no significant cost reduction and market adaptation were achieved, and as a result, R&D funding deteriorated. In the past few years, after several meetings between government and solar industry representatives, the approach and strategy for solar cooling programs have shifted. The major recommendation from these meetings was that, in the near-term (less than 5 years), solar cooling programs should support activities that can produce systems suitable for high-value niche markets such as remote applications or areas with a high cost of energy. One of the high-value niche markets proposed was the use of solar cooling to reduce summer peak electricity requirements in commercial buildings. The rationale for this strategy is that peak demand charges are high, and electric utilities are interested in reducing future generation and transmission capacity requirements, especially when the capacity expansion is required just to handle peak loads with a short duration; space cooling is such a load. Specifically, space cooling and air handling systems account for 16% of annual U.S. electricity use (418 billion kilowatt-hours per year [kWh/yr]), but 43% of summer peak demand (210 gigawatts) (Houghton et al., 1992, p. 25). Because of this disproportionately large peak demand requirement relative to base energy consumption, the cost of electric capacity to cover peak demand because of space cooling is more difficult for utilities to recover than for other end uses in which electric demand is more evenly distributed.

The objective of this study is to explore and analyze the justification and technical feasibility for peak reduction using solar cooling. The analysis includes an evaluation of climates and utility peak-load characteristics, and modeling of peak-load reduction using solar cooling in an office building for three locations.

NEAR-TERM TARGET MARKETS

Implementing solar cooling technologies faces significant market barriers which include:

- Low conventional energy costs
- High first-cost for the solar cooling systems
- Lack of a track record for performance and reliability
- Lack of a cohesive industry
- Resistance by the heating, ventilating, and air-conditioning industry to adopt new technologies in place of widely used existing technologies.

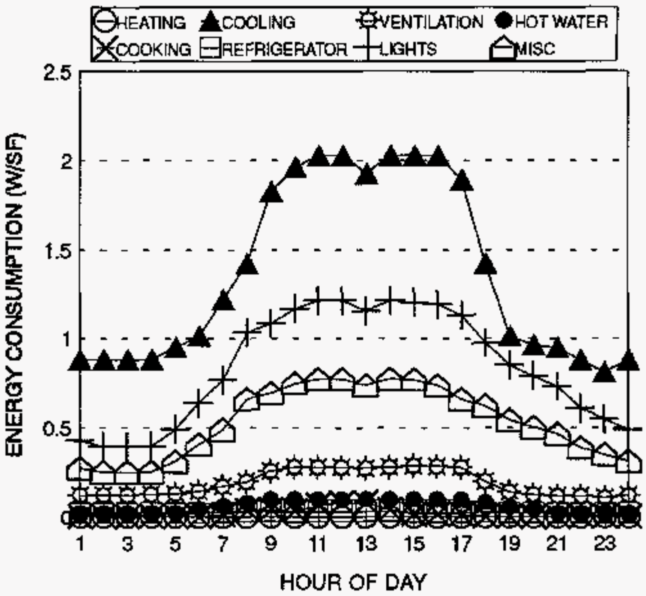

FIGURE 1. SUMMER PEAK DAY HOURLY LOADS FOR A SMALL OFFICE BUILDING (REGIONAL ECONOMIC RESEARCH INC., 1990, COMMEND SIMULATIONS)

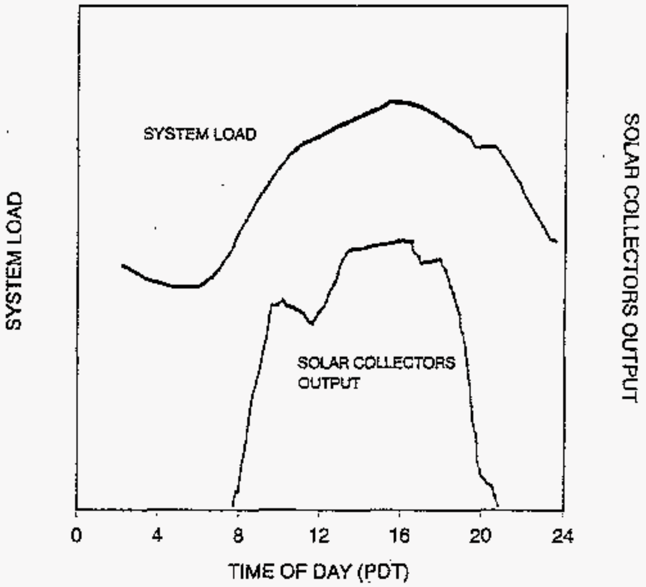

FIGURE 2. SUMMER ELECTRICITY LOAD PROFILE AND SOLAR COLLECTOR OUTPUT (SOLAR DATA FOR SAN RAMON, CA; SOURCE—PACIFIC GAS & ELECTRIC R&D CENTER)

To achieve long-term success in light of these issues, solar cooling must first establish its reliability and cost-effectiveness in some niche markets. As noted above, one possible market for solar-driven technologies is to reduce the peak electric demand generated by space cooling loads in commercial buildings. The reason, as shown in Figure 1, is that peak demand in many commercial buildings occurs between 9 a.m. and 4 p.m. because of space cooling loads. This peak approximately coincides with the solar resource, which is illustrated later in the Results and Discussion section for a commercial office building. Furthermore, other data (e.g., see Figure 2) indicate that the solar resource is coincident with the utility summer peak load. Thus, in warmer climates, an opportunity exists to use solar-driven space cooling to reduce peak demand. Adopting such a peak-reduction strategy would yield the following benefits to a utility:

- Reduced expense for conventional generation and distribution capacity
- Extended transformer life (because of reduced critical hours)

- Reduced transmission energy losses (I^2R, where I is current and R is resistance)
- Increased system reliability (because of reduced thermal overloading)
- Reduced capital costs (because of smaller lines and transformers)
- Avoided costs of producing expensive peak energy.

As a result, some electric utilities are willing to provide incentives or subsidize activities that can reduce peak load capacity. For example, Sacramento Municipal Utility District provides a rebate of $600 for each ton of cooling that can be reduced from the peak cooling load.

Solar cooling also has some other benefits:

- Reduced energy consumption
- Reduced use of chlorofluorocarbons, which contribute to the depletion of the Earth's ozone layer
- Reduced pollution emissions from using less fossil or nuclear fuels.

A number of factors should be considered to determine the viability of various locations for peak reduction with solar cooling. For this analysis, we included these parameters:

- Peak cooling load
- Solar resource
- Climate conditions, including humidity
- Utility summer versus winter peak demand
- Utility rates
- Cost and availability of piped natural gas
- Building type

In any further analysis, peak-reducing technology costs (cooling equipment and solar-collector array) and life-cycle cost should be considered.

We tabulated utility data and climate conditions for 30 major cities. Tables A-1 and A-2 contain various utility data including summer and winter peak, gas prices, and electricity rate structure, and Table A-3 contains climatic data for the same cities. To compare the data and select cities with more desirable climate-utility characteristics for solar cooling, we first ranked the cities by devising a climate score which is equal to *peak-month cooling degree days* multiplied by *peak-month available solar resources.* This score identifies cities that have the highest solar resources and highest cooling requirement in a month, and Table 1 presents cities ranked by climate score.

Because it is more likely that summer-peaking utilities give better incentives and reduced rates for peak-reducing strategies, we multiplied the climate score by the ratio of utility summer-peak kW to winter-peak kW to yield a climate-utility score. Cities ranked by climate-utility score are also presented in Table 1. In most locations, the price of natural gas is lower than the cost of delivered solar energy, and thus, solar cooling cannot compete with gas cooling. Therefore, solar cooling may be implemented most easily in markets and regions where natural gas pipelines are not readily available.

TABLE 1. MAJOR LOCATION RANKINGS BY CLIMATE AND UTILITY PEAK CHARACTERISTICS

Ranked by Climate Score		Ranked by Climate-Utility Score	
Location	Climate Score	Location	Climate-Utility Score
Phoenix	719	Las Vegas	937
Las Vegas	682	Phoenix	927
Fort Worth	528	Memphis	711
Tucson	512	San Antonio	674
Fresno	476	Tucson	672
San Antonio	450	Kansas City	623
El Paso	434	Fresno	612
Miami	414	Fort Worth	609
Tulsa	412	Tulsa	600
Memphis	392	Wichita	555
Kansas City	386	New Orleans	546
Wichita	386	El Paso	535
Tallaha/Orl	377	Miami	530
Little Rock	376	Mobile	508
Honolulu	372	Houston	496
Houston	370	Little Rock	467
Mobile	346	Omaha	435
Jackson	341	Sacramento	428
Albuquerque	325	Jackson	424
Tampa	325	Charleston	413
New Orleans	323	Tampa	397
Charleston	322	Tallaha/Orl	391
Sacramento	319	Atlanta	385
Omaha	296	Albuquerque	381
Atlanta	262	Honolulu	372
Denver	185	Chicago	225
Boston	176	Boston	196
Chicago	171	Denver	185
Hilo	142	Hilo	142
Seattle	46	Seattle	46

Climate Score: (peak-month cooling degree days) × (peak-month available solar)

Climate-Utility Score: (Climate Score) × [utility (summer peak kW)/(winter peak kW)]

Based on the above considerations and rankings, we suggest that near-term U.S. solar-cooling programs should be aimed at "all-electric" markets in the southern, south-central, southwestern, and parts of the western United States.

For the following reasons, we believe that peak demand reduction using solar cooling is more suitable in the commercial building sector (rather than in the residential sector):

- Occupancy of most commercial buildings (such as offices) is coincident with the availability of solar resources. Residential peaks usually occur in late afternoon or early evening when solar resources are not high, and thus, storage is required.
- Many commercial buildings require year-round cooling, enhancing energy savings from solar cooling system.
- Commercial buildings are more likely to have an existing maintenance infrastructure, so they are more adaptable to new technologies.

The residential sector should eventually be explored because although residential space cooling is estimated at only 5.5% of national electricity consumption, it is responsible for an estimated 22.7% of the national summer peak load (Houghton et al., 1992, p. 25). Additionally, the number of households with air conditioning has increased by about 15% from 1984 to 1989 (Houghton et al., 1992, p. 28) and could continue at the same rate in the coming years.

TECHNICAL FEASIBILITY METHODOLOGY

We performed the analysis discussed below to demonstrate the technical feasibility of solar cooling for peak reduction. Figure 3 summarizes the flow chart for the methodology of the technical analysis. The analysis is based on using a building energy simulation program—for this study, the DOE2.1D program (version 014). External weather data are from typical meteorological year (TMY) data for the three locations analyzed. The simulations assumed that the building temperature is maintained at a constant 72°F for the entire year, with the humidity range within the comfort zone established by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

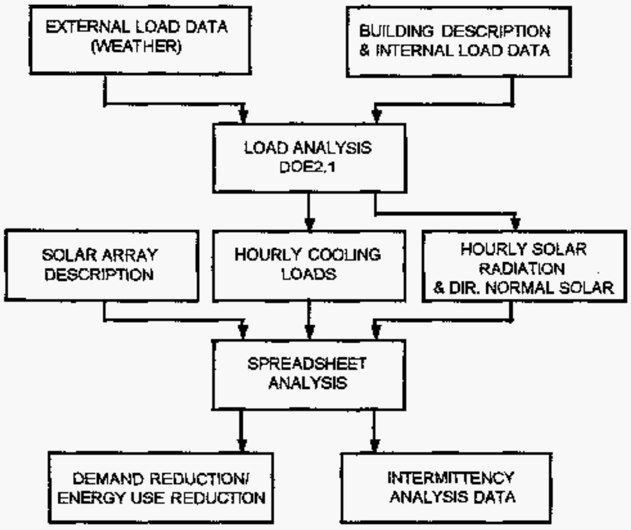

FIGURE 3. SIMULATION ANALYSIS METHODOLOGY

Building Selection

The occupancy, and therefore lighting and equipment schedule, in office buildings generally coincide with solar resources (see Figure 1). Single-floor buildings having 10,000–25,000 ft^2 of floor area constitute a major sector of commercial building stock (EIA, 1991). An average U.S. commercial building has about 14,000 ft^2. We selected a 20,600-ft^2, single-story office building for our analysis in this study. Table 2 provides the general building descriptions. The lighting, equipment, and occupancy schedules are similar to those recommended by Kaplan and Caner (1992) with more-conservative early evening ramp-downs (more like EPRI COMMEND end-use loads as shown in Figure 1). Weekend equipment schedules were not included, so if a peak cooling load occurred on a TMY weekend, it would not be missed in the analysis.

TABLE 2. DESCRIPTION AND CHARACTERISTICS OF BUILDING THAT WAS SIMULATED

General Building Description

- Small commercial office building
- Conditioned space of 20,569 ft^2
- Square geometry
- Single floor
- Five conditioned zones, 11.5-ft ceiling
    - Interior core zone, 12,829 ft^2
    - North perimeter zone, 1935 ft^2 (grouped as a core zone)
    - South perimeter zone, 1935 ft^2
    - West perimeter zone, 1935 ft^2
    - East perimeter zone, 1935 ft^2
- No plenum

Input Related to Internal Gains

- Lighting—2 W/ft^2, 100% on 7 a.m. to 5 p.m., 75% on 5 p.m. to 6 p.m., 50% on 6 p.m. to 11 p.m.
- Equipment—0.6 W/ft^2, 100% on 8 a.m. to 5 p.m., 50% on 5 p.m. to 11 p.m.
- Occupancy—250 ft^2/person, 100% occupancy 8 a.m. to noon, 1 p.m. to 5 p.m.
- No thermostat setbacks/setups
- No weekend end-use schedules

Input Related to External Gains

Facade Materials:

- Brick face walls with R7 insulation
- 29% glazed with double-pane, shading coefficient = 0.55
- Built-up roof with R11 insulation

Infiltration:

- Air change per hour = 0.5 (20 outside air CFM/person)
- Independent of wind speed

A heavier and better-than-average insulated building shell was chosen to account for thermal load lag because of mass and to reduce the amplitude of peaks because of external gains. This is a conservative approach, because it is more difficult for a solar cooling system to reduce peak. For example, during a period of cloudiness after several hours of high solar incidence, a higher-mass building shell would remain warm for a longer period of time than would a lower-mass building shell. Thus, the heavier shell could cause a greater occurrence of lower solar gains coincident with higher cooling loads (resulting in more undercooled hours for the building). In addition, the peak cooling load should be lower for a high thermal mass, well-insulated building than for a low thermal mass, poorly insulated building because of thermal storage and resistance effects.

Solar Cooling System Selection

For the purpose of this study, we selected an absorption chiller with a moderate performance (average thermal coefficient of performance [COP] of 0.8). The thermal COP of 0.8 for the absorption chiller represents a double-effect lithium bromide system that requires 120°C output for generation of the absorption fluid. Usually, the thermal COP of such an absorption chiller varies between 0.7 and 1.1, depending on the operating temperatures.

We selected high-temperature solar collectors with average collector efficiency of 50%. Two types of collector were considered:

- Single-axis tracking trough (N-S axis mount), with axis tilt optimized for summertime direct-normal collection

- Fixed integrated compound parabolic concentrator (ICPC) facing west with 45° tilt.

A 50% collector efficiency is obtainable from either a trough or ICPC array with an output temperature of 130°C (O'Gallagher et al., 1991). The solar collector system is assumed to have no storage capacity.

The chiller size is selected based on reducing 17% of the peak cooling load, and the array size is selected based on the solar resource coincident with the annual peak-cooling-load hour. These sizes are shown in Table 3. A better array-sizing scheme could be developed from the load/coincident solar plots presented in the Availability Analysis section.

TABLE 3. SOLAR COOLING SYSTEM SIZING FOR THREE LOCATIONS AND TWO COLLECTOR TYPES

	Solar-Array Size (ft^2)		Peak-Reduction Capacity (tons)		Maximum System Capacity (tons)	
Location	Trough	ICPC	Trough	ICPC	Trough	ICPC
Denver, CO	540	—	5	—	5	—
Miami, FL	1290	780	6	6	10	6
Phoenix, AZ	980	680	6.5	6.5	8	7.5

For this preliminary analysis, we assumed that the solar collector would deliver constant temperature throughout the day, and thus, the thermal COP was not affected by operating temperature. For the preliminary level of analysis conducted here, the results of the study could be applied to high-temperature, desiccant-assisted, evaporative cooling systems as well.

RESULTS AND DISCUSSION OF ANALYSIS

The analysis was conducted to answer a number of questions for various climates:

- What does the building cooling-load profile look like on a peak day?
- How much solar peak-reducing capacity is appropriate?
- What is the hourly performance of a solar cooling system designed for peak reduction on a peak day?
- What happens to peak reduction on a high-load day when clouds appear and there is no storage?
- How often do very high load and low solar-incidence hours coincide?
- How much solar resource is generally available during the peak load hours?
- What type of collectors should be used?

Peak Reduction and Energy Savings Results

Peak cooling-load reduction analysis was performed for Phoenix (dry climate with a long cooling season), Miami (humid climate with a long cooling season), and Denver (dry climate with a short cooling season). Figure 4 compares the annual peak-hour cooling loads for the 20,600-ft^2 office building and incident solar radiation on a west-facing 45°-tilted surface in the above locations.

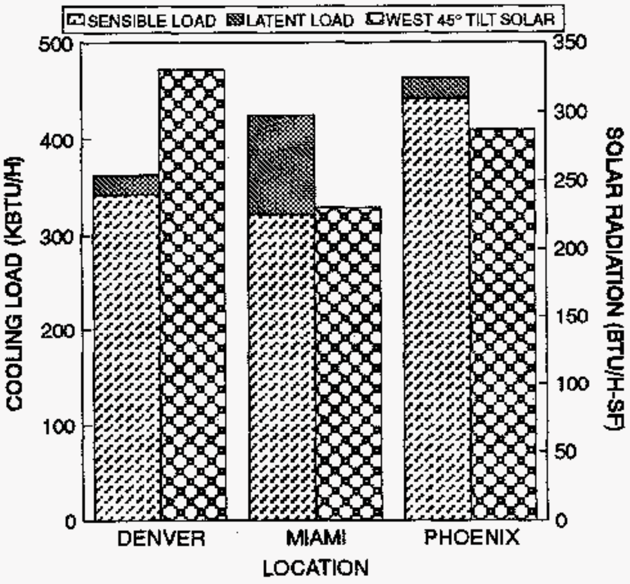

FIGURE 4. ANNUAL PEAK HOUR COOLING LOADS AND INCIDENT SOLAR RADIATION (20,600-FT^2 BUILDING; PHOENIX, NOT BEING ON DAYLIGHT SAVINGS TIME, HAS LESS SOLAR THAN DENVER)

Although Miami and Phoenix have similar levels of total cooling load, Miami has a greater latent load (much higher ambient humidity). Miami's higher humidity is combined with a lower solar resource than Denver or Phoenix. During the hour of highest cooling load, Denver has greater solar resources than Phoenix.

Figures 5 through 7 depict the hourly peak cooling load on the annual peak day and the amount that this peak load can be reduced in the three locations by a no-storage solar cooling system with a given array of tracking trough collectors. The trough collectors use only direct-normal solar radiation. The collector area shown in each figure is the amount required to shave 17% of the peak load—or 5, 6, and 6.5 tons in Denver, Miami, and Phoenix, respectively. The tonnages are the maximum cooling capacity the solar array would provide during annual peak hour. Note that for a conventional cooling system with a 3.5 electric COP, 1 ton of cooling would require about 1 kW of electricity; so the added solar cooling system would replace about 15–20 kW of peak electricity, assuming 10% for parasitic power for the solar systems. For all locations, the cooling load on the annual peak day is reduced so that the 4 p.m. to 5 p.m. load with the solar cooling system is the same as the 11 a.m. to noon load without the solar cooling system. Additionally, the solar collector system allows reduced energy consumption from the conventional chiller throughout the entire day.

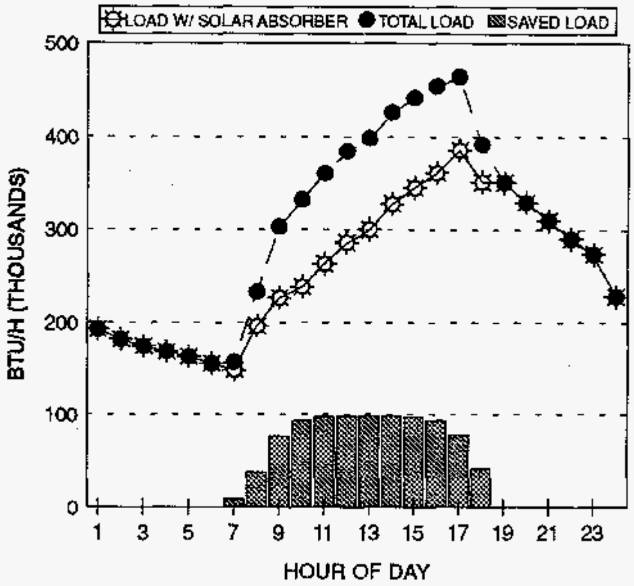

FIGURE 5. EFFECT OF SOLAR COOLING ON PEAK DAY LOADS FOR PHOENIX (TMY AUG.1; TROUGH COLLECTOR AREA = 980 FT^2; CAPACITY = 8 TONS; HOUR 17 IS 5 P.M. MST)

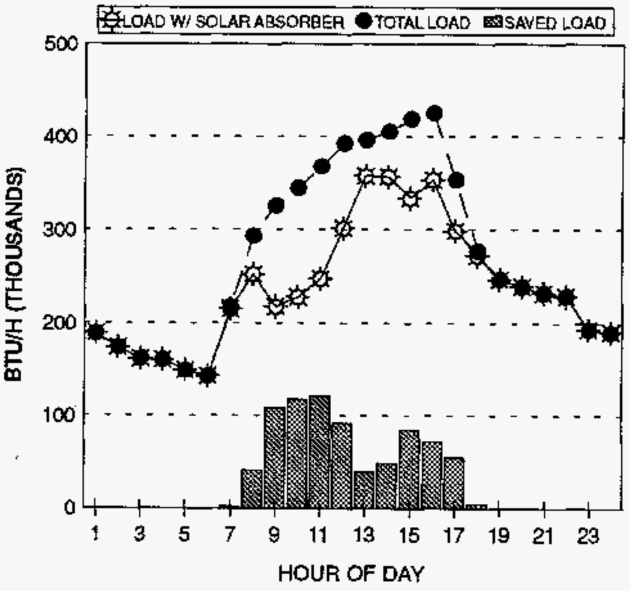

FIGURE 6. EFFECT OF SOLAR COOLING ON PEAK DAY LOADS FOR MIAMI (TMY AUG.11; TROUGH COLLECTOR AREA = 1290 FT^2; CAPACITY = 10 TONS; HOUR 16 IS 5 P.M. EDT)

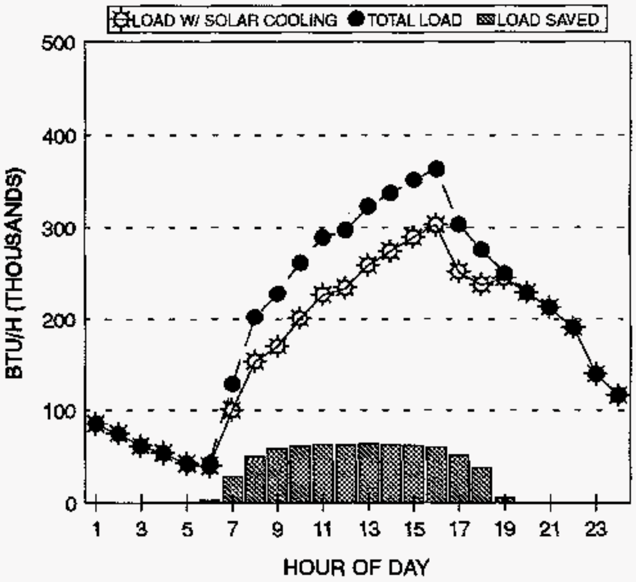

FIGURE 7. EFFECT OF SOLAR COOLING ON PEAK DAY LOADS FOR DENVER (TMY JULY 26; TROUGH COLLECTOR AREA = 540 FT^2; CAPACITY = 5 TONS; HOUR 16 IS 5 P.M. MDT)

Figures 8 and 9 are similar to the preceding figures except that an advanced fixed collector array is used for Miami and Phoenix. Such an advanced collector system may use evacuated-tube collectors with either flat-plate absorbers or integrated compound parabolic concentrators. This advanced collector array, which can use diffuse radiation as well as direct-normal radiation, faces west and is tilted at 45°. Again, the peak load is reduced so that the 4 p.m. to 5 p.m. peak with the solar cooling system is the same as the 11 a.m. to noon load without the solar cooling system.

Because the array is fixed, conventional chiller energy consumption cannot be reduced in the morning. However, the fixed array should have less initial construction costs and operating and maintenance costs than a tracking system.

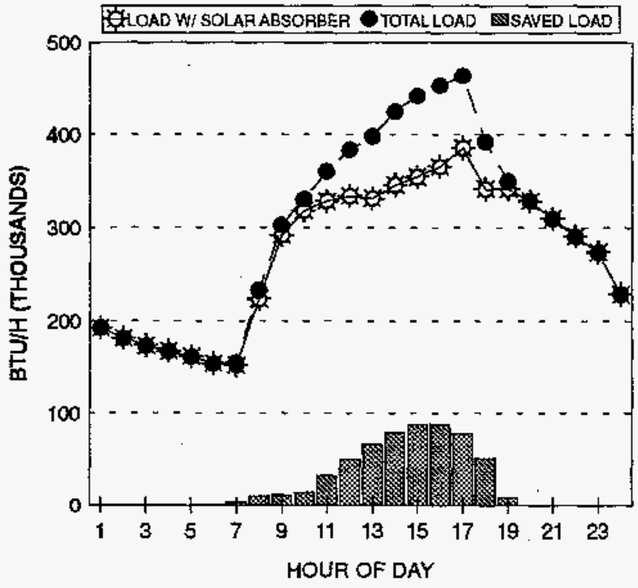

FIGURE 8. EFFECT OF SOLAR COOLING ON PEAK DAY LOADS FOR PHOENIX WITH ICPC COLLECTORS (TMY AUG. 1; ICPC COLLECTOR AREA = 680 FT^2; CAPACITY = 7.5 TONS; HOUR 17 IS 5 P.M. MST)

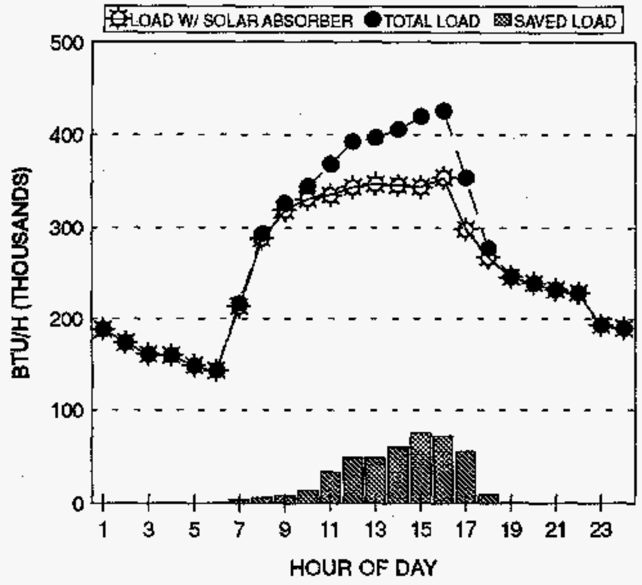

FIGURE 9. EFFECT OF SOLAR COOLING ON PEAK DAY LOADS FOR MIAMI WITH ICPC COLLECTORS (TMY AUG. 11; ICPC COLLECTOR AREA = 780 FT^2; CAPACITY = 6 TONS; HOUR 16 IS 5 P.M. EDT)

Availability Analysis

Figure 10 shows what happens to the cooling load during a worst-case hour (high cooling load and low solar incidence) in Denver. Here, the cooling load decreases when solar gains drop to zero (note hour 16). During this particular hour, the no-storage solar cooling system cannot provide any demand reduction. As long as this occurrence is rare, the building temperature could be allowed to float upward for 1 hour. Because the conventional chiller would be handling most of the cooling load, the temperature increase is expected to be of small enough magnitude and duration that occupant comfort would not be adversely affected. Further building energy simulations would help quantify the increase in building temperature above the thermostat setpoint during such an hour.

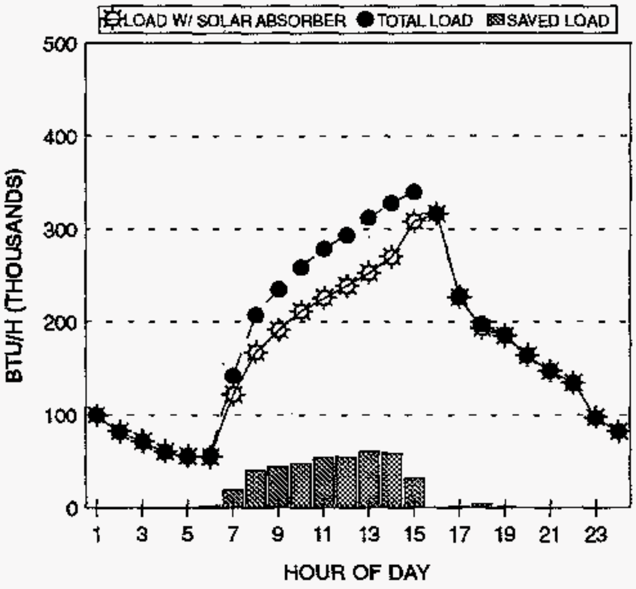

FIGURE 10. EFFECT OF SOLAR COOLING ON CLOUDY DAY LOADS FOR DENVER (TMY JULY 28; TROUGH COLLECTOR AREA = 540 FT^2; CAPACITY = 5 TONS; HOUR 16 IS 5 P.M. MDT)

To obtain information about the frequency of low solar radiation during hours of critically high loads, Figures 11 through 13 were developed for the three locations. In these figures, the hours of highest cooling load are presented along with the coincident solar radiation on a west-facing 45°-tilted surface and direct-normal solar radiation. The data (cooling load, solar radiation at hours that cooling load is within ±2 tons of annual peak cooling load) were sorted by increasing solar radiation on the west-facing 45°-tilted surface. In addition to describing the frequency of problem (low-solar) hours, the figures also indicate the amount and type (direct-normal or diffuse) of solar resource likely to be available during a high-load hour.

From these figures, a dry climate such as Phoenix or Denver generally has good solar resource (more than 250 Btu/h-ft^2 on the sloped surfaces, and more than 200 Btu/h-ft^2 for direct-normal) for reducing peak cooling loads for most of the high-load hours. These climates can probably use either tracking trough or advanced fixed collectors for peak reduction. However, Miami (Figure 12) does not have a consistent supply of direct-normal radiation and would require advanced fixed collectors or significant storage for successful, consistent peak reduction.

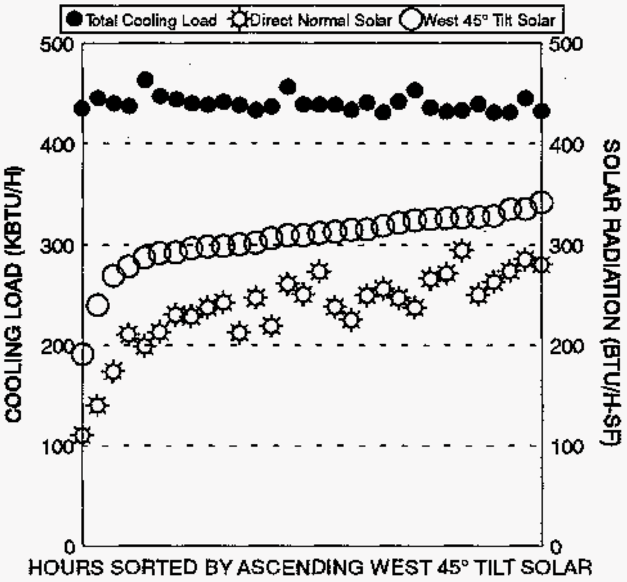

FIGURE 11. PEAK COOLING LOAD AND COINCIDENT SOLAR RESOURCES FOR PHOENIX (FOR HOURS WITH TOTAL COOLING LOAD > 430,000 BTU/H AND WITHIN 3 TONS OF ANNUAL PEAK-LOAD HOUR)

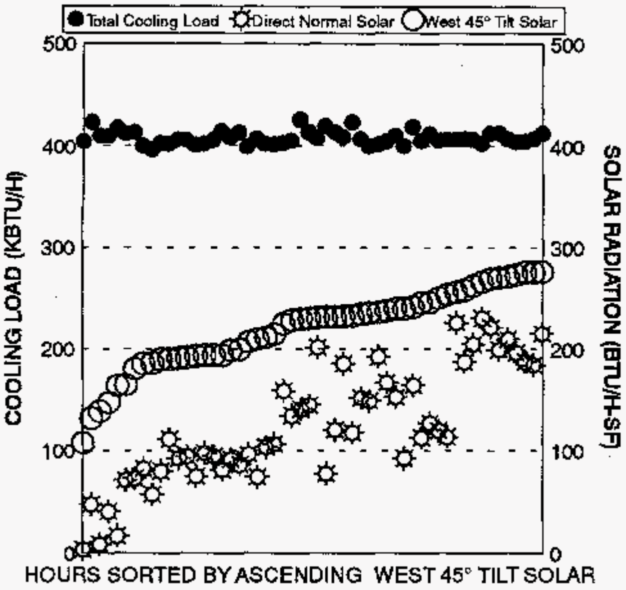

FIGURE 12. PEAK COOLING LOAD AND COINCIDENT SOLAR RESOURCES FOR MIAMI (FOR HOURS WITH TOTAL COOLING LOAD > 400,000 BTU/H AND WITHIN 2 TONS OF ANNUAL PEAK-LOAD HOUR)

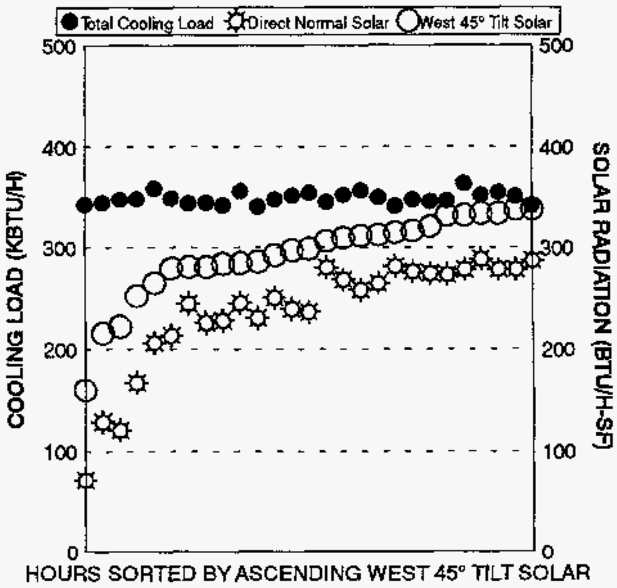

FIGURE 13. PEAK COOLING LOAD AND COINCIDENT SOLAR RESOURCES FOR DENVER (FOR HOURS WITH TOTAL COOLING LOAD > 340,000 BTU/H AND WITHIN 2 TONS OF ANNUAL PEAK-LOAD HOUR)

System Sizing Results

Table 3 summarizes the solar-array size, peak-reducing capacity, and maximum system capacity for the two collector types in the three locations (excluding advanced fixed collectors for Denver). For this table, *peak reducing capacity* is defined as the peak cooling-load reduction using the available solar radiation during the annual peak cooling hour; *maximum system capacity* is the amount of cooling load the solar array could support, given enough cooling equipment, during times when more solar energy is available. In this table, the collector area required for Denver is much less than that for Phoenix. This occurred because the coincident solar incidence for Denver during the annual peak-load hour was unusually high. If one of the lower solar hours were chosen from Figure 13, the Denver array size would increase, and the system would have higher reliability. Similarly, coincident solar radiation during the annual peak-load hour in Miami is unusually low, so that the array size could be reduced slightly without producing a large amount of undercooled hours in the building.

For further work, Figures 11 through 13 should be expanded to include the coincident solar radiation during every hour that the peak-reducing solar cooling system must perform. These figures could then be used to size collector arrays depending on the number of undercooled hours that can be tolerated.

CONCLUDING REMARKS

We found that solar-assisted cooling for peak demand reduction is technically feasible. Solar resources, peak loads of utility systems, and peak cooling loads of commercial office buildings generally coincide. Additionally, many utility rate structures are amenable to peak-shaving strategies.

The results of our preliminary analysis showed:

- About 17% of a building's peak load can be met satisfactorily with a solar-assisted cooling system without any thermal storage.
- The system should be designed for the lower amounts of solar resources that are coincident with the hours in which peak demand reduction will be required.
- In dry climates such as Phoenix or Denver, direct-normal concentrating collectors work well for solar cooling.
- In humid climates like Miami, collectors that absorb diffuse radiation will work better for solar cooling than concentrating collectors.

Recommendations for Further Work

The analysis should be continued for other climates, building types, and solar cooling technologies, and it should include the hourly performance of solar collectors and the cooling equipment. Impact of operating temperature on the performance of the collector and cooling system should be considered in determining the suitability of the system for peak electricity reductions. Other cooling systems, such as desiccant cooling systems, should be also considered. Additionally, a life-cycle cost analysis should be performed, and specific cities in which solar-assisted cooling is desirable should be identified.

The peak-load/coincident-solar-radiation plots should be expanded to include all of the hours in which solar cooling is required; array sizing requirements could be based on this information. Also, it may be desirable to revise some of the building parameters. It would be of value to study the temperature changes in the building during the infrequent occurrences of high cooling load and low incident solar radiation. Of interest too is the effect of building mass on peak cooling load. Finally, it may be preferable to use simulation software that employs 15-minute intervals and is equipped with detailed models of solar-driven systems. Such a model would be most useful in conjunction with 15-minute interval weather data.

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APPENDIX A

TABLE A-1. COMMERCIAL-SECTOR UTILITY DATA FOR VARIOUS METROPOLITAN AREAS

	Electric Utility	Summer Peak (MW)	Winter Peak (MW)	Ratio of Sum Pk/ Win Pk	Statewide Natural Gas ($/MMBtu)	Regional Propane ($/MMBtu)
Albuquerque	PSNM	1051	898	1.17	4.43	11.2
Atlanta	GP	13196	8977	1.47	5.76	9.6
Boston	BECO	2583	2318	1.11	6.35	11.7
Charleston	SCE&G	3222	2515	1.28	5.90	9.6
Chicago	CECO	17459	13295	1.31	4.64	7.8
Denver	PSCO	3568	3560	1.00	3.99	11.2
El Paso	EPEC	1098	891	1.23	4.14	9.6
Fort Worth	TU	18007	15620	1.15	4.14	9.6
Fresno	PG&E	19400	15100	1.28	5.12	11.2
Honolulu	HECI	none	1408	1.00	12.25	11.2
Houston	HL&P	12216	9125	1.34	4.14	9.6
Jackson	MP&L	2235	1794	1.25	4.48	9.6
Kansas City	KCP&L	2711	1680	1.61	4.53	7.8
Las Vegas	NP	2248	1636	1.37	4.38	11.2
Little Rock	AP&L	3691	2972	1.24	4.46	9.6
Memphis	MLG&W	2627	1450	1.81	4.80	9.6
Miami	FP&L	13754	10748	1.28	5.04	9.6
Mobile	AP	8663	5909	1.47	5.43	9.6
New Orleans	NOPSI	1159	686	1.69	5.25	9.6
Omaha	OPPD	1652	1121	1.47	3.86	7.8
Phoenix	APS, SRP	3680	2855	1.29	4.79	11.2
San Antonio	SAPSB	2741	1830	1.50	4.14	9.6
Sacramento	SMUD	2220	1656	1.34	5.12	11.2
Seattle	SCL	none	2060	1.00	4.14	11.2
Tallaha/Orl	TED	415	400	1.04	5.04	9.6
Tampa	TE	2630	2153	1.22	5.04	9.6
Tucson	TEP	1320	1006	1.31	4.79	11.2
Tulsa	PSCOO	3109	2134	1.46	3.92	9.6
Wichita	KG&E	1739	1210	1.44	3.36	7.8

Sources:

- Electric peaks from *Electric World 1992* (1991).
- For "Ratio of Sum Pk/Win Pk," a value of 1.00 is given where there is only a winter peak noted in the utility data. Statewide commercial sector natural gas prices are from *Natural Gas Annual 1990*, Vol. 1, DOE/Energy Information Administration (EIA), p. 64.
- Regional propane costs are from EIA's *Annual Energy Review 1991*, pp. 61–65. Propane costs are for 1986 and converted to 1989$ using price deflators from EIA, p. 321.
- *World Wide Natural Gas Industry Directory* has names and addresses for gas utilities, but no list of towns served.

TABLE A-2. COMMERCIAL-SECTOR ELECTRIC UTILITY SUMMER RATE DATA FOR VARIOUS METROPOLITAN AREAS

		General Service Rate		TOU or Other Rate	
City	Utility	$/kW	$/kWh	$/kW	$/kWh
Albuquerque	PSNM	0	0.112-0.084	0-4.0	0.152-0.040
Atlanta	GP	0		n/a	
Boston	BECO	18.87	0.029-0.006	18.87	0.029-0.006
Charleston	SCE&G	0		0	
Chicago	CECO	13.34		n/a	
Denver	PSCO	9.31	0.025	8.09	0.025
El Paso	EPEC	10		n/a	
Fort Worth	TU	6.74-1.00	0.056-0.006	n/a	n/a
Fresno	PG&E	4	0.097	15	0.111-0.057
Honolulu	HECI				
Houston	HL&P	0-2		n/a	
Jackson	MP&L	0	0.100-0.540	n/a	
Kansas City	KCP&L	7.85-5.66		n/a	
Las Vegas	NP				
Little Rock	AP&L	14.57	0.039	18.2	0.033
Memphis	MLG&W				
Miami	FP&L	6.25	0.019	0-6.25	0.038-0.014
Mobile	AP	4.54	0.044-0.024	4.54	n/a
New Orleans	NOPSI	0-6.8		n/a	
Omaha	OPPD				
Phoenix	APS	1.8	0.112-0.050	9.5	0.081
	SRP	3.7		5.5	
San Antonio	SAPSB				
Sacramento	SMUD				
Seattle	SCL				
Tallaha/Orl	TED				
Tampa	TE	6.75		6.75	
Tucson	TEP	0	0.125-0.082	n/a	n/a
Tulsa	PSCOO	6.5		6.5	
Wichita	KG&E				

Notes:

- TOU = time of use
- Utility billing data are from *Electric Rate Book*, Casazza, Schultz & Associates, Inc., 1990, and/or *Electric and Gas Rates for the Residential, Commercial, and Industrial Sectors: 1991*, Gas Research Institute. Because of different publication dates, these sources often show different rates for the same utility. Summer peak demand charges are based on 128-kW peak building load during the on-peak period. (Table not complete.)

TABLE A-3. CLIMATE DATA FOR VARIOUS SPACE COOLING LOCATIONS

City	Annual CDD	Month CDD	Peak Month	% Sun Peak Month	Peak/ Annual CDD	ASHRAE 1% Design d.b. °F	Elevation (ft)	Humidity Ratio (kg/kg)
Albuquerque	1254	428	Jul	76	0.34	96	5311	0.0046
Atlanta	1670	422	Jul	62	0.25	94	1010	0.0136
Boston	699	266	Jul	66	0.38	91	15	0.0134
Charleston	2093	481	Jul	67	0.23	94	3	0.0172
Chicago	740	252	Jul	68	0.34	94	590	0.0142
Denver	680	261	Jul	71	0.38	93	5283	0.0050
El Paso	2096	543	Jul	80	0.26	100	3918	0.0059
Fort Worth	2809	660	Jul	80	0.25	101	537	0.0118
Fresno	1769	496	Jul	96	0.28	102	328	0.0084
Hilo	3134	338	Aug	42	0.11	84	36	0.0150
Honolulu	4389	496	Aug	75	0.11	87	13	0.0144
Houston	2761	561	Jul	66	0.20	97	108	0.0154
Jackson	2290	524	Jul	65	0.23	97	310	0.0146
Kansas City	1681	508	Jul	76	0.30	99	791	0.0132
Las Vegas	3029	784	Jul	87	0.26	108	2178	0.0055
Little Rock	2045	530	Jul	71	0.26	99	257	0.0140
Memphis	2067	530	Jul	74	0.26	98	258	0.0152
Miami	4095	552	Aug	75	0.13	91	7	0.0168
Mobile	2643	533	Jul	65	0.20	95	211	0.0160
New Orleans	2686	530	Jul	61	0.20	93	4	0.0174
Omaha	1166	394	Jul	75	0.34	94	977	0.0152
Phoenix	3746	846	Jul	85	0.23	109	1112	0.0076
San Antonio	2983	608	Jul	74	0.20	99	788	0.0106
Sacramento	1198	329	Jul	97	0.27	101	17	0.0086
Seattle	184	70	Jul&Aug	65	0.38	84	20	0.0090
Tallaha/Orl	3401	539	Jul	70	0.16	94	55	0.0162
Tampa	3324	533	Jul&Aug	61	0.16	92	19	0.0176
Tucson	2840	657	Jul	78	0.23	104	2558	0.0064
Tulsa	2043	564	Jul	73	0.28	101	650	0.0118
Wichita	1684	508	Jul	76	0.30	101	1321	0.0117

Sources:

- Cooling Degree Days (CDD) and %Sun from *The Weather Almanac*, 5th ed., 1987.
- ASHRAE 1% Design dry-bulb temperature and elevation from *ASHRAE 1989 Fundamentals*, Chp. 24.
- Humidity ratio is based on ASHRAE 1% Design dry-bulb and mean coincident wet-bulb temperatures.