DEVELOPMENT OF COOLING DEGREE-HOUR WEATHER DATA FOR ASHRAE STANDARD 90.2-1993

Merle F. McBride, Ph.D.
Member ASHRAE

ABSTRACT

ASHRAE Standard 90.2-1993, "Energy-Efficient Design of New Low-Rise Residential Buildings," uses cooling degree-hours to base 74°F (CDH74) as a cooling weather variable. Because CDH74 was not readily available or published, it was developed for application with the standard. The basis for the development was a statistical autocorrelation technique derived by analyzing hourly data for a complete year from 101 locations. These 101 locations were weather stations in the United States. They accounted for almost all cooling climatic conditions in North America. They did not account for the most severe heating climatic conditions in North America, where the cooling impact is minimal. The theoretical development of the autocorrelation technique, the resulting terms derived from the analysis, and the extrapolation of those terms to extreme heating climatic locations are presented. Application of the procedure only requires knowledge of the monthly average dry-bulb temperature and the monthly average dry-bulb temperature standard deviation. This information is published by the National Oceanic and Atmospheric Administration in the United States and by the Atmospheric Environment Service in Canada. After the methodology was developed, it was used to create CDH74 for 3,349 locations in the United States and 1,847 locations in Canada. The resulting tables were published in the standard.

INTRODUCTION

ASHRAE Standard Project Committee (SPC) 90.2 was responsible for the development of ASHRAE Standard 90.2-1993, "Energy-Efficient Design of New Low-Rise Residential Buildings" (ASHRAE 1993). The SPC started the development by using the Departmetn of Engergy (DOE)-2.1A hourly simulation program to accurately predict the heating and cooling season envelope loads in multiple locations for each envelope component, including ceilings, walls, doors, and fenestration (LBL 1981). Heating and cooling season loads for foundations (basements, crawlspaces, and slabs) were developed using a two-dimensional finite-difference procedure with hourly weather data. All of these component loads were then used to develop a simplified heating and cooling load factor procedure that predicted envelope loads and evaluated trade-offs among envelope components (McBride et al. 1991). The load factors also were used in setting the envelope criteria (McBride 1991). The load factor procedure uses simple weather variables to correlate the heating and cooling season results of the hourly simulations. Heating results were correlated using heating degree-days to base 65°F (HDD65). Cooling results were correlated using cooling degree-hours to base 74°F (CDH74).

For the SPC development effort CDH74 was derived using hourly weather data tapes of test reference year (TRY) (Stamper 1977; NOAA 1976), California thermal zones (CTZ) (CEC 1988), and weather year for energy calculations (WYEC) (Crow 1981). However, for application of the standard, a list more extensive than 101 locations was desired. Hourly recordings of temperatures are only recorded at the first-order weather stations represented by the hourly weather data tapes. To expand the number of locations in Standard 90.2 required using alternate data. Monthly average dry-bulb temperatures and standard deviations are available for 3,349 locations in the United States and 1,847 locations in Canada. These data routinely are used to calculate heating and cooling degree-days to various base temperatures and were selected for development of CDH74.

BACKGROUND

Methods to calculate heating and cooling degree-days to any base temperature have been well established using monthly average dry-bulb temperatures and standard deviations (Thom 1952, 1954a, 1954b, 1954c). Typically, the monthly average temperatures and standard deviations are based on a 30-year period of record to ensure they are representative.

The first attempt in calculating CDH74 was to simply assume the dry-bulb temperatures within a month were uncorrelated and normally distributed. Then the

Merle F. McBride is with Owens-Corning Center of Science and Technology, Granville, Ohio.

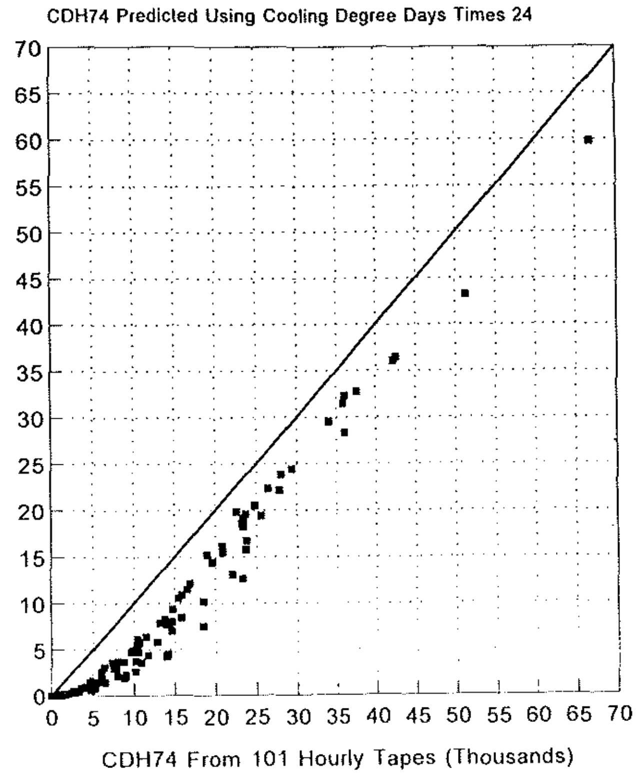

Figure 1 Comparisons of CDH74 calculated from CDD vs. hourly weather data tapes.

distribution was appropriately integrated and multiplied by 24 hours times the number of days to yield the monthly cooling degree-days. This procedure consistently underpredicted CDH74 for all 101 locations (Figure 1).

Failure of this simple approach led to discussions with Dr. Nathaniel B. Guttman (Guttman 1990). He suggested that estimates of the monthly standard deviations could be improved by accounting for the pairwise correlations among days. Further improvements would account for the autocorrelation of hourly dry-bulb temperatures. Autocorrelation is a measure of the time sequence dependence of successive values. It applies when successive values are not independent and random. Autocorrelation techniques are available that account for continuous variables such as hourly dry-bulb temperatures (Brooks and Carruthers 1953; Snedecor and Cochran 1967; Kenney 1939).

Currently, there is no universally accepted method available to calculate cooling degree-hours using monthly average dry-bulb temperatures and monthly average standard deviations.

OBJECTIVE

The objective of this research was to develop a procedure to calculate CDH74 using monthly average dry-bulb temperatures and monthly average standard deviations reported by NOAA (1951-1980) and AES (1951-1980) for 30-year periods of record.

TECHNICAL APPROACH

Multiple steps were required in developing a methodology to calculate CDH74. First, the specific autocorrelation coefficient for individual months and temperature intervals ($r_{i,j}$) had to be determined from hourly tapes. Second, a statistically average autocorrelation coefficient by month and temperature interval ($r_{AVGi,j}$) had to be determined. Third, $r_{AVGi,j}$ had to be tested against CDH74 from hourly weather data tapes. Fourth, $r_{AVGi,j}$ had to be extrapolated to account for all climates in the United States and Canada. Finally, $r_{AVGi,j}$ was used to calculate CDH74 for 3,349 locations in the United States and 1,847 locations in Canada. Each of these major steps will be presented.

Determination of Specific Autocorrelation Coefficients by Month and Temperature Interval

In equation form, the autocorrelation coefficient for the i^{th} month and the j^{th} temperature interval is

$$r_{i,j} = \frac{NH_i \cdot (\sigma_{N,i}/\sigma_{T,i})^2 - 1}{NH_i - 1} \quad (1)$$

where

$r_{i,j}$ = autocorrelation coefficient for the i^{th} month and the j^{th} temperature interval (dimensionless),
i = month,
j = temperature interval (10°F),
NH_i = number of hours in i^{th} month (h),
$\sigma_{N,i}$ = standard deviation of monthly average temperatures for the i^{th} month (°F) (derived from long-term data), and
$\sigma_{T,i}$ = standard deviation of temperatures within the i^{th} month (°F) (derived from hourly tapes).

Autocorrelation coefficients were determined for each month and the corresponding temperature interval from 101 hourly tapes using Equation 1. The locations and sources of the hourly tapes are presented in Table 1. There were 66 TRY, 16 CTZ, and 19 WYEC for a total of 1,212 months of hourly data. This was considered representative of U.S. and Canadian climates.

Average Autocorrelation Coefficients

The 1,212 individual monthly results were then statistically analyzed to determine the average autocorrelation coefficient for each month in 10°F temperature intervals. The statistical results are presented in Table 2, which contains the number of months available (NO.), the average autocorrelation coefficient by month and temperature interval ($r_{AVGi,j}$), and the standard deviation by month and temperature interval ($r_{SDi,j}$) of the autocorrelation coefficient.

TABLE 1 **Hourly Weather Locations**

TRY	CTZ	WYEC
1 Albany, NY	1 Arcata, CA	1 Albuquerque, NM
2 Albuquerque, NM	2 Santa Rosa, CA	2 Bismarck, ND
3 Amarillo, TX	3 Oakland, CA	3 Boise, ID
4 Atlanta, GA	4 Sunnyvale, CA	4 Brownsville, TX
5 Bangor, ME	5 Santa Maria, CA	5 Charleston, SC
6 Birmingham, AL	6 Los Angeles, CA	6 Cleveland, OH
7 Bismarck, ND	7 San Diego, CA	7 Dayton, OH
8 Boise, ID	8 El Toro, CA	8 El Paso, TX
9 Boston, MA	9 Pasadena, CA	9 Fort Worth, TX
10 Brownsville, TX	10 San Bernadino, CA	10 Lake Charles, LA
11 Buffalo, NY	11 Red Bluff, CA	11 Las Vegas, NV
12 Burlington, VT	12 Sacramento, CA	12 Los Angeles, CA
13 Charleston, SC	13 Fresno, CA	13 Madison, WI
14 Charleston, WV	14 China Lake, CA	14 Medford, OR
15 Cheyenne, WY	15 Blythe, Ca	15 Miami, FL
16 Chicago, IL	16 Mount Shasta, CA	16 Nashville, TN
17 Cincinnati, OH		17 New York, NY
18 Cleveland, OH		18 Seattle-Tacoma, WA
19 Columbia, MO		19 Tallahassee, FL
20 Detroit, MI		
21 Dodge City, KS		
22 Duluth, MN		
23 El Paso, CA		
24 Fort Worth, TX		
25 Fresno, CA		
26 Great Falls, MT		
27 Houston, TX		
28 Indianapolis, IN		
29 Jackson, MS		
30 Jacksonville, TN		
31 Kansas City, MO		
32 Lake Charles, LA		
33 Las Vegas, NV		
34 Little Rock, AR		
35 Los Angeles, CA		
36 Louisville, KY		
37 Lubbock, TX		
38 Madison, WI		
39 Medford, OR		
40 Memphis, TN		
41 Miami, FL		
42 Minneapolis, MN		
43 Nashville, TN		
44 New Orleans, LA		
45 New York, NY		
46 Norfolk, VA		
47 Oklahoma City, OK		
48 Omaha, NE		
49 Philadelphia, PA		
50 Phoenix, AZ		
51 Pittsburgh, PA		
52 Portland, ME		
53 Portland, OR		
54 Raleigh, NC		
55 Richmond, VA		
56 Sacramento, CA		
57 Salt Lake City, UT		
58 San Antonio, TX		
59 San Diego, CA		
60 San Francisco, CA		
61 Seattle,Tacoma,WA		
62 Sault St. Marie, MI		
63 Saint Louis, MO		
64 Tampa, FL		
65 Tulsa, OK		
66 Washington, DC		

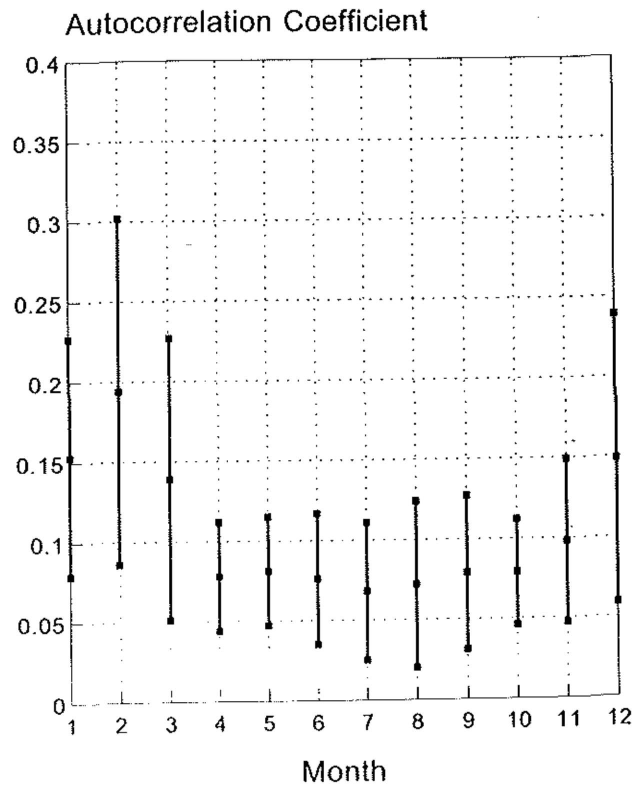

Figure 2 *Monthly autocorrelations.*

Figure 2 presents a summary of the monthly results. There is a rather consistent trend. The average autocorrelation coefficient is largest in the cold months and lowest in the hot months. The same trend is exhibited by the standard deviations.

Comparisons of Predicted CDH74 Against the 101 Hourly Weather Tapes

Figure 3 presents a comparison of the annual CDH74 calculated using the average autocorrelation coefficients and the annual CDH74 extracted from the 101 hourly tapes. The statistical correlation coefficient for the data is 0.904. The scatter is attributed to using an average autocorrelation coefficient, defining the average in 10°F intervals, and ignoring any location dependence such as coastal effects or elevation differences.

Extrapolations

The average autocorrelation coefficients derived from the 101 hourly tapes did not cover all climatic conditions that exist in the United States and Canada. To apply the calculation procedure to the 3,349 locations in the United States and the 1,847 locations in Canada the average autocorrelation coefficient had to be extrapolated to account for the extreme climatic conditions.

The data base of monthly average dry-bulb temperatures for 3,349 locations in the United States and the

TABLE 2 **Average Autocorrelation Coefficients by Month and 10°F Intervals**

Temperature Intervals in 10°F Increments

	MIN	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100	MON
	MAX	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100	110	AVG
JAN	NO.	0	0	0	0	4	5	22	21	28	13	4	0	0	0	0	97
	r_{avg}	.049	.069	.087	.105	.124	.143	.153	.182	.147	.125	.180	.180	.180			.153
	r_{SD}					.025	.026	.052	.109	.078	.045	.032					.074
FEB	NO.	0	0	0	0	1	6	14	21	31	19	5	0	0	0	0	97
	r_{avg}	.029	.060	.092	.123	.160	.172	.237	.244	.164	.169	.176	.182	.188			.194
	r_{SD}					NA	.029	.146	.131	.089	.079	.064					.108
MAR	NO.	0	0	0	0	0	1	4	20	27	34	9	2	0	0	0	97
	r_{avg}	.251	.236	.221	.206	.191	.177	.162	.157	.113	.127	.103	.185	.185			.139
	r_{SD}						NA	NA	.102	.043	.063	.043	.003				.088
APR	NO.	0	0	0	0	0	0	0	5	18	42	25	7	0	0	0	97
	r_{avg}			.149	.140	.131	.122	.113	.125	.073	.077	.073	.080	.075			.078
	r_{SD}								.060	.021	.038	.025	.030				.034
MAY	NO.	0	0	0	0	0	0	0	0	2	26	41	26	2	0	0	97
	r_{avg}						.081	.081	.081	.062	.087	.085	.070	.083			.081
	r_{SD}									.003	.035	.035	.031	.057			.034
JUN	NO.	0	0	0	0	0	0	0	0	0	7	35	42	13	0	0	97
	r_{avg}								.076	.076	.086	.078	.077	.064	.064		.076
	r_{SD}										.022	.056	.035	.015			.041
JUL	NO.	0	0	0	0	0	0	0	0	0	1	19	52	21	4	0	97
	r_{avg}								.068	.068	.042	.080	.062	.080	.033	.033	.068
	r_{SD}										NA	.058	.034	.047	.011		.043
AUG	NO.	0	0	0	0	0	0	0	0	0	2	20	55	19	1	0	97
	r_{avg}								.072	.072	.054	.116	.061	.061	.040		.072
	r_{SD}										.026	.090	.028	.025	NA		.052
SEP	NO.	0	0	0	0	0	0	0	0	0	14	40	35	8	0	0	97
	r_{avg}						.079	.079	.079	.079	.063	.086	.082	.066	.079		.079
	r_{SD}										.028	.057	.043	.038			.048
OCT	NO.	0	0	0	0	0	0	0	0	14	38	37	8	0	0	0	97
	r_{avg}				.079	.079	.079	.079	.079	.084	.080	.078	.071	.079			.079
	r_{SD}									.035	.033	.034	.034				.033
NOV	NO.	0	0	0	0	0	0	3	13	36	33	10	2	0	0	0	97
	r_{avg}	.199	.199	.199	.199	.199	.199	.199	.136	.090	.077	.104	.155	.190			.098
	r_{SD}							.058	.074	.036	.035	.024	.131				.051
DEC	NO.	0	0	0	0	0	5	13	26	31	17	4	1	0	0	0	97
	r_{avg}	.192	.192	.192	.192	.192	.197	.192	.187	.120	.104	.106	.249	.149			.149
	r_{SD}						.095	.116	.112	.054	.047	.017	NA				.090

Notes: Average autocorrelations underlined were extrapolated using Figures 2-13. NA = Not Available

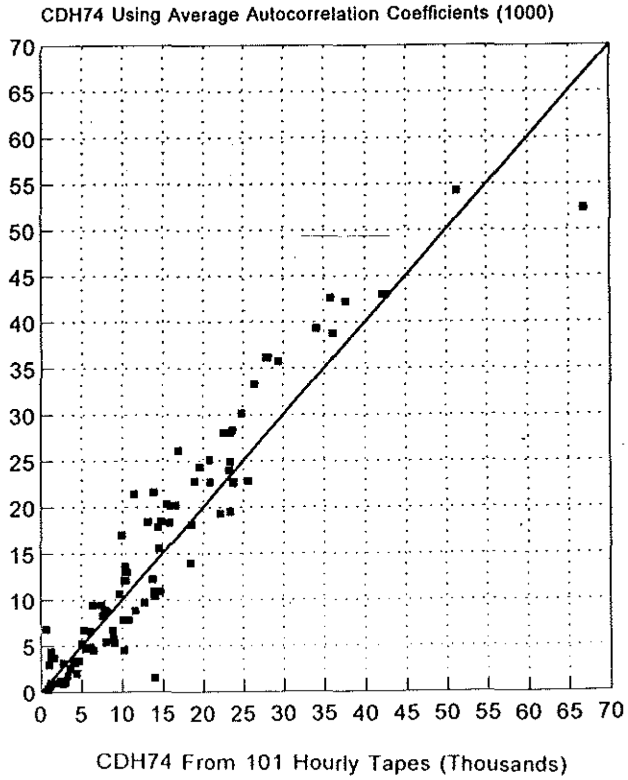

Figure 3 *Comparisons of CDH74 calculated using autocorrelations vs. hourly weather data tapes.*

1,847 locations in Canada was analyzed to determine whether the 1,212 months of hourly results accounted for the entire range of monthly temperatures. Table 3 presents the number of months within the 10°F temperature intervals contained in the United States temperature data base and Table 4 presents the number of months contained in the Canadian temperature data base. The underlined values represent the months where data exist in the respective country but not in the 101 hourly tapes.

The United States data base contained 40,188 months, and only 527 months, or 1.3%, were not covered by the 1,212 months available on hourly weather tapes. The majority of the extrapolations were in temperature intervals at or below 45°F and have no major impact in determining CDH74. The extrapolations in the temperature intervals of 75°F and above would have an impact in calculating CDH74. These extrapolations accounted for 112 months, which was only 0.27% of the total.

The Canadian data base contained 22,164 months, and 3,496 months, or 15.8%, were not covered by the 1,212 months available on hourly weather tapes. All of the extrapolations were in temperature intervals at or below 45°F and have no major impact in determining CDH74.

The basis for the extrapolations varied, depending on the specific data for each month. Furthermore, it also varied above and below the monthly average temperature. For example, in January, extrapolations below the monthly average temperature were based on extending the trend between 35°F and 5°F down to –35°F. Above the monthly average temperature, the extrapolation consisted of just repeating the average value at 65°F for 75°F and 85°F.

TABLE 3 Number of Months in 10°F Intervals for the United States

	Temperature Intervals in 10°F Increments													
MIN	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
MAX	-20	-10	0	10	20	30	40	50	60	70	80	90	100	110
JAN	1	7	14	188	541	1011	770	541	197	47	25	7	0	0
FEB	1	1	9	38	387	881	947	664	327	62	25	7	0	0
MAR	0	2	1	7	21	468	1110	915	615	168	35	7	0	0
APR	0	0	2	0	2	11	196	1359	1031	625	116	7	0	0
MAY	0	0	0	0	1	1	8	160	1419	1218	530	12	0	0
JUN	0	0	0	0	0	0	2	17	336	1450	1314	229	1	0
JUL	0	0	0	0	0	0	2	4	85	798	1771	655	33	1
AUG	0	0	0	0	0	0	2	4	109	1101	1595	521	17	0
SEP	0	0	0	0	0	0	2	56	811	1492	859	128	1	0
OCT	0	0	0	0	3	13	31	877	1496	750	165	14	0	0
NOV	0	0	4	10	4	226	1152	1127	635	138	43	10	0	0
DEC	0	7	7	19	332	969	998	682	246	53	29	7	0	0
TOT	2	17	37	262	1291	3580	5220	6406	7307	7902	6507	1604	52	1

Note: Underlined values represent months which exceeded temperature ranges of 101 hourly tapes.

TABLE 4 **Number of Months in 10°F Intervals for Canada**

	Temperature Intervals in 10°F Increments													
MIN	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80
MAX	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90
JAN	0	4	40	60	371	417	517	297	138	3	0	0	0	0
FEB	0	7	28	28	75	488	663	367	128	63	0	0	0	0
MAR	0	2	14	25	21	47	481	864	272	121	0	0	0	0
APR	0	0	0	5	23	18	23	64	1128	583	3	0	0	0
MAY	0	0	0	0	0	0	27	22	47	763	988	0	0	0
JUN	0	0	0	0	0	0	0	0	44	69	1033	701	0	0
JUL	0	0	0	0	0	0	0	0	11	36	287	1452	61	0
AUG	0	0	0	0	0	0	0	0	15	37	508	1263	24	0
SEP	0	0	0	0	0	0	3	15	35	344	1341	109	0	0
OCT	0	0	0	0	3	5	34	40	316	1330	119	0	0	0
NOV	0	0	1	11	30	36	129	709	743	188	0	0	0	0
DEC	0	1	11	47	58	451	591	492	170	26	0	0	0	0
TOT	0	14	94	176	1581	1462	2468	2870	3047	3563	4279	3525	85	0

Note: Underlined values represent months which exceeded temperature ranges of 101 hourly tapes.

CDH74 Calculation Procedure

The calculation procedure starts by determining the standard deviation of the dry-bulb temperature within a month. This requires using the data base of monthly average dry-bulb temperatures and the monthly standard deviations plus the average autocorrelation coefficients from Table 2 in Equation 2:

$$\sigma_{T_i} = \frac{\sqrt{NH_i} \cdot \sigma_{N,i}}{\sqrt{1 + (NH_i - 1) \cdot r_{AVG_{i,j}}}} \qquad (2)$$

where

$r_{AVG_{i,j}}$ = average autocorrelation coefficient for the i^{th} month and the j^{th} temperature interval (dimensionless).

Then CDH74 was calculated by integrating a normal distribution curve from a lower limit of 74°F to an upper limit defined as three standard deviations above the monthly average dry-bulb temperature. The integration was performed using standard mathematical functions (VNI 1982). All 12 months were analyzed and the results were summed to arrive at the annual CDH74.

RESULTS

The individual city results require about 50 pages to print and are contained in ASHRAE Standard 90.2-1993.

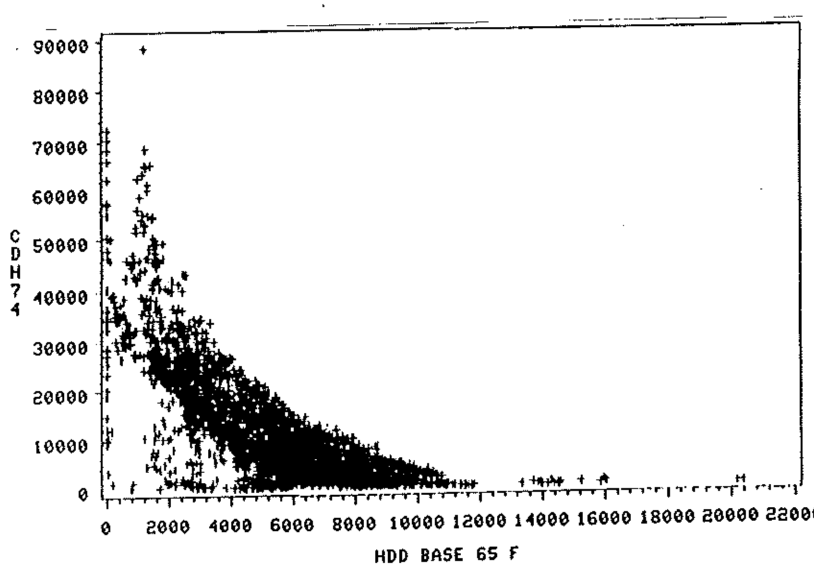

Figure 4 *Weather data for the United States.*

Considerable insight can be gained by plotting CDH74 vs. HDD65.

The U.S. results are presented in Figure 4. There are several interesting observations. First, there is a broad band between 2,000 and 10,000 HDD65, which accounts for most of the data. In general, as HDD65 increases, CDH74 decreases. It is interesting to note that the upper boundary of the broad band is so well defined. Second, there is a range of CDH74 from zero to 72,338 at HDD65 equal to zero. These primarily are from Puerto Rico, Cuba, the Virgin Islands, and the Pacific Islands. Third, the maximum CDH74 is 88,444, which occurs at Death

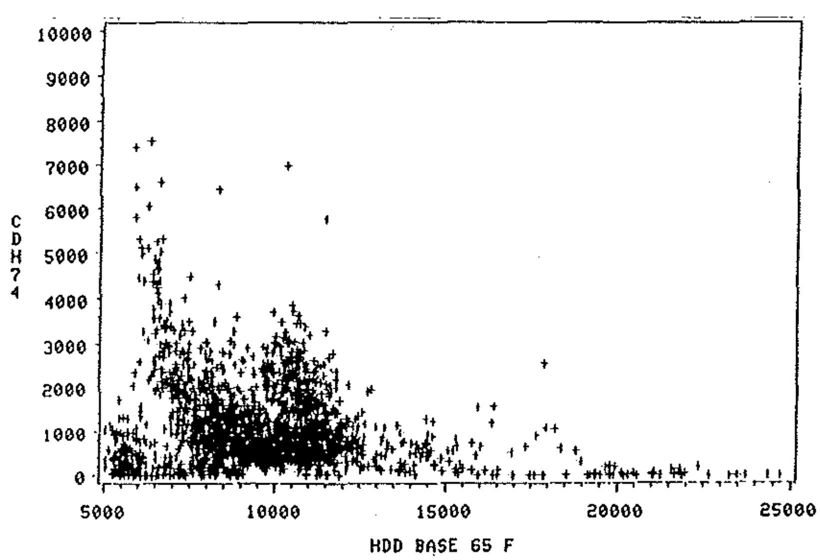

Figure 5 Weather data for Canada.

Valley, Calif. The next highest CDH74 in the continental United States is 68,577, which occurs at Parker Reservoir, Calif. Only 87 United States locations (2.6%) are above 40,000 CDH74, 38 locations (1.1%) are above 50,000, 15 locations are above 60,000 (0.4%), and 3 locations are above 70,000. Fourth, the West Coast cities represent the cluster of data between 2,000 and 3,000 HDD65 and zero and 10,000 CDH74. Fifth, there are only 18 locations above 12,000 HDD65 and only two locations above 16,000 HDD65.

The results for Canada are presented in Figure 5. Cooling is not a major issue, because 99.2% of the locations have less than 5,000 CDH74. There are only seven locations with more than 6,000 CDH74 and only two locations above 7,000 CDH74: Lytton, BC, with 7,414, and Pelee Island, Ontario, with 7,548.

CONCLUSIONS

A procedure has been developed to calculate CDH74 using monthly average dry-bulb temperatures and monthly average standard deviations reported by NOAA and AES for 30-year periods of record. The procedure was based on data from 101 hourly weather data tapes. Average autocorrelation coefficients were statistically determined and then extrapolated to encompass those climates not represented by the hourly tapes.

The monthly CDH74 were determined by integrating a normal distribution curve from a lower limit of 74°F to an upper limit defined as three standard deviations above the average temperature. The monthly results were summed to arrive at the annual CDH74.

Annual results for 3,349 locations in the United States and 1,847 locations in Canada were published as part of the climatic data for ASHRAE Standard 90.2-1993.

RECOMMENDATIONS

The CDH74 calculation procedure could be improved by reducing the scatter between the calculated results and those from the hourly weather data tapes. The primary reason for the scatter was the use of statistically averaged autocorrelation coefficients for 10°F temperature intervals. This approach completely ignored all location dependence, such as coastal effects or elevation differences. One method to account for specific rather than average autocorrelation coefficients would be to map each city to the closest station available from the 101 hourly tapes. This would eliminate the use of statistical averages, avoid the need for extrapolation, and give some account for coastal effects and elevation. The only additional information required to perform this type of mapping would be the latitude and longitude of each city. This is readily available and should be investigated for future revisions to the standard.

Another improvement to the calculation procedure would be to use more hourly data tapes. One source would be the TMY tapes, which have 234 stations (NCDC 1981). Also, there are 116 hourly tapes available for Canada (Hsieh 1991). Using additional tapes would allow for closer mapping and should improve the overall results.

ACKNOWLEDGMENTS

Special thanks are extended to Dr. Nathaniel B. Guttman of the National Oceanic and Atmospheric Administration in Asheville, NC, for his assistance in proposing the basic autocorrelation coefficient concept. Thanks also are extended to Mr. Ernie Klotz for his assistance in applying the statistics and to Mr. William Beiter for his assistance in processing the hourly data tapes. Without their collective assistance this research would not have been possible. All financial and computer support for this project was provided by the Owens-Corning Fiberglas Corp.

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