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**DISTRICT COOLING TECHNOLOGY
CHARACTERIZATION CASE STUDY:
AUSTIN, TEXAS**

FINAL REPORT

**R.T. Coughlan, J.W. Andrews, M. Piraino,
and J.J. Strasser**

JANUARY 1990

**Prepared for the
OFFICE OF BUILDINGS AND COMMUNITY SYSTEMS
UNITED STATES DEPARTMENT OF ENERGY**

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DEPARTMENT OF APPLIED SCIENCE

**BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973**

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Washington, D.C. 20545**

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ASSOCIATED UNIVERSITIES, INC.
UPTON, NY 11973**

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ABSTRACT

This report describes the work performed under Part II of the project entitled "District Heating and Cooling Market Potential and Penetration Study." The project's primary objective is to study the potential of conventional and innovative district heating and cooling (DHC) space conditioning systems in the United States, in particular, those areas with significant heating and cooling load requirements.

Part II entitled "Implementation and Application of the Conceptual Approach," employs the DHC characterization methodology, previously developed in the initial phase of the project, to compare the economic feasibility of selected DHC system types in a specific community. Task 1 of Part II explored a "broad-brush" DHC characterization study of a high-heating load location using Milwaukee, Wisconsin as a case area. This report addresses the completion of Task 2 of Part II which examines the potential of a few selected DHC systems in Austin, Texas, whose climate indicates a large demand for cooling.

The subject matter described in this report focuses on the study of some district cooling technologies in Austin using the DHC characterization computer model developed at BNL. The model was employed to compare the economic viability of selected DHC system types, particularly those involving the production of chilled water and slush ice from cogenerator waste heat. Thermal storage applications were also considered. The annualized delivered energy cost was taken as the economic figure-of-merit.

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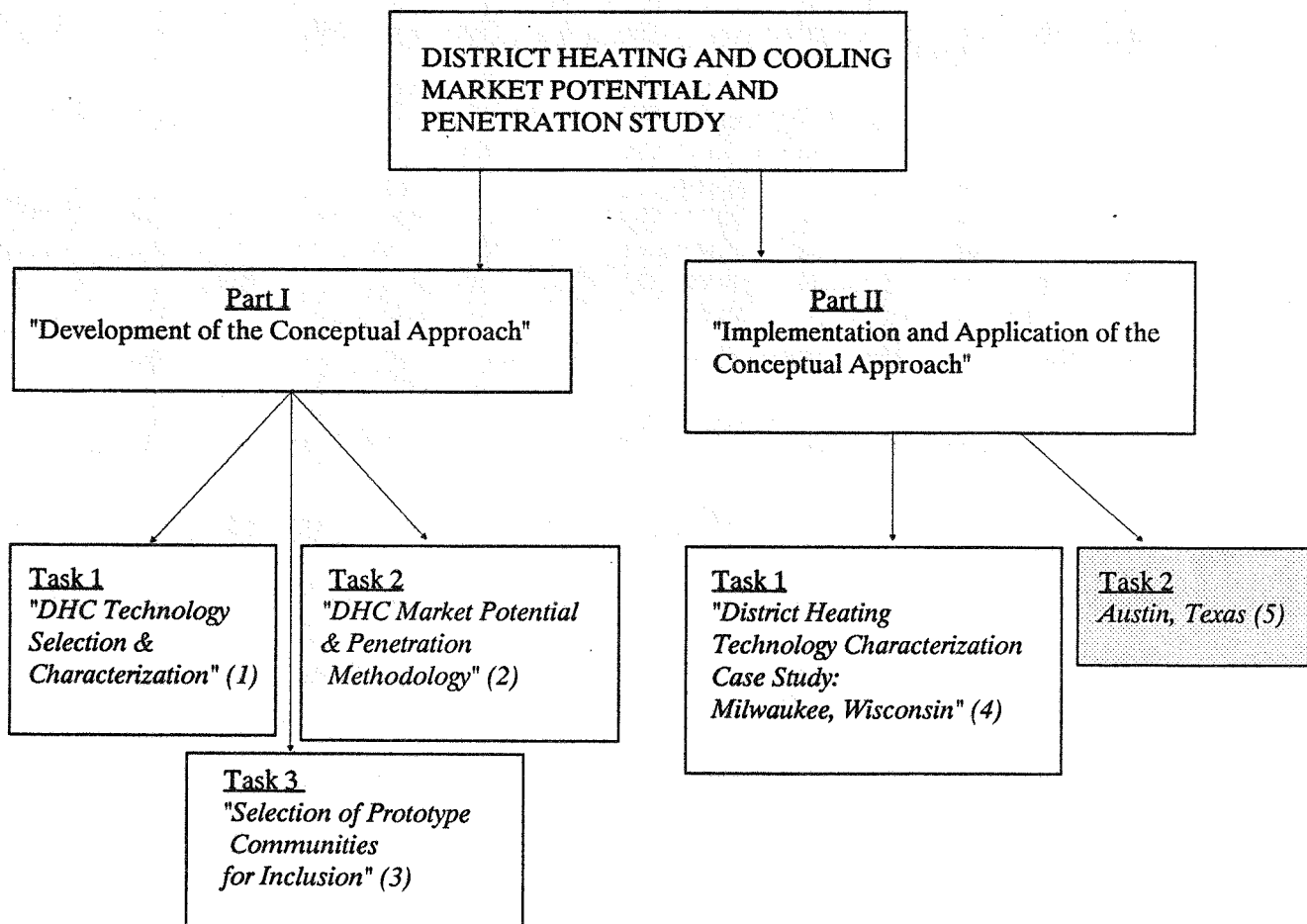
1.0 INTRODUCTION

1.1 Project Overview

This report was performed for the U.S. Department of Energy to describe the work completed under Part II of the project entitled "District Heating and Cooling Market Potential and Penetration Study." The project's primary objective is to study the potential of conventional and innovative district heating and cooling (DHC) space conditioning systems in the United States, in particular, those areas with significant heating and cooling load requirements, and to identify improvements that may enhance DHC potential.

1.2 Scope of Work

The scope of work described in this report involves the completion of Task 2 of Part II, Implementation and Application of the Conceptual Approach, as shown in the flow diagram below.



The work performed and completed under each task is described as follows:

- (1) District Heating and Cooling Technology Selection and Characterization.

A generic DHC model, sufficiently general to represent all the specific systems of interest, was developed. Nine main specific DHC systems were selected for inclusion in the analysis. These systems were then characterized, using a computer model developed for this purpose, in terms of their energy flows and costs for a wide range of load cases. Delivered energy cost was established as a figure of merit to evaluate the feasibility and competitiveness of each system in each load case. The sensitivity of system feasibility to changes in fuel prices, piping costs, and other factors was examined.

- (2) District Heating and Cooling Market Potential and Penetration Methodology.

Market potential and penetration methodologies were surveyed to identify those suitable for assessing the feasibility of DHC systems, i.e., of translating the characteristics of each system to its market response. Each methodology was evaluated in terms of its level of detail, data requirements, costs, and other factors.

- (3) Selection of Prototype Communities for Inclusion in the Study.

Prototypical communities which could serve as the basis of a market study to evaluate opportunities for DHC technologies were screened. Two locations were subsequently identified--one with predominantly high heating loads (Milwaukee, WI), and another with predominantly high cooling loads (Austin, TX). These host communities would ultimately be the subject of work to be performed under Tasks 1 and 2 of Part II.

- (4) District Heating Technology Characterization Case Study--Milwaukee, Wisconsin.

The DHC characterization methodology was employed to assess the feasibility of several district heating system types in a northern region with a high demand for heating. Each DHC system type was characterized, both technically and economically, to define the specific areas within the city which each can best serve. For all cases studied, the annualized delivered energy cost was used as the "figure of merit" by which to compare each different system.

- (5) District Cooling Technology Characterization Case Study--Austin, Texas.

This particular study is based on a southern region whose climatic conditions indicate a high demand for cooling. Austin, TX was identified as a promising location for modeling the feasibility of selected district cooling systems. The characterization methodology, developed in Part I, was employed to compare the economic viability of selected system types, particularly those involving the production

of chilled water and slush ice from cogenerator waste heat. Thermal storage applications were also considered. Delivered energy cost was taken as the economic figure of merit for comparing all systems in the study. The subject matter described in this report focuses on the study of district cooling technologies in Austin, Texas using the DHC characterization methodology developed at BNL. A comparison of the work performed on district heating technologies in Milwaukee, Wisconsin with this current study will also be discussed.

2.0 SELECTION OF PROTOTYPE COMMUNITY

Several communities were identified for DHC analysis based on a set of criteria which was developed to establish their candidacy for this study. Nine cities within the U.S. were initially identified. Each one was evaluated in terms of the following factors: land use database, energy use database, diversity of building stock, regional typicality, and potential for obtaining cooperative participation from key institutions, such as city planning agencies and energy utilities. Following this evaluation process, Milwaukee, Wisconsin was selected as a candidate for a prototype community in which to perform a district heating technology feasibility study. The results of this study are documented in Reference 4. At about the same time that Milwaukee was selected for the district heating study, a search for a suitable location for a companion study of district cooling resulted in the selection of Austin, Texas as the second prototype community. A major selection criterion was the existence of a building energy-use data base, disaggregated by building type and by location within the area to be studied. Although the actual transfer of data has resulted in some initial delay prior to conducting the analysis, it has also provided valuable experience in the type of situation likely to be encountered with real-world localities. Participation from key institutions, such as Austin Electric Utility, has been strong and supportive, which is another important element in the selection of Austin for this study.

From Austin's standpoint, district cooling may play an important role in planning for future growth. Forecasters predict that by the early 1990's, expansion of major commercial centers and new construction in both downtown and other peripheral areas will occur. Such facilities include offices, hotels, retail spaces, and other facilities, all of which are anticipated to have conventional air conditioning systems that employ electric chillers. This unprecedented growth is likely to lead towards increases in cooling loads, which undoubtedly will contribute to peak demand requirements placed on the electric utility.

The concept of district cooling offers Austin a potential solution to this problem. District cooling systems offer advantages over individual building systems by allowing the selection of central sites close to rivers or other low-summer-temperature heat sinks, or sites close to open spaces for cool storage. Further, it has the advantage of reducing chiller costs and costs for cool storage by economy of scale. Additional peaking capacity needed by the city in the near future is expected to be met by use of gas turbines. If used as a major component in a cogeneration system, fuel-use efficiency is enhanced, as waste heat is recovered as a source of thermal energy. This thermal energy can then be distributed to consumers in the form of steam, hot water, or chilled water through pipes. Ice slurry or "slush ice," a homogeneous mixture of ice and water, can also be distributed as a coolant. (In general, the slurry is formed when small quantities of a suitable substance are added to water to act as crystallization cores for ice formation. As heat is extracted from the solution at the central chiller, small ice crystals are formed. This mixture of ice and water can then be pumped and distributed. The advantage of ice slurries is that the lower temperatures of the fluid imply smaller piping for the distribution system, and thus lower capital costs).

Several integrated systems can be examined for their potential applicability. Chilled water, for example, could be produced centrally by any

of several methods -- absorption chillers fired by cogenerator waste heat, compressors driven by steam produced from waste heat, or by electric chillers. Chilled water could then be distributed directly to users at the local level. Rather than chilled water, another alternative is that steam could instead be produced centrally and distributed to users so that chilled water may be produced on site.

Full storage of chilled water or slush ice may also be considered at a central site for distribution to local users, such that the chiller runs during off-peak periods and stores enough cooling to meet on-peak demands. Alternatively, partial storage can be examined wherein the chiller operates continuously to meet a leveled-load. (For more on storage applications, see Section 5.3).

Such options would prove to be of great advantage to provide the additional capacity necessary to meet the needs of new customers for space cooling. This study, therefore, will help Austin to address the nominal merits of selected DHC system types in specific service areas.

3.0 GENERAL DHC TECHNOLOGY CHARACTERIZATION

3.1 General Approach

All district heating and cooling systems have four basic components: the fuel or resource, thermal production, transmission and distribution systems, and an end user or customer. The fuel may be oil, natural gas, heat, or electricity. Municipal waste or coal can also be utilized with other technologies to convert these energy sources into thermal energy.

Depending on community needs, the thermal production system can be either a centrally located facility or several interconnected plants. Numerous technologies are used to meet the thermal loads of a community, including coal and solid waste-fired boilers, internal combustion engines, heat exchangers, and central heat pumps, etc. DHC systems can also rely on cogeneration, the simultaneous production of electricity and thermal energy. Cogeneration is an important process in that it recaptures much of the heat usually lost during electrical generation and uses it directly, or converts it into thermal energy.

The transmission and distribution systems transports thermal energy to end users through a network of pipes. The piping system can be buried directly in the ground, placed in tunnels or located above ground. The thermal energy transported by pipes can be in the form of steam or hot water, chilled water, or slush ice. After reaching the user end, thermal energy is then converted into heat or cold, depending on the application needed.

3.2 BNL Computer Model for DHC Analysis

The concept of developing a model that could characterize different types of district heating and cooling systems stemmed in part from the need to better plan and match the suitability of a particular DHC system to the community it will serve. The computerized DHC analysis model developed at Brookhaven National Laboratory was intended to meet this need. The model serves as a basic planning tool and has two main objectives:

- a) to provide a broad picture of the economic potential of DHC in a specific area, and
- b) to allow comparisons of competing DHC technologies based on their cost-effectiveness.

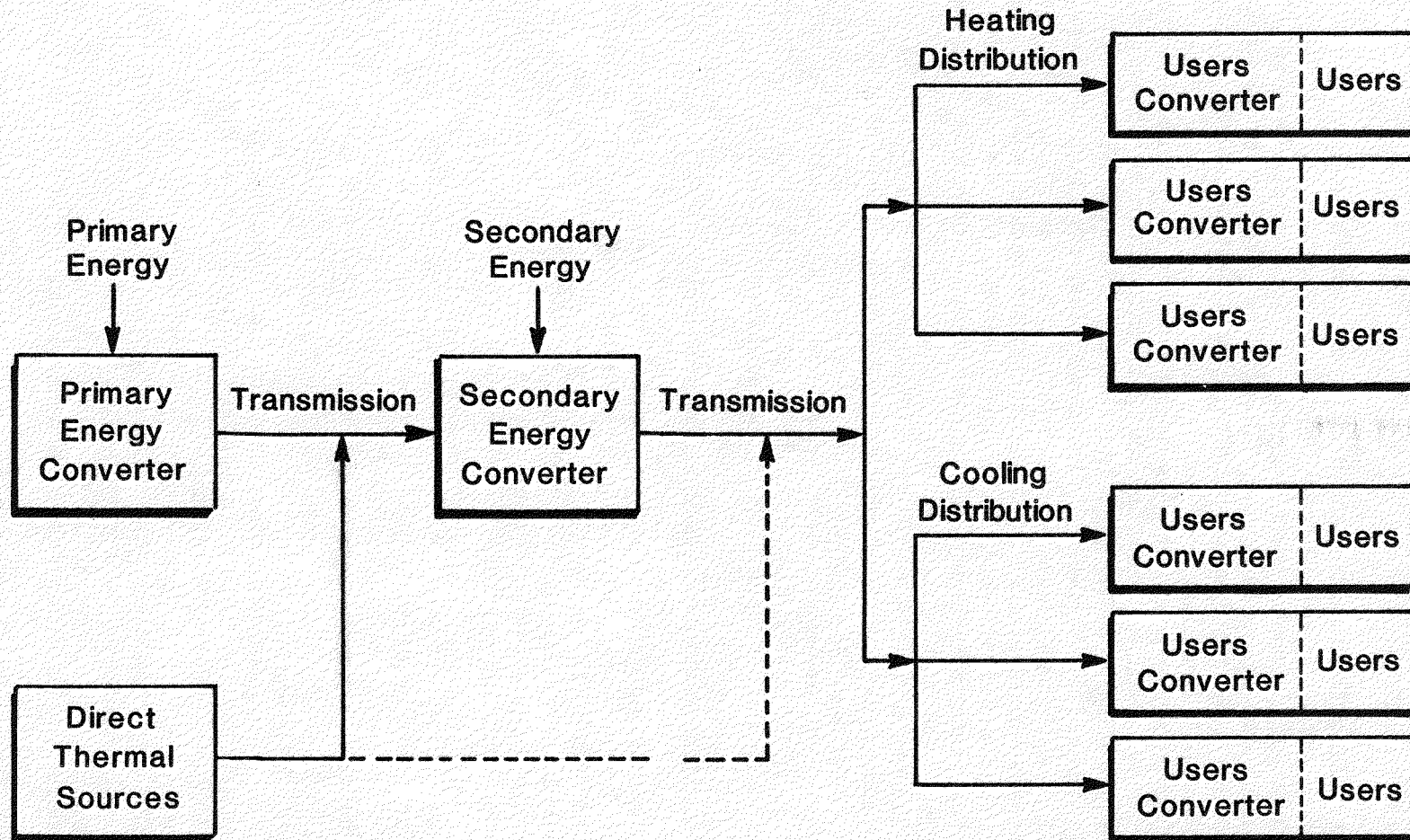
The model is programmed in Fortran, and is operated by a menu-driven program written in Basic. It requires a hard disk drive for operation and runs on an IBM PC or compatible unit.

The basis of this model uses a generalized structure of a DHC system, as typified by the block diagram shown in Figure 3-1. The major subsystems are a primary energy converter (or direct thermal source), a secondary energy converter, a user's converter, and transmission and distribution piping.

The primary energy converter is the central source of heating (or cooling) which is transmitted to the secondary converter. This secondary converter may not be present in all systems, but is included to provide flexibility. In some systems it may actually be near the primary converter, for example, a central

Figure 3-1

GENERAL DISTRICT HEATING/COOLING SYSTEM



absorption chiller that makes chilled water from steam. In others, it may be located farther from the primary energy source, for example, an electric chiller using cool water piped over a distance as a heat sink. It might also consist of a multiplicity of smaller converters distributed closer to the point of use, but still within the DHC system. The user's converter is whatever equipment exists within individual buildings. The user might, for example, have an absorption chiller to make cooling from hot water or steam that is distributed by the DHC system. The alternative, a central chiller with chilled water or slush ice distribution, requires the user at least to have an appropriate heat exchanger.

The sequence of calculations followed by the computer program is shown in Figure 3-2. Each box in the flowchart refers to a single subroutine.

- o READFL and GETPAR are input routines. READFL inputs all data pertaining to the components, including economic assumptions. GETPAR inputs information describing the specific system to be run, including configuration, thermal parameters, and pipe materials.
- o A set of load cases is specified for each system configuration. A load case is a complete description of the thermal load, including building load-duration data and DHC piping layout. The subroutine ITERAT reads data from a load case file that contains processed information concerning the transmission and distribution system layout and the load-duration curve (see below).
- o The next set of subroutines is called once for each energy converter: Beginning with the user's converter, it works upstream, generating a file of load-duration data that specifies the inputs that the given converter must have in order to deliver the required output. In this way, the model works its way in three iterations back to the primary converter, for which the required inputs of fuel, thermal energy, and electricity are derived. OPTPIP or OPTSTM is used to optimize the piping subsystem (if any) upstream of the converter currently being worked on, for water or steam distribution, respectively. THRMLS calculates the thermal losses to the ground. Then the loop returns to ANCCOST to move to the next energy converter upstream.
- o After the third iteration of ANCCOST, SAVEIT saves all the energy flow data and returns to ITERAT to get the inputs for another load case. After all the load cases have been run, the OUTPUT and SUMMARY routines prepare and deliver the output presentation. Calculations required for combined heating and cooling systems are performed, if necessary, by COMOUT.

One example of the versatility of the model is its ability to optimize pipe sizes. All it needs to do this is a blockwise distribution system array such as that shown in Figure 3-3, together with the length and width of a block and the value of the peak heating or cooling load in the area served by the system. To enable the computer to use this information, the concept of levels was developed. A level represents the number of blocks served by a given section of pipe, where a section is defined as a one-block run of pipe, along either the length or the width of the block. For each section of pipe, the question is asked, "How many blocks must be served by the fluid flowing through this section,

Figure 3-2

CHARACTERIZATION PROGRAM FLOW

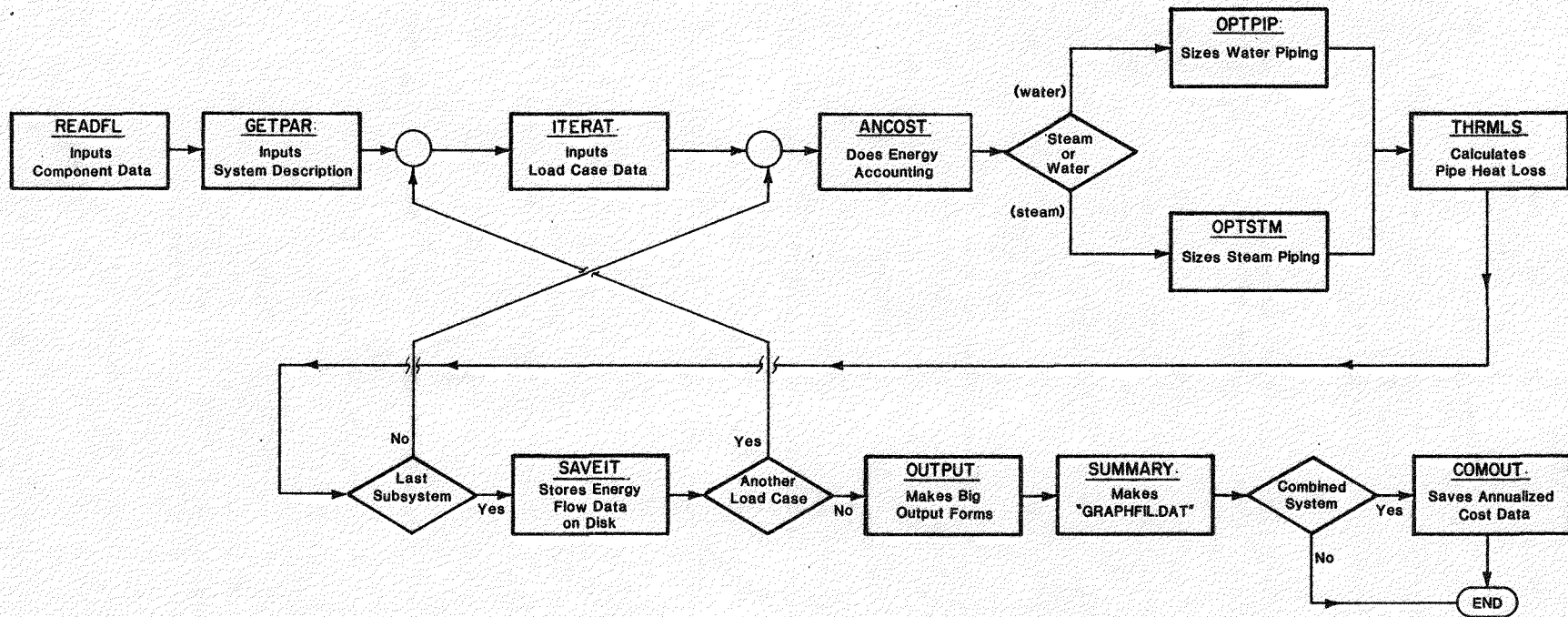
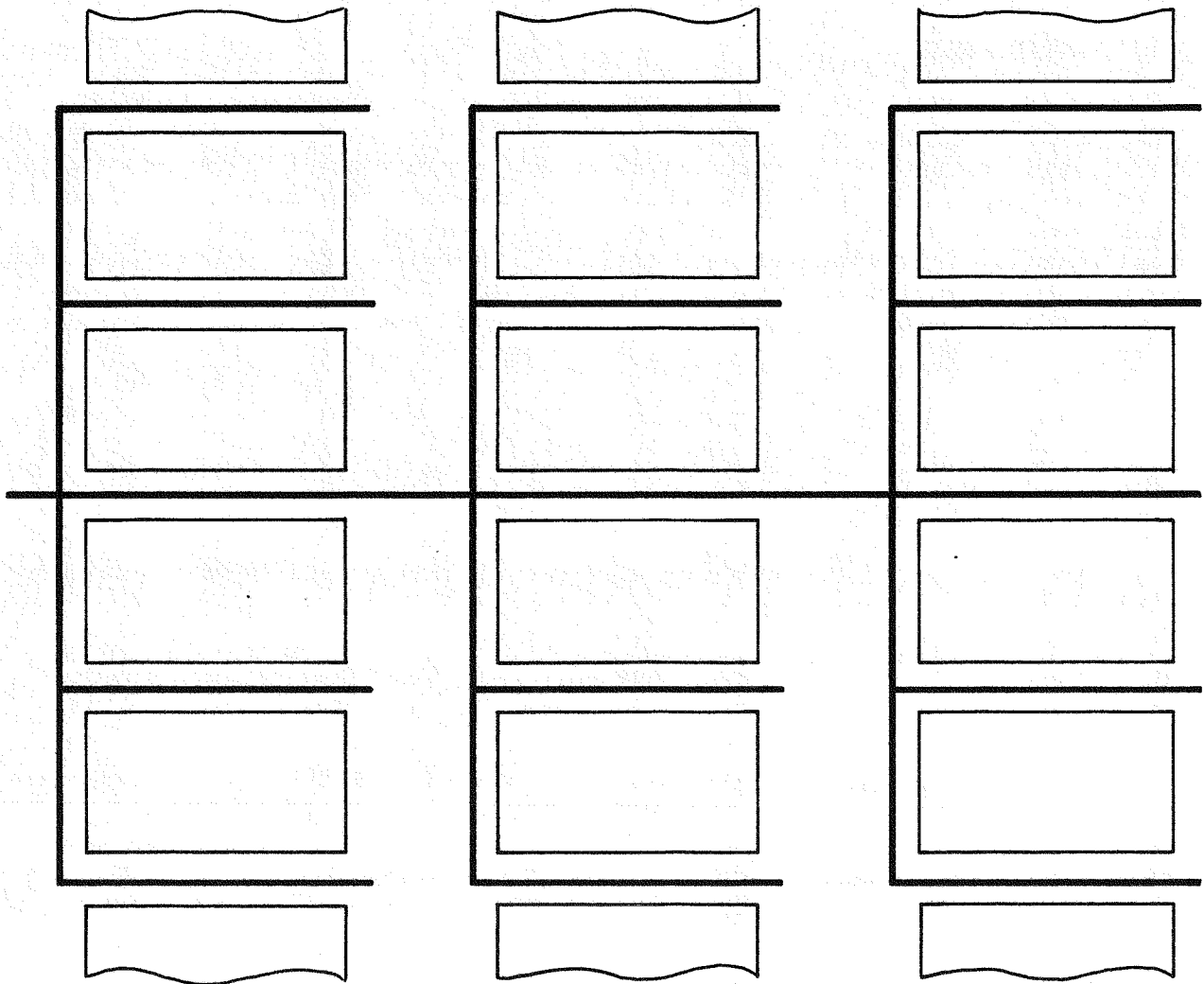


Figure 3-3

DHC PIPING LAYOUT



either directly (through hookups from the particular block where the pipe resides) or indirectly (because the section feeds other sections downstream). In Figure 3-3, it is assumed that all hookups are to lengthwise sections, with pipes laid crosswise serving as connectors only. Thus, of the 15 length-wise pipe sections, 13 are level 1, while one each are level 6 and level 11. Of the 12 crosswise sections, six are level 1 and six are level 2. Giving the number of lengthwise and crosswise sections at each level provides enough information for the program to optimize the sizes of the pipes for the network. This is only one of many examples of the kind of problem that needed to be solved in order to develop a model with a sufficient degree of comprehensiveness.

3.3 Program Inputs

During the course of a run, the model accesses several input files to obtain the needed information regarding the DHC system. The user assembles the characteristics of the desired system by identifying specific elements within the general DHC structure. These choices are selected from menus in various data files (some of which are shown on Figure 3-4). The files can be modified by the user to change component characteristics if need be. The program then links together the specified components, along with other information, such as component cost/performance characteristics, load case characteristics, etc. to conduct individual runs.

Component Cost/Performance Characteristics. DHC component characteristics are described by several data files. The database contains files describing energy converters and piping subsystems. New component types can be added by creating new data files.

For each energy converter data file, the following information must be specified:

- o converter capital cost;
- o converter technical behavior;
- o unit fuel costs.

Converter capital cost is modeled as a linear function of converter size. A nonzero minimum size is usually imposed. Converter technical behavior is described by a matrix of numbers, called Energy Input Factors (EIF) which specify the ratios of input energy of a given type to the output thermal energy of the converter. Five input energy types are considered: oil, natural gas, coal, electricity, and thermal. The EIFs are modeled as the product of linear functions of converter thermal output and temperature. The EIFs may be positive or negative, e.g., to represent cooling or electricity production. Constant unit fuel costs are used.

For each piping subsystem data file, the following information is required:

- o piping unit installed cost;

Figure 3-4

CONVERTER DATA FILE

CONVERTER TYPES-28		WATER DAT		FIXED ANN. MIN.		
NUMBER OF BINS-01		SLOPE		CONST	OP. COST	Ptr. #
CONVERTER TYPE		(\$/Kw)		(\$)	(%)	(Kw)
FLD LN.10	20	29	6	10	10	3
NOTHING			0.0	0.0	2.0	0.0
DIESEL COGENERATOR			272.00	000000.00	2.00	100.0
LOW TEMP. SOURCE			0.00	000000.00	2.00	0.0
10 F TD HEAT EXCHANGER			10.24	0.0	2.0	0.0
SMALL ELEC A/C A,W	C		240.00	0000.00	2.0	7.0
LARGE ELEC A/C A,W	C		200.00	0000.00	2.0	860.0
SMALL ELEC H.P. W,W	C		200.00	0000.00	2.0	7.0
LARGE ELEC H.P. W,W	C		160.00	0000.00	2.0	860.0
SMALL GAS-FIRED A/C A,W	C		335.00	0000.00	2.00	100.0
LARGE GAS-FIRED A/C A,W	C		295.00	0000.00	2.00	860.0
SMALL GAS-FIRED H/P W,W	C		295.00	0000.00	2.00	100.0
LARGE GAS-FIRED H/P W,W	C		255.00	0000.00	2.00	860.0
SMALL S.E. ABS. CH. A,W	C		359.5	-654.00	2.00	10.0
LARGE S.E. ABS. CH. A,W	C		190.00	580000.00	2.00	347.0
SMALL D.E. ABS. CH. A,W	C		359.5	-654.00	2.00	10.0
LARGE D.E. ABS. CH. A,W	C		211.00	913000.00	2.00	747.0
SMALL HYBRID SE W,W	C		293.00	-654.00	2.0	418.0
LARGE HYBRID SE W,W	C		244.00	-654.00	2.0	1042.0
SMALL HYBRID SE W,A	C		367.00	-654.00	2.0	284.0
LARGE HYBRID SE W,A	C		317.00	-654.00	2.0	1103.0
COGEN/S S.E. ABS CHILLER			731.87	-654.00	2.0	100.0
COGEN/L S.E. ABS CHILLER			562.37	580000.00	2.0	347.0
COGEN/S D.E. ABS CHILLER			731.87	-654.00	2.0	100.0
COGEN/L D.E. ABS CHILLER			472.66	913000.00	2.0	747.0
SMALL GAS TURBINE COGEN.			1459.50	-162.00	2.0	500.0
LARGE GAS TURBINE COGEN.			868.50	-22.00	2.0	4000.0
SMALL STM.DRIVEN CHILLER			324.50	120800.00	2.0	10.0
LARGE STM.DRIVEN CHILLER			780.20	398000.00	2.0	1000.0

RATE TYPE		RATE (\$/KwH)		
OIL	0.0177	.0177	.0229	.0269 (W#6, W#2, R#6,R#2)
GAS	0.0023	.0050		(W,R) W- WHOLESALE
COAL/GARBAGE	0.0085-	.0075		R- RETAIL
ELECTR.	0.0000			
THERMAL	0.0000			
SELL RATE ELECT.	0.0023			

1
03 LOW TEMP. SOURCE 0.0

NUMBER OF COEFFICIENTS-28

Q(LOAD)-DEP T-DEP

CONVERTER-01	
0. 0. 0. 0.	FUEL OIL
0. 0. 0. 0.	NATURAL GAS
0. 0. 0. 0.	COAL
0. 0. 0. 0.	ELECTRICAL
1. 0. 0. 0.	THERMAL

CONVERTER-02	
2.0 0. 0. 0.	
0. 0. 0. 0.	
0. 0. 0. 0.	
- .6502 0. 0. 0.	

PIPES DATA FILE[illegible]

ELECTRIC RATE FILE

RATE DATA FOR AUSTIN - General Service Demand Rates

00.0	0.039	0.0	(SN)	M - Monthly Charge (\$)
00.0	0.058	7.31	(SD)	K - Kwh Charge (\$/kwh)
00.0	0.031	0.0	(WN)	D - Demand Charge (\$/kw)
00.0	0.051	6.29	(WD)	
M	K	D		

- o piping thermal conductivity;
- o pipe burial depth.

Piping characteristics depend not only on pipe type and size, but also on the nature of the site where the pipe is installed. Accordingly, four "installation classes" have been defined. The piping technical behavior, including its flow resistance and thermal losses, is computed by the program based on data files which specify the thermal conductivity and depth.

Load Case Characteristics. The performance of a DHC system variation depends on the geographical arrangement, size, and time-dependence of its thermal load. The characterization program requires two types of information about each load case examined:

- o transmission/distribution pipe length (based on level and number of users);
- o building load/duration curve (based on building type, local climate, or based on available energy-use data).

The geographical arrangement of the thermal load determines the lengths and structures of the transmission and distribution subsystems. These consist of one or more levels of not necessarily contiguous lengths of pipe which serve the same number of users. This means that when a system is operating at a given load fraction, the fluid flowrates for all pipes in a given level are the same. The program requires the total length of pipe for each level and the number of buildings served by each level. The only information about the load that is required to obtain this information are the locations of the individual buildings and the layout of the pipes connecting them.

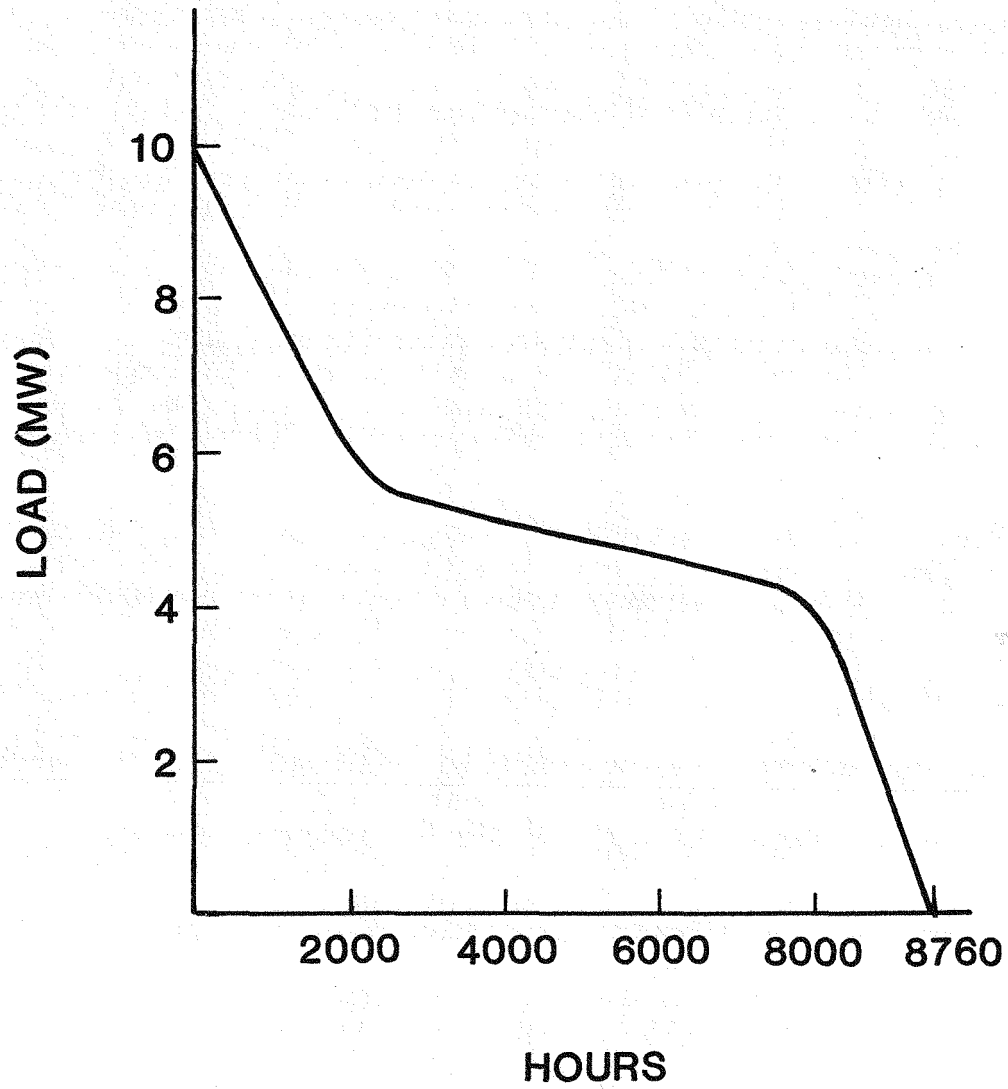
The thermal description of the load is specified by a building load/duration curve, i.e., a list of instantaneous thermal demand per building versus the number of hours of that demand per year. A typical load duration curve is shown in Figure 3-5. In this hypothetical example (in which the load could be heating, cooling, or electrical), the peak load is 10 MW. Except for this peak, the load profile is reasonably well behaved. For 6000 hours of the year (8000-2000) the load is between 4 MW and 6 MW. The spike below 2000 hours represents capacity that must be present to serve the load, but which is used only a small fraction of the time. The downsloping portion of the curve above 8000 hours represents underutilization of the base-load capacity.

Other Miscellaneous Information. The program requires certain miscellaneous information:

- o capital recovery factor for economic analyses;
- o ground temperature;
- o transmission fluid temperature, temperature drop;

Figure 3-5

LOAD-DURATION CURVE



- o distribution fluid temperature, temperature drop;
- o other.

The capital recovery factor (CRF) is the fraction of capital cost allocated annually to energy delivery. An average ground temperature is required to compute piping thermal losses. Fluid temperatures and temperature drops determine fluid flow rates and frictional losses. The fluid temperature information is inputted by the user.

3.4 Program Calculations

Component Sizing. Given the load case thermal requirements and the selected DHC system component types, the characterization program first determines the size of each DHC system component. The calculation process begins with the User converter, stepping backward through the system to the primary converter. The maximum demand of an individual user, given by its load/duration curve, determines the required capacity to the User subsystem. The fuel consumed and the energy required from the distribution subsystem are then calculated using the EIFs of the user converter.

For water-based distribution systems the program selects the piping size for each level of the distribution subsystem which minimizes its total annualized cost, taking into account installed piping cost and pumping energy cost. Steam systems are optimized by selecting the smallest piping size at each level consistent with a preset maximum total system pressure drop and pressure drop/unit length.

Once the distribution subsystem pipe sizes are known, the associated thermal losses and the demand on the secondary converter can be calculated. The secondary converter, transmission subsystem, and primary converter are sized analogously to the user converter and distribution subsystem.

Energy Calculations. Once all components are sized, the program computes all instantaneous energy flows for each bin of the load/duration curve. These flows are multiplied by the corresponding hours of operation of each bin and summed over all bins to yield the total annual energy flows. An energy balance is performed on each system component to check these calculations.

Economic Calculations. All annual energy costs are computed from the annual fuel use totals and corresponding unit fuel costs. Revenue from cogenerator electricity sales is treated as a negative energy cost. The capital cost of each component is computed based on its size, according to the component characteristics specified in the component data file.

Annualized cash flows are then computed by component and by cost source (e.g., energy, capital, electricity sales). The annualized cost, A_j , associated with each system component is given by

$$A_j = E_j + \text{CRF} \times C_j \quad (1)$$

where

E_j is the energy cost associated with j 'th component,
CRF is the capital recovery factor,
 C_j is the capital cost of the j 'th component.

The total annualized delivered energy cost, A , is then the sum of the costs associated with each component:

$$A = \sum_j A_j = \sum_j (E_j + \text{CRF} \times C_j) \quad (2)$$

The annualized delivered energy cost per unit energy delivered is taken as the economic figure-of-merit of each DHC system. The program computes annual cash flows using a real (after inflation) annual discount rate, i , assuming an amortization period of n years, and constant (after inflation) fuel costs. The CRF is the inverse of the present value of an annuity of \$1/year:

$$\text{CRF} = \frac{i}{1 - (1+i)^{-n}} \quad (3)$$

For this study, the discount rate was assumed at 6%, with an amortization period of 12 years. Thus, the capital recovery factor is 12%. Income taxes and depreciation were not considered.

3.5 Program Outputs

Outputs which follow a program run apply to one load case at a time only. The printout sheet summarizes the particular district cooling system selected, and describes each component in terms of energy and costs incurred.

First, the output form reviews the configuration of the system and the characteristics of the load case. The transmission and distribution subsystems and the load/duration data are identified by descriptive titles which come from the data files. Also included are the maximum outputs of each of the converters and the number of branches, or users, that the distribution system serves.

Next, the output shows the result of the pipe optimization routine, and selects the pipe diameter which gives the minimum annualized cost. Annualized cost for both transmission and distribution piping subsystems are given.

Following this, information on the system energy flows is displayed to show the energy transferred from one component of the DHC system to another. These tabulated values also give the costs associated with the inputs and revenues associated with the outputs.

An energy balance is then performed as a check that all energy flows have been accounted for. All inputs (fuel, electric and thermal) are subtracted from the outputs (thermal and electric) to get the net energy flow for each component.

Finally, annual costs and revenues for each component subsystem are shown in terms of energy purchased, electricity sold, operating costs, and capital costs. Then cash flows are divided by the total energy delivered to the user to obtain the annualized delivered energy cost.

4.0 THE PROBLEM OF VARIANT CITY DATA

4.1 BNL Experience with Milwaukee and Austin Data

As mentioned in previous sections, the basic approach in performing the DHC analysis on specific communities calls for a definition of the load characteristics of the district, based on given land-use and energy-use data. This information needs to be sufficiently detailed to enable a load-duration curve to be developed.

The Milwaukee and Austin experience illustrates how very different types of data may have to be used to arrive at the load-duration curve. The city of Milwaukee has very good data on its building stock, disaggregated both by location and by building type. The city map was broken into a grid system such that each cell in the grid is one-quarter of a square mile in area. Within each of the 430 one-quarter square mile cells, the total square footage of building stock is given for each building type and size category.

Two additional inputs are needed to translate this information into a load-duration curve. The first is bin weather data, which gives the number of hours in the year that the outdoor temperature falls within each 5 F temperature interval. The second is a function that translates the outdoor temperature into a heating load. This function was assumed to be linear, in the form

$$\text{Heating Load} = A + B (65 - T) \quad (4)$$

where T is the outdoor temperature, and A and B are coefficients. If the design temperature is T_{des} , then the peak load is given by

$$\text{Peak Load} = A + B (65 - T_{\text{des}}) \quad (5)$$

Generally, there is some temperature T_{bal} , called the balance point, where the heating load drops to zero. This is usually considered to be about 5 F below the setpoint for small, moderately insulated buildings and lower for better insulated small buildings and for most larger buildings. If T_{bal} is known, then one can write

$$0 = A + B (65 - T_{\text{bal}}) \quad (6)$$

Equations 5 and 6 then allow the coefficients A and B to be determined.

In the case of Austin, actual load data was more readily available. Here, we were given a city map converted to a grid system consisting of a square matrix of 120x120 cells. Total monthly electric-use data for residential and commercial buildings for each of the cells were also provided. However, cooling loads for these cells were not given, so a means of relating electrical load to cooling load was required. This was done using additional test data provided by Austin. This new information then enabled us to construct a load-duration profile for each of the given cells.

Our experience to date with these participating municipalities has shown that land-use and energy-use data, when it exists, varies widely from city to city, as each city differs in the type of data it gathers and the format in which this data is available. This routinely becomes a problem when inputting new sets

of data for the model. The computer program must continually be modified to accept and work with each city's database information to create an appropriate load-duration curve. Currently, the model has been set up to accept two specific sets of information such as that for Milwaukee and Austin (see Figure 4-1).

It would be unrealistic to expect all cities to have exactly identical formats for land and energy-use information, much as it would be a major undertaking to construct general algorithms for the computer program to accept varying data sets from all cities. The problem of variable data then becomes a limiting factor as it necessitates time and involvement to sort out each new city's data set. This was indeed encountered in handling the new data for Austin.

4.2 Summary of Austin Data

Data on land- and energy-use which represented the Austin community were required prior to initializing the study. Although the data provided was formatted similarly to the data from Milwaukee, there were enough differences between them to necessitate writing an entirely new routine to accept and manage the information from Austin. The following sets of data were provided by Austin Electric Utility:

1. A city map broken into a 120 x 120 grid system. This gives a square matrix of cells, each being 1/16th of a square mile in area (each cell is 1/4 the size of a cell in Milwaukee).
2. Total monthly electric use for all cells (for both residential and commercial customers). Each cell was characterized by its coordinates within the matrix, the number of residential and commercial customers, monthly electricity use and total annual use in kwh.
3. Metered hourly A/C data and total electric use data for a representative residential and commercial building. Cooling load ratios were then calculated for each month for both types of buildings.
4. Miscellaneous: Gas rate schedule, electric rate schedule, etc.

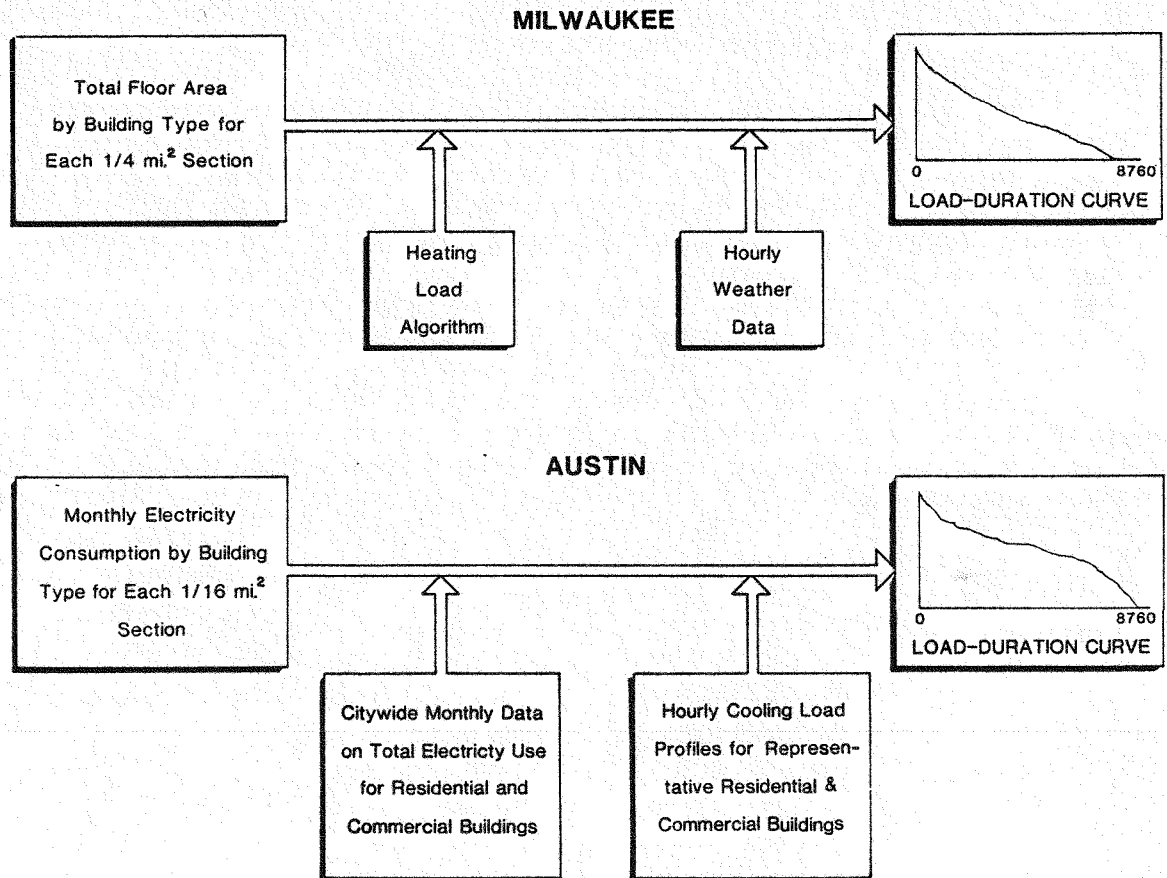
All data for cells within the territory were stored on 5 1/4" floppy disks and transferred to BNL for data reduction.

The first step in preliminary data reduction was to "boil down" the data through elimination of all cells with no customers or no electric loads. This procedure cut down the amount of data in the set by neglecting cells with zero fields. The following step was to modify the Austin grid system to a 60 x 60 matrix rather than the original 120 x 120. This was done because total loads for each 1/16 mi² cell were too low to work with. Therefore, groups of four cells (two across and two below) were merged to form one cell (each now 1/4 mi²). A new coordinate system was then developed and totals for number of customers and electricity use was determined for each cell.

In order for the computer model to access the DHC needs of a given area, its load-characteristics must first be defined by way of a load-duration curve. Thus, cooling load profiles for each of the cells were needed. Since the only information we had for each individual cell pertained to total monthly electric

Figure 4-1

BUILDING-LOAD DATA COMPARISON



use, a method was needed to get the electric use due to cooling. This was accomplished by using Austin test data.

Test data from Austin Electric was in the form of metered, hourly cooling power and total electric power usage for a residential customer for each day in each month of the year. For a representative commercial customer, hourly cooling and total electric power usage for a typical day in each month was given. Both sets of data were for 12 months of the year. (In order to use the commercial data, an assumption was made that the hourly profile for a typical day of the month was true for every day of that month.)

Then, the total cooling power and total electric power for each month was calculated for both residential and commercial buildings. This gave us a representative cooling ratio for each month of the year, which we then multiplied by each cell's total electric use to obtain an approximate measure of each cells's cooling usage for each month.

Through this method, hourly cooling ratios for each month were calculated from the representative commercial and residential building data. This information then gave us hourly cooling kwh for each of the cells when multiplied by each cell's monthly electric use total. An average COP of 3.0 for air conditioning units was used as an assumption to determine the actual amount of heat removed from buildings, or the actual cooling load. The total hourly cooling load for each residential and commercial customer in that cell was then summed, and a maximum peak load was determined through an iteration routine.

Finally, the peak load was divided into ten equal binned loads such that the hours are totaled in which a given binned load is used. It is this binned load versus the number of hours that load is used which finally constructs our load-duration curve.

5.0 DHC SYSTEMS EVALUATION

5.1 General District Characteristics and List of Assumptions

Prior to each run, the district must be defined in terms of physical size, the number of blocks, average block length and width, etc. The DHC system which serves the district must also be defined in terms of the types of energy converters used, its thermal performance, type of distribution piping used, temperature of distributed fluid, type of thermal load, etc. Miscellaneous data files which need to be used are also required. Such information is readily accessed with a "casefile sheet" shown in Figure 5-1. The sheet represents a menu of items which describes the profile of the particular run in terms of the above-mentioned criteria. The profile is then changed by substituting new values or by defining new data files to perform another type of run.

There are several parameters that must be assigned values in order to completely perform each DHC run. In most instances, these values were assigned using source information from reference material, handbooks or through consultants. Other instances called for the use of engineering judgment whenever this sufficed.

For the Austin study, the following general assumptions were utilized:

District Description

Average block size:	660' x 320'
District size:	30 blocks (approx. area of 1 cell)
Type of buildings:	Residential and Commercial
Type of thermal load:	Space Cooling
Summer months:	May-October
Peak load hours:	9 am - 9 pm

Fuel Rates - (Exists in converter data file)

Natural Gas:	0.0023 \$/kwh (Electric cogeneration rate)
Electricity Sell Rate:	0.0023 \$/kwh (Assumed same as gas purchase price)

Electricity Rates - (Exists in rate file)

	<u>Energy charge</u>	<u>Monthly charge</u>	<u>Demand charge</u>
Residential			
Rates: Summer off-peak	0.079 \$/kwh	-	-
Summer on-peak	0.079 \$/kwh	\$3.00	-
Winter off-peak	0.059 \$/kwh	-	-
Winter on-peak	0.050 \$/kwh	\$3.00	-
General Service Demand			
Rates: Summer off-peak	0.039 \$/kwh	-	-
Summer on-peak	0.058 \$/kwh	-	7.31 \$/kwh
Winter off-peak	0.031 \$/kwh	-	-
Winter on-peak	0.051 \$/kwh	-	6.29 \$/kwh

Figure 5-1

MASTER CASE FILE NAME:
CASEFIL.TMP

CASES OF INTEREST WITH TRANSMISSION/DISTRIBUTION INSTALLATION CLASSES:

BLDG/ACRE	PEAK LOAD (KW) OR CELL NUMBER			
	2473	2455	6775	10603
* 0.10	33	22	22	21
* 0.75				
* 3.0				
* 7.5				
* 15.0				

LOAD RATIOS (# OF CASES AND A/B RATIO VALUES FOR EACH) A/B NOT NEEDED FOR AUSTIN:

1
10

LOAD TIME OF DAY (# OF CASES AND VALUES - ALL DAY(A) OR ON-PEAK ONLY(O)):

1
A

LOAD DURATION CURVE DATA TYPE (WEATHER=1, POWER CONSUMPTION=2):

2

DISTRICT DESCRIPTION (# BLOCKS, BLOCK LENGTH(FT), WIDTH (FT)):
30,660,320

TRANSMISSION SYSTEM LENGTH (FT):

1

SYSTEM DESCRIPTION:

```

CONVERTERS (PRIMARY,SECONDARY,USER).....: 5,1,4
PIPE TYPE (TRANSMISSION,DISTRIBUTION).....: 5,5
FLUID TEMPS(F) (PRIMARY,TRANSMISSION,DISTRIBUTION).....: 0,42,42
FLUID LATENT HEAT (TRANSMISSION,DISTRIBUTION).....: 0,0
FLUID VISCOSITY (DEFAULT=0) (TRANSMISSION,DISTRIBUTION)...: 0,0
TEMP DROPS(F) (TRANSMISSION,DISTRIBUTION).....: 10,16
SUMMER ELECTRIC RATE MONTHS (BEGIN,END).....: 5,10
COAL OR GARBAGE (C OR G).....: G
OIL RATE (WHOLESALE (W) OR RETAIL (R)).....: W
OIL GRADE (2 OR 6).....: 2
AUTOMATIC PIPE SELECTION (Y).....: Y
SERVICE (COOLING(C) OR HEATING(H)).....: C
COOLING/HEATING PEAK LOAD RATIO.....: 1
TRANSMISSION FLUID (STEAM (S) OR WATER (W)).....: W
DISTRIBUTION FLUID (STEAM (S) OR WATER (W)).....: W

```

ELECTRIC RATE FILE NAME:

RATEAUST.DAT

CONVERTER COST/PERFORMANCE FILE NAME:

WATER.DAT

LOAD DURATION SOURCE(S), EITHER WEATHER DATA OR RESIDENTIAL, COMMERCIAL
COPRES3.DAT, COPCOMM3.DAT

PIPING SYSTEM PARAMETER FILE NAME:

PARPIP.DAT

END OF FILE

Pipe Costs - Installed cost (in \$/ft) based on type of pipe, pipe diameter, and construction situation (installation) are tabulated in a separate pipe file (see Appendix).

Converter Costs - Exists in converter data files. Converter costs are represented as linear functions $[y = mx + b]$ of the converter capacity, given in the following format:

$$\text{Capital Cost} = \text{greater of } [(\$M \times \text{Capacity}) + \$B] \text{ or } [\$Z] \quad (7)$$

where \$M and \$B are the slope and intercept of the linear function, and \$Z is the cost of the minimum capacity imposed for that converter.

A linear function does not apply in many cases since it cannot show economies of scale. However, if different straight-line functions are defined for different capacity ranges, with a lower size limit defined for each line, then the cost-vs-capacity linear model would be more acceptable. Thus, for energy converters that are described by two different cost-vs-capacity functions, the units are distinguished by the terms "small-scale" and "large-scale." Fixed annual operating costs are assumed to be 2% of the converter capital costs.

5.2 Selected District Cooling Systems

In cooperation with the City of Austin Electric Utility Department, six generic district cooling system types have been identified for inclusion in the analysis. All of the systems below were to be compared against a baseline non-district case consisting of individual building electric chillers (Figure 5-2). The selected systems are as follows:

- o An electric chiller using available low-temperature water (70°F) as a heat sink (Figure 5-3). Town Lake and Lake Austin, which are impoundments of the Colorado River located near the downtown area, are potentially available heat sinks.
- o On-site absorption chillers driven by hot water or steam derived from a cogenerator (Figure 5-4).
- o A central absorption chiller driven by hot water or steam derived from cogenerator, with chilled-water distribution to the buildings (Figure 5-5).
- o A central steam-driven vapor-compression chiller, working from cogenerated heat, with chilled-water or slush ice distribution to the buildings (Figure 5-6). This is a variation of the previous system.
- o A central electric chiller, with chilled-water or ice-slurry distribution, with storage at the users' facilities (Figure 5-7).
- o A central electric chiller and storage, with chilled-water or ice-slurry distribution (Figure 5-8).

Figure 5-2

BASELINE CASE = INDIVIDUAL BUILDING ELECTRIC CHILLERS

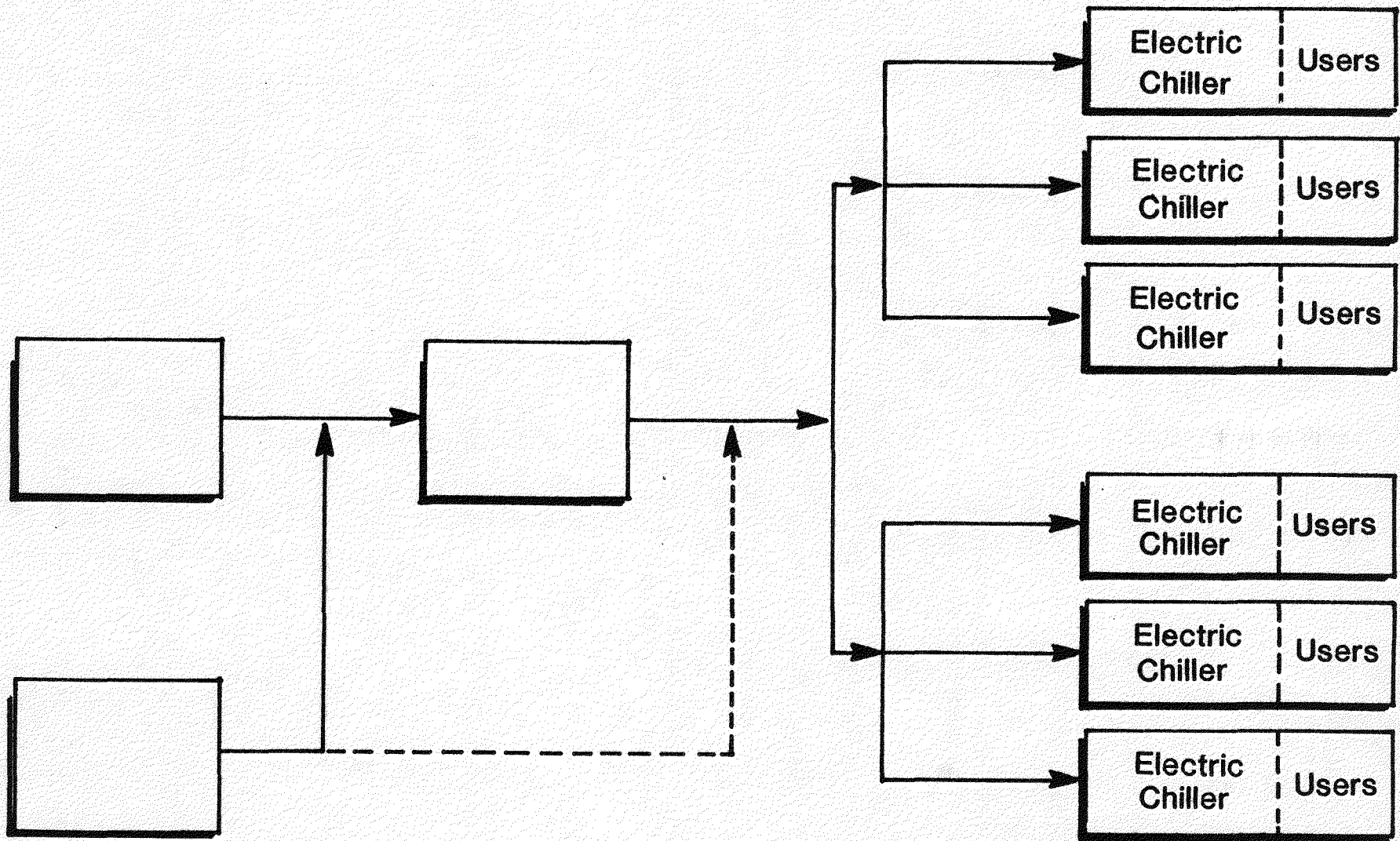


Figure 5-3

ELECTRIC CHILLER USING COOL-WATER HEAT SINK

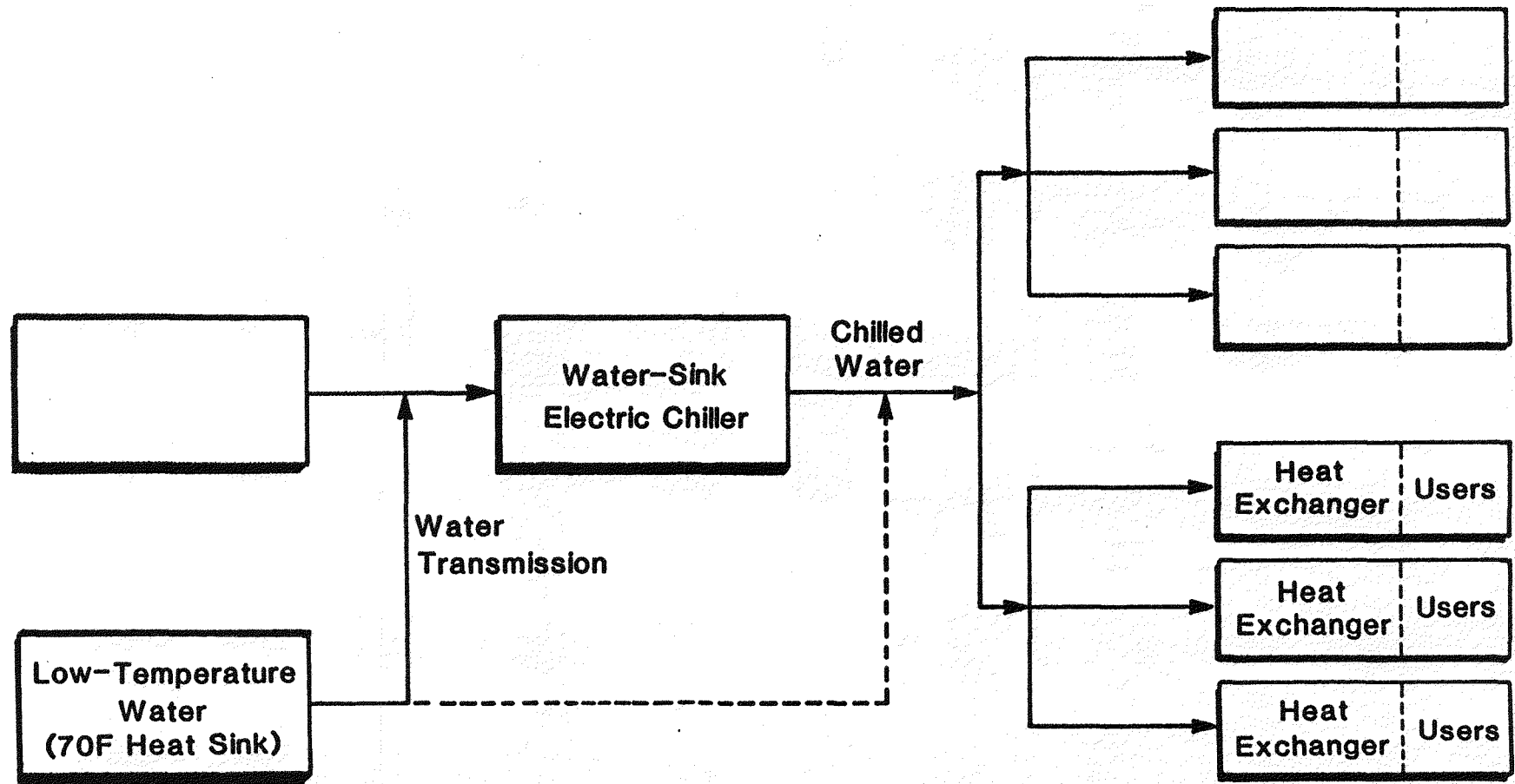


Figure 5-4

HOT-FLUID DISTRIBUTION, USER CHILLERS

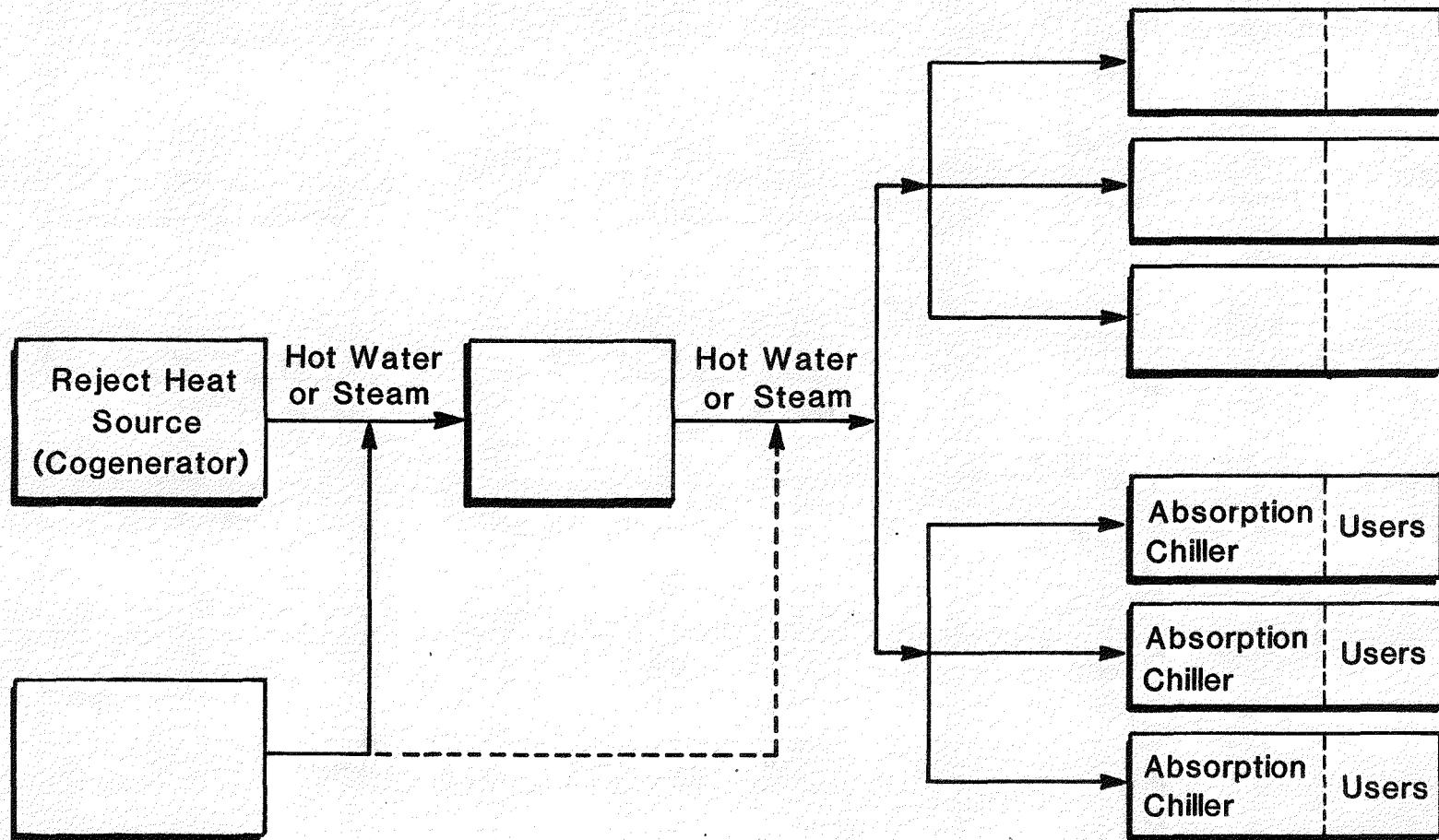


Figure 5-5

CENTRAL ABSORPTION CHILLER

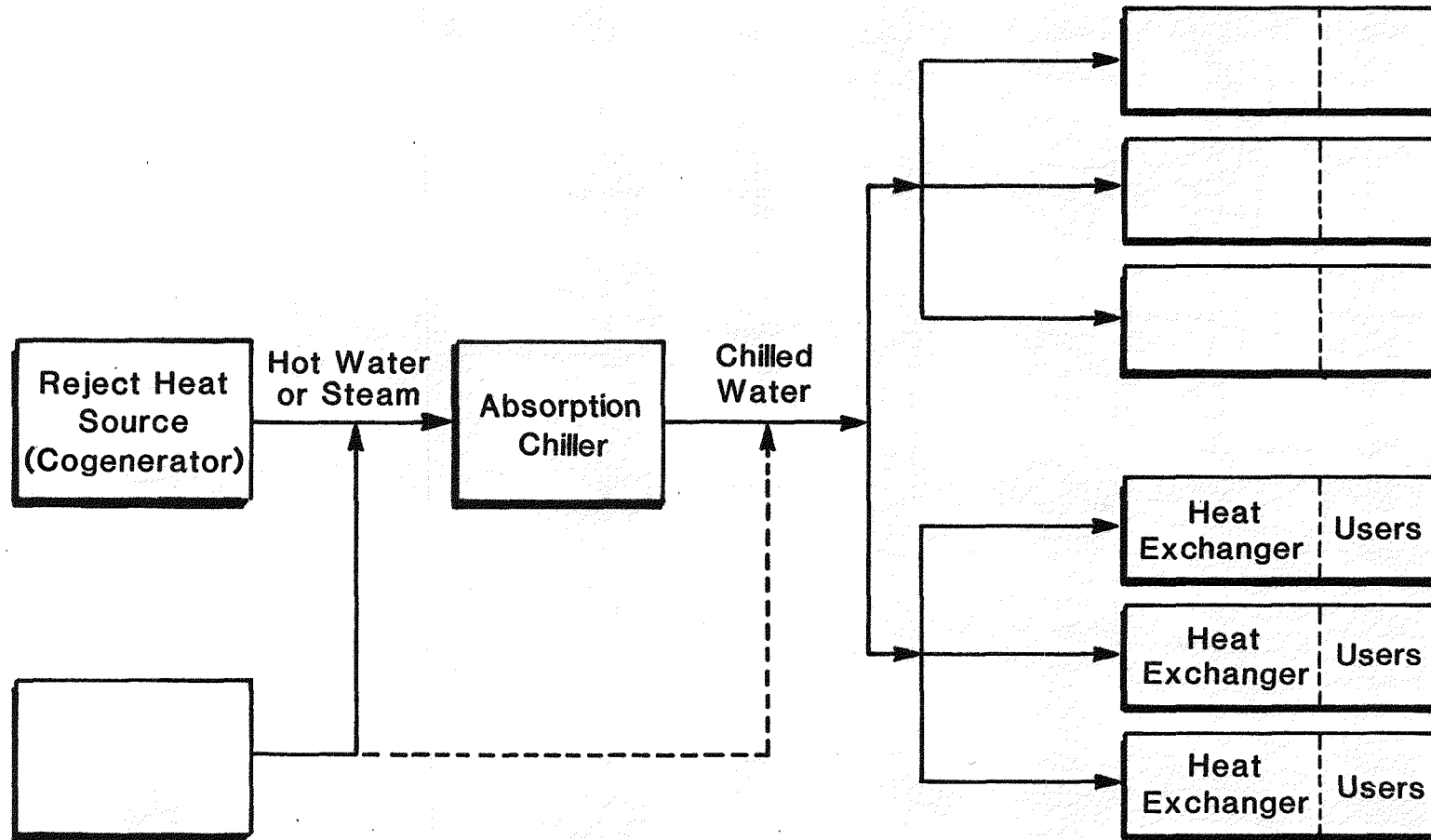


Figure 5-6

CENTRAL STEAM-DRIVEN CHILLER

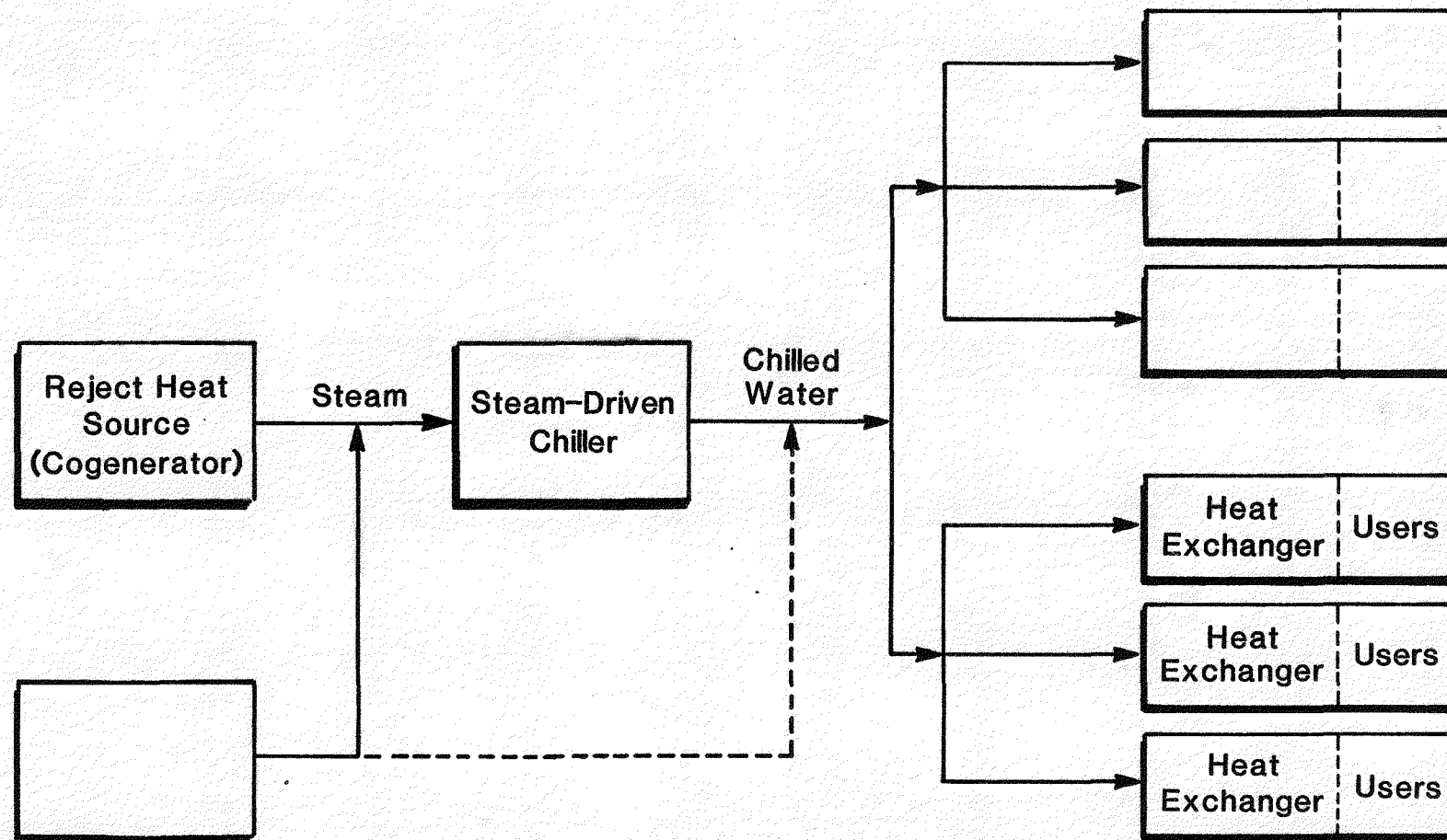


Figure 5-7

CENTRAL ELECTRIC CHILLER, USER STORAGE

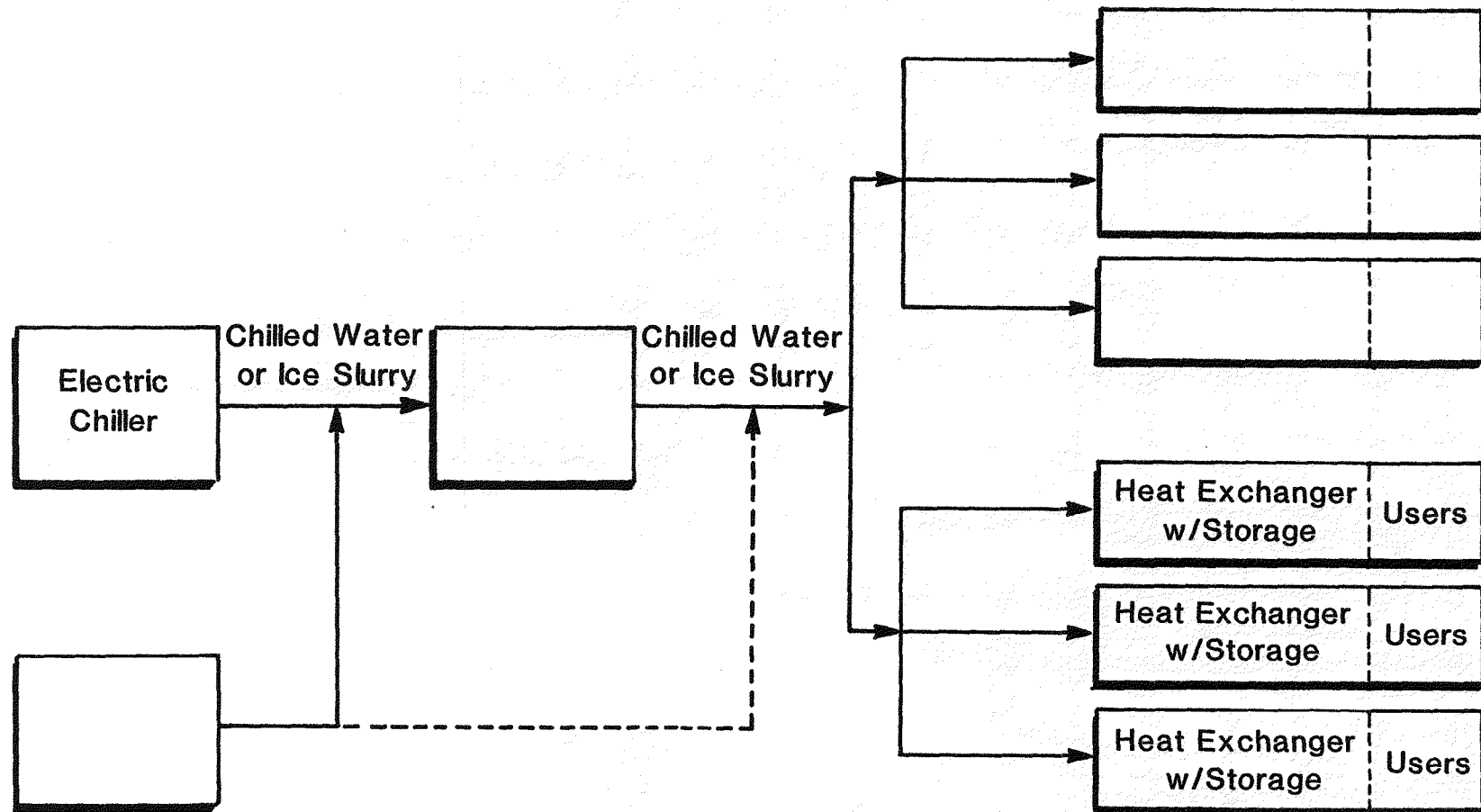
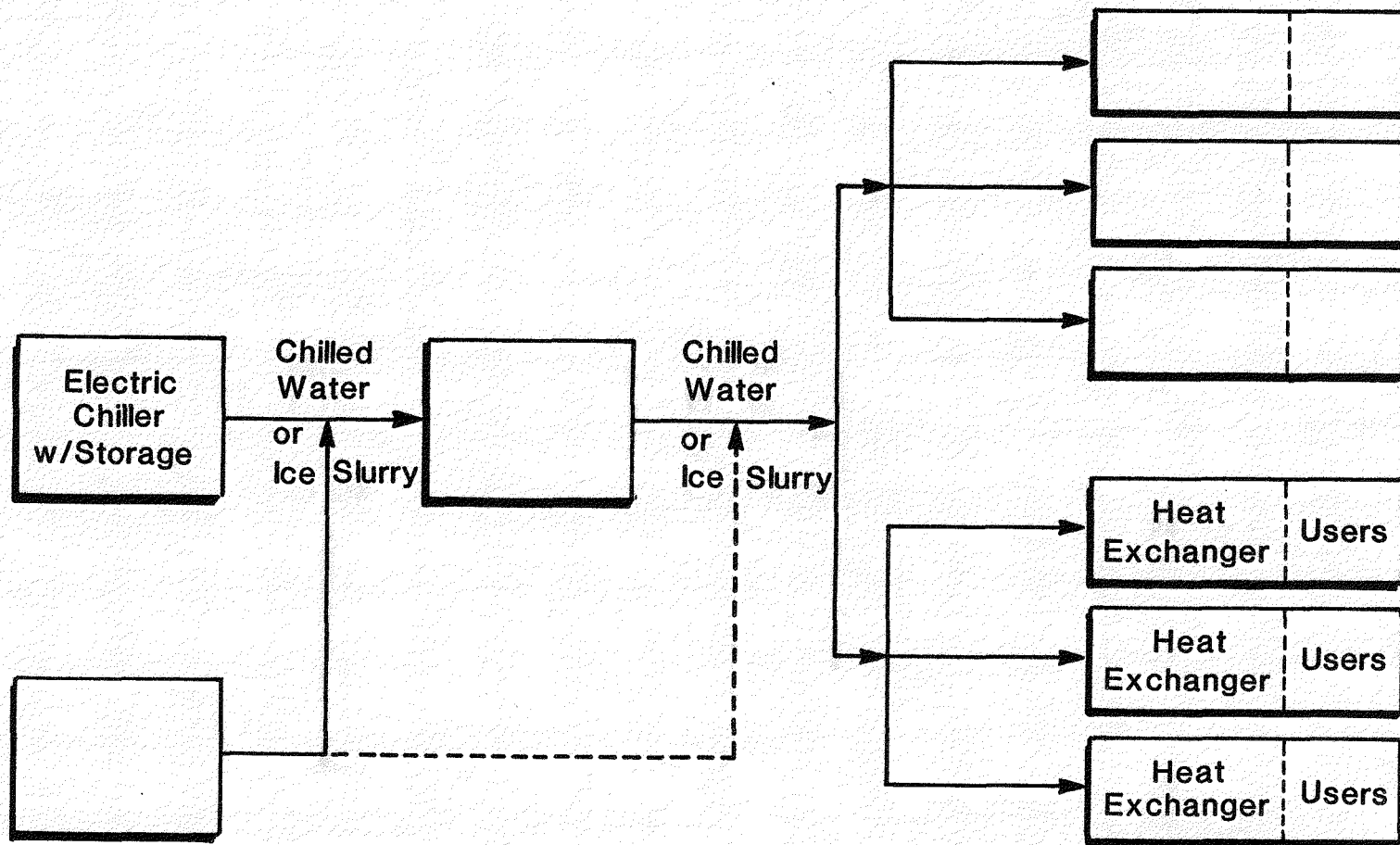


Figure 5-8

CENTRAL ELECTRIC CHILLER, CENTRAL STORAGE



Thermal storage of chilled water and slush ice was considered using two different modes of operation: full storage and partial storage. These will be described in the following sections.

The final annualized delivered energy cost (in cents per delivered energy, kwh) will be used as the point of comparison. Table 5-1 tabulates the district cooling options considered (16 in all). Inputs for these options and their respective modes of thermal distribution are described in Table 5-2 and in Table 5-2a.

5.3 About Cool Storage

Thermal storage of chilled water or slush ice is a method for shifting air conditioning demand to off-peak periods. In conventional air conditioning systems, the chiller operates to meet the building cooling load at the time of need; in a storage system the chillers operate at designated times to build up a store of ice or chilled water in an insulated tank; this refrigerated water is subsequently used to meet the cooling load as needed. A cool storage system is essentially a conventional air conditioning system with a cool storage medium contained in a storage vessel between the chiller and the cold water distribution system of the building. Energy is extracted from the medium by the chiller, usually at night, and the resulting cold reservoir (e.g., ice or chilled water) is used the following day for cooling. The storage system must have enough instantaneous cooling capacity to meet the building's peak cooling load and enough total refrigeration capacity to meet the maximum daily cooling requirement of the building; in addition, the chiller must be able to recharge the store within the designated charging period.

There are two basic operating strategies for cool storage: a) the chillers are run only during the off-peak period (full storage mode), or b) they are run day and night (partial storage mode). Full storage results in a complete shifting of demand to the off-peak period; partial storage results in a leveling of demand.

In the full-storage mode, the chiller is switched off during the on-peak period. In this mode the electric load due to the chiller is shifted so there is no coincidence whatever with the cooling load of the building during the utility peak demand period. In the partial storage or load-leveling mode, the storage and chiller capacities are chosen to meet the design-day building load by continuous operation of the chiller.

5.4 Sizing of Cool Storage for DHC Analysis

Cool storage was introduced into the model by smoothing the daily load profile to a constant, in the case of 24-hr chiller (continuous) operation, or to a step function, in the case of 12-hr off-peak chiller operation. Although this produced acceptable technical results, it still left unanswered the question of how large the storage must be to achieve this smoothing. As storage size is directly related to storage cost, this question must be answered before the delivered cost of cooling with storage can be assessed.

In order to determine the required storage size, we began with the monthly load-duration curves, information contained in the output file for each run. Since these curves were constructed on a month-by-month basis, we select the

Table 5-1. Selected DHC Systems

System I.D. #	Description
1 (Baseline Case)	Individual building electric chillers
2	Central electric chiller using low-temp. heat sink w/chilled water distribution
3A	Distributed absorption chillers driven by hot water
3B	Distributed absorption chillers driven by steam
4	Central absorption chiller driven by hot water, w/chilled water distribution
4A	Central absorption chiller driven by steam, w/chilled water distribution
5	Central electric chiller w/chilled water distribution
5A	Central electric chiller w/distributed chilled water storage*
5B	Central electric chiller w/distributed slush ice storage*
6	Central steam-driven chiller w/chilled water distribution
7A	Central electric chiller w/distributed chilled water storage**
7B	Central electric chiller w/distributed slush ice storage**
8A	Central electric chiller w/central chilled water storage*
8B	Central electric chiller w/central slush ice storage*
9A	Central electric chiller w/central chilled water storage**
9B	Central electric chiller w/central slush ice storage**

*All day chiller operation (partial storage)

**Off-peak chiller operation (full storage)

Table 5-2. Energy Converter Inputs

System I.D. #	Primary Energy Converter	Secondary Energy Converter	User Energy Converter
1 (Baseline Case)	-	-	Electric A/C
2	Low Temp. Water Source	Electric A/C	H/X
3A	GT Cogen	-	SE Abs. Ch.
3B	GT Cogen	-	DE Abs. Ch.
4	GT Cogen	SE Abs. Ch.	H/X
4A	GT Cogen	DE Abs. Ch.	H/X
5	Electric A/C	-	H/X
5A	Electric A/C	-	H/X with D.S. (chilled water)*
5B	Electric A/C	-	H/X with D.S. (ice slurry)*
6	GT Cogen	Steam-Driven Chiller	H/X
7A	Electric A/C	-	H/X with D.S. (chilled water)**
7B	Electric A/C	-	H/X with D.S.** (ice slurry)
8A	Electric A/C w/C.S. (chilled water)*	-	H/X
8B	Electric A/C w/C.S. (ice slurry)*	-	H/X
9A	Electric A/C w/C.S. (chilled water)**	-	H/X
9B	Electric A/C w/C.S. (ice slurry)**	-	H/X

Legend: Electric A/C = Electric Chiller
 H/X = Heat Exchanger
 G.T. Cogen = Gas Turbine Cogenerator
 SE Abs. Ch. = Single-Effect Absorption Chiller
 DE Abs. Ch. = Double-Effect Absorption Chiller
 * = all day chiller operation
 ** = off-peak chiller operation
 CS = Central Storage
 DS = Distributed Storage

Table 5-2a. Inputs for DHC Systems

INPUTS	System I.D. #															
	1	2	3A	3B	4	4A	5	5A	5B	6	7A	7B	8A	8B	9A	9B
<u>Service:</u>																
(H)eating or (C)ooling	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
<u>Transmission:</u>																
Heat Transfer Fluid	-	W	HW	S	HW	S	CW	CW	IS	S	CW	IS	CW	IS	CW	IS
Pipe Type	-	2	2	3	2	3	2	2	2	3	2	2	2	2	2	2
Fluid Temp. (°F)	-	70	250	340	250	340	42	42	28	340	42	28	42	28	42	28
Temp. Drop, (°F)	-	10	100	0	100	0	10	10	10	0	10	10	10	10	10	10
<u>Distribution:</u>																
Heat Transfer Fluid	-	CW	HW	S	CW	CW	CW	CW	IS	CW	CW	IS	CW	IS	CW	IS
Pipe Type	-	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2
Fluid Temp. (°F)	-	42	250	340	42	42	42	42	28	42	42	28	42	28	42	28
Temp. Drop, T (°F)	-	16	100	0	16	16	16	16	16	16	16	16	16	16	16	16
Fluids: W = Water CW = Chilled Water IS = Ice Slurry HW = Hot water ST = Steam																
Pipe Types: 1 = Uninsulated Polyethylene 2 = RICWIL Fiberglass reinforced polyethylene - insulated 3 = RICWIL Insulated steel - one pipe/trench 4 = RICWIL Insulated steel - two pipes/trench 5 = No pipe needed																

month for which the peak load is the greatest. This will give us enough storage to accommodate a typical day during the peak month, though perhaps not the actual peak day. Some may criticize this: on the other hand, the balance of the system is likely to have enough thermal inertia to carry the difference between the typical day during the peak month and the peak day for the year, so we feel this method is as realistic as any available to us.

In order to assess the amount of storage necessary for levelized 24-hr chiller operation, we assumed that the load profile was symmetrically distributed around the peak, as shown in Figure 5-9. This figure is normalized on both axes, so that the horizontal axis represents the fraction of hours in a day, and the vertical axis represents the fraction of the peak load. The stepped curve represents the cooling load as a function of time, as implied by the load-duration curve. The dotted line represents the fraction of the peak load that the chiller must put out to provide cooling equal to the daily demand. The area under the dotted line must equal the area under the step function, to the extent that losses can be ignored.

The operation of the system during the course of the day can be described as follows. From the low point of the load (left-hand side of the figure) the chiller puts out cooling at a rate indicated by the dotted line. The load takes cooling indicated by the step function. The difference, the shaded area of Figure 5-9, is what goes into storage.

When the step function comes up to meet the dotted line, there is no longer any extra cooling to put into storage. As the step function exceeds the dotted line, cooling is removed from storage. This continues until the step function again comes down to meet the dotted line, on the right-hand side of Figure 5-9. As the step function descends still further, cooling is again placed into storage. The shaded area of Figure 5-9 thus represents the amount of cooling that must be stored, as a fraction of the cooling that would be delivered by a chiller sized to meet the peak load. We call this shaded area the Storage Fraction. It is given by the relation:

$$\text{Storage Fraction} = \frac{\text{Storage Required (kwh)}}{\text{Peak Load (kw) x 24 (hr)}}$$

Calculating the storage fraction from the load duration curve, and knowing the peak load, we can determine the required storage.

The case where the chiller runs only during the off-peak period is treated in a similar manner, as shown in Figure 5-10. Here the output of the chiller, normalized to the peak load, is shown by the dotted lines that cover half of the figure, during the lowest portions of the load profile. The height of the dotted line in this case is exactly twice that of Figure 5-9, since the chiller runs only half the hours, and the same load must be met. As in Figure 5-9, the shaded portion of the graph represents the cooling placed in storage. The area under the step function during the on-peak period must equal the shaded area under the dotted lines, since all of the cooling required during the on-peak period must be taken from storage. Clearly, the storage required for this mode of operation will be considerably greater than that for the continuous-run mode.

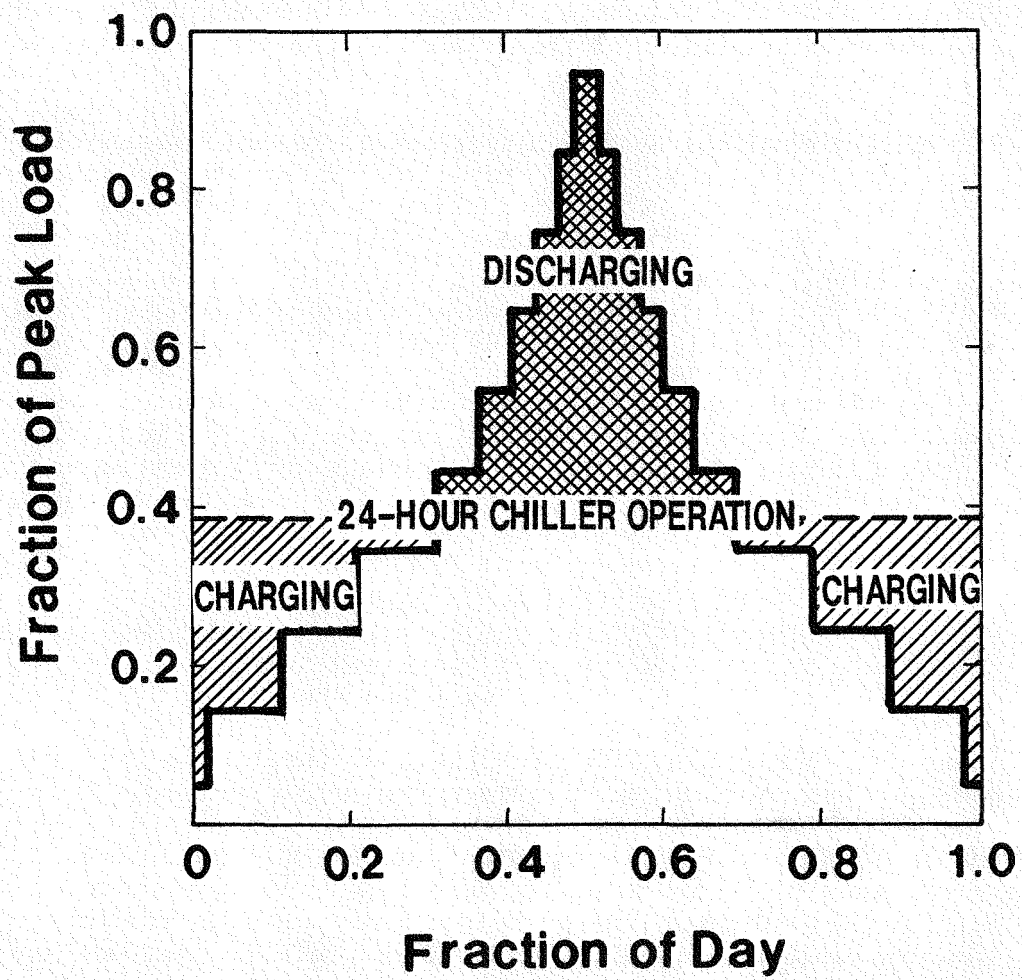


Figure 5-9. Peak-Day Load Profile for 24-Hour Chiller Operation with Storage. Solid Line--Cooling Load. Dotted Line--Chiller Output. Shaded Area---Required Storage Capacity.

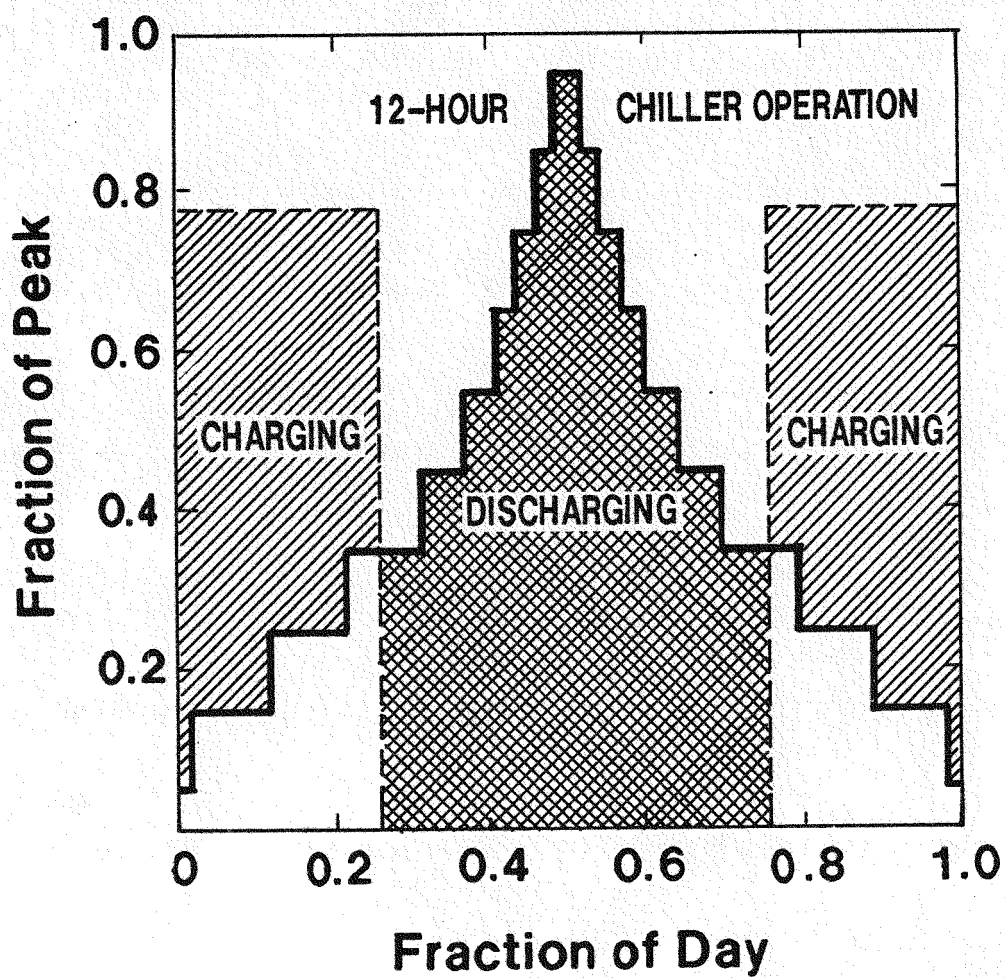


Figure 5-10. Peak-Day Load Profile for 12-Hour Off-Peak Chiller Operation with Storage. Solid Line--Cooling Load. Dotted Line--Chiller Output. Shaded Area--Required Storage Capacity.

5.5 Cost of Storage

For the systems that use water or ice storage, either central or distributed, it was necessary to develop estimates of the storage's cost. This was done by contacting manufacturers of large tanks and packaged storage systems. Several quotes were obtained for tanks of 200,000 to 6,000,000 gallons. These are plotted in Figure 5-11. The dotted line, given by the equation

$$\text{Cost} = \$300,000 + \$0.20 \times \text{Capacity}$$

represents all but the leftmost point (capacity in gallons).

Also, two manufacturers of ice storage systems quoted their cost as \$60 per ton-hour, within the range of sizes offered, generally smaller than the numbers quoted above, but larger than residential size.

The conversion, for chilled water storage, from gallons to kwh was done as follows. We assumed a 20 °F temperature difference between sendout and return water. At 8.33 pounds per gallon, this implies a capacity of 167 Btu/gallon. Since one kwh is 3415 Btu, a volume of 20.5 gallons is required per kwh of storage.

For ice slurries in large tanks, the conversion was obtained assuming 50% ice. The available cooling is then 0.5 x 144 Btu for the latent heat of fusion and another 23 Btu for the sensible cooling obtained in warming the meltwater from 32°F to 55°F. The total is then 95 Btu/lb, or 791 Btu/gallon. This converts to 4.3 gallons per kwh.

If we take the dotted line in Figure 5-12 as the cost of tankage above 500,000 gallons, and assume that this represents the major portion of the storage cost (land costs are ignored, for example), then the cost of water storage is given by

$$\text{Cost} = \$300,000 + \$4.10 \times \text{Capacity (kwh)}$$

where the capacity exceeds 25,000 kwh. This equation is plotted as line A in Figure 5-12.

Similarly, the cost of ice slurry storage in the same tank is given by

$$\text{Cost} = \$300,000 + \$0.86 \times \text{Capacity (kwh)}$$

where the capacity exceeds 116,000 kwh. This is plotted as line B in Figure 5-12.

To complete the picture, the quoted cost of ice storage for smaller tanks, \$60 per ton-hour, converts to \$17/kwh. This is plotted as line C in Figure 5-12. The leftmost quote for tankage, \$200,000 for a 200,000 gallon tank, if used for water storage shows up as point D in Figure 5-12.

With these data in hand, we have done the following. For water, we have used the equation

$$\text{Cost} = \$300,000 + \$4.10 \times \text{Capacity (kwh)} \quad \text{kwh} > 23,000$$

$$\text{Cost} = \$17 \times \text{Capacity (kwh)} \quad \text{kwh} < 23,000$$

For the very small tanks used in distributed storage, we have imposed a lower limit of \$2,000 per tank, on the basis of engineering judgment.

For ice storage, we have extended line B over to line C, with an intersection point at 10,000 kwh, and used

$$\text{Cost} = \$300,000 + \$0.86 \times \text{Capacity (kwh)} \quad \text{kwh} > 18,500$$

$$\text{Cost} = \$17 \times \text{Capacity (kwh)} \quad \text{kwh} < 18,500$$

Because of the complexity of ice storage, especially in small sizes, we have imposed a minimum of \$2,000 for the storage in distributed systems, and doubt that it could be done that cheaply.

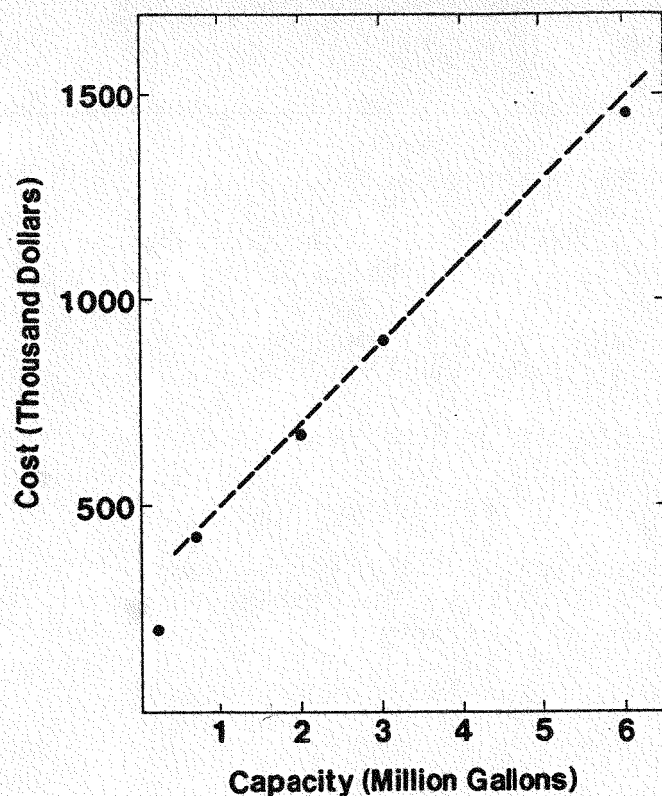


Figure 5-11. Estimated Cost Functions for Cool Storage
(Cost vs. storage capacity in million gallons)

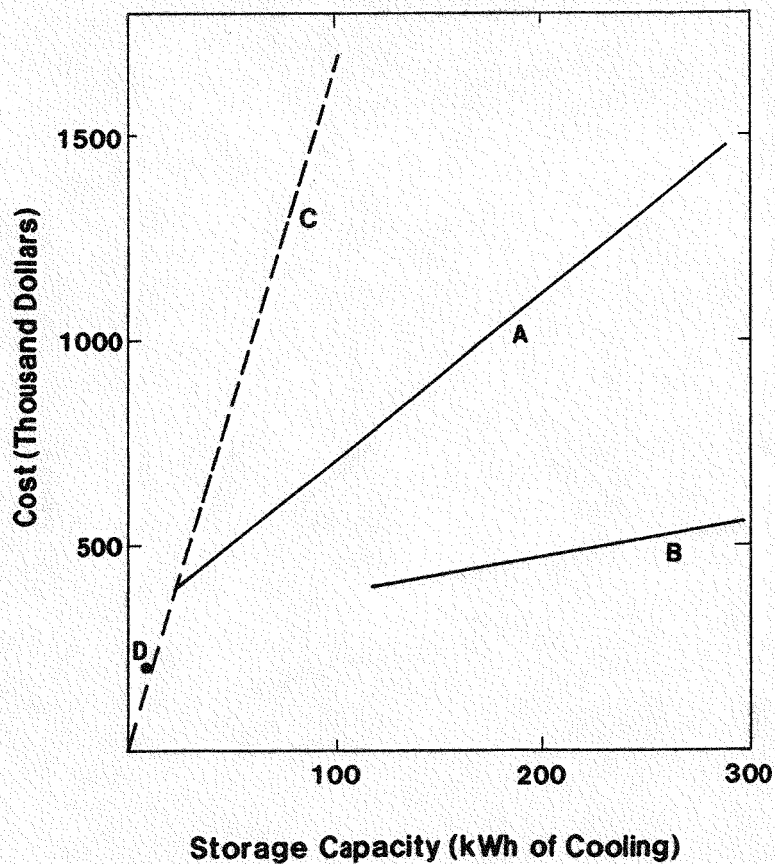


Figure 5-12. Estimated Cost Functions for Cool Storage
(Cost vs. storage capacity in kWh of cooling)

5.6 Performing Batch Runs

Each of the cells in the new 60 x 60 grid of the city map represents a district with a specific cooling load requirement. By using the test data provided by Austin, the load/duration profile and peak cooling loads for each cell were determined. The total district peak cooling load was then divided by the total number of buildings contained in that 1/4-mi² section cell to obtain an average building peak load (in KW).

Since there are over 1100 cells in this data file with non-zero cooling loads, a simplified method was required to reduce the number of overall computer runs. Thus, similarly to Milwaukee, a representative set of cells was selected to give a range of total district cooling loads. These 1/4-mi² section cells were chosen on the basis of their being nearly homogeneous in character (nearly all commercial buildings or nearly all residential) and to provide a broad range of loads.

Using the land-use information given for each cell, and knowing the mix of commercial and residential buildings in each cell, representative cells were hand-picked to select only those with almost all-commercial buildings or all-residential buildings. Then cells with different peak cooling loads were preferentially selected. In all, 15 sample cells with all-commercial buildings and another 15 cells with all-residential buildings were chosen.

Each of the cells above was then run for each of the DHC options described in Table 5-1, yielding a total of 480 program runs in total.

Delivered energy costs for each of these runs (for both residential and commercial groups) are tabulated in the next section.

After obtaining the annualized cost of delivered energy for the sample cells selected, a method was then required to predict the nominal cost of delivered energy for all the other remaining cells in the grid. Thus, a mathematical function was derived to correlate the total district peak load of the cells with the final delivered energy cost of the cells for that DHC system. Other cells were then compared with the prediction of the curve fits. If agreement was good, the curve fits were used to predict the cost of delivered energy for all DHC systems using the remaining 1/4-mi² cells. As with the Milwaukee study, a second-order inverse polynomial was used to correlate total load with the final delivered energy cost. That is, for all 16 DHC cases presented, any 1/4-mi² cell's delivered energy cost may be approximated by the relationship:

$$P_p = X \left(A + \frac{B}{Y} + \frac{C}{Y^2} \right) + (1-X) \left(D + \frac{E}{Y} + \frac{F}{Y^2} \right) \quad (8)$$

where P_p = predicted delivered energy cost in ¢/kwh

X = fraction of residential buildings in each cell

and Y = total district peak load in MW

The parameters A through F form a six-component vector which takes on a unique set of values for each DHC system, on the basis of the least-squares fit for that system. Each of the results from the sample residential and commercial cells was then fitted to equation (8) for each DHC system to obtain the values

for A through F. Thus, the predicted delivered energy cost is defined by a set equation for each individual DHC system. To check the accuracy of this approach, additional cells were run to compare the model's resulting delivered energy cost versus the predicted delivered energy cost P_p .

Agreement between the two were deemed sufficiently close to justify the use of the predicted cost equation to determine the delivered energy costs for all the remaining cells in the city.

Subsequently, the predicted delivered energy cost for each cell for each of the DHC systems was tabulated. Maps showing the distribution of costs along the city lines were then generated to illustrate the specific areas where each system may or may not exhibit some potential when compared to the baseline case. Specific cost ranges for each map were defined by textured blocks, shown in the following section.

6.0 DISTRICT COOLING TECHNOLOGY CHARACTERIZATION RESULTS

6.1 General

The cost allocations which results from the preliminary program runs performed for sample residential and commercial cells are presented in Tables 6-1 and 6-2. Each table shows the annualized delivered energy cost for 15 representative cells with buildings that are nearly all-residential or all-commercial, for each DHC system listed on the left-hand column. The description of each sample cell is shown on the bottom of the table and describes the total district peak load, the number of buildings in the district, and the average peak load for each in the district. The costs resulting from running each sample cell for each DHC system were then used to generate a curve for each system, and a predictive cost curve for each system using equation 8 was obtained. Using each separate equation, all the other remaining cells were then fit to each of the curves to get a predicted delivered energy cost for each cell. Then, once the predicted costs were obtained for each cell in the city, a map for each DHC system was drawn which demarcated specific cost ranges in the city area (shown as textured blocks. Again the maps show predicted cost values derived from specific cost functions.

Maps for each system are illustrated in Figures 6-1 through 6-15. A brief discussion of each map and the cost implications associated with each DHC system are also presented.

6.2 Results

System 1 - Baseline Case

The baseline case consisted of electric chillers installed in individual buildings, the simplest space-cooling scenario. Table 6-1 shows the annualized delivered energy cost results for sample cells with all residential buildings at nominally ~4 to 5 cents/kwh. For buildings with higher cooling loads, such as shown in Table 6-2 for sample cells with all-commercial buildings, the delivered energy cost is nominally ~2 to 3 cents/kwh. The complete map highlighting cost distributions for this first system is presented in Figure 6-1.

System 2

In this system, cooling is achieved by distribution of chilled water produced from a central chiller using low-temperature sources, such as a nearby river or lake as a heat sink. The use of such low-temperature heat recipients is advantageous in that it reduces both the cost of chillers and the amount of electricity required to drive the chiller unit. Resulting costs for this system show that the delivered energy cost is competitive with the baseline mainly in cases where the cooling loads are high, such as in areas with large commercial-building majority. The costs are most heavily influenced by capital costs, thus making cooling costs strongly sensitive to building size. Distribution costs are also an important factor, and show that areas with low building densities have higher distribution costs than more dense urban areas. Figure 6-2 illustrates the cost map for this system, and shows several areas with some potential. However, only these areas that actually fall close to the low-temperature water source can be considered competitive since the model assumes

Table 6-1
Sample Cells w/ Residential-Building Majority

System I.D. #	Annualized Delivered Energy Cost (cents/kwh) for space cooling														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	4.53	4.4	4.51	4.53	4.53	4.58	4.74	4.74	4.35	4.54	4.36	4.53	4.63	3.95	3.71
2	9.17	6.99	7.3	6.13	7.21	6.81	6.92	6.96	5.92	6.06	6.11	5.41	7.92	5.67	3.74
3A	15.61	11.64	12.36	10.92	15.67	16.05	16.52	16.87	13.51	14.8	13.79	14.14	16.92	11.07	8.35
3B	27.46	19.53	20.69	16.83	21.5	21.11	21.61	21.89	17.35	18.76	18.06	17.06	20.7	13.41	9.82
4	13.65	10.13	10.74	9.61	14.52	15.03	15.6	15.95	12.75	14.06	12.86	13.39	16.22	10.84	7.9
4A	12.26	8.97	9.5	8.3	9.11	9.04	12.68	12.93	10.32	11.32	10.45	10.64	13.36	8.88	6.24
5	9.17	6.99	6.79	6.13	7.21	6.81	6.92	6.96	5.65	6.06	6.12	5.22	7.40	5.67	3.74
5A	12.23	8.87	10.80	7.62	8.196	7.23	8.95	7.905	7.28	6.24	6.83	5.806	9.27	6.57	3.62
5B	13.72	10.00	12.10	7.56	8.78	7.76	9.55	8.47	7.80	6.72	7.31	6.276	9.74	7.44	3.93
6	13.70	10.77	11.52	11.26	12.54	17.14	17.95	18.50	14.72	16.43	14.87	15.85	18.92	12.53	9.22
7A	9.832	7.75	8.11	6.74	7.956	7.47	7.61	7.695	6.60	6.39	7.08	5.89	8.78	6.12	4.28
7B	10.90	8.62	9.0	7.54	8.53	8.01	8.16	8.26	7.08	6.89	7.55	6.36	9.19	6.50	4.64
8A	9.25	7.24	7.31	6.24	6.56	5.80	6.28	6.06	5.213	5.13	5.47	4.54	6.56	5.18	3.37
8B	10.76	8.40	8.65	6.22	7.27	6.46	7.02	6.76	5.90	5.76	6.11	5.17	7.21	5.72	3.87
9A	9.78	7.706	7.497	6.84	7.86	7.46	7.532	7.51	8.18	6.212	6.35	5.66	7.78	5.83	4.00
9B	10.90	8.22	8.46	7.72	8.61	8.12	8.18	8.17	6.71	7.11	7.17	6.24	8.36	6.37	4.50
District Peak (MW)	1	1.3	1.3	2	3	3.9	4.4	5.1	5.6	6.1	6.4	7.1	9.6	11.6	11.7
Building Peak (KW)	10.2	9.3	9.3	13.2	10.2	13.5	12.9	12.3	11.7	13.8	9.3	24.6	9.6	9.9	21.6
Residential fraction	1	1	1	0.999	0.999	0.996	1	0.999	1	0.99	1	0.998	0.998	0.944	0.956
# Buildings	96	137	140	150	292	290	341	417	473	435	674	289	997	1160	538

Table 6-2
Sample Cells w/ Commercial-Building Majority

System I.D. #	Annualized Delivered Energy Cost (cents/kwh) for space cooling														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2.98	3.05	3.03	3.02	2.85	2.93	2.94	2.99	2.98	3.04	2.95	2.92	2.17	2.98	2.16
2	3.97	3.88	3.31	3.02	2.66	2.7	2.92	2.97	2.9	2.95	2.71	2.64	2.48	2.63	2.36
3A	5.71	5.61	4.81	6.52	5.27	5.56	5.64	5.99	5.85	6.26	5.55	5.3	4.54	5.89	4.48
3B	9.25	8.93	6.81	8.23	6.4	6.62	6.51	6.81	6.53	6.99	6	5.74	3.75	5.96	3.63
4	4.95	5.01	4.24	5.91	4.79	5.06	5.41	5.69	5.65	5.93	5.26	5	4.64	5.23	4.5
4A	4.63	4.37	3.59	3.32	3.75	3.95	4.26	4.47	4.42	4.35	4.08	3.87	3.44	4.03	3.43
5	3.97	3.84	3.31	3.02	2.66	2.7	2.92	2.97	2.91	2.95	2.71	2.64	2.48	2.63	2.36
5A	4.42	3.69	3.18	2.89	2.51	2.49	2.72	2.71	2.66	2.75	2.49	2.43	2.27	2.46	2.24
5B	5.16	4.23	3.66	3.34	2.92	2.89	3.02	3.03	2.95	3.06	2.80	2.73	2.58	2.80	2.61
6	4.63	4.98	4.74	6.49	5.2	5.57	6.03	6.44	6.45	6.68	6.05	5.75	5.33	6.1	5.21
7A	4.39	4.35	3.83	3.76	3.29	3.23	3.60	3.58	3.47	3.58	3.30	3.20	3.12	3.19	2.92
7B	4.98	4.93	4.35	4.25	3.74	3.67	3.83	3.88	3.78	3.91	3.61	3.54	3.50	3.62	3.35
8A	4.43	3.65	3.07	2.80	2.48	2.49	2.73	2.74	2.69	2.45	2.505	2.44	2.27	2.42	2.17
8B	5.21	4.23	3.59	3.89	2.94	2.95	3.184	3.188	3.13	2.900	2.945	2.86	2.69	2.86	2.64
9A	4.53	4.47	3.87	3.57	3.11	3.066	3.32	3.29	3.189	2.98	2.97	2.89	2.78	2.87	2.59
9B	5.18	6.34	4.42	4.66	3.56	3.51	3.71	3.73	3.612	3.42	3.41	3.36	3.23	3.32	3.02
District Peak (MW)	0.97	1.17	2.11	3.63	4.13	4.55	5.76	7.16	9.08	14.15	15.24	20.55	26.61	36.07	62.47
Building Peak (KW)	108	586	34	32	54	79	411	116	146	47	126	86	1565	81	1301
Residential fraction	.012	0	.001	0	0	.001	0	.003	.001	.001	.001	.006	0	0.238	.003
# Buildings	9	2	62	113	77	58	14	62	62	300	121	232	17	447	48

that all cells are near the heat sink. If the transmission line costs were added to the delivered energy cost of those cells that are far from the lake or river, then these would probably not remain competitive with the baseline case.

System 3A

This example describes a system where cogenerated waste heat is used to produce hot water, which is then used to drive distributed absorption chillers (single-effect). Results show that stand-alone cooling costs are not competitive with the baseline non-district cooling system for most areas within the city, due to the dominating cost associated with the primary converter and chillers (see Figure 6-3).

System 3B

This case is similar to system 3 described above but uses steam rather than hot water as the input fluid for distributed absorption chiller units (double-effect). Again, resulting delivered energy costs are uncompetitive with the baseline case due to high equipment capital costs (see Figure 6-4).

System 4

This system is comprised of a central absorption chiller driven by hot water produced from a cogenerator; chilled water is then distributed through pipes to the users who use heat exchangers to cool the building air. This case is not favored economically as it shows higher delivered energy costs than the baseline system in all load cases. Although the total energy cost was partially reduced by revenue from electricity production, high capital costs for the cogenerator rendered this option uncompetitive with the baseline case (Figure 6-5).

System 4A

Similar to the previous example, this case also uses a central absorption chiller but is driven by steam produced from a cogenerator. Although the delivered energy cost is lower in some areas than the previous example showed, it still does not compete with the baseline cooling case (see Figure 6-6).

System 5

This example shows a general district cooling scheme where a central electric chiller is used to produce chilled water for distribution to end users. Results show that the greatest potential for this system lies mostly in highly commercial areas with large cooling loads. This is primarily due to the large economy of scale of the chiller, thus bringing converter capital costs down (see Figure 6-7).

System 5A

In this case, the same central electric chiller is used to produce chilled water (in a 24-hour continuous operation mode) to distributed storage vessels at the user end. This chiller operation strategy implies a leveled cooling load demand for partial storage of chilled water so that the storage capacity is only a fraction of the full amount. This presents lower overall storage costs.

This central cooling system with distributed chilled water storage proves to be competitive in largely commercial areas with high cooling demands. It is also marginally better than the previous system shown (#5) with no thermal storage. It also suggests that water-based systems do best in situations where cooling load profiles are level or flat. However, it must be noted that delivered energy costs presented are exclusive of the land or space costs associated with thermal storage (see Figure 6-8).

System 5B

This system uses slush ice produced from the central chiller (also in a 24-hour continuous operation mode) to distribute to users who then employ thermal storage of the ice slurry. The system operates in the same mode as the case above, however, it uses a homogenous mixture of fine ice particles in water as the distribution fluid.

Results from this test system show that the production, distribution, and thermal storage of slush ice finds fewer applications than with its chilled water counterpart. This is mainly due to the fact that ice-making chiller efficiency is about 20% lower. Although distribution piping costs were reduced as compared to the chilled water case, they were not lowered enough to offset the cost of the primary energy converter.

System 6

This system employs a central steam-driven chiller which uses high temperature reject heat from a gas turbine cogenerator to produce chilled water for distribution to users. Delivered energy costs for this central cooling scheme were not economically favorable, showing much higher costs than the baseline. Results show this is mainly attributed to high capital costs of the cogenerator system and the chiller itself, which rendered it uncompetitive with the base case (see Figure 6-9).

System 7A

Similar to system 5A, this example also uses a central electric chiller with distributed chilled water storage; however, the chiller only operates during off-peak periods to take advantage of reduced nighttime electricity rates. This mode of storage implies that the chiller will operate at full capacity only a certain number of hours (off-peak) to charge the storage. During on-peak hours, the chiller is not allowed to operate and the building cooling load is met by the stored chilled water.

Since the chiller runs in 12-hour cycles, the only advantage here is the lower electrical energy requirement for chiller operation. However, the storage is charged to full capacity, therefore, storage costs will be much higher than with the previous 24-hour chiller operation example. Resulting delivered energy costs show that this system does not appear competitive with the base case, nor does it appear economically favorable as compared to system 5A (Figure 6-10).

System 7B

This system is identical to system 7A but employs slush ice as the distribution fluid for user storage and cooling. Resulting delivered energy costs show that similar to system 5B, the slush ice-producing chiller's capital costs dominate and do not compete with the baseline case. In all load cases studied, this system produced higher overall costs than any of the distributed user thermal storage cases examined (Figure 6-11).

System 8A

This example uses a central electric chiller at 24-hour continuous operation with central storage of chilled water at the chiller site; chilled water is then discharged to the user end. Again, this chiller operation strategy implies a lower cooling load demand for partial storage of chilled water. It appears to be competitive with the baseline in high load areas with largely commercial buildings (see Figure 6-12).

Delivered energy costs for central chilled water storage applications appear to be slightly better than delivered energy costs for distributed chilled water storage primarily because the chiller size (capacity) is reduced, thereby also reducing concomitant chiller costs. Central storage costs are also lower here than in the distributed storage examples because during 24-hr chiller operation, the chilled water store is only at partial mode.

System 8B

In this case, slush ice is produced from a central electric chiller operating in a 24-hour continuous mode and stored at the chiller site for distribution to the customer end. Results show that this example is marginally competitive with the baseline cooling case and uncompetitive with the central chilled water storage case discussed above (system 8A). Although storage costs are lower due to the smaller capacity tanks needed, chiller costs for ice production still add a substantial amount to the final delivered energy cost (see Figure 6-13).

System 9A

This central chiller example is similar to system 8A in that it produces chilled water centrally; however, chiller operation is only for 12 hours a day (similar to system 7A), thus, storage of chilled water is at full capacity. Delivered energy costs are higher than for the case where the chiller runs continuously all day as storage costs obviously are increased, although costs are marginally competitive with the baseline case in a few areas (see Figure 6-14).

System 9B

This last case illustrates a central chiller operating for 12-hours to produce slush ice and storing at full capacity. Although costs for central storage are less than what it could be for distributed slush ice storage the chiller capital costs dominate and makes this option uncompetitive with the baseline (see Figure 6-15).

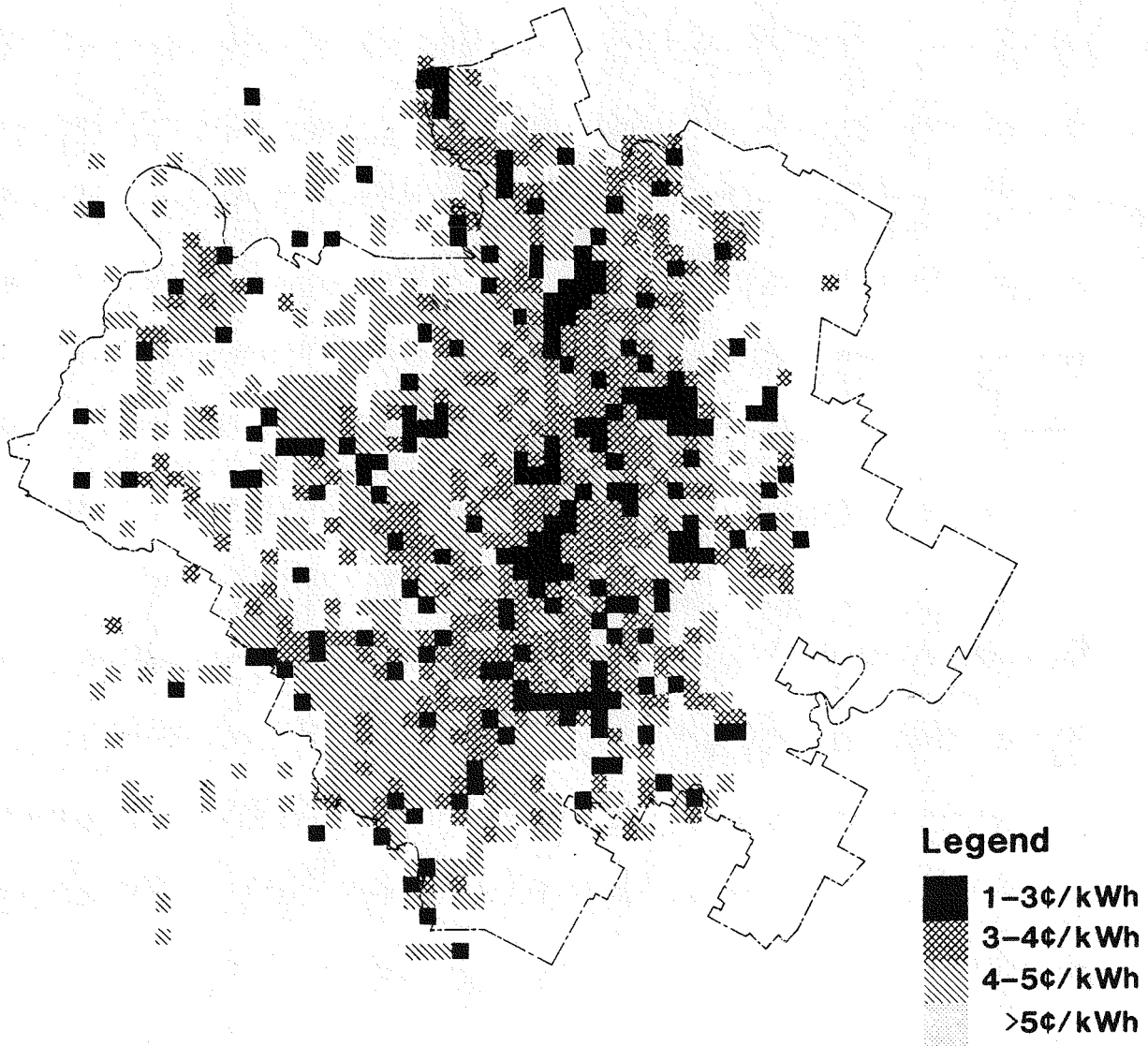


Figure 6.1 Individual Building Electric Chillers

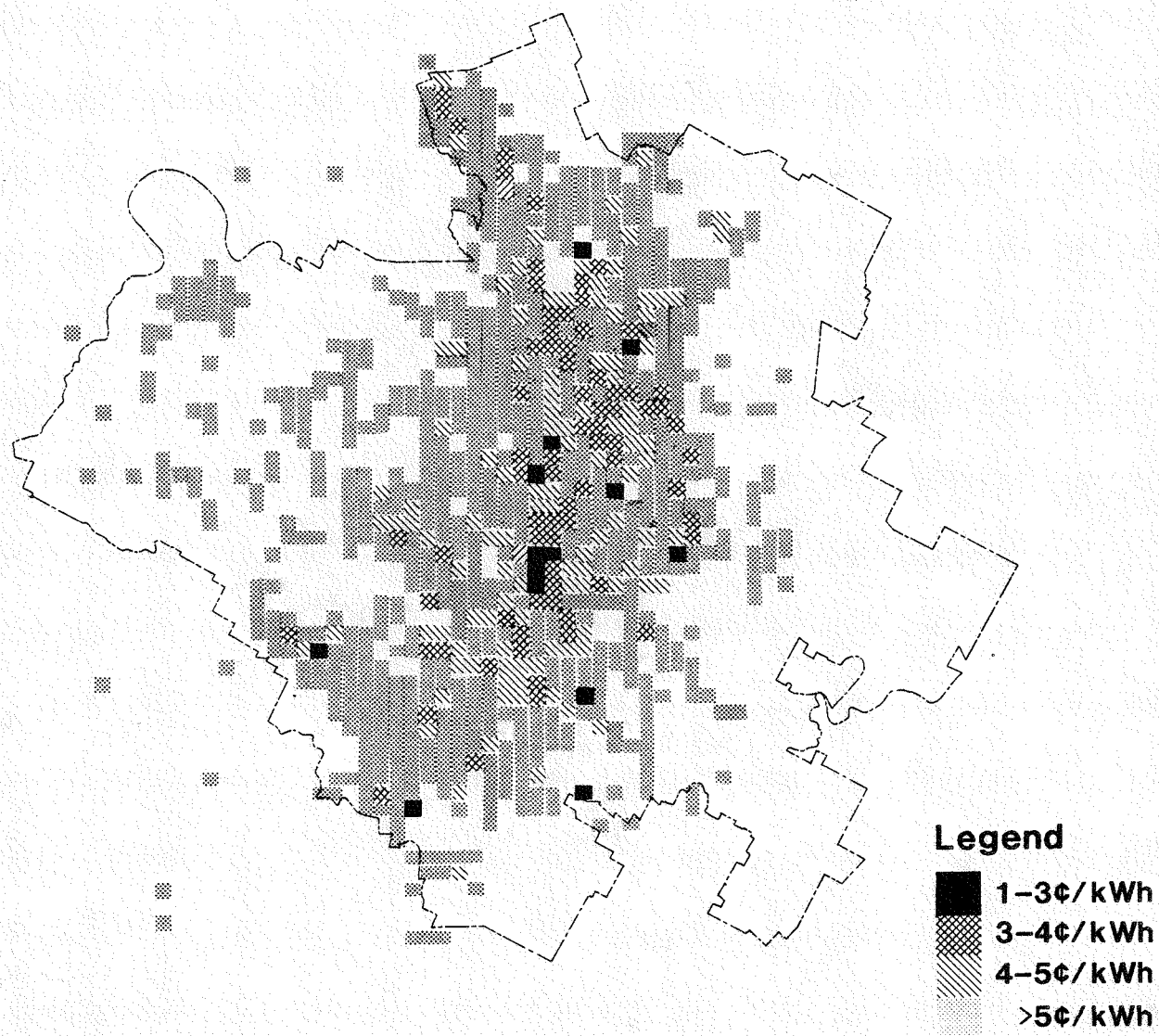


Figure 6.2 Central Electric Chiller Using Low-Temperature Heat Sink
w/Chilled Water Distribution

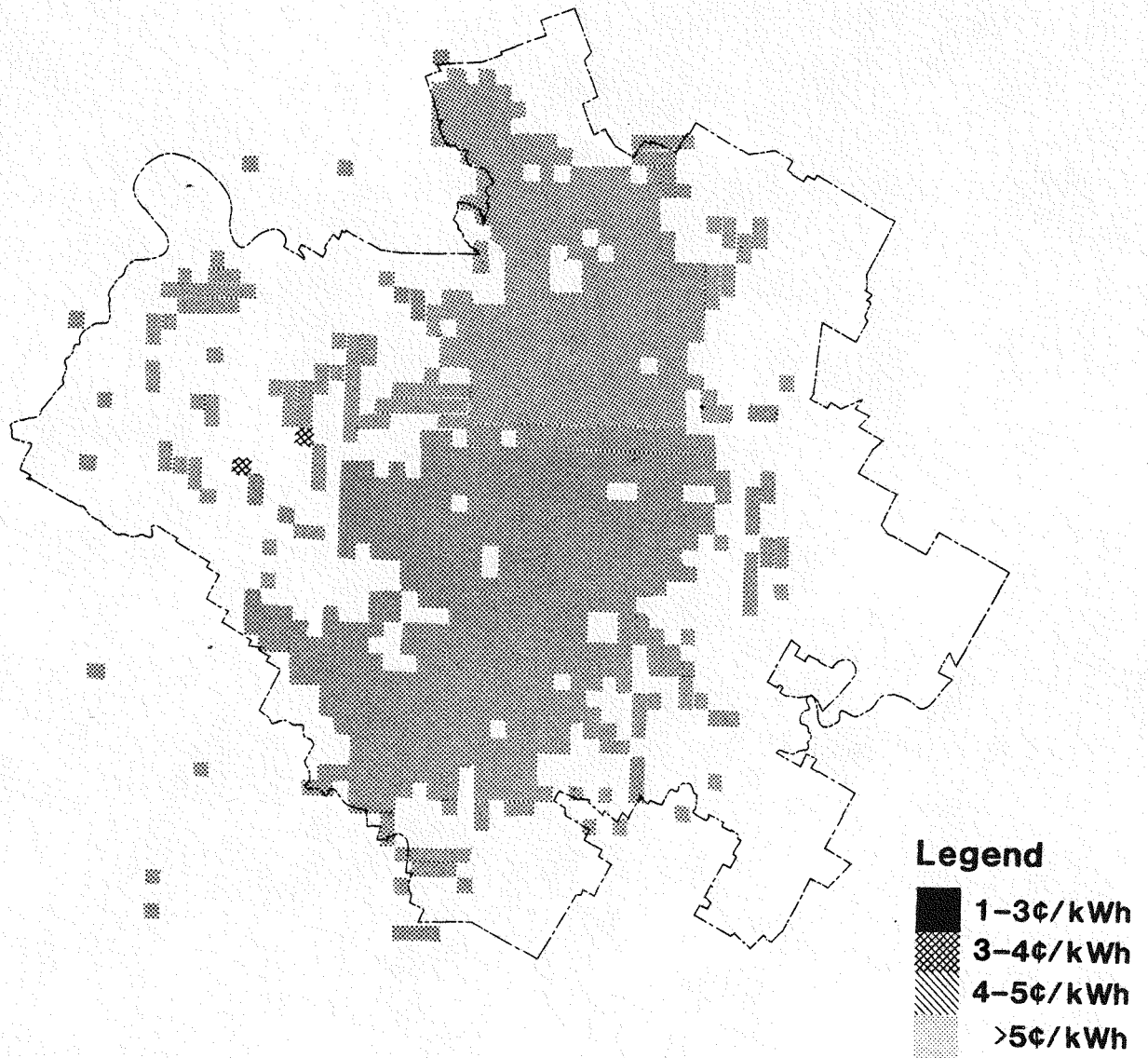


Figure 6.3. Distributed Absorption Chillers Driven by Hot Water.

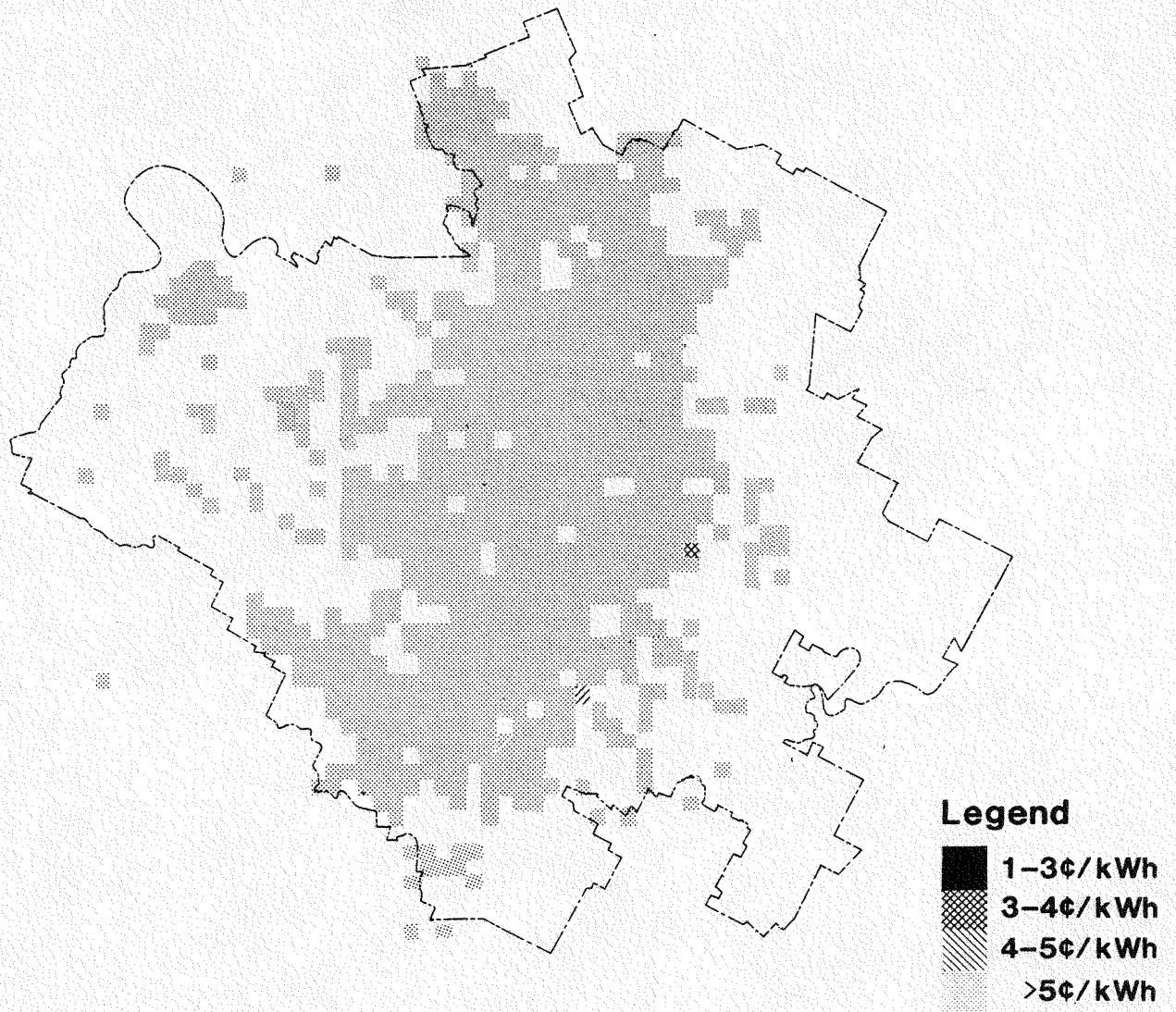


Figure 6.4. Distributed Absorption Chillers Driven by Steam.

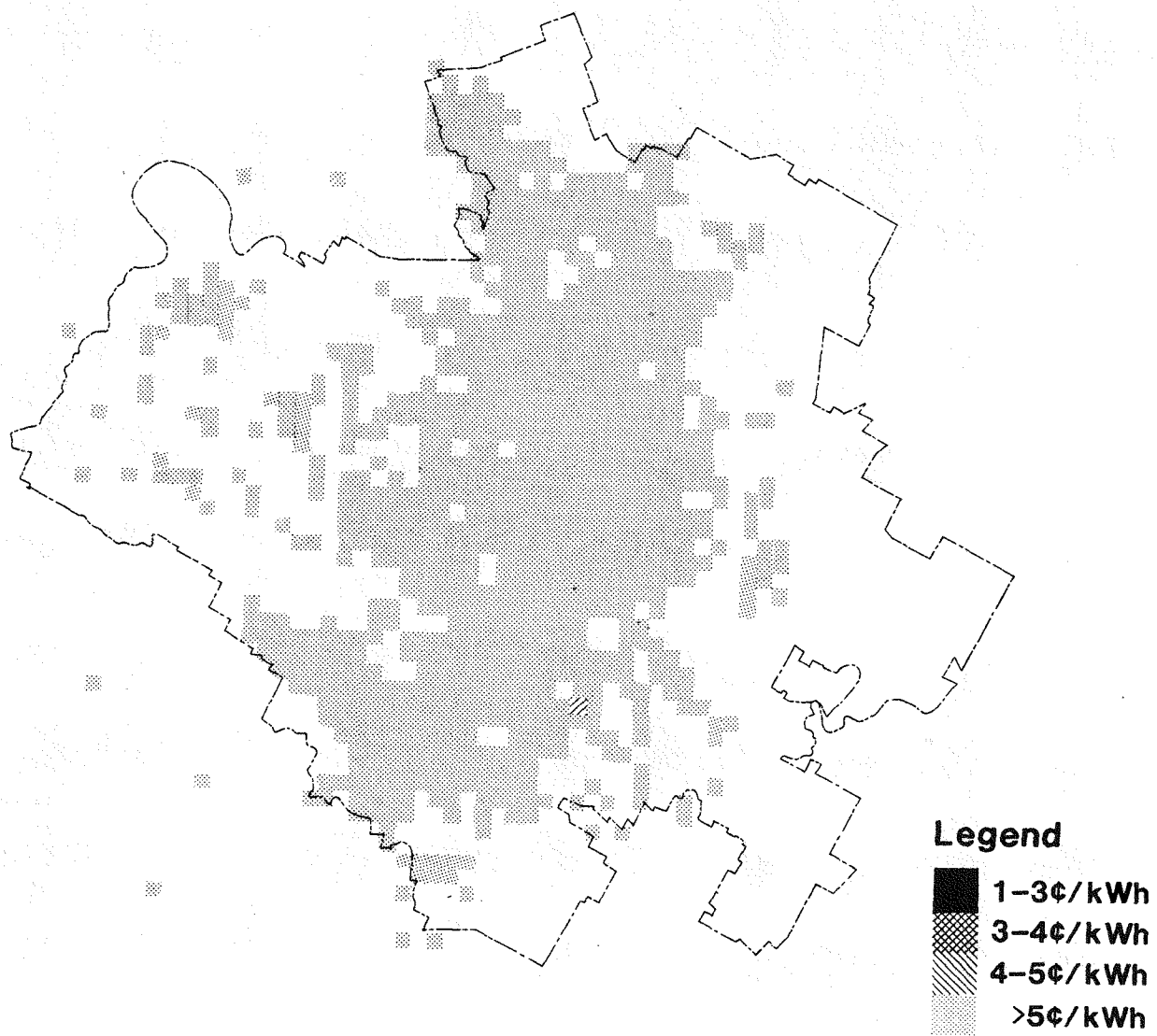


Figure 6.5. Central Absorption Chiller Driven by Hot Water, w/Chilled Water Distribution.

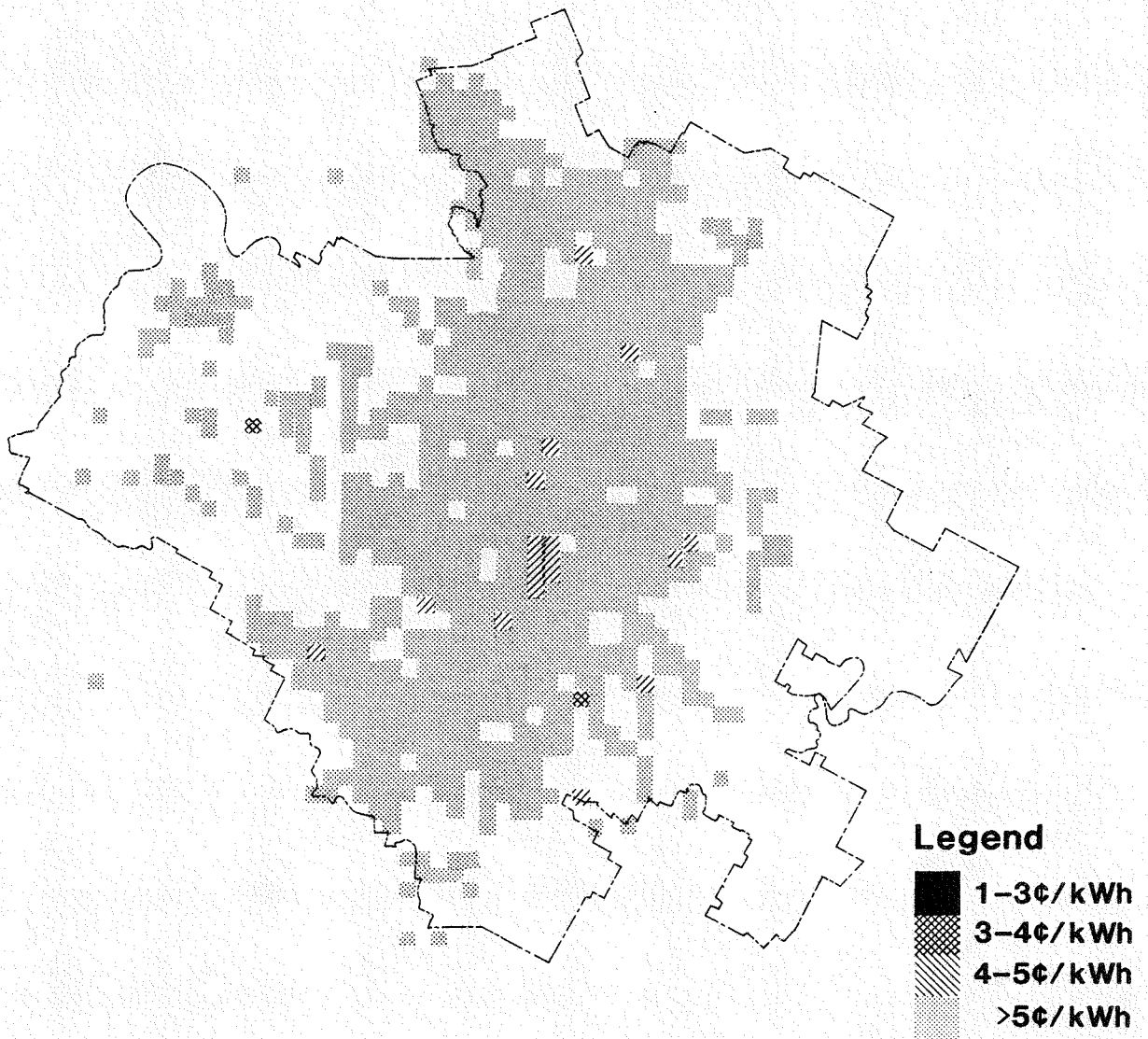


Figure 6.6 Central Absorption Chiller Driven by Steam,
w/Chilled Water Distribution.

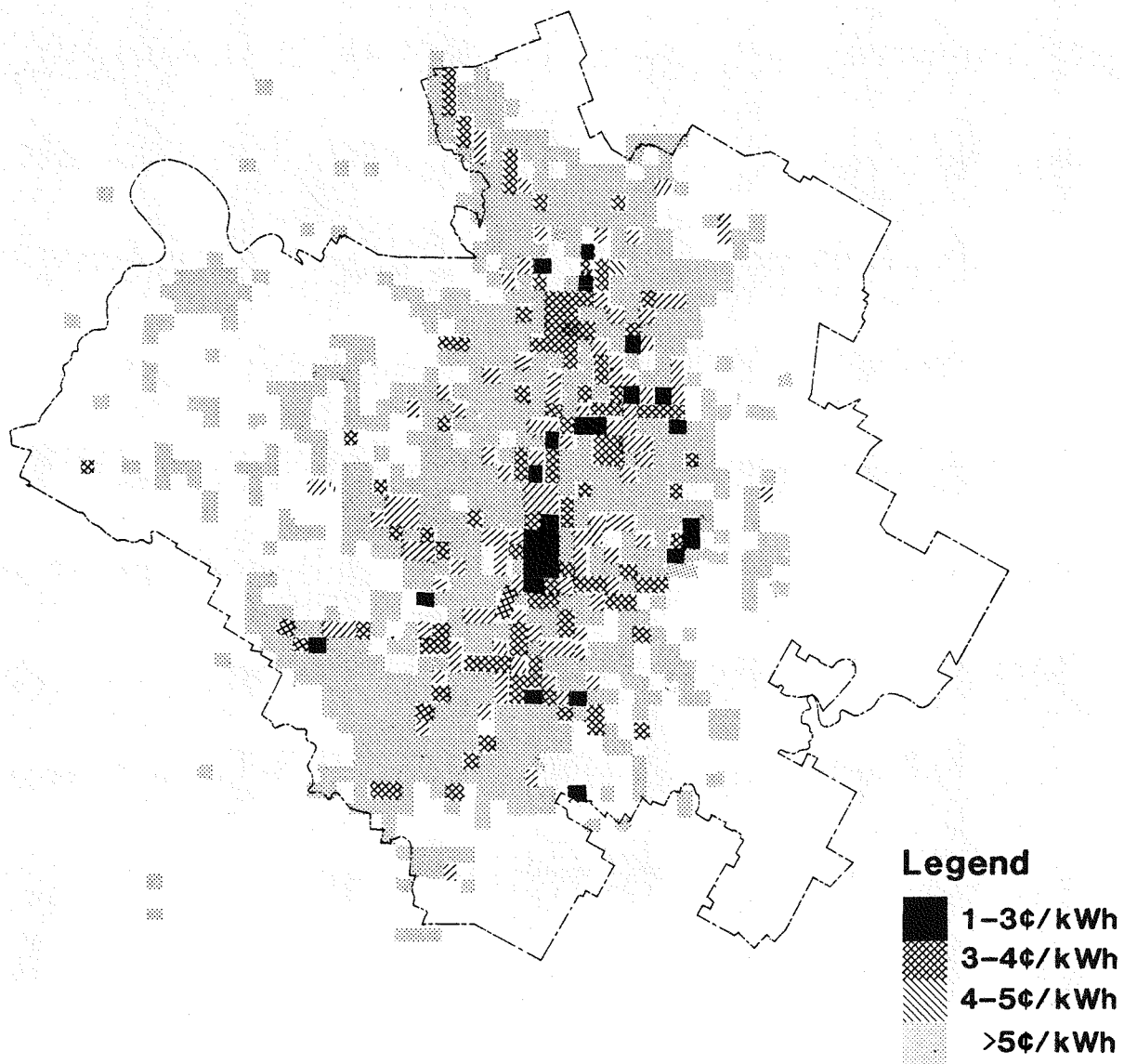


Figure 6-7. Central Electric Chiller w/Chilled Water Distribution.

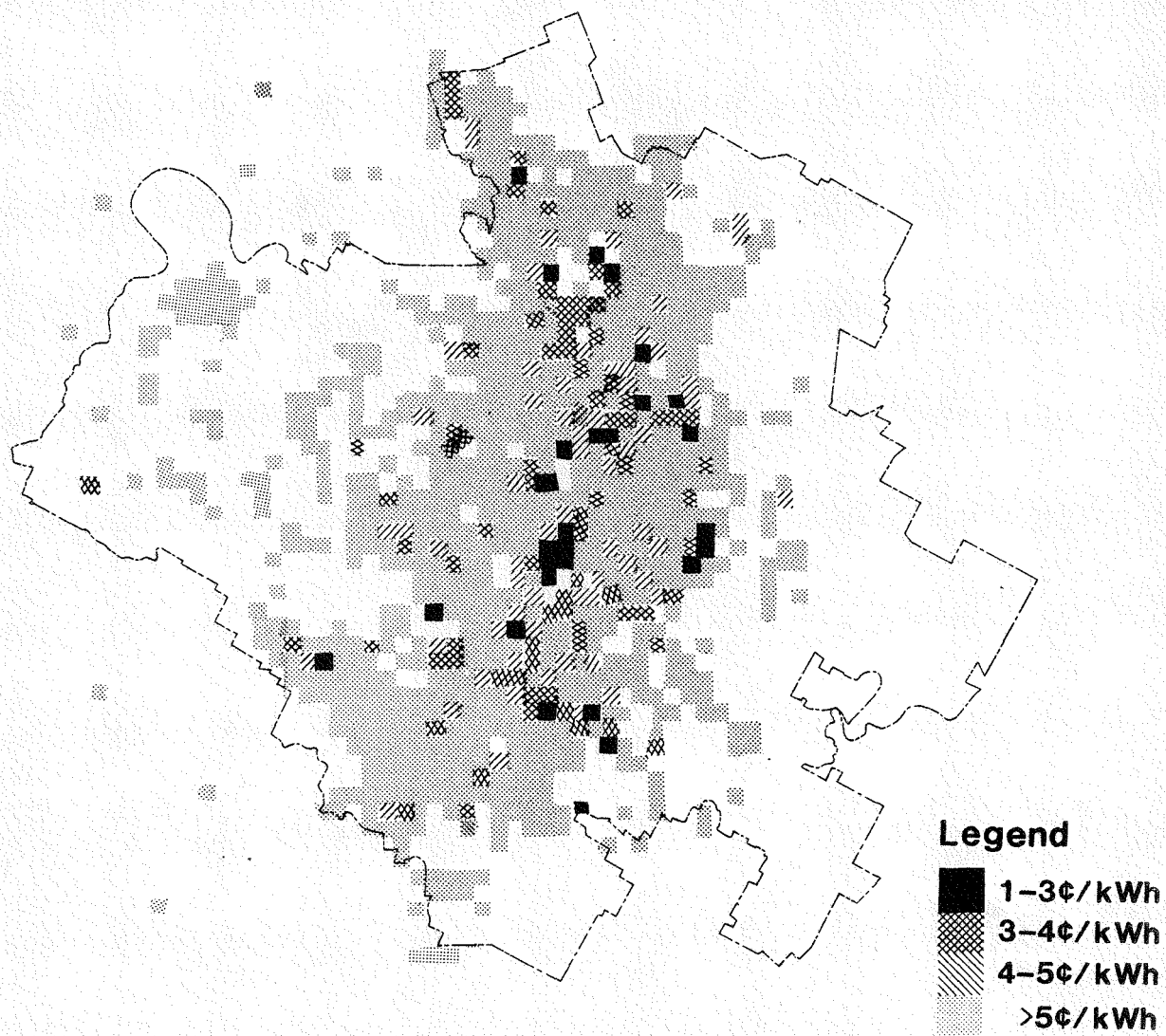


Figure 6-8. Central Electric Chiller w/Distributed Chilled Water Storage.
(All day chiller operation)

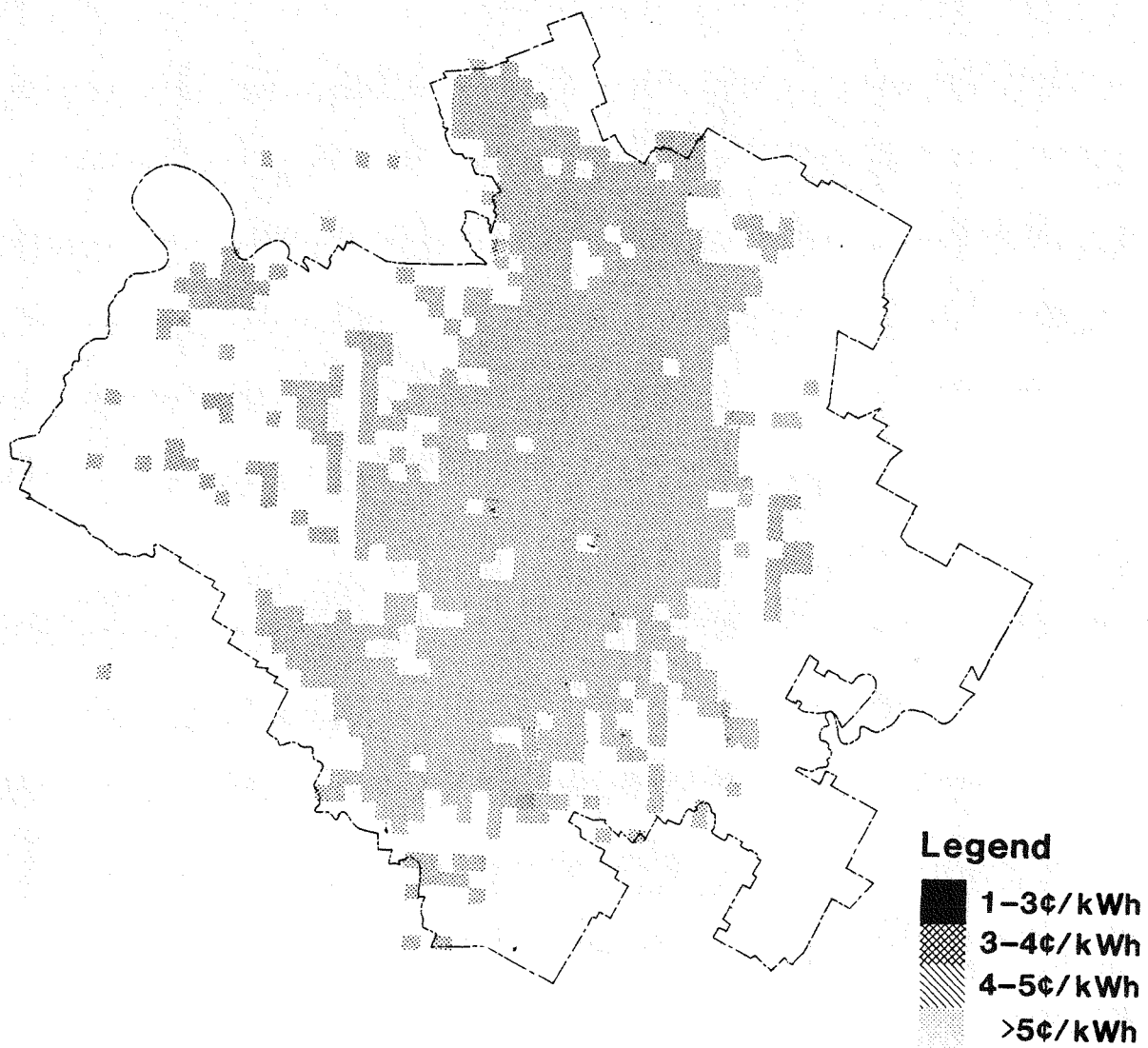


Figure 6-9. Central Steam-Driven Chiller w/Chilled Water Distribution.

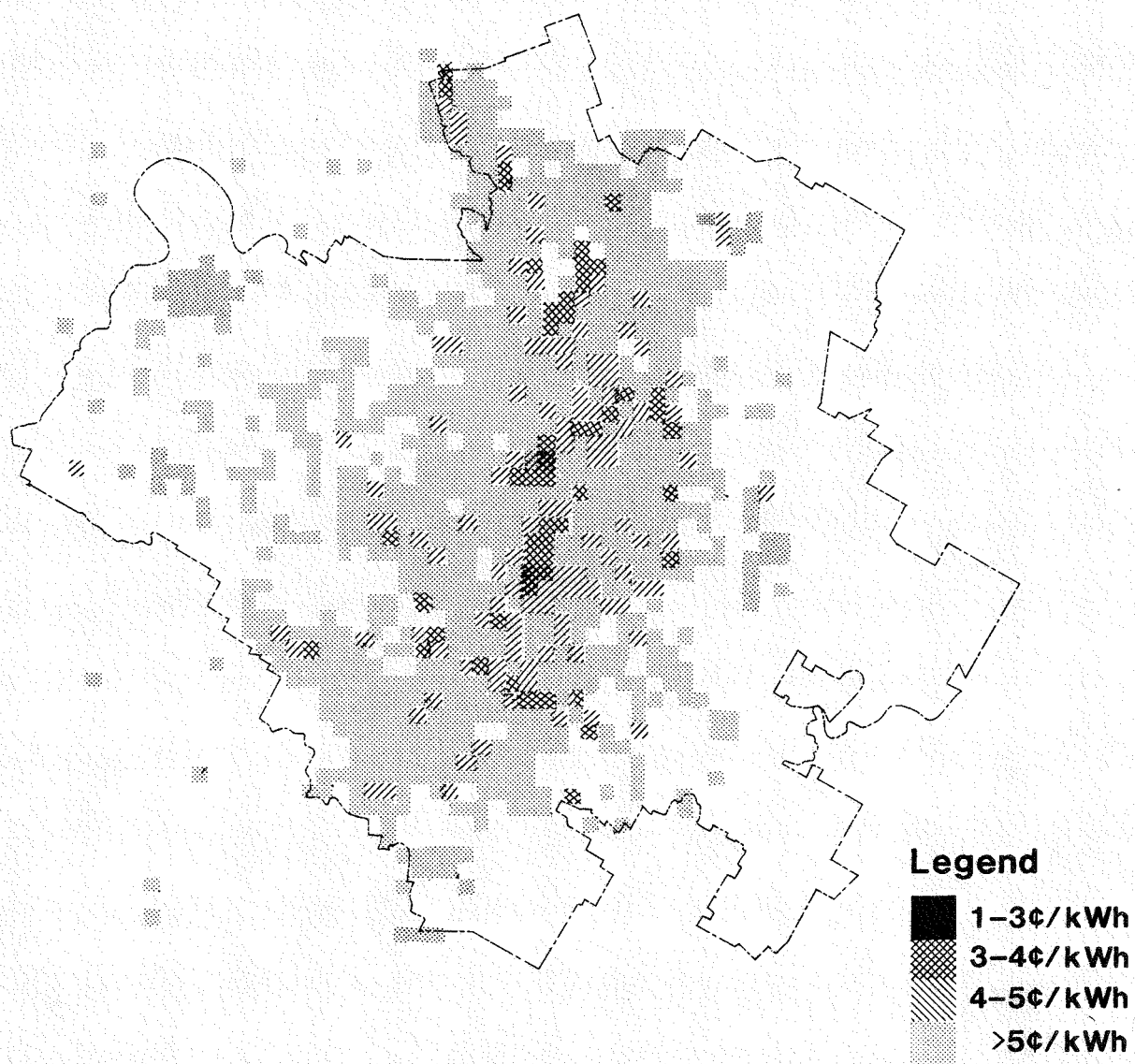


Figure 6-10. Central Electric Chiller w/Distributed Chilled Water Storage.
(Off-peak chiller operation)

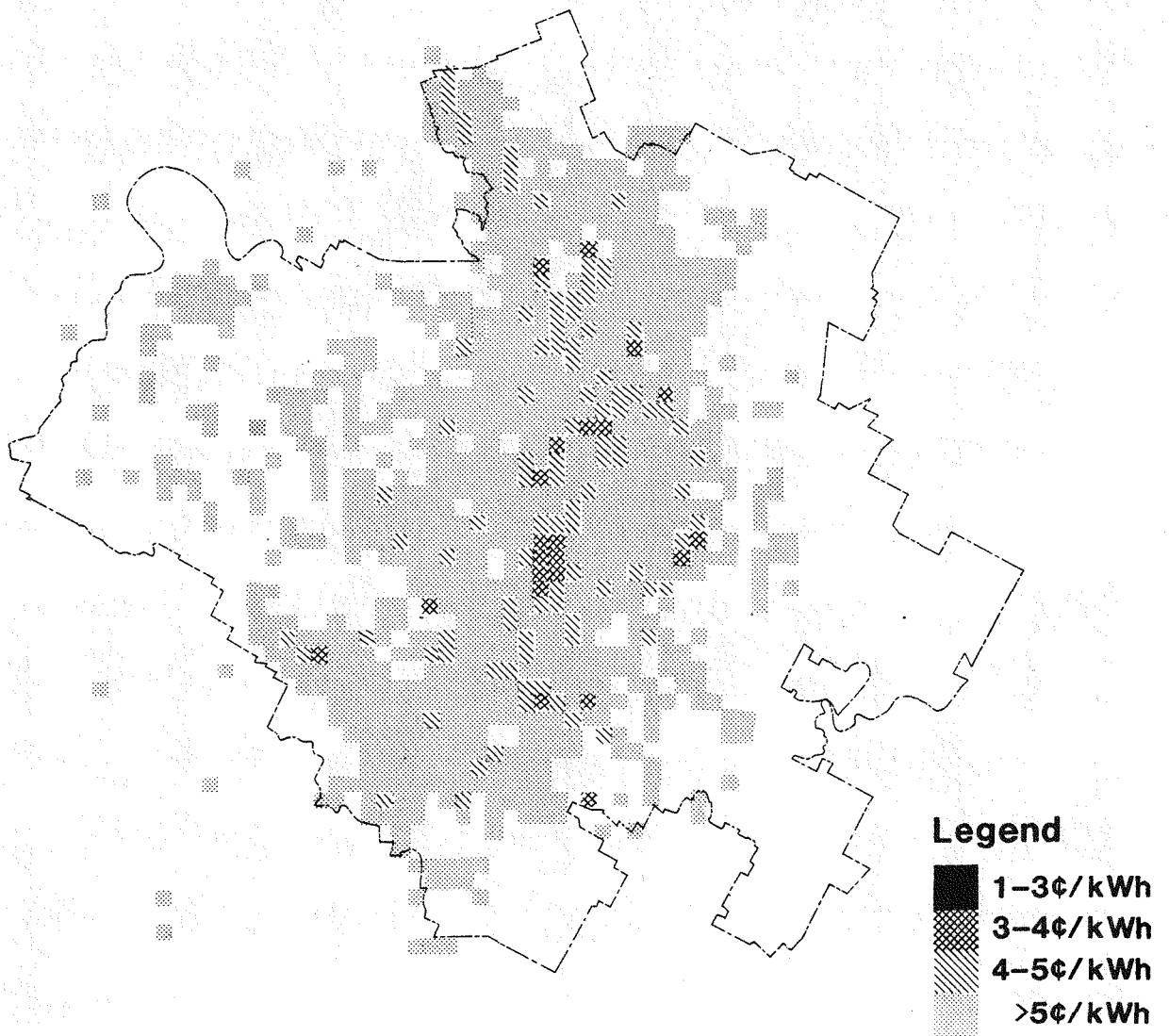


Figure 6-11. Central Electric Chiller w/Distributed Slush Ice Storage.
(Off-peak chiller operation)

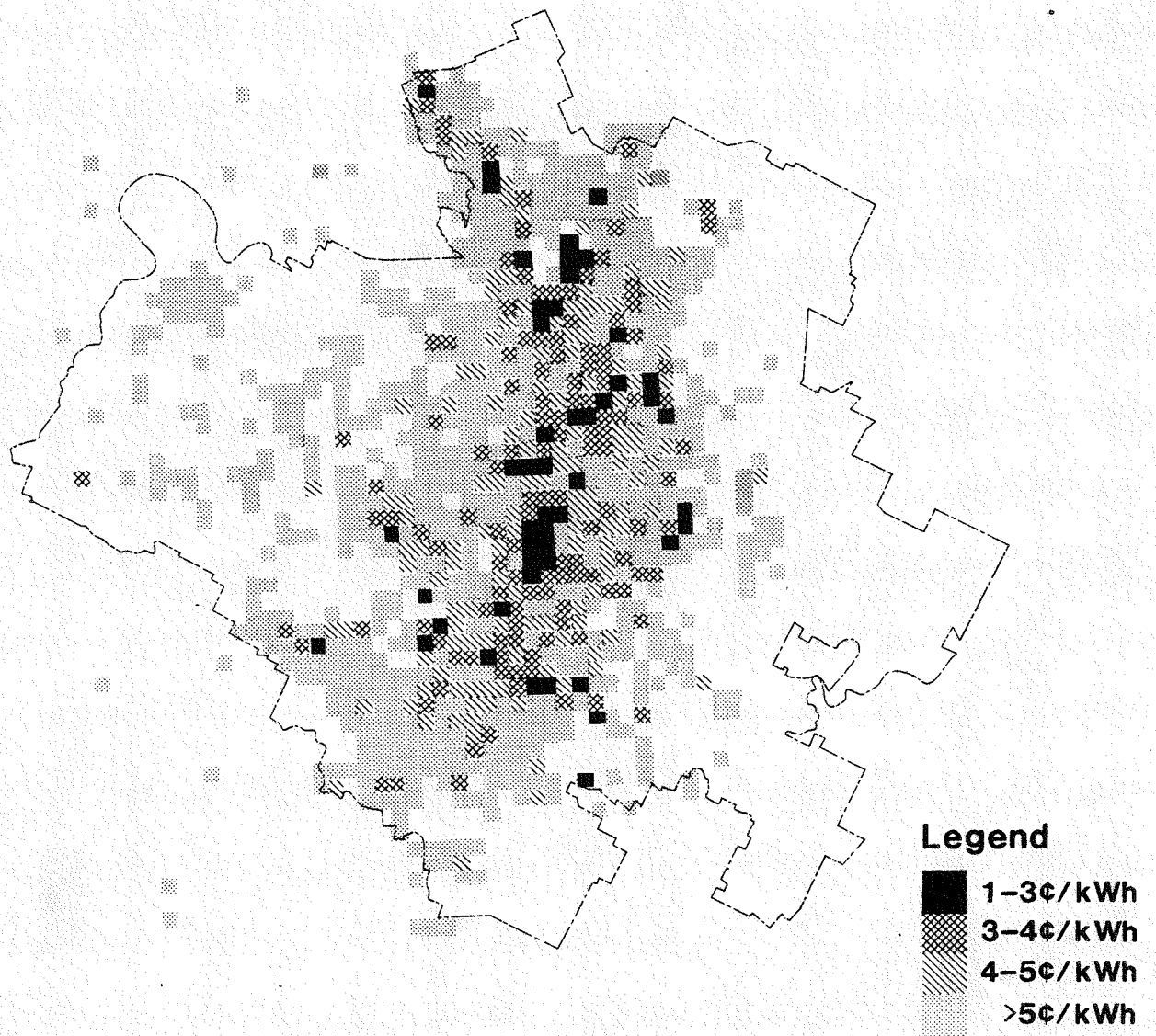


Figure 6-12. Central Electric Chiller w/Central Chilled Water Storage.
(All day chiller operation)

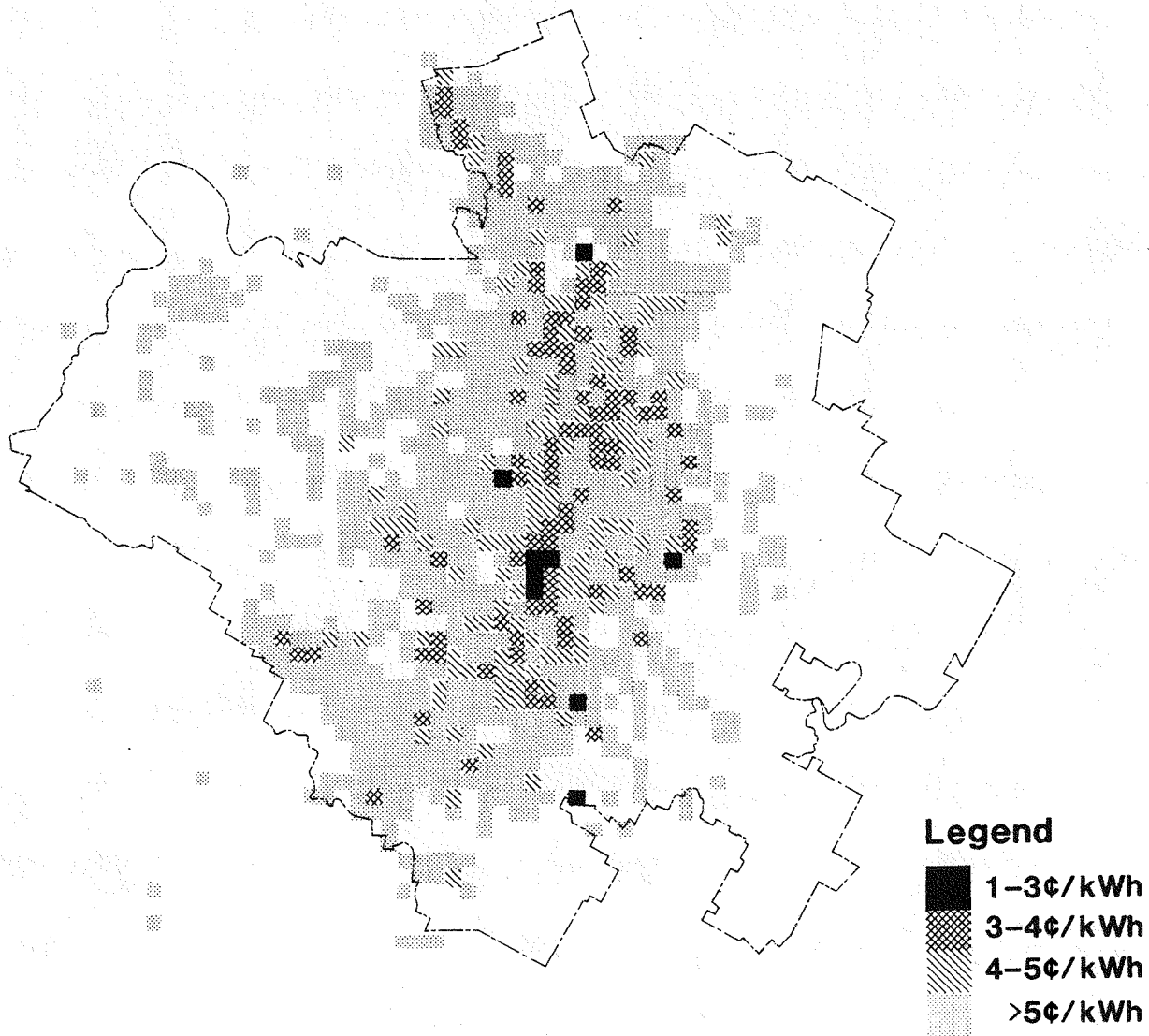


Figure 6-13. Central Electric Chiller w/Central Slush Ice Storage.
(All day chiller operation)

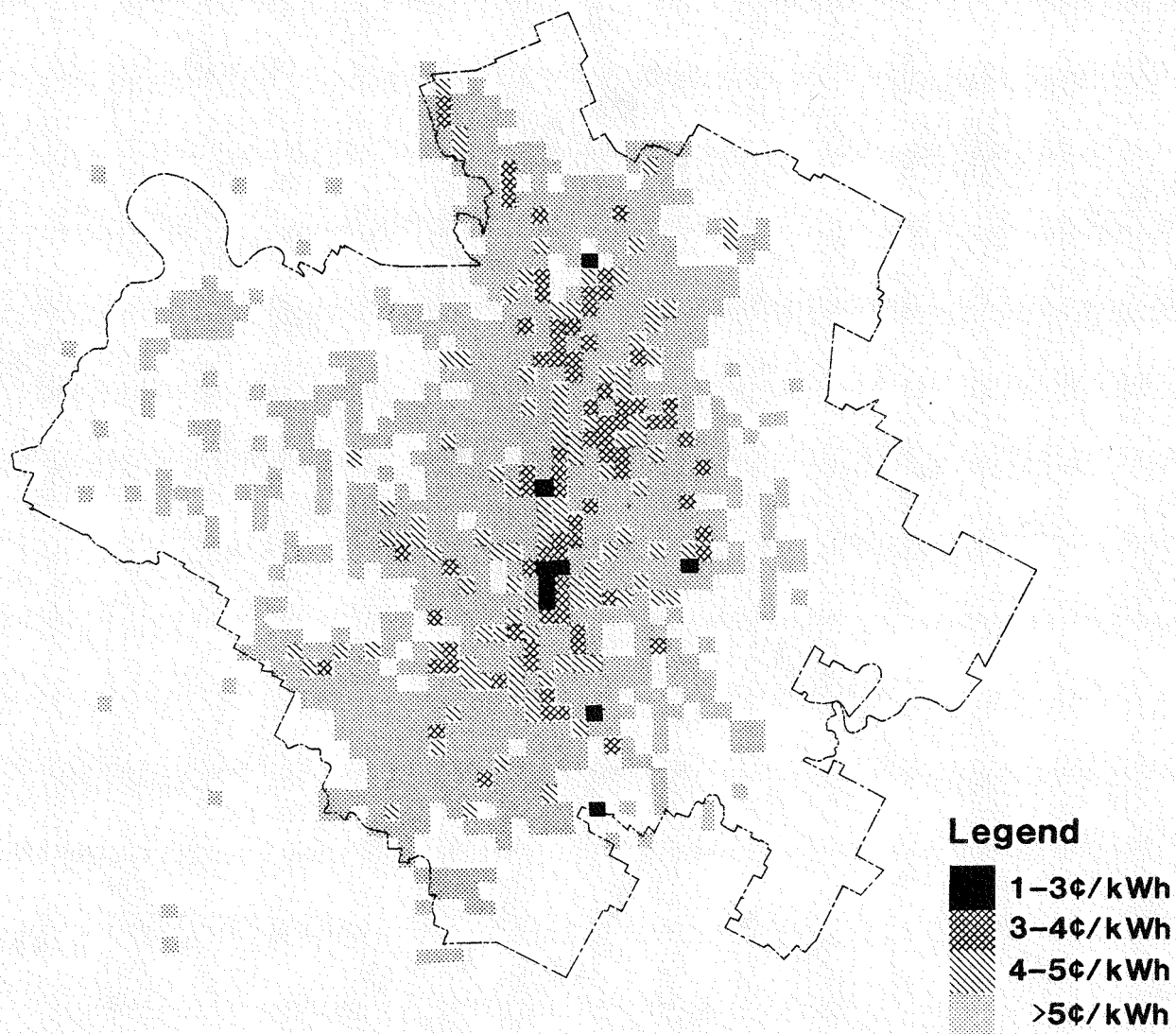


Figure 6-14. Central Electric Chiller w/Central Chilled Water Storage.
(Off-peak chiller operation)

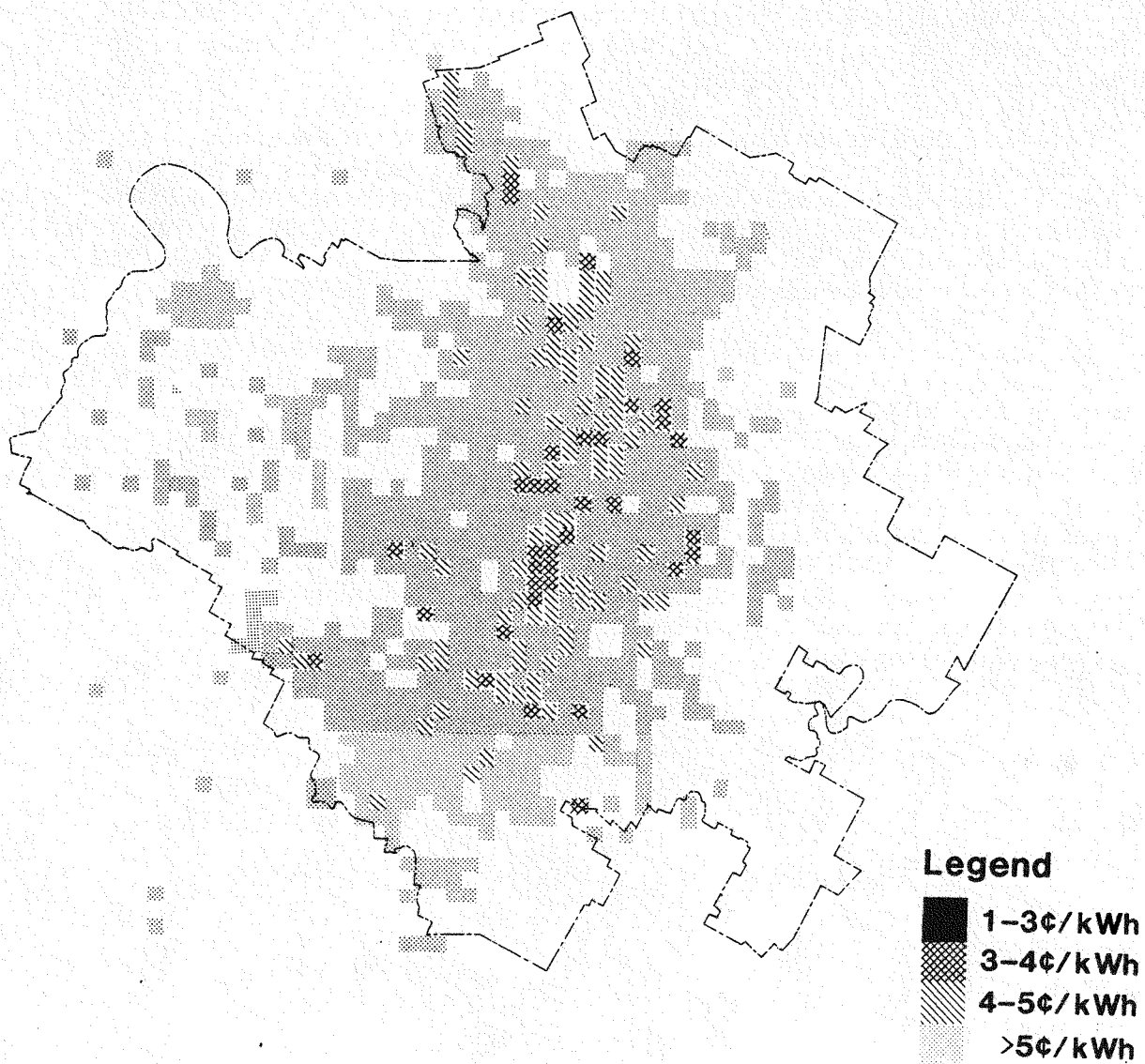


Figure 6-15. Central Electric Chiller w/Central Slush Ice Storage.
(Off-peak chiller operation)

7.0 CONCLUSIONS

A computer-aided study geared towards examining the economic potential of some selected district cooling scenarios in the Austin area was performed as a first-cut analysis of DHC potential. For comparison purposes, a reference case consisting of electric chiller units installed in individual buildings was chosen as the baseline system from which the district cooling systems were gauged. In each given system, annualized delivered energy cost was used as the figure-of-merit.

From results of the district cooling systems examined, only a few areas in a few of the cases given can be identified as having any economic potential over the baseline cooling system. System 2, where cooling is achieved by chilled water distribution from a central electric chiller with low-summer-temperature heat sink, appeared to be competitive in those few areas with high cooling loads close to the low-temperature source.

System 5 also appears to be competitive with the baseline case, especially in areas that are largely commercial with high cooling loads. This is primarily due to the large economy of scale associated with the electric chiller which reduced the capital costs. Of the cases where storage was considered, the partial storage mode wherein the chiller operated on a 24-hour basis, appeared to be more advantageous than when the chiller was only allowed to run at off-peak hours (full storage). This is presumably due to higher costs of storage for the latter case since the store is charged to full capacity. Results also show that under the conditions given, chilled water storage appeared more economically favorable than ice storage, due to the lower efficiency of slush ice-producing equipment.

8.0 REFERENCES

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