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The End-Use Load and Consumer Assessment Program: Characterization of Commercial Load Shapes by Weather Day Type

D. L. Hadley

July 1990

Prepared for
the Bonneville Power Administration
under a Related Services Agreement
with the U.S. Department of Energy
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Pacific Northwest Laboratory
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THE END-USE LOAD AND CONSUMER ASSESSMENT PROGRAM: CHARACTERIZATION OF COMMERCIAL LOAD SHAPES BY WEATHER DAY TYPE

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Richland, Washington 99352

SUMMARY

The Bonneville Power Administration (Bonneville) began the End-Use Load and Consumer Assessment Program (ELCAP) in 1983. Prior to beginning ELCAP, there was an abundance of information regarding total power consumption for residential structures in the Pacific Northwest, through billing records for example, and limited information regarding power consumption by various end uses (such as hot ware, heating and cooling). This program, conducted for Bonneville by the Pacific Northwest Laboratory[(a)], involves collecting and analyzing hourly end-use data in commercial and residential buildings in the Pacific Northwest.

An objective synoptic climatological classification methodology was used to determine the characteristics of daily heating, ventilation, and air conditioning (HVAC) system load profiles for typical weather day types. This methodology used a combination of principal component analyses and cluster analyses to derive 20 weather day types for a 1-year period (September 1986 through August 1987). The resultant day types condense the extensive information contained in the annual set of daily data into representative weather days which convey the requisite core information, yet physically and conceptually take up less space.

As part of ELCAP, electrical energy consumption data from four commercial buildings in the Pacific Northwest were monitored for the same period of time. Hourly HVAC system load data for each day were binned into weather day types. From this, the characteristics of variations in the daily loads and load profiles were determined.

The weather day type classification of the commercial building load data has provided additional information, particularly with regard to response of the HVAC system to the typical day-to-day changes in the weather, about the relationship between climate and the pattern of HVAC system consumption not

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obtainable from more traditional approaches. From this exploratory study, we have been able to

- identify distinctive weather day types and describe typical HVAC system loads for the selected buildings
- describe the weather day types responsible for peak HVAC system loads
- document the variation in load profiles for typical weather conditions occurring during a given month or season.

Using this information, it is possible to define the load shape for a building type based on the HVAC system and the climatology of the site. This would allow a utility to plan load requirements based on projected growth in the commercial sector.

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INTRODUCTION

Recently, an objective methodology to characterize air masses for a given locale was developed by Kalkstein and Corrigan (1986). This methodology was used to determine which air masses had the greatest potential for high atmospheric concentrations of sulfur dioxide. Referred to as the temporal synoptic index (TSI), this approach uses a combination of principal component analysis (PCA) and cluster analysis to identify days considered to be meteorologically homogeneous. The PCA transforms the original set of intercorrelated meteorological variables into a new set of components that are linear combinations of the original variables. This transformation simplifies the amount of data being processed and eliminates the intercorrelations that exist among weather variables. The next step in the methodology is to apply an objective clustering scheme to the most significant of the transformed variables. This application converts the group's days into meteorologically homogeneous clusters.

The analysis routine used in the cluster analysis allows an arbitrary specification for the number of clusters to be created. The correct number of naturally occurring clusters is site specific, depending on the local climatology and the period of data being used, seasonal or annual. A number of available techniques are used to determine the number of naturally occurring clusters (Kalkstein and Corrigan 1986; Kalkstein et al. 1987). If more than the correct number of clusters is generated, the natural clusters will be artificially split into two or more similar clusters. If the number of clusters decreases below the correct number, two or more dissimilar clusters are forced together. For this exploratory study, we did not complete a rigorous determination of the actual number of naturally occurring clusters. Other work applying the same TSI methodology to typical meteorological year (TMY) data indicated a 10-cluster analysis was insufficient to readily differentiate the expected day types, while 25 to 30 clusters usually resulted in duplicate day types. For this study, it was felt that to error on the conservative side and specify more than the correct number of clusters would be less of a problem than specifying too few. Therefore, the cluster analysis routine was set to generate 20 clusters.

Once the number of clusters has been specified, each day in the data set is assigned to a cluster and the meteorological characteristics of each cluster are determined. The resulting day types are representative of synoptic weather day types occurring at that location during the period analyzed.

The work presented in this report is the result of an exploratory study of the application of the TSI approach to the analysis of commercial building energy consumption data. In this study, the hourly HVAC consumption data for four commercial buildings, monitored as part of ELCAP, were analyzed for patterns of consumption by weather day types derived from the TSI methodology.

DATA

This section identifies suitable building qualifications and classifies the data for commercial electrical end-use consumption. It also identifies weather data for the period coinciding with the end-use consumption data.

COMMERCIAL ELECTRICAL END-USE CONSUMPTION DATA

As a test application of the TSI methodology to the analysis of commercial end-use data, suitable buildings monitored as part of ELCAP were identified. Screening criteria used to identify acceptable buildings were

- a minimum of 1 year of quality data
- a single tenant
- readily available, meteorological data representative of the building location
- to be located in different climate regions of the northwest.

Using the above criteria, four buildings were selected for analyses, one in Eugene, Oregon and three in Richland, Washington. Although numerous other buildings were qualified by the above criteria, the initial analyses for this exploratory study were limited to these four. Characteristics of each building are summarized in Table 1. Only the metered HVAC system energy-use data for the period of September 1986 through August 1987 were used.

TABLE 1. Building Characteristics

ID No.	Location	Classification	Size ft^2	Year Built	Number of Stories
556	Richland	Drygood retail	69,986	1969	1
607	Richland	Office	50,758	1978	4
714	Richland	Office	25,678	1976	3
295	Eugene	Drygood retail	99,616	1954	4

WEATHER DATA

Weather data for the period coinciding with the building energy data were obtained from the ELCAP meteorological database. Representative weather data for the building in Eugene were from the National Weather Service station in Eugene, Oregon. Data for the three buildings in Richland were from the Hanford Meteorological Station, located approximately 25 miles northwest of Richland, Washington. The Hanford station is part of the Pacific Northwest Laboratory.

Each day was defined in terms of the daily values of the following parameters:

- mean dry-bulb temperature
- diurnal temperature range
- mean wet-bulb temperature
- total global horizontal solar radiation
- mean cloudiness index
- mean wind speed.

The total global horizontal radiation was a measured variable at the Hanford station. At Eugene, it was a calculated quantity, based on a physical model using the observed hourly cloud cover. The cloudiness index is the ratio of the global horizontal radiation to the extraterrestrial radiation and provides a relative measure of the cloudiness or attenuation of the solar radiation during daylight hours.

RESULTS

WEATHER DAY CHARACTERISTICS

The character of each of the 20 weather day types is established from 1) the mean value of each of the original weather variables within each day type, 2) the frequency of occurrence of the day type by month, and 3) the hourly profile for each of the weather variables within each day type. The characteristics of the 20 day types are shown in Tables 2 and 3. The day types have been sorted in ascending order of mean temperature, and day-type numbers have been reassigned. The left sides of these tables show the occurrence of each day type in each month, while the right sides contain the mean values of the weather variables. The unique character of each day type is readily evident, both in terms of weather conditions represented and months of occurrence. The meteorological validity of the weather day types determined by this methodology have been established by others (Ladd and Driscoll 1980) and the validity of these weather day types is accepted without question. However, because of the somewhat arbitrary specification of 20 day types, some may not be significantly different from others.

AVERAGE HEATING AND COOLING CONSUMPTION BY WEATHER DAY TYPE

Because weather is one of the principal determinates of day-to-day variations in commercial building heating and cooling loads, this approach should provide invaluable information on the impact of the weather on patterns of heating and cooling consumption. As each of the 20 day types represents a different weather condition, a distinct pattern of heating and cooling energy use is expected to be associated with each day type.

The three buildings in Richland each have a different type of heating and cooling system. Building No. 556 has a single heating and cooling system (heat pump), however the ELCAP metering protocol does not allow us to differentiate between heating and cooling. Building No. 607 has separate heating and cooling systems, which allowed for the separation of the heating and cooling loads. Building No. 714 has both types of systems, that together classify as a mixed HVAC system.

TABLE 2. Mean Values for the Meteorological Variables - Hanford (9/1/86 through 8/30/87)

Cluster	Month												Meteorological Variables					
	S	O	N	D	J	F	M	A	M	J	J	A	TD	TW	GHZ	WSP	SOL	N
1					1	2							-6.4	-6.5	15	1.0	0.10	3
2					2	4							-5.5	-5.8	23	1.1	0.15	6
3					7	1							-1.0	-1.2	19	1.2	0.13	8
4				1	11	6	2						0.2	-0.3	24	2.0	0.16	20
5				5	2	5	2						1.0	0.1	40	1.9	0.23	14
6				8	2	6	2	1					1.8	0.4	49	2.4	0.27	19
7				2	3	1	3						3.3	1.4	49	3.2	0.28	9
8	2	1	2	2	4	1	3						6.8	4.8	58	3.2	0.27	15
9		1	8	1	2	13	5						7.0	4.2	78	4.0	0.37	30
10		3	3			3	4	2					8.6	5.6	105	2.9	0.40	15
11	6	6				2	7	3	1				11.0	7.3	124	3.3	0.41	25
12	4	12	1				6	1	1	1	2		11.9	7.5	144	3.4	0.46	28
13	4	1					3	6	1		1		13.4	7.8	191	3.3	0.52	16
14	4	6					2	10	6	2	1	1	15.6	9.5	198	3.6	0.51	32
15	3	1						4	6	3	4	2	18.1	10.9	238	3.9	0.55	23
16	3							2	4	4	2	3	20.6	12.2	261	3.8	0.59	18
17	4							2	6	7	8	15	23.1	13.4	280	3.7	0.63	42
18									5	8	9	7	25.9	14.9	299	3.4	0.65	29
19									1	3	3		27.9	15.7	325	3.8	0.68	7
20										2	1	2	29.8	16.4	315	4.3	0.67	5

TD = dry-bulb temperature (°C)
TW = wet-bulb temperature (°C)
GHZ = global horizontal radiation (watts/m^2)
WSP = wind speed (m/s)
SOL = cloudiness index
N = number of days in day type

TABLE 3. Mean Values for the Meteorological Variables - Eugene, Oregon (9/1/86 through 8/30/87)

Cluster	MONTH												Meteorological Variables					
	S	O	N	D	J	F	M	A	M	J	J	A	TD	TW	GHZ	WSP	SOL	N
1			1	3	4								-0.2	-0.3	24	1.6	0.19	8
2				3	5	1							0.2	-0.7	73	1.9	0.49	9
3				5	1								2.6	2.4	21	3.2	0.16	6
4		3	3	8	5	2	1						4.2	3.8	41	2.5	0.26	22
5		1	5	2	1	7	1						5.9	5.2	75	2.1	0.39	17
6		2	6	7	5	4	5	1					7.6	6.9	55	3.5	0.30	30
7	3		9	2	8	5	2	1	1				8.6	7.9	53	4.9	0.27	31
8	3	3	6	1	1	5	9	1	2	1			8.9	7.8	95	3.0	0.36	32
9	2	4				3	6	2	2		1		9.4	7.8	147	2.5	0.46	20
10	1				1								10.4	9.6	69	8.0	0.29	2
11	2	3					2	4	3		2		11.5	10.3	121	4.3	0.34	16
12		9					2	9	4		1		12.3	9.5	237	2.5	0.67	25
13	9	4				1	2	4	2	1	1	2	12.5	10.5	152	3.2	0.44	26
14	1	2					1	7	4	1	3	1	13.2	10.3	229	3.2	0.56	20
15	1								5	3	9	1	15.2	12.6	174	3.9	0.38	19
16	3								2	5	6	4	16.5	12.8	287	3.6	0.65	20
17	1									1	2	2	17.3	14.2	271	5.3	0.61	6
18	2							1	2	9	1	8	18.6	13.6	315	3.0	0.72	23
19	1									3	2	6	19.3	14.1	332	5.0	0.75	12
20	1								4	6	3	6	22.2	16.2	350	3.6	0.77	20

TD = dry-bulb temperature (°C)
TW = wet-bulb temperature (°C)
GHZ = global horizontal radiation (watts/m²)
WSP = wind speed (m/s)
SOL = cloudiness index
N = number of days in day type

Building No. 295 in Eugene uses city-supplied steam for heating, so there was no measure of heating energy consumption. The building is cooled from a ventilation system with a ground-coupled chiller using ground water as the heat sink.

For each building, the difference in the average heating and cooling loads among the weather day types is obvious (see Tables 4 and 5). The variation in consumption with day types is as expected, with the maximum loads occurring in the coldest day types (predominately heating) and the secondary loads occurring during the warmest day types (predominately cooling). The minimum consumption typically occurs during transition season weather conditions. In this analysis, there was no attempt to disaggregate the energy data into

TABLE 4. Mean Loads for Richland Buildings (kilowatt-hours)

Cluster	Building No. 714				Building No. 607			Building No. 556
	Cool	Heat	Mix	Total	Cool	Heat	Total	Mix
1	1751	36105	28278	66134	11138	179971	191109	107616
2	1802	32512	27345	61659	12104	168973	181077	92405
3	2042	29924	23776	55742	12747	134898	147645	114223
4	1784	25364	19187	46335	13383	123948	137331	76051
5	1822	22117	17100	41039	14449	119560	134009	57286
6	1904	20939	16592	39435	15215	111609	126824	48231
7	1909	20388	14755	37052	14795	102414	117209	50069
8	2689	13152	9495	25336	20072	79548	99620	42778
9	2356	14458	10558	27372	18316	83635	101951	32710
10	2850	8790	6678	18318	24232	65849	90081	31443
11	3044	7052	5793	15889	25741	54974	80715	28972
12	3662	6382	5511	15555	26860	51066	77926	31122
13	4504	5086	4396	13986	30666	43347	74013	39016
14	5750	3656	4512	13918	34427	34712	69139	40740
15	6589	2631	4579	13799	35885	24318	60203	45856
16	8451	2324	6264	17039	41211	18006	59217	56253
17	10224	2081	7866	20171	44960	12938	57898	63116
18	12480	2113	9898	24491	50721	10279	61000	73282
19	14030	2219	11574	27823	54398	8861	63259	74055
20	15435	2074	12847	30356	58107	5821	63928	83444

TABLE 5. Mean Loads for the Eugene Building (Kilowatt-hours)

Cluster	Building No. 295 Cool	Mix	Total
1	-9[a]	3056	3056
2	-9[a]	3762	3762
3	-9[a]	4169	4169
4	-9[a]	4531	4535
5	-9[a]	5031	5031
6	0	4749	4749
7	0	5460	5460
8	1379	7262	8641
9	0	7508	7508
10	-9[a]	8194	8194
11	1517	10208	11725
12	7	9515	9522
13	25	9954	9979
14	5289	10514	15803
15	5210	12508	17718
16	6331	11666	17997
17	3869	12075	15944
18	16413	12453	35760
19	19347	12589	31936
20	24491	12958	37449

(a) Cooling system shutdown

weekday or weekend categories to account for differences in the HVAC system operating schedules. With the exception of those few potential day types, consisting of only a few days, the data does not appear to be biased because of the combined analysis.

Because of the uniqueness of the heating and cooling systems in building No. 295, the minimum daily average consumption occurred during the coldest day types and the maximums during the warmest day types.

WEATHER DAY TYPE LOAD PROFILES - RICHLAND

Average hourly load profiles have been generated for each of the weather day types for the three buildings located in Richland (see Appendix A, Figures A.1 through A.3). For example, Figure A.1 shows the load profile for one of the buildings for three winter day types. Day-type 1 represents the coldest days of the winter; day-type 4, the most frequently occurring winter day type; and day-type 9, a typically warm winter day.

With the exception of day-type 1, the basic shape of the load profiles for the remaining winter day types (2 through 9) is similar to the characteristic morning peak and secondary evening peak. The lower consumption during the mid-day hours is a result of increased internal gains and a decrease in the differences between the indoor and outdoor temperatures. The only difference in the profiles for the winter day types is the gradual decrease in average hourly use of warmer daily temperatures.

In contrast with winter load profiles, Figures A.4 through A.6 illustrate the load profiles for three typical summer day types. Day-type 17 represents the most frequently occurring of the summer day types, which occurred on 33% of the summer days. Forty-eight percent of those summer days occurred in August. For all summer day types, the cooling load dominates the profile with a characteristic afternoon peak. The shape of the profile remains essentially the same, with the only difference being the magnitude of the hourly load.

WEATHER DAY TYPE LOAD PROFILES - EUGENE

Because of the generally milder climate in Eugene, Oregon, the distinction between seasons is not as clear as that found in the more severe climates east of the Cascade Mountain range where Richland, Washington is located. As a result, fewer weather day types distinctly represent summer or winter conditions and more of the day types span a greater number of months. For example, day-type 8 (see Table 3) was found to occur in 10 different months.

Six hourly load profiles for the Eugene commercial building are presented in Appendix B to illustrate the variation in hourly profiles. The loads examined are for a particular building, an older, four-story, drygood retail store, located in the downtown area. Because of the uniqueness of the heating system, only the cooling system loads could be analyzed.

The hourly load profile for day-type 7 (see Appendix B, Figure B.1) illustrates the profile of a typical winter day for a particular building. The meteorological conditions are indicative of a cloudy, windy, cool fall, or warm winter day. We see a low level of operation of the mixed HVAC system occurring during the day with no significant cooling.

Day-type 15 illustrates a load profile for this particular building for a cool, cloudy summer day. This profile maintains the maximum consumption for the mixed HVAC load, while the cooling load operates at a lower level from 7 a.m. through 11 p.m. In contrast to this day, the load profile for day-type 18 is typical of a sunny, warm/hot summer day. The warmest conditions in the Eugene area (day type-20) show a strong cooling peak occurring between 1 p.m. and 4 p.m.

CONCLUSION

Using this information, it is possible to define the load shape for a building type based on the HVAC system and climatology of the site. This definition will ultimately allow utilities to 1) plan load requirements based on projected growth in the commercial sectors, 2) better understand how energy is used, and 3) predict more accurate weather forecasts in the future.

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APPENDIX A

WEATHER DAY TYPES AND LOAD PROFILES - RICHLAND, WASHINGTON

APPENDIX A

WEATHER DAY TYPES AND LOAD PROFILES - RICHLAND, WASHINGTON

Average hourly heating and cooling profiles were generated for each of the weather day types for the three Richland, Washington buildings. The results are tabulated for each building and displayed graphically for selected day types in Figures A.1 through A.3. These particular day types were chosen because they illustrate the typical variation in load profiles among the different day types. Figures A.1 through A.3 show the hourly load profiles for three winter weather day types for Richland building Nos. 556, 607, and 714, respectively. Day-type 1 occurred only in January and February (3 days) and typifies the coldest weather during the 1986 and 1987 winters; temperatures remained below freezing throughout those days. The small, wet-bulb depressions and low values of insolation were indicative of a period with low clouds and/or fog. Wind speeds were light and it is not known if any precipitation occurred during these days.

Day-type 4 occurred on 35% of the days in December and on 17% of the winter days (winter is defined as extending from November through February). The weather characteristics for this day are similar to day-type 1, except that the daily temperatures averaged 6.6°C (44°F) warmer.

Day-type 9 is typical of the warmest winter days. This day type occurred on 20% of the days during the winter months and most frequently in February with 46%.

During day-type 1, daily total heating and cooling consumption for building Nos. 714 and 607 was at the highest level of all the day types. For building No. 556, it was the second highest consumption. The basic shape of the load profile for winter day types (1 through 9) was similar to the characteristic morning peak and a secondary evening peak. The only difference in the two was a gradual decrease in the average hourly consumption of warmer daily temperatures. The lower consumption during the mid-day hours was a result of increased internal gains and a decrease in the indoor/outdoor temperature difference.

In contrast with these winter load profiles, Figures A.4, A.5, and A.6 illustrate the load profiles for typical summer day types. Day-type 20 (the hottest) occurred on 5 days during the summer months (June through August). Daily averaged temperatures in this group were 29.8°C (86°F) with daily maximums averaging 38.9°C (102°F). The most frequently occurring summer day, day-type 17, occurred on 33% of the summer days. Forty-eight percent of those summer days occurred in August. The coolest of the summer days, day-type 12, was also one of the more frequently occurring day types in the transition months. Thus, the load profiles were representative of that period as well. Heating and cooling loads were relatively low with heating occurring in the mornings and cooling in the afternoons.

For day-types 17 through 20, the cooling load dominates the profile with a characteristic afternoon peak. The shape of the profile remains essentially the same from day type to day type, the only difference being the magnitude of the hourly loads.

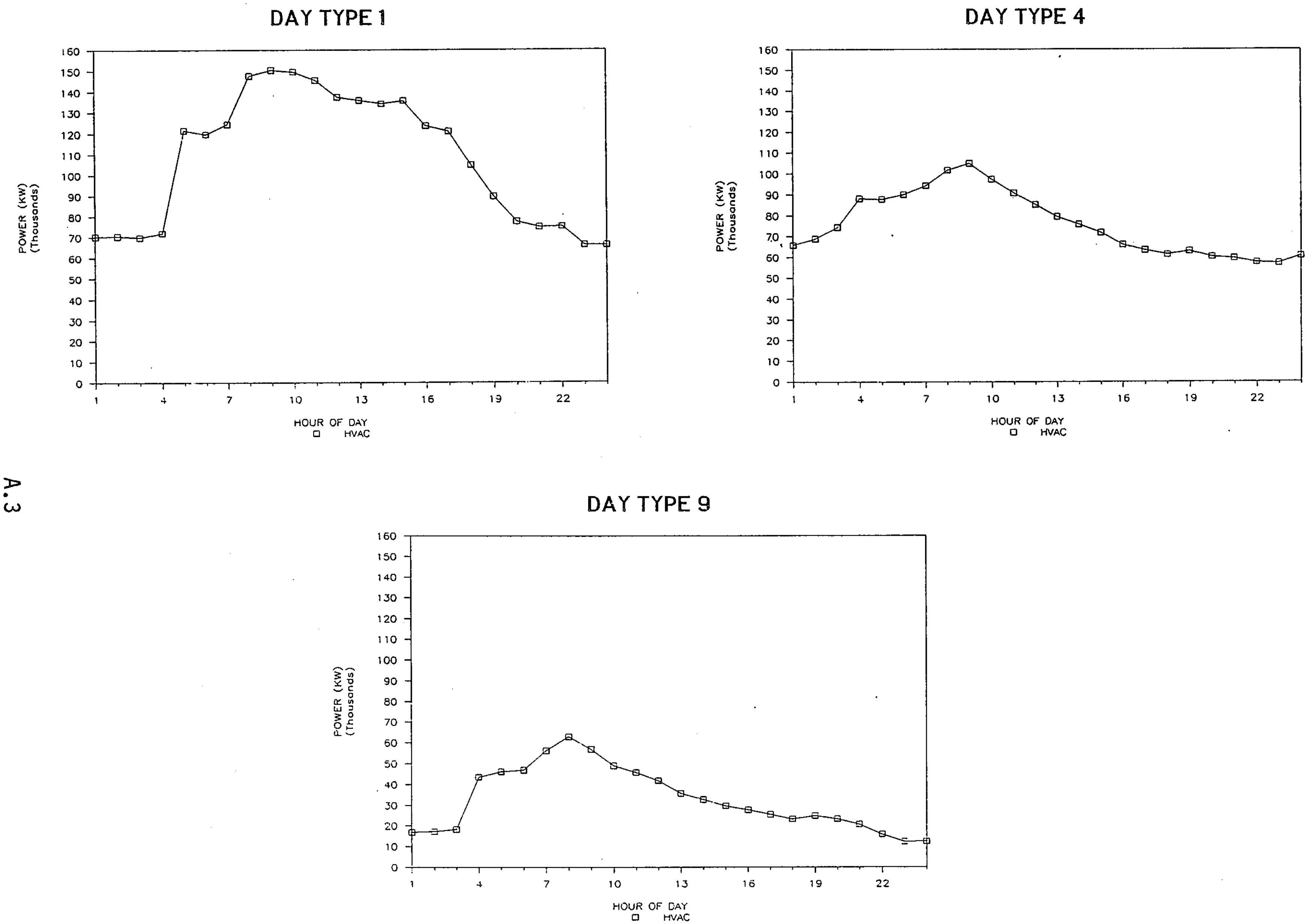


FIGURE A.1. Hourly Load Profile for Building No. 556 (day-types 1, 4, and 9)

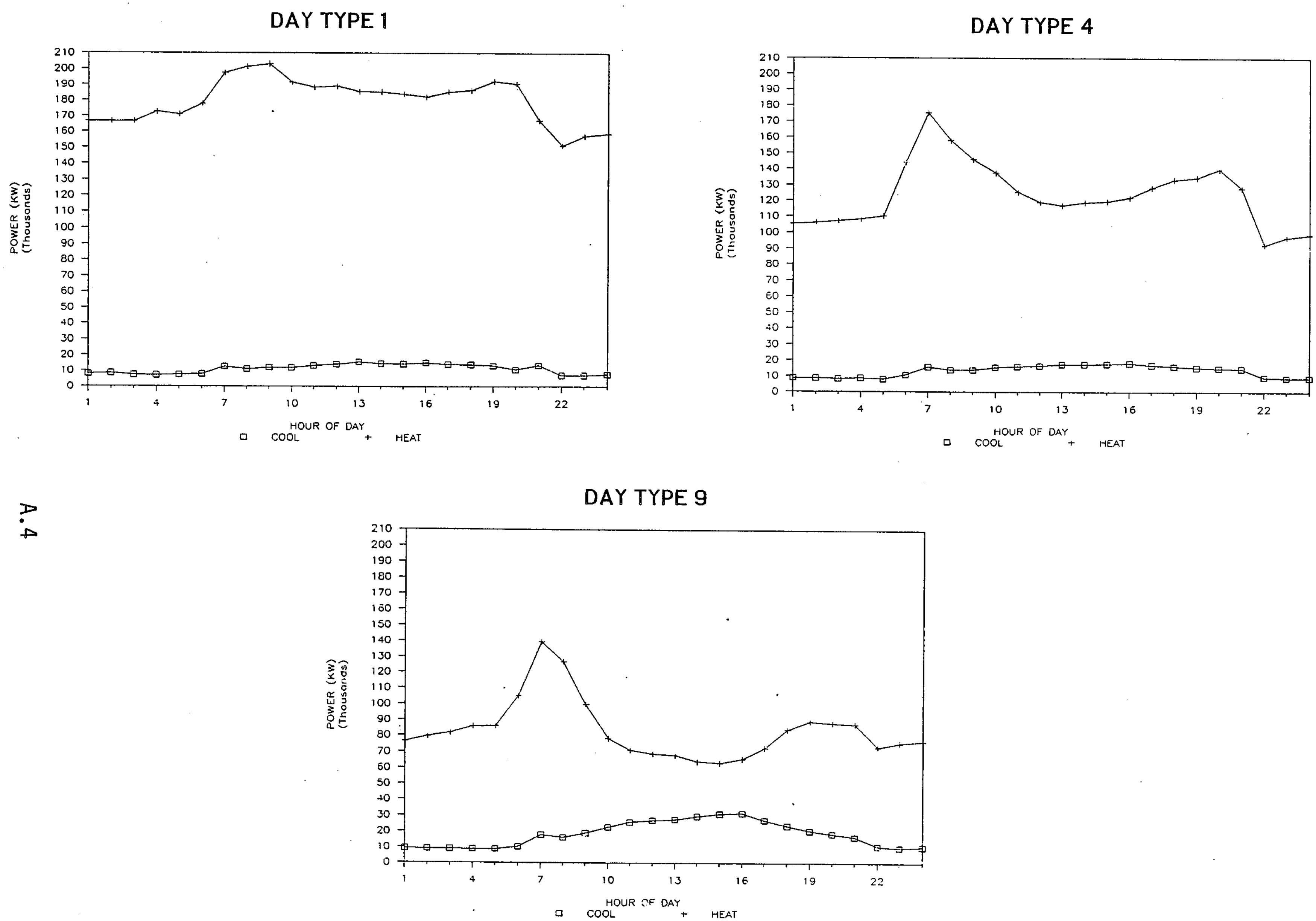


FIGURE A.2. Hourly Load Profile for Building No. 607 (day-types 1, 4, and 9)

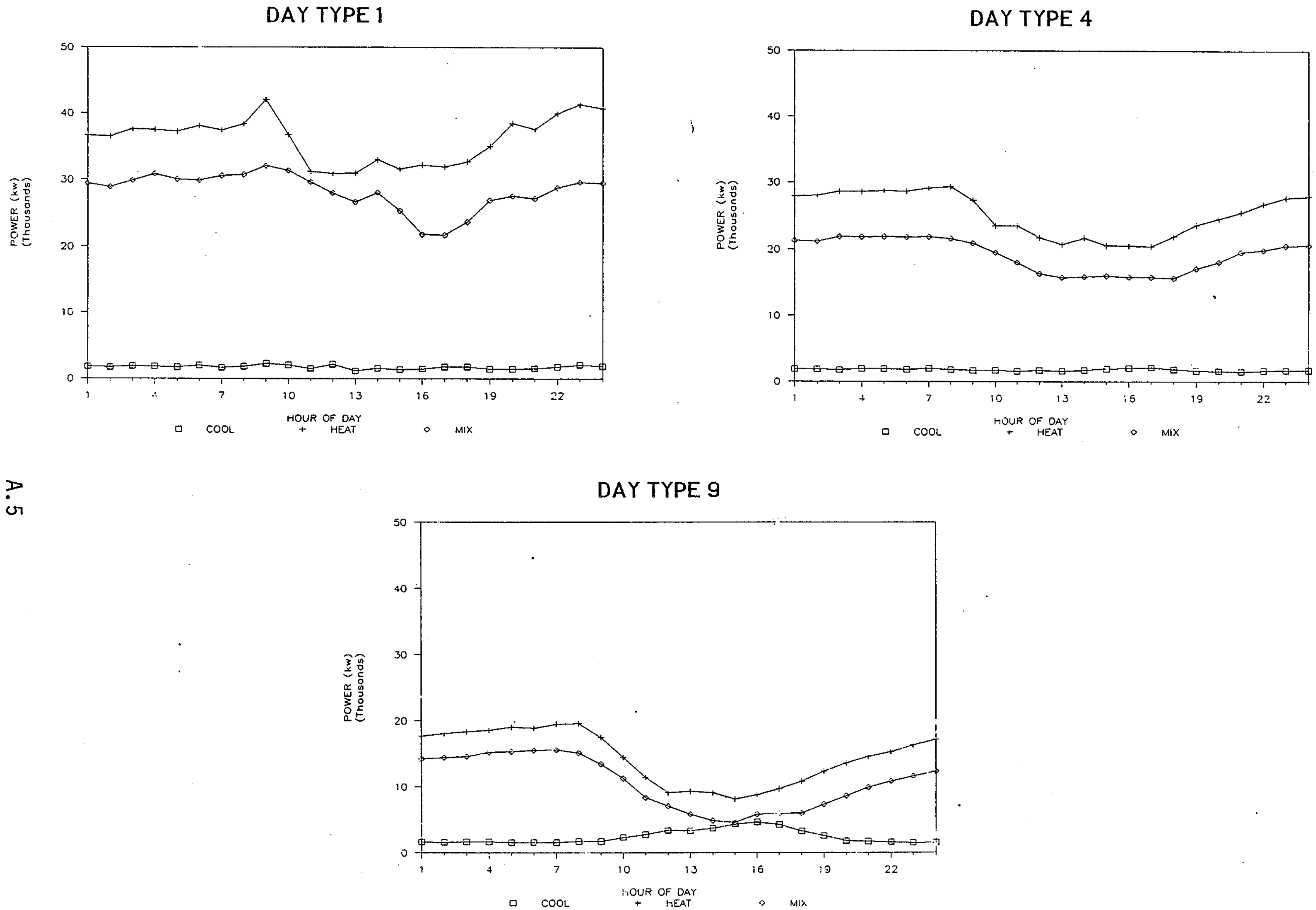


FIGURE A.3. Hourly Load Profile for Building No. 714 (day-types 1, 4, and 9)

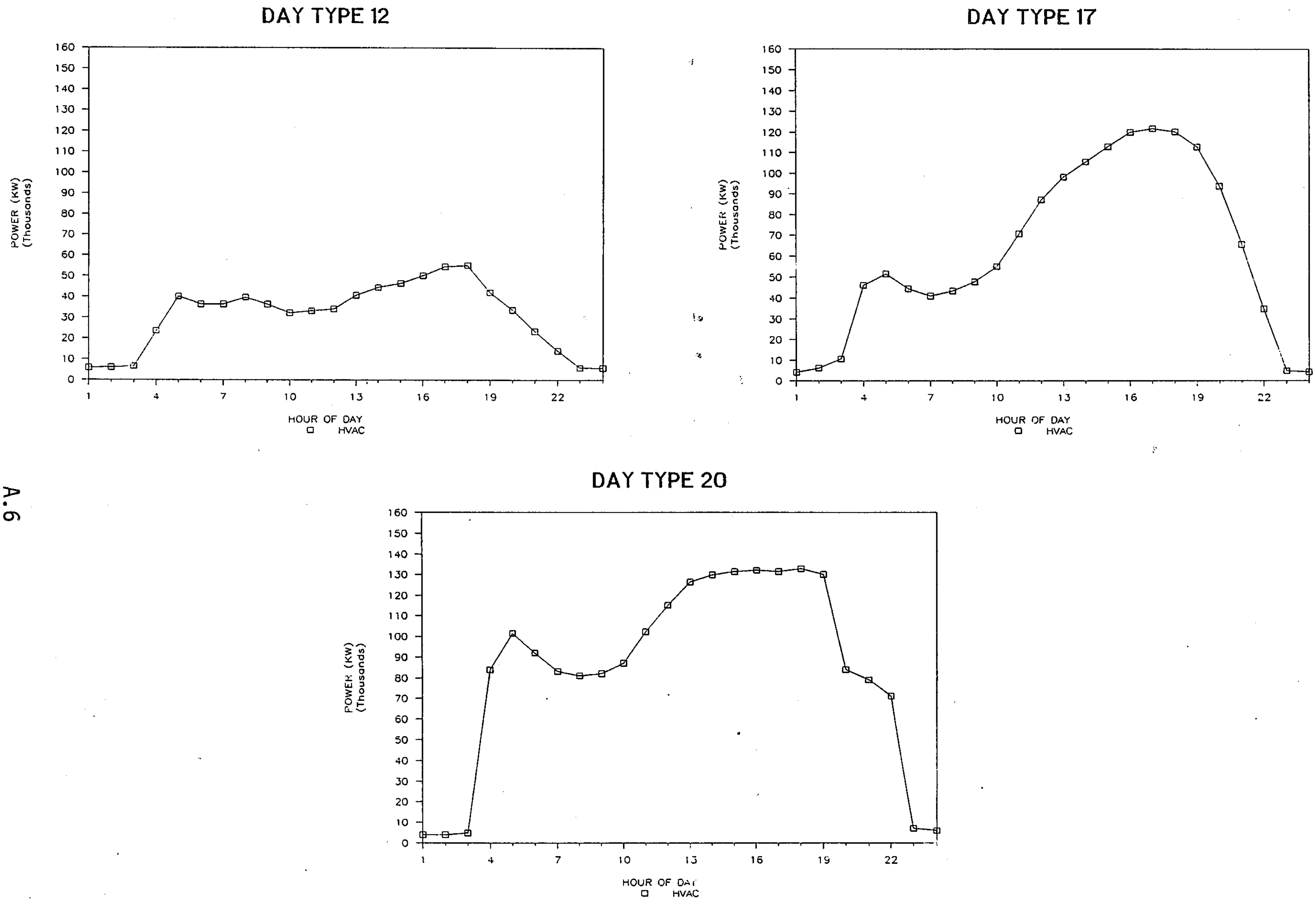


FIGURE A.4. Hourly Load Profile for Building No. 556 (day-types 12, 17, and 20)

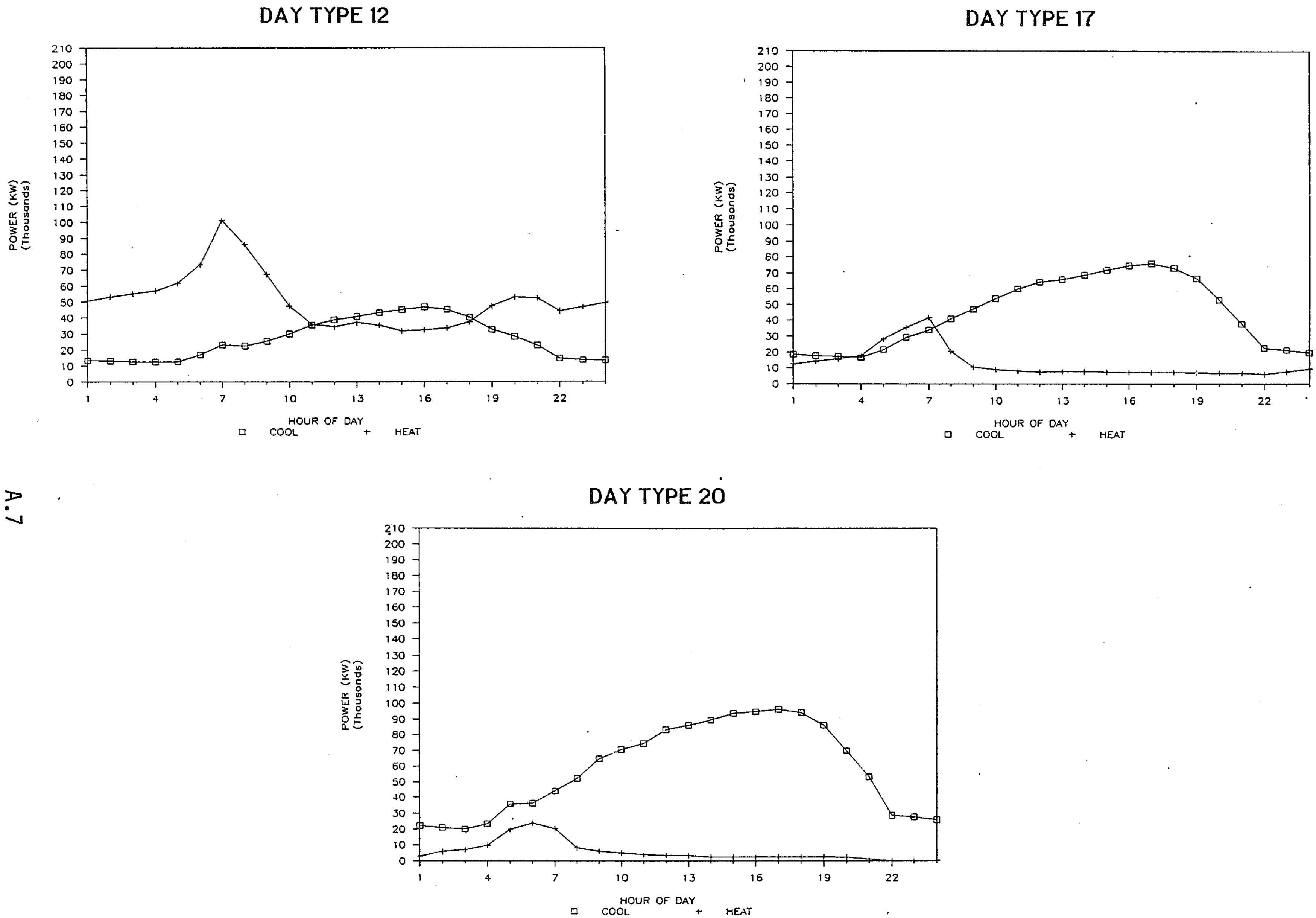


FIGURE A.5. Hourly Load Profile for Building No. 607 (day-types 12, 17, and 20)

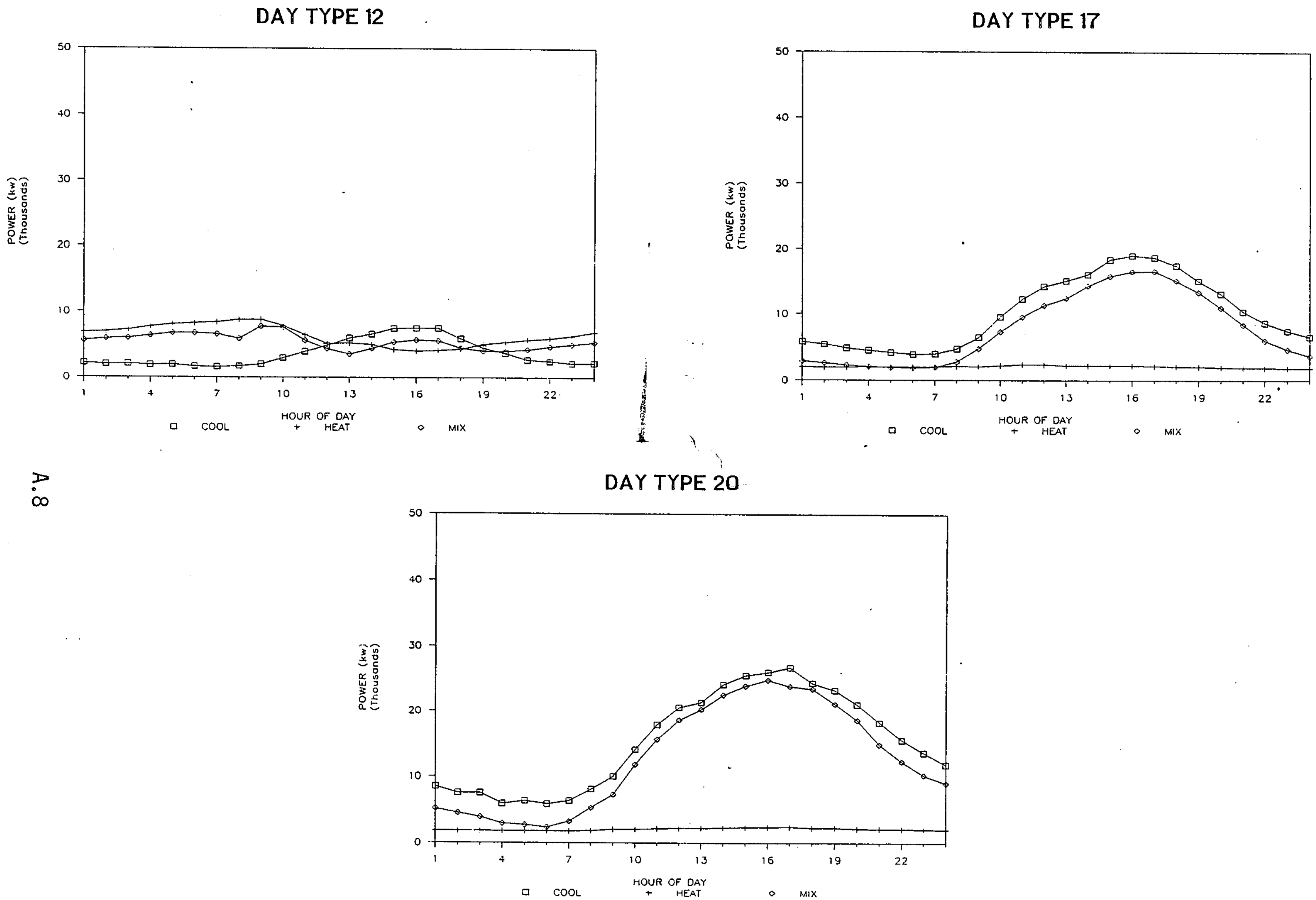


FIGURE A.6. Hourly Load Profile for Building No. 714 (day-types 12, 17, and 20)

APPENDIX B

WEATHER DAY TYPES AND LOAD PROFILES - EUGENE, OREGON

APPENDIX B

WEATHER DAY TYPES AND LOAD PROFILES - EUGENE, OREGON

Because of the generally milder climate in Eugene, there is not as clear a distinction between seasons as found in the more severe climates east of the Cascade Mountain range. As a result, there are fewer weather day types that distinctly represent summer or winter conditions and more of the day types that span a greater number of months. For example, day-type 8 (see Table 3) was found to occur in 10 different months.

Six hourly load profiles for the one commercial building analyzed were selected to illustrate the variation in profiles that occurred (see Figure B.1). This particular building is an older, four-story, drygood retail store located in the downtown area. Because of the uniqueness of the heating system, only the cooling system loads could be analyzed.

Load profiles for two winter day types are shown in Figure B.1. Day-type 1 is the coldest day type represented for Eugene during the winters of 1986 and 1987. This day type occurred on 8 of the days during the November through February period. The cooling profile for this day type indicates a low level of operation of the mixed HVAC system during the daytime. In fact, there was no significant difference in the load profile for the first four day types, even though the mean temperature increased from 0.2°C to 4.2°C (33°F to 40°F).

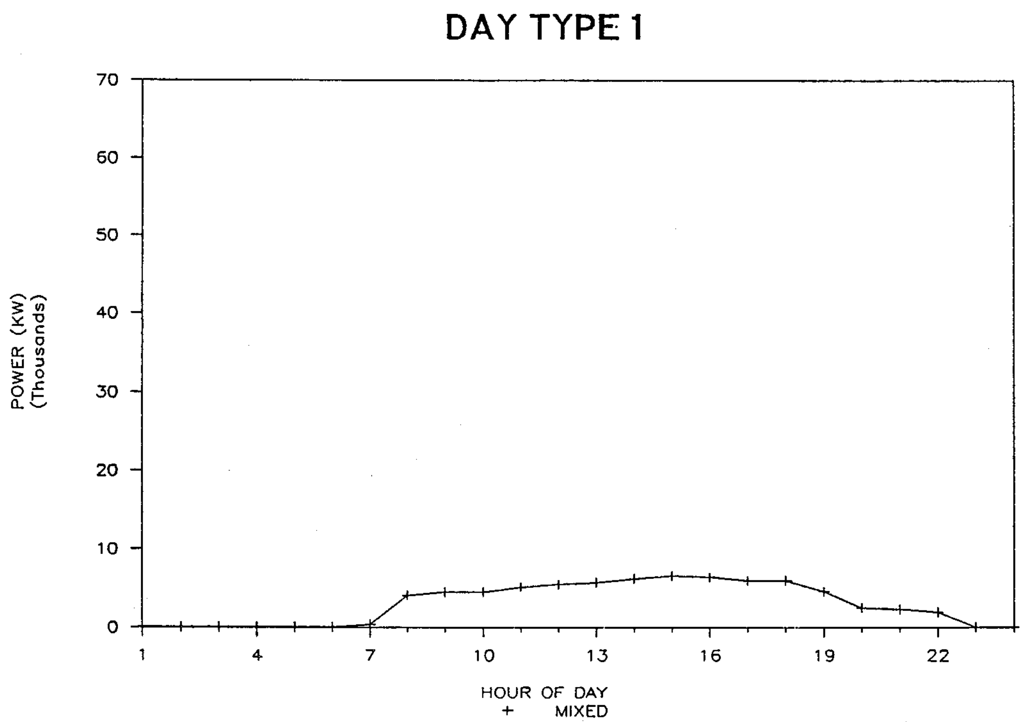
Day-type 7 occurred 31 times during the September through May period, but most frequently in November and February. It is representative of a cloudy, windy, cool fall or warm winter day. Again, a low level of HVAC system operation occurred during the daytime, although the average middle of the day consumption had increased by approximately 60% over day-type 1.

Day-type 11 (see Figure B.2) is representative of transitional season conditions, with mild temperatures and cloudy to partly cloudy skies. The mixed HVAC system appears to have reached the maximum consumption level, allowing the secondary cooling system (chillers) to operate for a 5-hour period during the middle of the day.

Typical summer load profiles are shown in Figure B.3. Day-type 15 occurred in the May through September period (19 days) and is characteristic of the cooler, cloudy, summer days. Peak frequency of occurrence was in July (9 days). The load profile maintains the maximum consumption for the mixed HVAC, while the chiller system is now operating at a lower level during the the 7 a.m. through 11 p.m period.

During day-types 15 through 20, the only change in the character of the load profile is an overall gradual increase in chiller system consumption and the development of the characteristic afternoon peak. Day-type 18 is representative of the warm, sunny summer days that occur in the Willamette Valley.

Day-type 20 is the warmest of the day types occurring during this period and is representative of 20 days during the May through September period. Cooling loads are performing at maximum capacity during this day type, with a strong peak occurring between 1 p.m. and 4 p.m.



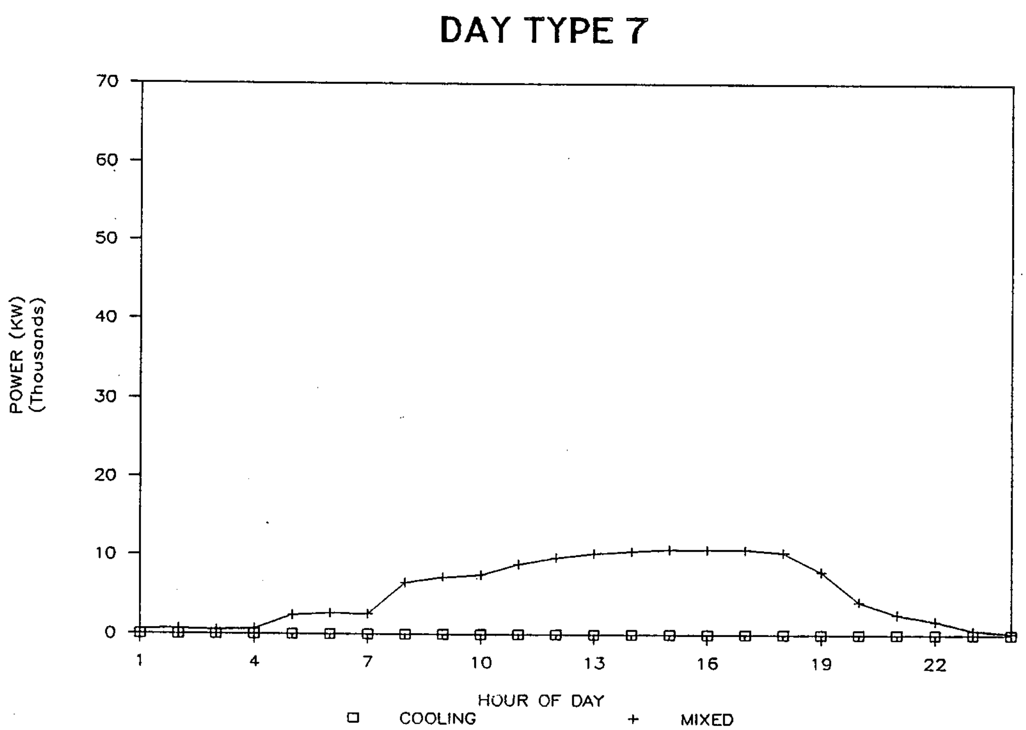


FIGURE B.1. Hourly Load Profile for Building No. 295 (for day-types 1 and 7)

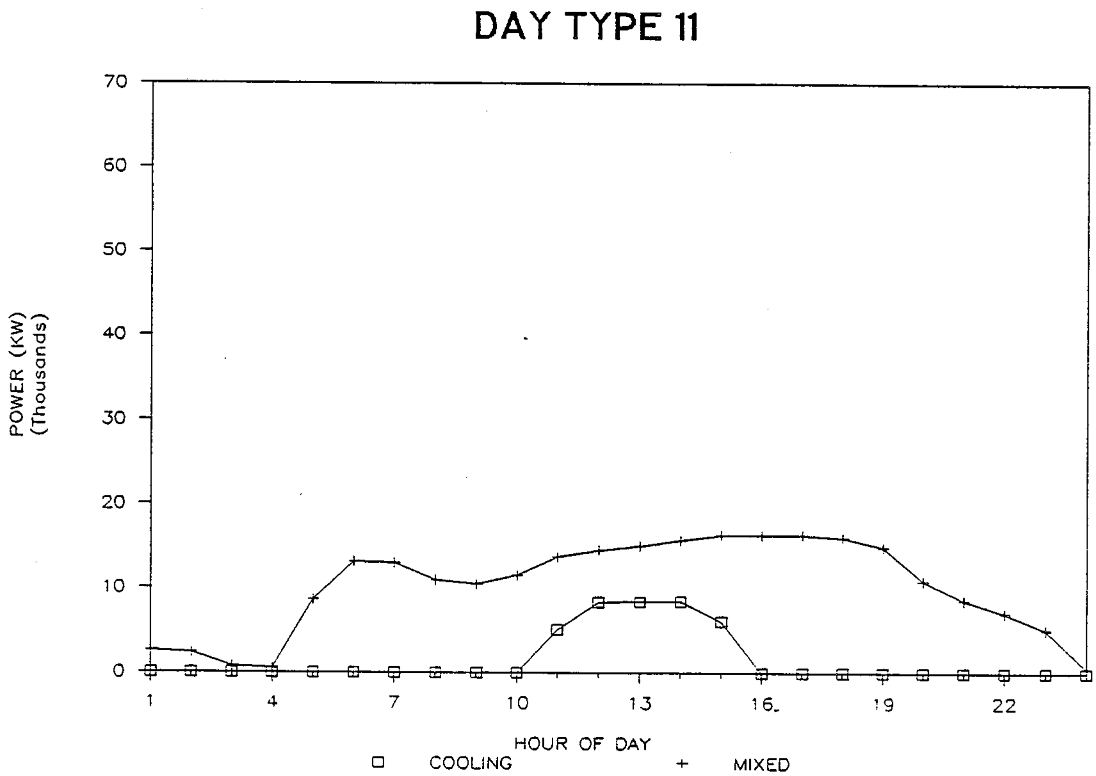


FIGURE B.2. Hourly Load Profile for Building No. 295 (day type-11)

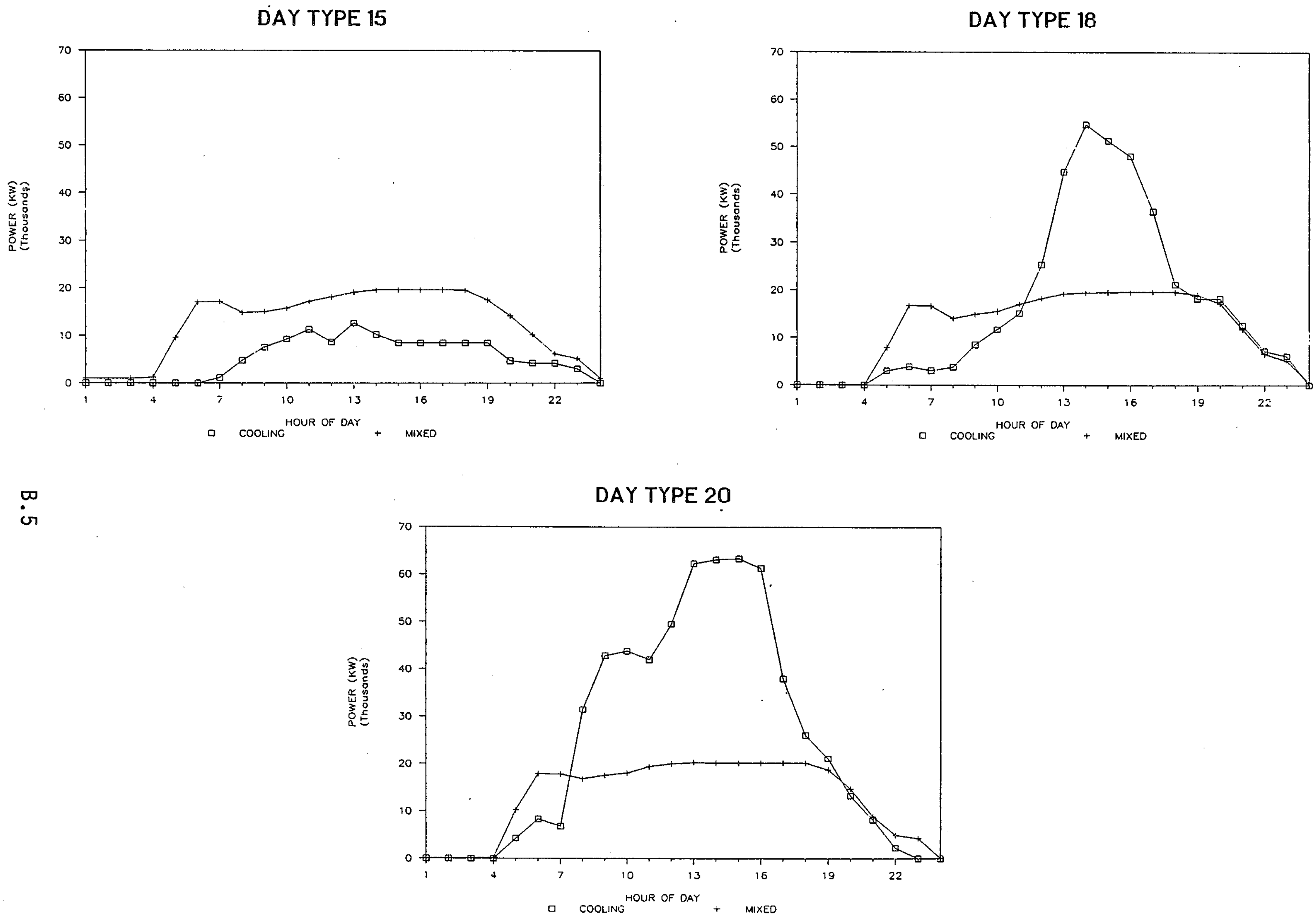


FIGURE B.3. Hourly Load Profile for Building No. 295 (day-types 15, 18, and 20)

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