BNL--52001

DE87 000208

BNL 52001
UC-95d
(Energy Conservation — Buildings and
Community Systems — TIC-4500)

DISTRICT HEATING AND COOLING TECHNOLOGY SELECTION AND CHARACTERIZATION

FINAL REPORT

Philip D. Metz, Mark Catan, and Michael Piraino
Brookhaven National Laboratory

Robert W. Timmerman, P.E.
Consultant
Boston, Massachusetts

Jack Gleason
Consultant
Washington, D.C.

March 1986

A. MEZZINA
ENERGY APPLICATIONS AND ANALYSIS DIVISION
DEPARTMENT OF APPLIED SCIENCE
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, LONG ISLAND, NEW YORK 11973

UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE
UNITED STATES DEPARTMENT OF ENERGY

EHB

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes:
Printed Copy: A09; Microfiche Copy: A01

CONTENTS

TABLES

Page

TABLES

FIGURES

EXECUTIVE SUMMARY

Overview

This report describes the district heating and cooling (DHC) technology selection and characterization tasks performed under Part I of the project "District Heating and Cooling Market Potential and Penetration Study" for the U.S. DOE. The purpose of this project is to determine the applicability of various DHC technologies to different community types and regions of the country. The results will be used by DOE to guide R&D program planning.

The project is divided into two parts. Part I "Development of the Conceptual Approach" consists of three sets of related tasks:

- DHC technology selection and characterization,
- development of the market potential and penetration methodology,
- selection of prototype communities for inclusion in the study.

Part II, "Implementation and Application of the Conceptual Approach", will employ the methodology developed in Part I to evaluate selected DHC technologies in the prototype community.

Technology Selection

The purpose of this task is to define and select the specific DHC technologies to be included in the assessment. Both conventional and innovative system types were considered.

A general DHC system model was developed to provide a framework in which to describe each system type. Three separate methods were employed to select DHC system types:

- Delphi
- Exhaustive
- Ranking

The Delphi approach relies on expert judgment and hence is highly subjective. The exhaustive method is objective, but led to inconclusive results. The ranking method, with intermediate subjectivity, uses expert judgment to select weighted criteria against which all systems are evaluated and ranked.

Ultimately 9 DHC system types - plus 2 baseline nondistrict systems for comparison - were selected for characterization, as shown in Table 1.

Technology Characterization Approach

The purpose of this task is to characterize, both technically and economically, the 9 selected DHC system types to define the community types which each can serve. In all, over 30 system variations were evaluated for 10 load cases and 2 district sizes in a Philadelphia-New York City climate.

Table 1. Selected DHC System Types

DHC system type	Application (heating, cooling)	Transmission/Distribution Medium
Urban oil-fired cogenerator retrofit	H, C	Steam above 250°F
Coal boiler	H, C	Steam above 250°F
Diesel cogenerator with central absorption chiller	H, C	Hot water 180-250° (Cold Water <50°F)
Coal-fired cogenerator (Scandinavian system)	H, C	Hot water 180-250°F
Low-backpressure central cogenerator	H, C	Hot water 120°F
Distributed water-source electric heat pumps	H, C	Water 50-90°F
Central fuel-driven heat pumps	H, C	Water: Primary 50-90°F Secondary 150°F/40°F
Ice pile	C	Cold water 50°F
Municipal waste incinerator	H C	Hot water 180-250°F
Baseline System Type		
Individual gas boilers	H	---
Individual electric air conditioners	C	---

Delivered energy cost was selected as the economic figure-of-merit for comparing systems. A microcomputer program, including a DHC component database, was developed to carry out the characterization. This program, suitable for characterizing other DHC systems and documented in Appendix I, is available from the authors.

To characterize a DHC system, the thermal load served must be described in terms of its total size, density, and time-dependence. For this analysis the concept of "abstract" loads was developed to permit rapid examination of a wide range of load characteristics. In this approach each load case represents a set of identical buildings, equally-spaced on a square mesh. The abstract loads don't represent particular real communities. Instead they provide a set of "templates" against which real communities can be compared.

Technology Characterization Results

Heating. Table 2 ranks the district heating systems studied by their competitiveness with the non-district baseline heating system - individual gas boilers. Systems are described as "very competitive" - delivered energy cost more than 25% below the baseline, or "competitive" - delivered energy cost 0 to 25% below the baseline. Important sensitivity factors and the nature of scale economics are also identified.

Tables 3 and 4 summarize those results for all system types by load case. The top-ranked system - the diesel cogenerator with an electricity sales price of 10¢/kWh is very competitive in all 10 load cases. The low-back pressure cogenerator is very competitive in 6 load cases, the urban oil-fired cogenerator in 5, and the municipal waste incinerator/cogenerator in 4. The diesel cogenerator with 5¢ electricity is competitive in only 1 load case, and the coal boiler - the lowest ranked heating system - in none.

Cooling. Stand-alone cooling costs are competitive only for the distributed water-source heat pump system.* The small number of annual cooling hours in the climate studied makes it difficult to amortize the capital cost of a district cooling system.

Combined heating/cooling systems - which share capital equipment - are much more competitive. The incremental cooling costs of combined heating/cooling systems are at least "competitive" for almost all load cases. In fact, all system types, except the urban oil-fired cogenerator retrofit and the diesel cogenerator with distributed absorption chillers, are very competitive (more than 25% below the baseline) in almost all load cases.

Conclusions

Several general conclusions are clear from these results.

- A revenue-producing co-product is essential. Most of the most-competitive systems co-produce, e.g., electricity or waste incineration.
- Many competitive systems have large scale economics. The competitiveness of these systems depends mainly on total system load.
- Some competitive systems have small-scale economies. The competitiveness of these systems is very sensitive to external factors, e.g., electricity price or distribution piping capital cost.
- Optimal distribution systems are important. Use of the lowest-cost piping option was essential to the competitiveness of most systems.

---

*In pathological cases, e.g., very high electricity sales price or waste tipping fee, other stand-alone systems might be competitive.

Table 2. Ranking of District Heating System Competitiveness

Rank	System	Load Cases Where Delivered Energy Cost Is Very Competitive (More than 25% Below Baseline)	Load Cases Where Delivered Energy Cost Is Competitive (0-25% Below Baseline)	Important Sensitivity Factors	Nature of Scale Economy
1	Diesel Cogenerator Electricity Sales Price 10¢/kWh	10 Cases (All)	0 Cases	Extremely sensitive to Electricity Sales (or Avoided Purchase) Price	Small
2	Low-Backpressure Cogenerator	6 Cases (Large Bldg, High Density)	2 Cases (Large-Bldg, High Density)	Total System Load, Transmission Distance, Temperature Drop (and Piping Size)	Large
3	Urban Oil-Fired Cogenerator Retrofit*	5 Cases (High-Density, Large Bldg)	0 Cases	Total System Load, Purchased Thermal Energy Cost	Large
4	Municipal Waste Incinerator/Cogenerator	4 Cases (100, 1000 kW Peak; High Density)	1 Case (100 kW Peak, 5 Bldg/Block)	All Primary Costs (Capital, Tipping Fees, Handling Expenses, Electricity Revenues)	Large
5	Fuel-Driven Heat Pump	2 Cases (1000 kW Peak)	5 Cases (10, 100, 5000 kW Peak)	Distribution Capital Cost	Small
6	Coal-Fired Cogenerator	2 Cases (1000 kW Peak)	3 Cases (Large-Bldg, High Density)	Total System Load	Large
7	Distributed Water-Source Electric Heat Pumps	0 Cases	2 Cases (Small Bldg, Low Density)	Purchased Electricity Cost	Small, Negative
8	Diesel Cogenerator Electricity Sales Price 5¢/kWh	0 Cases	1 Case (1000 kW Peak, 5 Bldg/Block)	Extremely sensitive to Electricity Sales (or Avoided Purchase) Price	Small
9	Coal Boiler	0 Cases	0 Cases	Boiler Capital Cost	Large

*Hot Water Distribution

Table 3. District Heating Systems with Delivered Energy Costs More than 25% Below Baseline for 15 Block District

Building density		Building Peak load (kW)			
Buildings/ block	(Buildings/ acre)	10	100	1000	5000
1	(.15)	---	3*	1,3*,4,5,7,11	1,3*,5
5	(.74)	3*	3*,5	1,3*,4,5,7,11	---
20	(3.0)	3*	1,3*,5,11	---	---
50	(7.4)	3*	1,3*,5,11	---	---

System Type Key

Number	System Type	Distributed fluid
1	Urban oil generator retrofit	Water
2	Coal boiler	Steam
3	Oil-fired diesel cogenerator (5¢/kWh electricity sales)	Water
3*	Oil-fired diesel cogenerator (10¢/kWh electricity sales)	Water
4	Coal-fired cogenerator	Water
5	Low-backpressure central cogenerator	Water
6	Distributed water-source electric heat pumps	Water
7	Central gas-fired heat pumps	Water
11	Municipal waste incinerator/cogenerator	Water

Table 4. District Heating Systems with Delivered Energy Costs 0-25% Below Baseline

Building density		Building Peak load (kW)			
Buildings/ block	(Buildings/ acre)	10	100	1000	5000
1	(.15)	---	None	None	4,7
5	(.74)	6	7,11	3	---
20	(3.0)	5,6,7	4,7	---	---
50	(7.4)	5	4,7	---	---

System Type Key

Number	System Type	Distributed fluid
1	Urban oil generator retrofit	Water
2	Coal boiler	Steam
3	Oil-fired diesel cogenerator (5¢/kWh electricity sales)	Water
4	Coal-fired cogenerator	Water
5	Low-backpressure central cogenerator	Water
6	Distributed water-source electric heat pumps	Water
7	Central gas-fired heat pumps	Water
11	Municipal waste incinerator/cogenerator	Water

- Low-temperature transmission/distribution systems are important. Several of the most competitive heating systems operated below 200°F.

- Piping thermal capacity enhancement is desirable, especially for low-temperature systems with restricted temperature ranges.

Several conclusions emerge regarding specific systems:

- The urban oil-fired cogenerator retrofit is surprisingly competitive.

- Stand-alone central boilers cannot compete with modern distributed boilers.

- The competitiveness of small diesel cogenerators is <u>extremely</u> sensitive to electricity sales (or avoided purchase) price. These systems are very competitive even in small load cases if electricity prices are high.

- The coal-fired cogenerator is competitive where Scandinavian experience would indicate.

- The low-backpressure cogenerator is competitive in a wide range of load cases.

- Distributed water-source electric heat pumps are competitive for small buildings, especially if electricity costs are low compared to gas.

- The fuel-fired heat pump competitiveness would be enhanced by reduced distribution costs.

- The municipal waste system can be very competitive if tipping fees are high.

Recommendations

<u>General</u>. DOE should work to implement the most competitive DHC systems because they further DOE goals and benefit system users and owners economically.

<u>Conventional Technology</u>. Development is not required for competitive conventional systems. Instead, DOE should focus on understanding the problems which limit implementation of these systems--institutional impediments and market wants, needs, and preferences.

<u>Innovative Technology</u>. DOE should support R&D to develop potentially-competitive innovative systems:

- combined heating/cooling systems,

- low-backpressure cogenerator,

- fuel-driven heat pumps,

- low-temperature piping systems,
- piping thermal capacity enhancement,
- low-temperature building distribution systems--especially in retrofit.

Contingent Technology. For systems where competitiveness depends on "uncontrollables," DOE should:

- identify likely future scenarios
- target R&D to systems most competitive in likely future environments.

New District Heating Markets. A number of systems have been identified which are competitive in small load cases. DOE should investigate these systems to extend the district concept to small loads where institutional impediments are likely to be smaller. Attempts should be made to "break" the scale economies of those systems now competitive only for large loads. Through such innovative approaches, future district heating markets may be quite different from those of the past.

District Cooling. Combined heating/cooling systems should be given greater attention. The finer cooling system issues were not resolved by this study, and should be addressed in a study of a southern U.S. climate.

Revenue-Producing Component. Because the most competitive DHC systems have a revenue-producing coproduct, future DHC R&D should address issues and problems associated with these coproducts.

ACKNOWLEDGMENTS

The authors wish to acknowledge major contributions from Ann Reisman of BNL who initiated this project and Jake Kaminski of DOE who has been its guiding light. We would also like to thank John Andrews of BNL, who participated in DHC technology selection, and Dave Kaplan who performed some of the computer programming. Finally, we would like to thank all the people who provided information used to assemble the DHC component data base.

1.0 INTRODUCTION

1.1 Project Overview

The work described in this report was performed for the U.S. Department of Energy as part of the project "District Heating and Cooling Market Potential and Penetration Study."

Purpose

The purpose of this project is to quantify the potential of conventional and innovative district heating and cooling (DHC) space conditioning systems in the U.S. More specifically, its goal is to determine the applicability of alternative DHC system types to different regions of the country and to identify improvements that enhance system potential.

This information will be used by DOE to establish program direction, and to identify and prioritize R&D targets. The results will also be made available to communities, A&E Firms, and manufacturers to help them evaluate DHC systems.

Technical Approach

The project is divided into two parts. Part I "Development of the Conceptual Approach", part of which is the subject of this report consists of three related sets of tasks:

o DHC Technology Selection and Characterization

A generic DHC system model, sufficiently general to represent all the specific systems of interest, was developed. Nine main specific DHC system types 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. The most competitive systems were identified.

o Development of the 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. A "preferred" methodology was developed, and a prognosis for implementing the preferred methodology was made.

- Selection of Prototype Communities for Inclusion in the Study

Criteria were developed to select prototype communities in which to assess the feasibility of the selected DHC system types. A large number of candidate communities were investigated. Recommendations were made to DOE for selection of single community to be studied in Part II.

Part II, "Implementation and Application of the Conceptual Approach," will employ the characterization methodology developed in Part I to compare economically the selected DHC system types in the various service areas of the prototype community. After taking into account local energy resource locations and institutional barriers, the potential service area of each system will be computed for a range of future scenarios.

1.2 Scope of this Report

This report describes the results of the DHC technology selection and characterization tasks described above. The microcomputer program (and the associated DHC system data files) developed to characterize the selected DHC system types is thoroughly documented in an appendix organized as a stand-alone users manual.

2.0 TECHNOLOGY SELECTION

2.1 Task Description

The purpose of this task is to define and select the specific DHC technologies to be included in the assessment. Both conventional and innovative system types were considered. Ultimately nine main system types were selected for characterization. A number of options, such as space heating or cooling service and steam versus hot water distribution fluid, were identified for each main system type. A general DHC system model was developed to provide a framework in which to describe each system type.

2.2 Technology Selection Approach

General System Description

Based on analysis of the structures of candidate system types, a general DHC system model, shown in Figure 2-1, was developed. The general DHC system model includes the following elements:

- Primary Energy Converter

The primary energy converter uses primary energy (e.g., oil, gas or coal) to produce thermal energy and possibly electricity. Examples include a coal boiler or a gas-fired cogenerator.

- Direct Thermal Source

The direct thermal source provides thermal energy from an ambient source either to the secondary energy converter or directly to the users. Examples include a lake or an ice pile (for cooling).

- Secondary Energy Converter

The secondary energy converter receives thermal energy from the primary converter or the direct thermal source. It may also input fuel or electricity. It produces thermal energy and possibly electricity. Many secondary converters may exist in one system, each serving a separate group of buildings. Examples include a gas-fired heat pump or an oil-fired peaking boiler.

- User Energy Converter

The user energy converter, located in each individual building, receives thermal energy from the secondary converter or direct thermal source. It may also input fuel or electricity. It produces thermal energy for the user. Examples include a heat exchanger, an absorption chiller or a gas boiler.

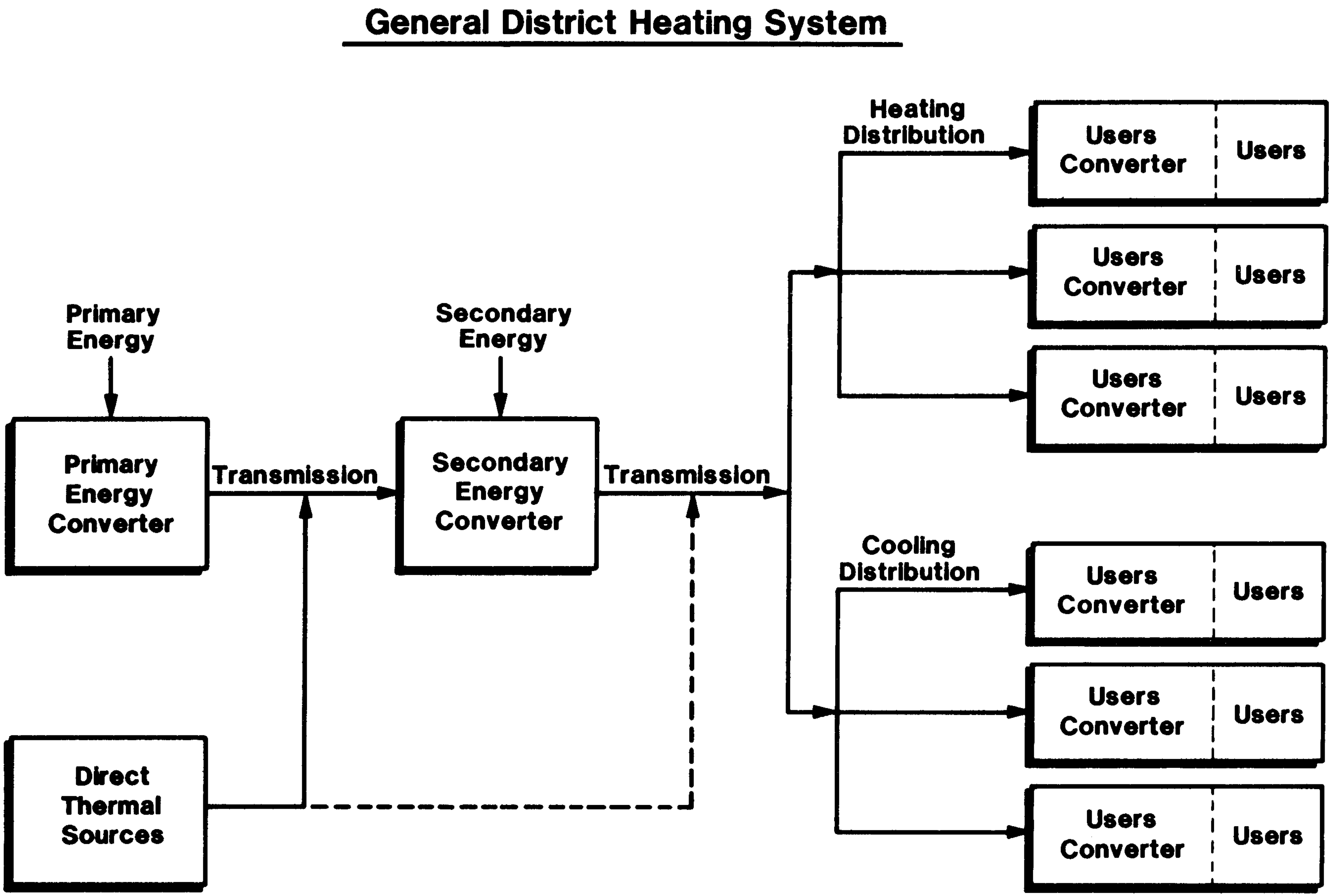
General District Heating System
Primary Energy
Secondary Energy
Primary Energy Converter
Transmission
Secondary Energy Converter
Transmission
Direct Thermal Sources
Heating Distribution
Cooling Distribution
Users Converter
Users
Users Converter
Users
Users Converter
Users
Users Converter
Users
Users Converter
Users
Users Converter
Users

FIGURE 2-1

- Transmission and Distribution Subsystems

The transmission and distribution subsystems comprise a piping network which delivers thermal energy from the primary converter and direct thermal source to the secondary converter(s) and users via a heat transfer medium such as water or steam.

Selection of Specific System Types

Each specific DHC system type is defined by specifying a hardware component (e.g., gas cogenerator, plastic pipe, etc.) for each element in the general DHC system model. Three separate methods were employed to select DHC system types:

- Delphi Method

In this method participants make independent selections which are collated, discussed, and revised. It relies on "expert judgment" and hence is highly subjective.

- Exhaustive Method

In this approach all possibilities known are identified and described within a classification system. Selection rules are developed to eliminate illogical systems. This method is objective and results in a comprehensive taxonomy of systems. However, in this case the results were found to be inconclusive because logical systems exist which are not desirable.

- Ranking Method

This method is a compromise between the previous two. Expert judgment is employed to identify weighted criteria for rating all systems. Each system is then evaluated in terms of these criteria and then ranked by its score. This method has intermediate subjectivity as the criteria are subjective, but all systems are evaluated on clearly-defined equal footing.

2.3 Technology Selection Methodology

In this section the selection procedure carried out is briefly outlined to highlight the thought processes that went into it and some of the findings which emerged.

Delphi Method

Independent evaluations were performed by three project participant to develop system recommendations and rationales for inclusion. The results were compiled to eliminated duplication and clarify differences of opinion. Meetings and discussions were held to resolve these differences.

These evaluations and discussions identified several grey issues related to system selection:

- the historical context of DHC in the U.S., especially the role of cogeneration in the development of steam district heating systems;
- the complexity of the DHC problem in the U.S., especially the market and institutional barriers;
- the importance of space cooling which is unique to the U.S. market;
- the importance of new, improved DHC systems for economic feasibility, in particular;
  - lower temperature heating systems,
  - capital cost reductions via efficient use and minimization of capital equipment.
- the importance of using process and load synergies, e.g., low-cost - or free - energy sources in DHC systems.

Technical disagreements were resolved by engineering analysis where possible and by concensus if analysis was not feasible. Uneasiness over complete reliance on the Delphi method led to the employment of other selection approaches.

Exhaustive Method

A set of six classifiers, shown in Table 2-1, was developed to describe the set of possible systems. It was found to be instructive to consider systems within this taxonomy. A total of 1440 possibilities were identified. All but 129 systems were eliminated by application of general selection rules.

Table 2-1. DHC System Exhaustive Method Classification Scheme

Classifier	Units	Value
Typical Temperature	°F	250, 180, 120, 70, 45
Primary Energy Source	--	Oil or Gas, Coal, Waste, Renewables
Scale	MW	1, 10, 100
Secondary Energy Converter for Heating	--	Direct, Heat Pump, No Heating
Secondary Energy Converter for Cooling	--	Direct, Heat Pump, No Cooling
By-Products	--	Heat, Electricity

The resulting 129 systems were compared with the Delphi method results. The systems selected via the Delphi method were found to span all temperature ranges cited in Table 2-1, with some clustering at higher temperatures. The wide distribution of the Delphi systems over the exhaustive method temperature categories bolstered confidence in the Delphi results - at least that no glaring omissions had been made.

The exhaustive method ultimately led to 23 system types, each with several options. No further simplification was identifiable via general selection rules.

These results, while encouraging and instructive, were judged inconclusive. For this reason it was decided to rank selected systems which spanned the exhaustive method taxonomy.

Ranking Method

Project participants independently identified and weighted proposed ranking criteria. Unimportant criteria were eliminated and overlapping criteria consolidated in group meetings. Final criteria weights were established by consensus decision.

The result was a set of four equally-weighted criteria and a simple scoring system, as presented in Table 2-2. The first criterion, breadth, encompasses three subcriteria:

- Range of Applicability, i.e., load density and size, and temperature range,
- Need for a site-specific in-place energy source,
- Regional Specificity.

Table 2-2. Ranking Method Selection Criteria and Scoring System

Criterion	Score				
	0	1	2	3	4
Breadth (# of Factors)	0	1	2	3	---
Furtherance of DOE Goals (# of Goals Promoted)	0	1	2	3	4
Low Capital Cost ($\$/10^6$ Btu)	$>10^6$	300k-10^6	100-300k	30-100k	10k-30k
Low Delivered Energy Cost ($\$/10^6$ Btu)	>12	9-12	6-9	3-6	0-3

The second criterion, furtherance of DOE goals, depends on four subcriteria selected from DOE mission statements:

- o Environmental Acceptability,
- o High Energy Efficiency,
- o Flexibility re Energy Source and Conversion Technology,
- o Use of Renewables, Coal, and Refuse.

While delivered energy cost is considered the prime measure of system economic feasibility, it is felt that low-capital-cost systems--requiring less up-front capital--are less risky and hence more likely to actually be constructed. This effect was judged sufficiently important to retain low capital cost as a separate ranking criterion.

All systems identified in the Delphi method plus a number of others were evaluated independently by project participants. The results were compiled, and differences of opinion were resolved where possible.

A total of 10 system types plus 8 options emerged from this analysis, indicating the need for great flexibility in the characterization methodology. Ranking method results were found to be sensitive to the criteria weights, reflecting the difficulty to picking the "best" systems without detailed technoeconomic analysis.

2.4 Technology Selection Results

System Descriptions:

As a result of the analysis described above and discussion with DOE, 9 DHC system types--plus 2 baseline non-district systems for comparison--were selected for charcterization. The system types are tabulated in Table 2-3, followed by detailed system descriptions and diagrams (Figure 2-2 through Figure 2-9). Each diagram follows the format of the general DHC system diagram, Figure 2-1, with the elements used by each system type highlighted.

Note that distributed absorption chillers have been selected for space cooling, except for the diesel cogenerator where engine reject heat can be used to power a central chiller without a Carnot penalty.

Table 2-3. Selected DHC System Types

DHC System Type	Application (Heating, Cooling)		Transmission/Distribution Medium
Urban Oil-Fired Cogenerator Retrofit	H,	C	Steam above 250°F
Coal Boiler	H,	C	Steam above 250°F
Diesel Cogenerator with Central Absorption Chiller	H,	C	Hot water 180-250° (Cold Water <50°F)
Coal-Fired Cogenerator (Scandinavian System)	H,	C	Hot water 180-250°F
Low-Backpressure Central Cogenerator	H,	C	Hot water 120°F
Distributed Water-Source Electric Heat Pumps	H,	C	Water 50-90°F
Central Fuel-Driven Heat Pumps	H,	C	Water: Primary 50-90°F Secondary 150°F/40°F
Ice Pile	C		Cold water 50°F; slush
Municipal Waste Incinerator/ Cogenerator	H	C	Hot water 180-250°F
Baseline System Type			
Individual Gas Boilers	H		--
Individual Electric Air Conditioners	C		--

OIL-FIRED URBAN GENERATING STATION RETROFIT

Description:

An oil-fired urban generating station is retrofitted to allow cogeneration of steam at temperatures above 250F and electricity. Cooling supplied via distributed adsorption chillers.

Service Area:

Existing district heating systems requiring steam at 250 to 340°F temperatures.

Options:

none.

Rationale:

This cogenerator would serve as a more efficient replacement for some existing district heating sources such as boilers.

Oil-Fired Urban Generating Station Retrofit

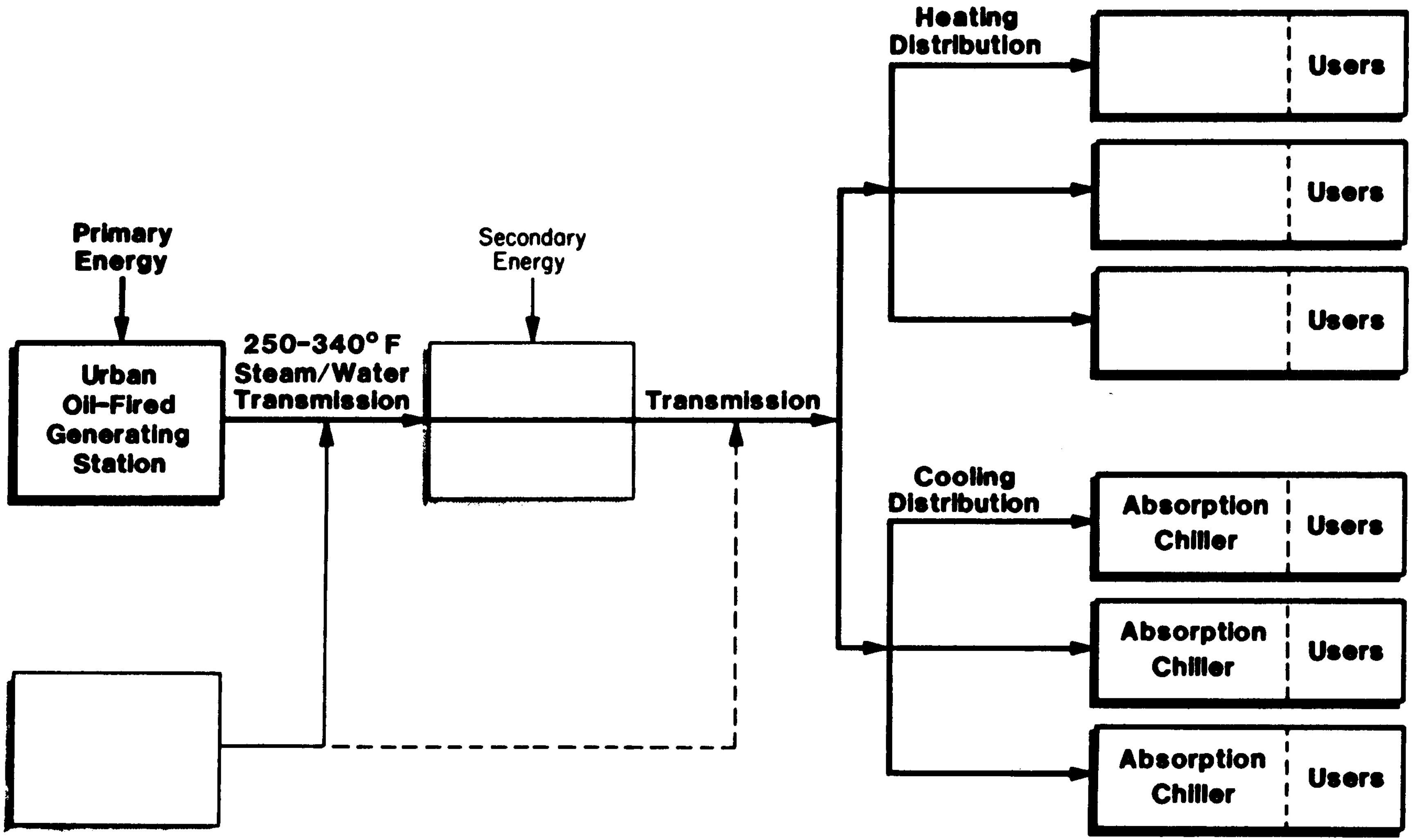

FIGURE 2-2

COAL BOILER

Description:

A new coal boiler supplies high pressure steam to a new or existing district heating system. Cooling supplied via distributed absorption chillers.

Service Area:

Cities where a coal burning plant is acceptable; suburban industrial parks.

Options:

Cogeneration of steam and electricity via a topping turbine; fluidized bed combustion.

Rationale:

Capable of serving users requiring high temperature steam; can replace less efficient sources of heat or sources requiring high grade fuel in existing district heating systems.

Coal Boiler

Options: Fluidized Bed Combustion Cogeneration with Topping Turbine

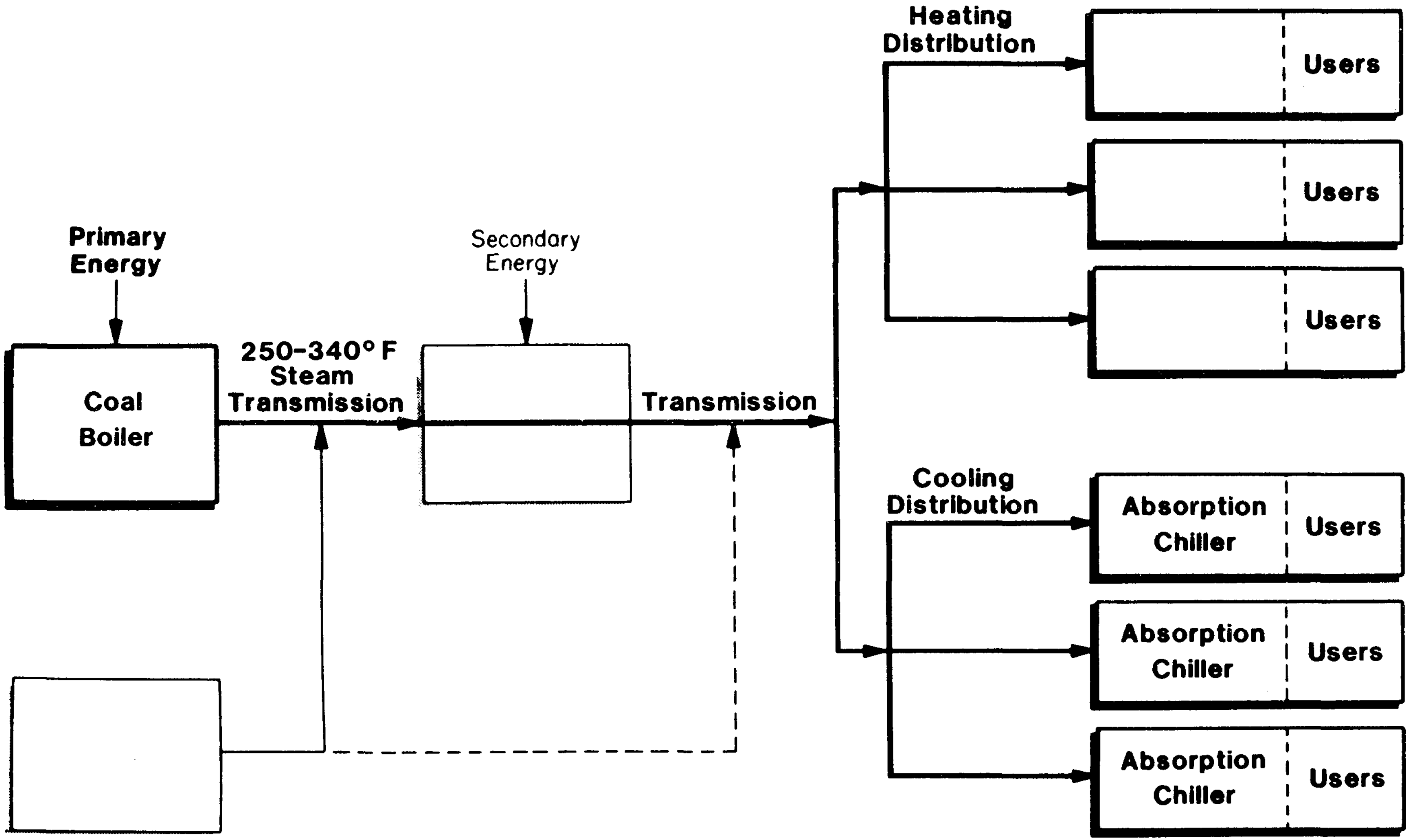

FIGURE 2-3

DIESEL COGENERATOR WITH CENTRAL ABSORPTION CHILLER

Description:

Diesel engine generator with heat recovery from engine cooling and exhause gases; supplies heat and electricity. Heat is used to generate cooling via a central absorption chiller.

Service Area:

City blocks, urban residencs, suburban residences and office buildings.

Options:

Alternate sources of heat for the central absorption chiller include: coal boiler and urban generating station.

Rationale:

Heat recovery does not affect efficiency of electrical generation; wide breadth of applicability; primary source can be relatively small and still achieve good economy.

Diesel Cogenerator with Central Absorption Chiller

Options: Coal Boiler Primary Source

Urban Oil Power Plant Primary Source

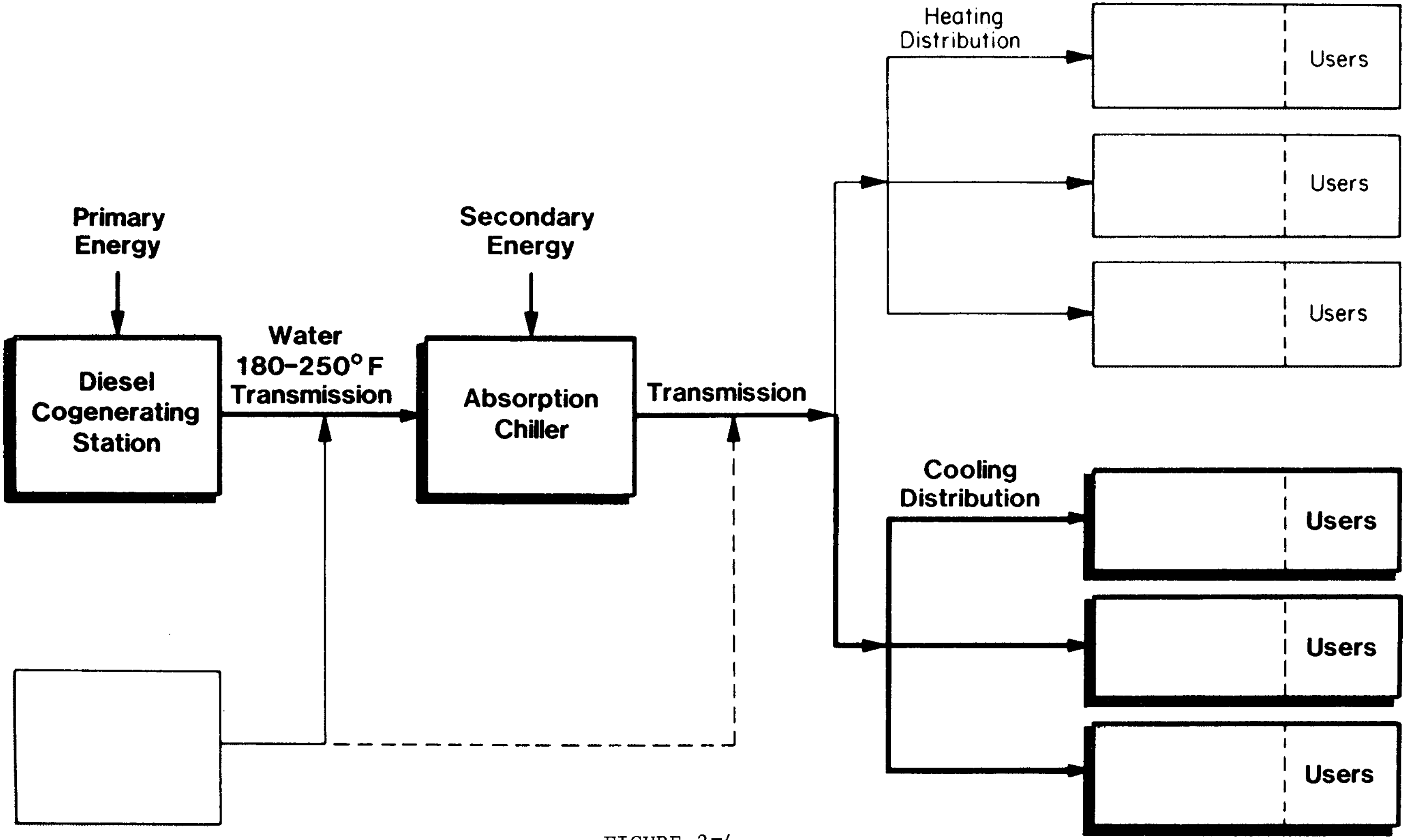

FIGURE 2-4

COAL-FIRED COGENERATOR

Description:

Coal fired cogenerating station which produces moderate temperature hot water and electricity. Cooling via distributed absorption chillers.

Service area:

Urban areas where coal burning is acceptable.

Options:

None.

Rationale:

Uses coal; low temperature allows the use of state-of-the-art distribution system and relatively low sacrifice of electrical generating efficiency.

Coal-Fired Cogenerator

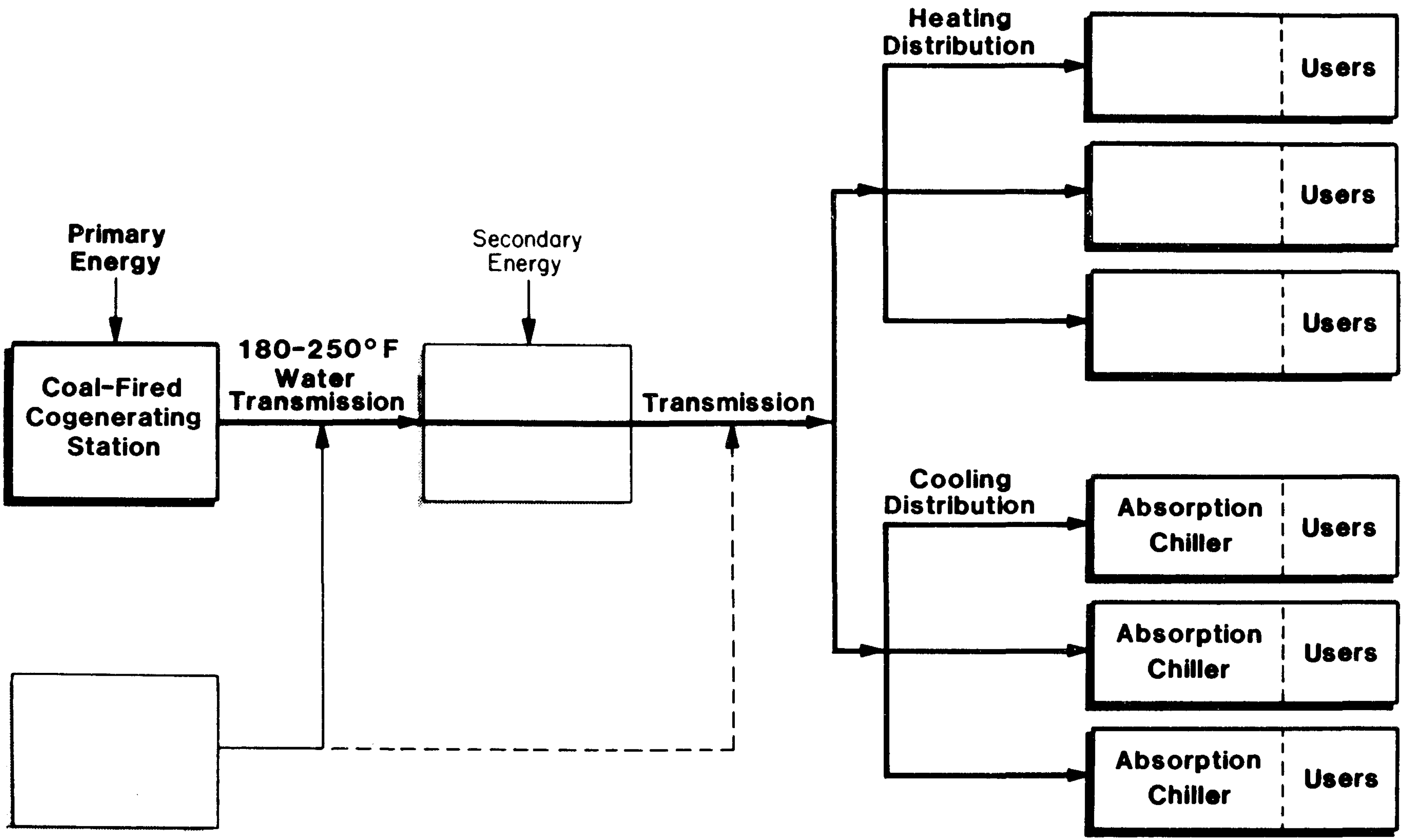

FIGURE 2-5

LOW-BACKPRESSURE CENTRAL COGENERATOR

Description:

Modification of operating conditions of conventional generating station with associated minor impact on electrical generating efficiency allows the extraction of heat at approximately 120F.

Service area:

Low temperature customers in the vicinity of existing generating stations.

Options:

Central or distributed heat pumps can be used to increase supply temperatures for users requiring them.

Rationale:

The heat, since its extraction has little effect on the efficiency of electricity generation, is extremely low-cost. The heat is extracted at a temperature which can be used directly for some applications, such as space heating. The primary source has a low capital cost for the thermal capacity. The distribution system can be very low cost uninsulated plastic piping.

Low-Backpressure Central Cogenerator

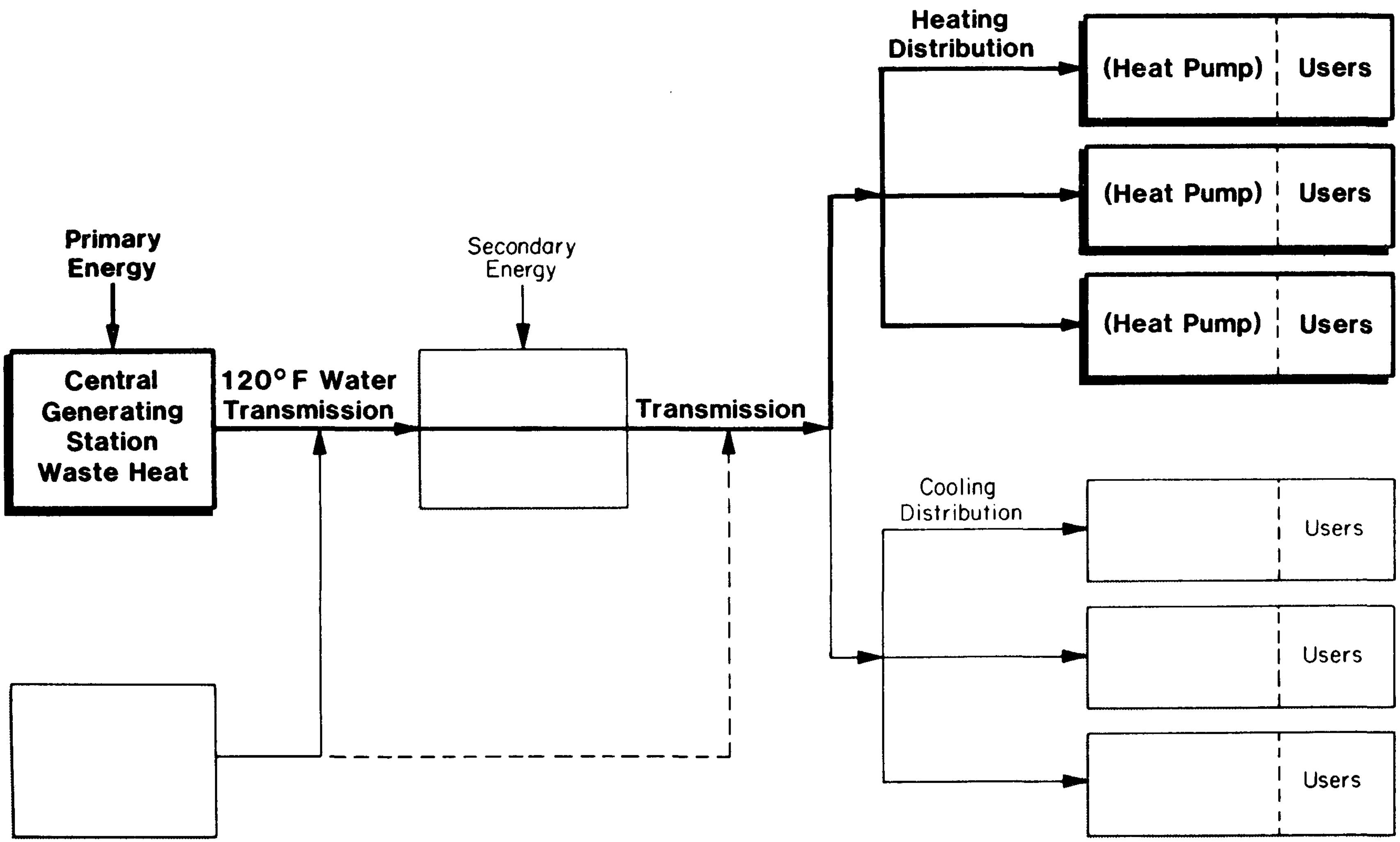

FIGURE 2-6

DISTRIBUTED WATER SOURCE ELECTRIC HEAT PUMPS

Description:

Low temperature (50-90F) source(s) or sinks of heat are coupled to a network of user owned heat pumps which withdraw heat from or reject heat to, the distribution system.

Service area:

System will be most effective in areas where there is a high degree of load diversity. Most applicable to space heating and cooling in the vicinity of a low temperature sources such as a generating station, moderate temperature lake, accessible aquifer.

Options:

Possible sources of supplemental heat include: electrical generator coolant, aquifer, lake, earth heat exchanger, and solar.

Rationale:

Low capital cost, low distribution cost, fairly low delivered energy cost.

Distributed Water Source Heat Pumps

Options: Solar or Generating Station Thermal Source

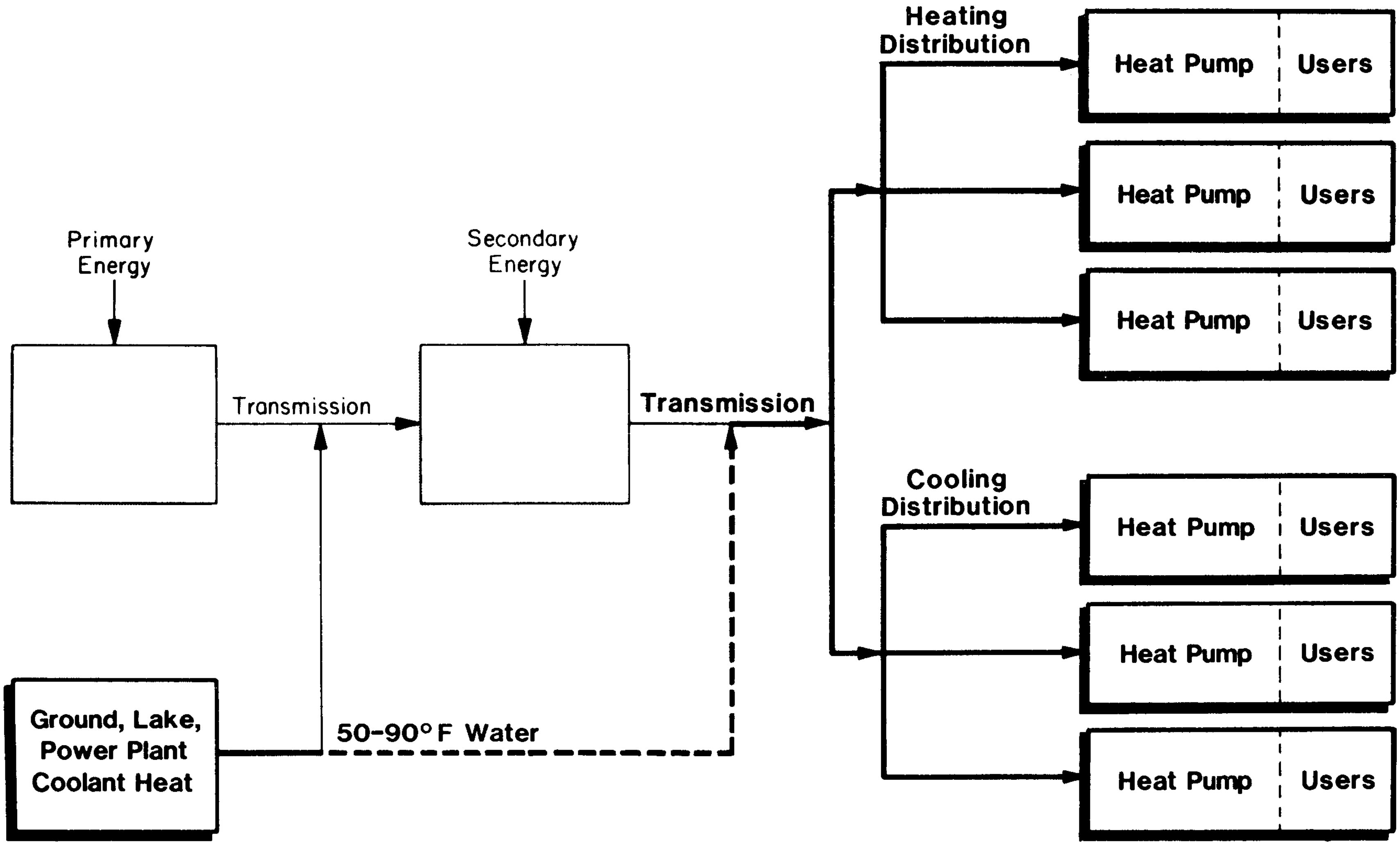

FIGURE 2-7

CENTRAL FUEL-DRIVEN HEAT PUMP

Description:

A central fuel driven heat pump using an ambient temperature source supplies heating and cooling.

Service Area:

Residential customers with sufficient load density such as urban or planned suburban housing projects.

Options:

Possible sources of heat include: electrical generator coolant, aquifer, lake, earth heat exchanger, and solar.

Rationale:

Low capital cost, low distribution cost, low delivered energy cost. The high efficiencies possible with fuel driven heat pumps are realizable, with good economy, in units that are fairly small, i.e., Block-Scale.

Central Fuel-Driven Heat Pump Using Free Heat Source

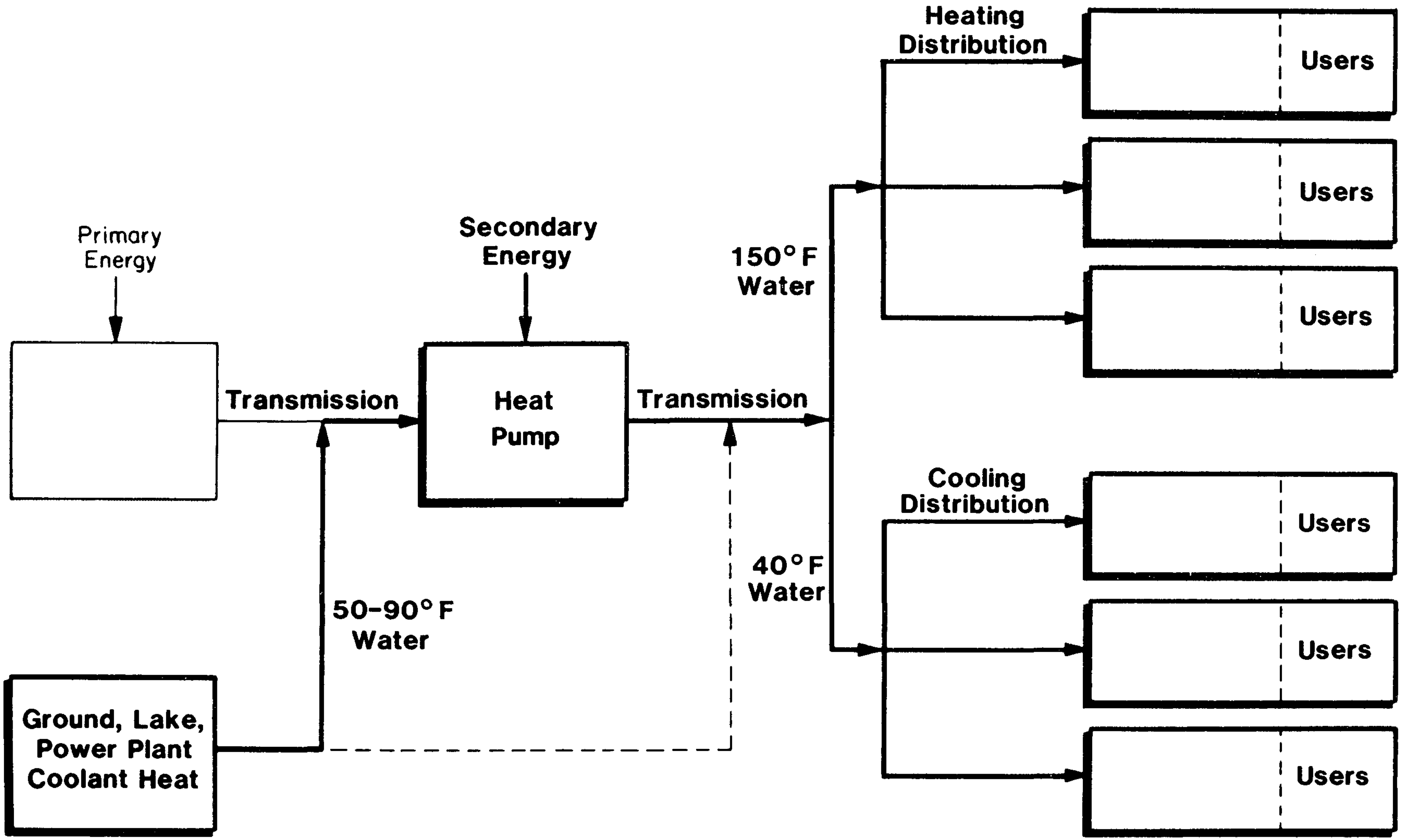

FIGURE 2-8

ICE PILE

Description:

An ice pile is used to store ambient cold in the winter to supply cold water or slush for cooling in the summer.

Service area:

Space cooling users in locations where value of land and aesthetics allow ice pile.

Options:

Distribution medium can be chilled water.

Rationale:

Low delivered energy cost, low capital cost.

Ice Pile

Option: Chilled Water Transmission/Distribution

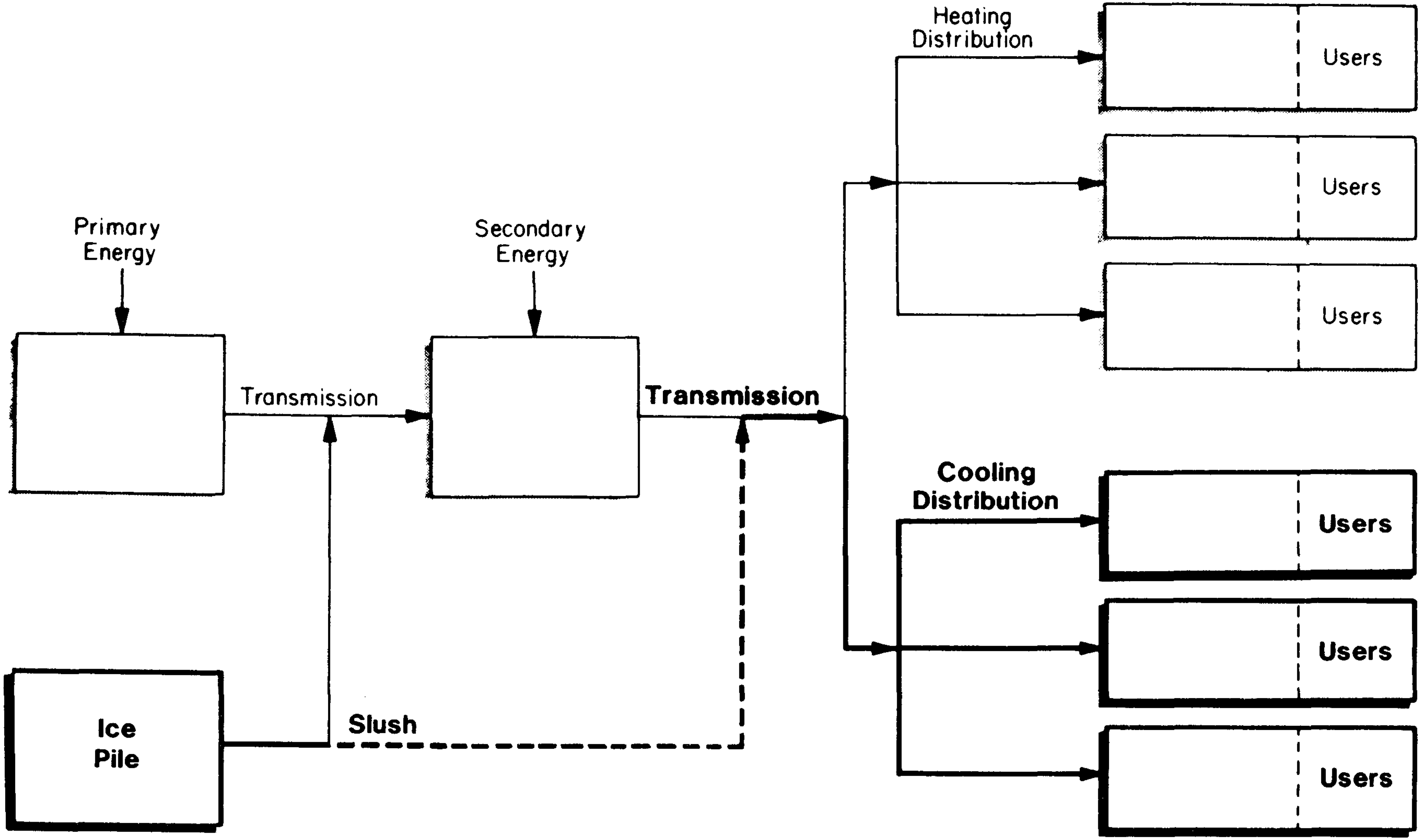

FIGURE 2-9

MUNICIPAL WASTE INCINERATOR

Description:

A municipal waste incinerator which produces moderate temperature, hot water and possibly electricity, cooling via distributor absorption chillers.

Service area:

Urban areas where waste incineration is acceptable.

Options:

Electricity Cogeneration

Rationale:

Uses municipal waste; low temperature allows the use of state-of-the-art distribution system and relatively low sacrifice of electrical generating efficiency (if desired).

Note: No diagram is provided for this system which is structurally identical to the coal-fired cogeneration.

SELECTION SENSITIVITIES AND OTHER OPTIONS

As noted above, selection results were found to be sensitive to the criteria weights selected. The subjectivity of these weights dictates that the characterization methodology be flexible enough to consider many options, e.g. central vs. distributed absorption chillers for cooling, water vs. steam heat transport, electricity price, and piping material type.

A number of more futuristic options such as advanced fuel cells, adiabatic engines, or chemical heat pumps (beyond state-of-the-art absorption technology) have not been considered for selection. However, the ability to consider such options under a range of future energy scenarios has been retained in the characterization methodology developed.

3.0 TECHNOLOGY CHARACTERIZATION

3.1 Task Description

The purpose of this task is to characterize, both technically and economically, the nine selected DHC system types to define the community types which each can serve. In all, over thirty system options were considered for ten load cases and two district sizes. A microcomputer program, including a DHC component database, was developed to carry out the characterization. This program, documented in Appendix I, is suitable for characterizing other DHC systems. It is available on request from the authors.

3.2 Technology Characterization Approach

DHC System Description

To characterize a DHC system variation, each element of the system must be described in terms of its technical and economic attributes (e.g., fuels used, conversion efficiency, thermal losses, capital cost, size, and so on). For this purpose, a database was developed to describe each of the energy converters and transmission/distribution lines used in the selected systems.

Thermal Load Selection and Description

The thermal load (space heating or cooling) which the DHC system serves must be described in terms of its total size, density, and time-dependence. For this analysis, "abstract" loads were developed. In this approach each load case represents a set of buildings, each of identical thermal load, equally spaced on a square mesh. This simplified approach permits rapid examination of a wide range of building load sizes, densities, and district sizes. The abstract loads don't represent particular real communities. They instead provide a set of "templates" against which real communities can be compared.

The time-dependence of the thermal load is described by a load/duration curve which specifies the number of hours per year a given amount of energy is required. Two load/duration curves were developed--one for residential and one for commercial buildings.

Microcomputer Program Development and Operation

A microcomputer program was written to characterize the selected DHC systems. The program is based on the general DHC system description in section 2. Individual DHC systems are characterized by selecting the required energy converters and piping types from the database. New DHC systems can be studied by developing new data files for any new elements needed.

The program can be operated to characterize a given DHC system over 20 load cases at once. After optimizing energy converter and piping sizes, the program computes all system energy flows and costs. Delivered energy cost was selected as the figure of merit of system economic goodness.

Evaluation of Results

Over 30 DHC system variations were characterized for 10 load cases and two district sizes, for a total of about 600 cases. The delivered energy cost of each system variation was compared to baseline nondistrict systems--natural gas boilers for space heating and electric air conditioners for space cooling. The sensitivity of system performance to key system factors (e.g., electricity price for cogenerators, tipping fee for municipal waste, piping type, steam vs. water, etc.) was examined.

3.3 DHC System Characterization Computer Program

Introduction

The purpose of the BNL DHC system characterization computer program is to quantify the important technical and economic attributes of selected DHC systems. The program is not a detailed system design tool. Instead, it is required to:

- characterize selected DHC system variations for a range of load cases;
- consider many DHC system and load types;
- examine variations and sensitivities rapidly;
- permit the user to add or modify systems, loads, and components easily; and
- help the user to understand the causes of program results.

To meet these requirements, four general goals were established for the characterization program design--simplicity, transparency, breadth, and ease of use.

Program Information Requirements

The characterization program operates on an IBM PC XT. It requires five types of information to characterize a selected DHC system:

- general DHC system structure;
- specific DHC system of interest;
- component cost/performance characteristics;
- load case characteristics; and
- other miscellaneous information.

General DHC System Structure. The characterization program uses a general DHC system structure slightly simpler than the general system shown in Figure 2-1. This structure, shown in Figure 3-1, is embodied in the program. It consists of three energy converters which can consume fuel, heat, or electricity to produce heat or "cool." Examples include cogenerators, heat pumps, or boilers.

The energy converters transfer thermal energy within the DHC system via two piping networks. Heat flows from the primary converter through the transmission subsystem to the secondary energy converter and from there via the distribution subsystem to the user converters. A system may contain many secondary and user energy converters.

Specific DHC System of Interest. Each DHC system evaluated by the program must conform to the general DHC system structure of Figure 3-1. Guided by program prompts, the user assembles the desired DHC system by selecting a specific component for each element in the general DHC system structure from a menu of the program's database of energy converters and piping subsystems. The program then links together the specific components which have been "plugged in" according to the general system structure.

Component Cost/Performance Characteristics. DHC component characteristics are described by data files discussed in detail in Appendix I. The database currently contains files describing twenty-six energy converters and five types of 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 as a function of the quantities in parentheses:

- converter capital cost (site);
- converter technical behavior (size, temperature);
- 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 as a function of the quantities in parentheses:

- piping unit installed cost (type, size, installation class);
- piping thermal conductivity (type, size, installation class);
- pipe burial depth (type, size, installation class).

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 as described in section 3.4. 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 (type, size, installation class).

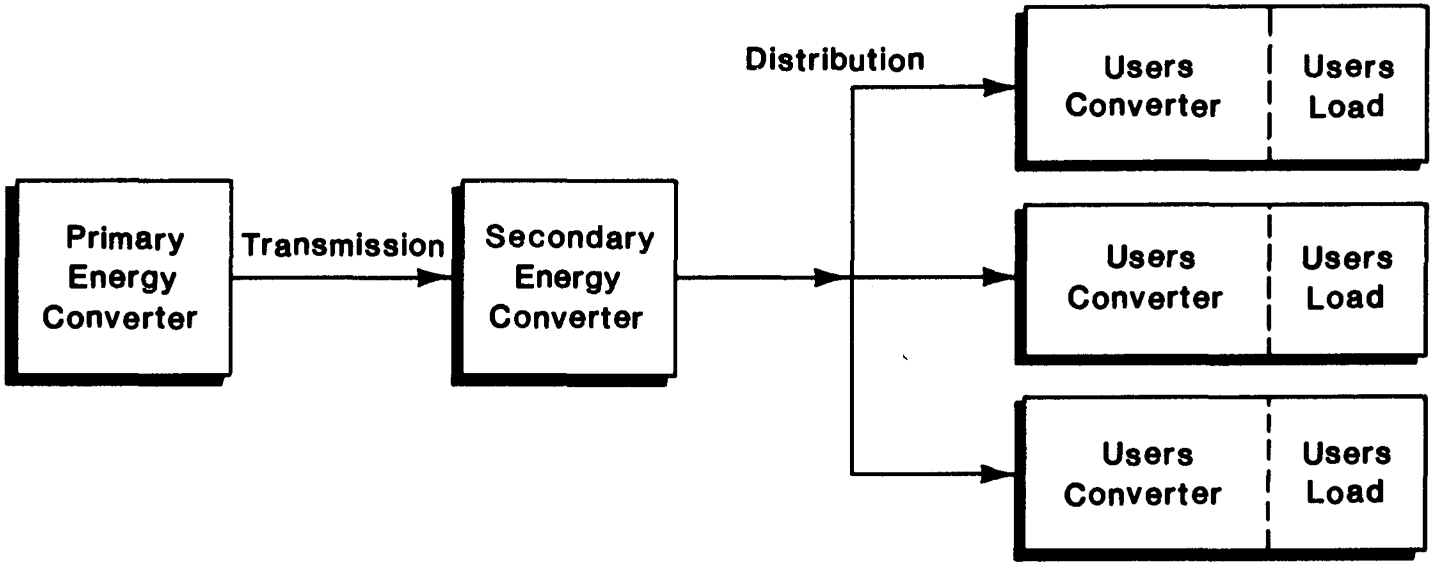

Figure 3-1. Characterization Program - General DHC System Structure

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, specified as a function of the quantities in parentheses:

- transmission/distribution pipe length (level, number of users);
- building load/duration curve (building type and use, local climate).

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 (all assumed to be identical at present) versus the number of hours of that demand per year. Typically, the load/duration curve is represented by 10-15 discrete bins of load data.

The load cases studied to date are discussed in section 3.4. All load cases are described by data files discussed in Appendix I.

Other Miscellaneous Information. The program requires certain miscellaneous information:

- capital recovery factor;
- ground temperature;
- transmission fluid temperature, temperature drop;
- distribution fluid temperature, temperature drop.

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 CRF and ground temperature are provided by data files discussed in Appendix I. The fluid temperature information is input by the user.

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

$$A_j = E_j + CRF \times C_j$$

where

E_j is the energy cost associated with the 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 associted with each component:

$$A = \sum_j A_j = \sum_j (E_j + CRF \times C_j)$$

The annualized delivered energy cost per unit energy delivered is taken as the economic figure-of-merit of each DHC system.

Discussion of Sample Program Output

The sample output applies to one load. A given system would usually be evaluated for a number of load cases, each of which would produce a similar output. The characteristics of the system and the load case used for the sample run are given in Table 3-1.

Table 3-1. Description of Sample System and Load

Primary Converter:	Diesel Cogenerator
Secondary Converter:	Nothing
User Converter:	Heat Exchanger
Transmission Pipe:	Ricwil Fiberglass Reinforced Polyester
Distribution Pipe:	Ricwil Fiberglass Reinforced Polyester
Transmission Temperature:	200 F
Distribution Temperature	200 F
Transmission Temp. Drop:	50 F
Distribution Temp. Drop:	50 F
Peak Thermal Load/Bldg:	100 kW
Load/Duration Char:	Residential, Space-Heating
Buildings/Block:	1
Number of Blocks:	15
Total System Area:	4.4 million square feet (100 Acres)
Transmission Length:	Negligible

---

*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:

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

Income taxes and depreciation are not considered.

The first section of 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 in the first section are the maximum outputs, per unit, of the energy converters and the number of terminals the distribution and transmission subsystems branch into.

```
.P01
 -- ENERGY CONVERTERS--                -- PIPING NETWORK --                                          -- MAXIMUM CAPACITIE

PRIMARY:   DIESEL COGENERATOR          TRANS:            1 FOOT TRANSMISSION LINE                     PRI:   1651.2
SECONDARY: NOTHING                     DISTR:            DISTR=15 BLOCKS & 1 USER/BLOCK               SEC:   1651.2
USER:      10 F TD HEAT EXCHANGER      TRAN. PIPE TYPE:  F.R.P. INSUL.             CLASS 3            USR:    100.0
                                       DIST. PIPE TYPE:  F.R.P. INSUL.             CLASS 3
                                       THERMAL LOAD   :  100 KW/USER RES. HTG. LOAD


 DISTRIBUTION BRANCHES INTO           15 TERMINALS
 TRANSMISSION BRANCHES INTO            1 TERMINALS

-----------------------------------------------------------------------------------------------------------------------
```

The second section recounts the calculated annualized operating costs for each pipe diameter, for all the levels of the transmission and distribution subsystems. The diameter in each level which gave the minimum annualized cost is indicated for each level.

```
               DISTRIBUTION

 LEVEL=  1  LEN=     780.  NO TER=     1.

  NO.       PIPE DIA.     AN. COST
   1        .167E+00     .187E+04
   2        .250E+00     .206E+04


 PIPE NO.   1 GAVE MIN AN COST


 LEVEL=  2  LEN=  11620.  NO TER=     1.

  NO.       PIPE DIA.     AN. COST
   1        .167E+00     .279E+05
   2        .250E+00     .307E+05

 PIPE NO.   1 GAVE MIN AN COST


 LEVEL=  3  LEN=   2520.  NO TER=     2.

  NO.       PIPE DIA.     AN. COST
   1        .167E+00     .608E+04
   2        .250E+00     .666E+04

 PIPE NO.   1 GAVE MIN AN COST


 LEVEL=  4  LEN=     700.  NO TER=     6.

  NO.       PIPE DIA.     AN. COST
   1        .167E+00     .189E+04
   2        .250E+00     .188E+04
   3        .333E+00     .222E+04

 PIPE NO.   2 GAVE MIN AN COST


 LEVEL=  5  LEN=     700.  NO TER=    11.

  NO.       PIPE DIA.     AN. COST
   1        .167E+00     .286E+04
   2        .250E+00     .201E+04
   3        .333E+00     .226E+04

 PIPE NO.   2 GAVE MIN AN COST
```

```
               TRANSMISSION

 LEVEL=  1  LEN=       1.  NO TER=     1.

  NO.       PIPE DIA.     AN. COST
   1        .167E+00     .866E+01
   2        .250E+00     .352E+01
   3        .333E+00     .339E+01
   4        .500E+00     .445E+01

 PIPE NO.   3 GAVE MIN AN COST
```

The System Energy Flows tables show the energy transferred from the system's environment to the system, the Inputs, and the energy transferred from the system to the environment, or to supply the building loads (User), the Outputs. The data are broken down in terms of the types of energy and the system component energy flowed into or out of. The tables also give the costs associated with the inputs and revenues associated with the outputs. These tables have nonzero values only where energy was transferred directly between a component and the environment or load, and not where energy flowed from one component to another.

```
-----------------------------------------------------------------------------------------------------------------------------------------

                                                      SYSTEM ENERGY FLOWS
                                                      -------------------

                                                         -- INPUTS --
                                  ENERGY                                                       COST
FUEL TYPE¦RATE COST¦ PRIM     TRANS    SECOND   DISTR    USER     TOTAL  ¦ PRIM     TRANS    SECOND   DISTR    USER     TOTAL  ¦
         ¦   [$]   ¦ [KWH]    [KWH]    [KWH]    [KWH]    [KWH]    [KWH]  ¦ [$]      [$]      [$]      [$]      [$]      [$]    ¦
---------------------------------------------------------------------------------------------------------------------------------

 OIL     ¦ .209E-01¦ .925E+07 .000E+00 .000E+00 .000E+00 .000E+00 .925E+07 ¦ .193E+06 .000E+00 .000E+00 .000E+00 .000E+00 .193E+06 ¦
 GAS     ¦ .125E-01¦ .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 ¦ .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 ¦
 COAL/GAR¦ .850E-02¦ .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 ¦ .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 ¦
 ELECTR. ¦ .800E-01¦ .000E+00 .276E+01 .000E+00 .322E+04 .000E+00 .323E+04 ¦ .000E+00 .221E+00 .000E+00 .258E+03 .000E+00 .258E+03 ¦
 THERMAL ¦ .000E+00¦ .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 ¦ .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 .000E+00 ¦
---------------------------------------------------------------------------------------------------------------------------------
TOTAL    ¦         ¦ .925E+07 .276E+01 .000E+00 .322E+04 .000E+00 .926E+07 ¦ .193E+06 .221E+00 .000E+00 .258E+03 .000E+00 .194E+06 ¦


                                                         -- OUTPUTS--
                                  ENERGY                                                       REVENUES
FUEL TYPE¦RATE COST¦ PRIM     TRANS    SECOND   DISTR    USER     TOTAL  ¦ PRIM     TRANS    SECOND   DISTR    USER     TOTAL  ¦
         ¦   [$]   ¦ [KWH]    [KWH]    [KWH]    [KWH]    [KWH]    [KWH]  ¦ [$]      [$]      [$]      [$]      [$]      [$]    ¦
---------------------------------------------------------------------------------------------------------------------------------

THERMAL LOSSES       .162E+07 .907E+02 .000E+00 .903E+06 .000E+00 .252E+07 ¦
ELEC PRODUCTION      .301E+07 .000E+00 .000E+00 .000E+00 .000E+00 .301E+07 ¦ .301E+06 .000E+00 .000E+00 .000E+00 .000E+00 .301E+06 ¦
THERMAL PRODUCTION   .000E+00 .000E+00 .000E+00 .000E+00 .373E+07 .373E+07 ¦
---------------------------------------------------------------------------------------------------------------------------------
TOTAL                .463E+07 .907E+02 .000E+00 .903E+06 .373E+07 .926E+07 ¦ .301E+06 .000E+00 .000E+00 .000E+00 .000E+00 .301E+06 ¦


--------------------------------------------------------------------------------------------------------------------------------
```

The Energy Balances table breaks down the annual flows of energy on a component basis. The inputs, fuel, electric, and thermal are subtracted from the outputs, thermal (both losses and production) and electric, to obtain an energy balance, the bottom line in the table. This table serves as a check that all energy flows have been accounted for by verifying that the net energy flow of each component is zero. It also allows seasonal coefficients of performance to be calculated for each component.

```
-----------------------------------------------------------------------------

                     ENERGY BALANCES [KWH/YR]
                     ------------------------

                 !    PRIM       TRANS      SECOND      DISTR       USER
-----------------------------------------------------------------------------

FUEL INPUTS      !  .925E+07   .276E+01   .000E+00   .322E+04   .000E+00
THERMAL INPUTS   !  .000E+00   .463E+07   .463E+07   .463E+07   .373E+07
THERMAL LOSSES   !  .162E+07   .907E+02   .000E+00   .903E+06   .000E+00
ELECTRIC OUTPUT  !  .301E+07   .000E+00   .000E+00   .000E+00   .000E+00
THERMAL OUTPUT   !  .463E+07   .463E+07   .463E+07   .373E+07   .373E+07
-----------------------------------------------------------------------------
SUM OF IN/OUTPUTS !  .000E+00   .000E+00   .000E+00   .000E+00   .000E+00
-----------------------------------------------------------------------------
```

The following four tables focus on costs and revenues. The Total Capital Costs table shows the capital costs for each component. The Cash Outflow and Inflow tables give the annual costs and revenues for each susbystem in terms of energy purchased, electricity sold, operating costs, and capital. The "Energy" and "Electricity Produced" lines come from the bottom lines of the cost part of the respective "System Energy Flows" Tables. The figures in the next two tables differ from those in the Cash Outflow and Inflow table by a constant factor. In the table entitled "Cost in Terms of Energy Supplied to User," the cash flows are divided by the total energy delivered to the user. In the table entitled "Cost as Percent of Total Annualized Cost," the cash flows are divided by the total annualized cost for the system.

TOTAL CAPITAL COSTS :

	PRIM	TRANS	SECOND	DISTR	USER	TOTAL
CAPITAL COST	449139.00	26.39	.00	329200.00	15360.00	793725.40

CASH OUTFLOW (+) AND INFLOW (-)

	PRIM	TRANS	SECOND	DISTR	USER	TOTAL
ENERGY	193417.30	.22	.00	257.96	.00	193675.50
ELECTRICITY PRODUCED	-300861.10	.00	.00	.00	.00	-300861.10
FIXED ANNUAL	.00	.00	.00	.00	.00	.00
CAPITAL * CRF	53896.68	3.17	.00	39504.00	1843.20	95247.04
TOTAL	-53547.09	3.39	.00	39761.96	1843.20	-11938.54

COST IN TERMS OF ENERGY SUPPLIED TO USER ($/KWH) :

	PRIM	TRANS	SECOND	DISTR	USER	TOTAL
ENERGY	.05190	.00000	.00000	.00007	.00000	.05197
ELECTRICITY PRODUCED	-.08072	.00000	.00000	.00000	.00000	-.08072
FIXED ANNUAL	.00000	.00000	.00000	.00000	.00000	.00000
CAPITAL * CRF	.01446	.00000	.00000	.01060	.00049	.02556
TOTAL	-.01437	.00000	.00000	.01067	.00049	-.00320

```
-----------------------------------------------------------------------------------------------------
 AS A PERCENT OF TOTAL ANNUALIZED COST :

                 |      PRIM       TRANS        SECOND        DISTR         USER        TOTAL
-----------------------------------------------------------------------------------------------------
Y                |   -1620.11        .00           .00        -2.16          .00     -1622.27
RICITY PRODUCED  |    2520.08        .00           .00          .00          .00      2520.08
 ANNUAL          |        .00        .00           .00          .00          .00          .00
AL * CRF         |    -451.45       -.03           .00      -330.89       -15.44      -797.81
-----------------------------------------------------------------------------------------------------
                 |     448.52       -.03           .00      -333.06       -15.44       100.00
-----------------------------------------------------------------------------------------------------
```

In the next set of output data, the first two lines give the peak and minimum per-unit capacities of the energy converters for the pertinent system and load. Next, the transmission and distribution temperatures and temperature drops are shown.

```
MAXIMUM CAPACITIES (KW) - PRI:  .165E+04  SEC:  .165E+04  USR:  .100E+03

MINIMUM CAPACITIES (KW) - PRI:  .000E+00  SEC:  .100E+02  USR:  .120E+04


TRANSMISSION TEMPERATURE (F) :        200.00
DISTRIBUTION TEMPERATURE (F) :        200.00
TRANSMISSION TEMPERATURE DROP (F) :    50.00
DISTRIBUTION TEMPERATURE DROP (F) :    50.00
```

A simple histogram plot of the load/duration data follows. This plot shows the duration, in hours, associated with each instantaneous capacity level (in kW).

```
DAD DURATION DATA :
-----------------------------------------------------------------------------------------------------------------------------------
       0.0                                                                                                                  .798E+03
        !                                              OPERATING TIME (HOURS)                                                    !
700E+01 ******************************************************************************************************************
180E+02 ***************************************************************************************************************
270E+02 ******************************************************************************************************
360E+02 *********************************************************************************************************
450E+02 ******************************************************************************************************************
550E+02 *************************************************************************************************************************
540E+02 *********************************************************************************************************
730E+02 *********************************************************
390E+02 ********************************
710E+02 *****************
100E+03 **********
-----------------------------------------------------------------------------------------------------------------------------------
```

The last section of the output, Table 5, shows the instantaneous energy flows for each load bin used in the calculations. Unit "1" refers to the primary, "2" to the secondary, and "3" to the User.

```
ENERGY FLOWS FOR EACH BIN (KW)
------------------------------------------------------------------------------------------------------------------------------------
BIN Q.in.1  Fuel.1  Fuel.1 Q.out.1 Tr.Pmp  Tr.Lss  Q.in.2  Fuel.2  Fuel.2 Q.out.2 Ds.Pmp  Ds.Lss  Q.in.3  Fuel.3  Fuel.3 Q.out.3
-----------------------------------------------------------------------------------------------------------------------------------
  1      .0   579.2  -188.3   289.6      .0      .0   289.6      .0      .0   289.6      .0   154.6     9.0      .0      .0     9.0
  2      .0   849.2  -276.1   424.6      .0      .0   424.6      .0      .0   424.6      .0   154.6    18.0      .0      .0    18.0
  3      .0  1119.1  -363.8   559.5      .0      .0   559.5      .0      .0   559.5      .1   154.6    27.0      .0      .0    27.0
  4      .0  1388.8  -451.5   694.4      .0      .0   694.4      .0      .0   694.4      .2   154.6    36.0      .0      .0    36.0
  5      .0  1658.5  -539.2   829.3      .0      .0   829.2      .0      .0   829.2      .4   154.6    45.0      .0      .0    45.0
  6      .0  1958.0  -636.5   979.0      .0      .0   979.0      .0      .0   979.0      .6   154.6    55.0      .0      .0    55.0
  7      .0  2227.3  -724.1  1113.7      .0      .0  1113.6      .0      .0  1113.6     1.0   154.6    64.0      .0      .0    64.0
  8      .0  2496.4  -811.6  1248.2      .0      .0  1248.2      .0      .0  1248.2     1.4   154.6    73.0      .0      .0    73.0
  9      .0  2974.4  -967.0  1487.2      .0      .0  1487.2      .0      .0  1487.2     2.4   154.6    89.0      .0      .0    89.0
 10      .0  3034.1  -986.4  1517.0      .0      .0  1517.0      .0      .0  1517.0     2.6   154.6    91.0      .0      .0    91.0
 11      .0  3302.5 -1073.6  1651.2      .0      .0  1651.2      .0      .0  1651.2     3.4   154.6   100.0      .0      .0   100.0
```

3.4 Individual DHC System Characterization Results

DHC System Descriptions

Initially, 32 system variations were characterized. Additional sensitivity runs were performed for five system types. This section gives detailed system descriptions for each run.

Table 3-2 outlines the initial 32 characterization runs. Table 3-3 outlines the sensitivity runs.

Table 3-4 presents a numbered list of the energy converters used, while Table 3-5 identifies the piping types. Converter and piping cost/performance details are presented in Appendix I.

Using the energy converter and piping number keys from Tables 3-4 and 3-5, tables 3-6 through 3-11 detail the inputs used for all 32 initial characterization runs. Included are the mode of operation (heating, cooling, or both), heat transfer fluid (steam or water), energy converters, and transmission and distribution piping types, inlet temperatures, and temperature drops.

Thermal Load Case Descriptions

As discussed above, a load case is a complete description of thermal load consisting of:

- the physical layout of the transmission subsystem,
- the physical layout of the distribution subsystem, and
- the load-duration data.

This section defines and discusses the twenty load cases for which the systems described in the preceding section were evaluated.

Overall, the twenty load cases were derived from the following list of characteristics.

Climate:	New York/Philadelphia
Building peak heating or cooling load:	10 - 5000 kW
Type of thermal load:	Space heating and space cooling
Types of buildings:	Residential and commerical
Building densities:	1-50 buildings/block (0.15-7.4 buildings/acre)
Geographical sizes of district:	3 and 15 blocks (20 and 100 acres)
Installation classes (site construction characteristics):	Rural - Dense Urban

Table 3-2. Initial DHC System Characterization Runs

Run identifier	DHC system type	Distribution/ transmission fluid	Service
1A	Urban oil-fired cogenerator retrofit	Steam	Heating
1B	" " " " "	"	Cooling
1C	" " " " "	Water	Heating
1D	" " " " "	"	Cooling
1E	" " " " "	Steam	Combined
1F	" " " " "	Water	"
2A	Coal boiler	Steam	Heating
2B	" "	"	Cooling
2C	" "	"	Combined
3A	Diesel cogenerator		Heating
3B	" " - Distributed absorption chiller	Water	Cooling
3C	" " - Central absorption chiller		"
3D	" " - Distributed absorption chiller		Combined
3E	" " - Central absorption chiller		"
4A	Coal fired cogenerator		Heating
4B	" " "	Water	Cooling
4C	" " "		Combined
5A	Low backpressure cogenerator		Heating
5B	" " "	Water	Cooling
5C	" " "		Combined
6A	Distributed water source heat pumps		Heating
6B	" " " " "	Water	Cooling
6C	" " " " "		Combined
7A	Fuel-driven heat pump		Heating
7B	" " " "	Water	Cooling
7C	" " " "		Combined
9	Ice pile	Water	Cooling
10	Distributed gas furnaces (nondistrict baseline heating system)	-	Heating
11A	Municipal waste incinerator		Heating
11B	" " "	Water	Cooling
12	Distributed electric air conditioners (nondistrict baseline cooling system)	-	Cooling

Table 3-3. DHC System Characterization Sensitivity Runs

Run identifier	DHC system type	Distribution/ transmission fluid	Service	Variation
1G	Urban oil-fired cogenerator retrofit	Water	Heating	Steel pipe
2D	Coal boiler	Steam	Heating	$140/kW cap. cost
3F	Diesel cogenerator	Water	Heating	$0.10/kWh elec. sale
3G	Distributed absorption chiller		Cooling	" " " "
5D	Low backpressure cogenerator	Water	Heating	Polyethylene pipe
5E	" " "		Cooling	" "
5F	" " "		Heating	$0.01/kWh Thermal, 5 mi. Trans., 20°F temp. drop
6D	Distributed water source heat pumps	Water	Heating	80°F input temperature 25,000 ft. transmission line

Tables 3-4 and 3-5 provide converter and piping keys for use in Tables 3-6 to 3-11.

Table 3-4. Energy Converters

Converter number	Converter name
1	Nothing
2	Small electric heat pump - heating mode
3	Large electric heat pump - heating mode
4	Small electric heat pump - cooling mode
5	Large electric heat pump - cooling mode
6	Residential cast iron oil boiler
7	Commercial cast iron oil boiler
8	Scotch-Marine oil boilers
9	Diesel cogenerator
10	Urban oil cogenerator
11	Coal boiler
12	Small single effect absorption chiller
13	Large single effect absorption chiller
14	Small double effect absorption chiller
15	Large double effect absorption chiller
16	Coal-fired cogenerator
17	Low backpressure cogenerator
18	Low temperature source
19	Ice pile
20	Fuel-driven heat pump - heating mode
21	Fuel-driven heat pump - cooling mode
22	Water-water heat exchanger
23	Gas-fired hot water boiler
24	Small electric air conditioner
25	Large electric air conditioner
26	Municipal waste incinerator/cogenerator

Table 3-5. Piping Types

Piping numbers	Piping description
1	Polyethylene - uninsulated
2	RICWIL fiberglass reinforced polyester
3	RICWIL schedule 40 steel - one pipe/trench
4	RICWIL schedule 40 steel - two pipes/trench
5	No pipe needed

Table 3-6. Inputs for the Urban Oil-Fired Retrofit Systems

Inputs	Run					
	1A	1B	1C	1D	1E	1F
Mode (H)eating, (C)ooling or Combined (H/C)	H	C	H	C	H/C	H/C
Heat transfer fluid (S)team or (W)ater	S	S	W	W	S	W
Converters:						
Primary	10	10	10	10	10	10
Secondary	1	1	1	1	1	1
User	22	14	22	12	14+22	12+22
Piping Systems:						
Transmission Pipe	3	3	2	2	3	2
" Temp (F)	338	338	250	250	338	250
" Temp Drop (F)	-	-	100	100	-	100
Distribution Pipe	3	3	2	2	3	2
" Temp (F)	338	338	250	250	338	250
" Temp Drop (F)	-	-	100	100	-	100

Table 3-7. Inputs for the Coal Boiler and Coal Cogenerator Systems

Inputs	Run					
	2A	2B	2C	4A	4B	4C
Mode (H)eating, (C)ooling or Combined (H/C)	H	C	H/C	H	C	H/C
Heat transfer fluid (S)team or (W)ater	S	S	S	W	W	W
Converters:						
Primary	11	11	11	16	16	16
Secondary	1	1	1	1	1	1
User	22	14	14/22	22	12	12/22
Piping Systems:						
Transmission Pipe	3	3	3	2	2	2
" Temp (F)	338	338	338	250	250	250
" Temp Drop (F)	-	-	-	100	100	100
Distribution Pipe	3	3	3	2	2	2
" Temp (F)	338	338	338	250	250	250
" Temp Drop (F)	-	-	-	100	100	100

Table 3-8. Inputs for the Diesel Cogenerator Systems

Inputs	Run 3A	 3B	 3C	 3D	 3E
Mode (H)eating, (C)ooling or Combined (H/C)	H	C	C	H/C	H/C
Heat transfer fluid (S)team or (W)ater	W	W	W	W	W
Converters:					
Primary	9	9	9	9	9
Secondary	1	1	12	1	12
User	22	12	22	12	22
Piping Systems:					
Transmission Pipe	2	2	2	2	2
" Temp (F)	200	200	200	200	200
" Temp Drop (F)	50	50	50	50	50
Distribution Pipe	2	2	2	2	2
" Temp (F)	200	200	40	200	200/40
" Temp Drop (F)	50	50	15	50	15

Table 3-9. Inputs for the Low Backpressure Cogenerator and Distributed Heat Pump Systems

Inputs	Run 5A	 5B	 5C	 6A	 6B	 6C
Mode (H)eating, (C)ooling or Combined (H/C)	H	C	H/C	H	C	H/C
Heat transfer fluid (S)team or (W)ater	W	W	W	W	W	W
Converters:						
Primary	17	18	17/18	18	18	18
Secondary	1	1	1	1	1	1
User	22	4	4/22	2	4	2/4
Piping Systems:						
Transmission Pipe	2	2	2	1	1	1
" Temp (F)	120	55	120/55	55	55	55
" Temp Drop (F)	30	15	30/15	15	15	15
Distribution Pipe	2	2	2	1	1	1
" Temp (F)	120	55	120/55	55	55	55
" Temp Drop (F)	30	15	20/15	15	15	15

Table 3-10. Inputs for the Fuel Driven Heat Pump and Baseline Systems

Inputs	Run 7A	 7B	 7C	 10	 12
Mode (H)eating, (C)ooling or Combined (H/C)	H	C	H/C	H	C
Heat transfer fluid (S)team or (W)ater	W	W	W	-	-
Converters:					
Primary	18	18	18	1	1
Secondary	20	21	20/21	1	1
User	22	22	22	23	24
Piping Systems:					
Transmission Pipe	1	1	1	5	5
" Temp (F)	55	55	55	-	-
" Temp Drop (F)	15	15	15	-	-
Distribution Pipe	2	2	2	5	5
" Temp (F)	150	40	40/150	-	-
" Temp Drop (F)	50	10	10/50	-	-

Table 3-11. Inputs for the Ice Pile and Municipal Waste Incinerator Cogenerator Systems

Inputs	Run 9	 11A	 11B
Mode (H)eating, (C)ooling or Combined (H/C)	C	H	C
Heat transfer fluid (S)team or (W)ater	W	S	S
Converters:			
Primary	19	26	26
Secondary	1	1	1
User	22	22	12
Piping Systems:			
Transmission Pipe			
" Temp (F)	40	250	250
" Temp Drop (F)	10	100	100
Distribution Pipe			
" Temp (F)	40	250	250
" Temp Drop (F)	10	100	100

Building Peak Loads. Identical peak loads were used for stand-alone heating and cooling cases. For combined systems, the peak cooling load was taken as 50% of the peak heating load. The peak thermal load range (10-5000 kW) was selected to span a wide variety of building types from single family residences to large commercial buildings. Within this range, four peak loads were considered, as shown in Table 3-12.

Table 3-12. Building Peak Heating or Cooling Loads

Peak load (kW)	Typical size (ft^2)	Annual energy requirement (kWh)	Typical load type
10	1,000-2,000	25,000	Single-family house
100	10,000-20,000	249,000	Multi-family, small office building
1000	100,000-200,000	2,487,000	Large apartment bldg., warehouse, large office bldg., office park
5000	500,000-1,000,000	8,933,000	Very large office bldg., large shopping center

Building Densities. Building densities range from 1 - 50 buildings per block (0.15 - 7.4 buildings/acre), i.e., from those one might find in a suburban office park to those consistent with a high density urban residential area. Within this range four densities were chosen--1, 5, 20, and 50 buildings per block.

Districts Considered. Two district sizes were chosen--3 blocks (20 acres), a quite small district system, and 15 blocks (100 acres), near the upper end of the range of existing DHC system modules.

Certain combinations of building peak loads and densities were eliminated as unrealistic: building densities above 5/block with peak loads above 100 kW, and the 5000 kW peak load with a density of 5 buildings/block. The 1 building/block 10 kW peak load case was rejected as too low density. Table 3-13 presents the annual heating loads of the remaining allowed combinations of 15 block (100 acre) systems as a function of building peak load and density. The loads of the 3 block load cases were 20% of these.

Table 3-14 presents the annual building heating load densities, i.e., the annual load per unit land area which apply to both district sizes. Densities well above and below the Swedish rule of thumb for district heating--3 kWh/ft^2 yr--are considered.

Table 3-13. Annual Heating Loads of 15 Block Systems (kWh/year)

Building density		Building peak load (kW)			
buildings/ block	(buildings/ acre)	10	100	1000	5000
1	(.15)	---	3.73×10^6	3.73×10^7	1.34×10^8
5	(.74)	1.86×10^6	1.86×10^7	1.86×10^8	---
20	(3.0)	7.45×10^6	7.45×10^7	---	---
50	(7.4)	1.86×10^7	1.86×10^8	---	---

Table 3-14. Annual Heating Load Density (kWh/ft^2-yr)

Building density		Building peak load (kW)			
buildings/ block	(buildings/ acre)	10	100	1000	5000
1	(.15)	---	0.8	8.5	30.4
5	(.74)	0.4	4.2	42.2	---
20	(3.0)	1.7	16.9	---	---
50	(7.4)	4.2	42.2	---	---

Piping Installation Classes. Piping installed cost and burial depth depend not only on pipe type and size, but also on the nature of the site where the piping is installed. Accordingly, four installation classes which summarize site construction characteristics, such as pavement thickness and type, existing underground utilities, and the impact of the site on labor productivity, have been devised. The four installation classes, described in detail in Appendix I, are identified in Table 3-15.

The installation classes are correlated to building density and peak load in Table 3-16. Separate classes have been assigned to transmission and distribution system installation for each building density/peak load combination.

Table 3-15. Piping Installation Classes

Class number	Description	
0	High-Density Urban	(downtown Minneapolis)
1	Low-Density Urban	(downtown Des Moines)
2	Suburban, Office Park	(pavement, few existing utilities)
3	Rural (no pavement)	

Table 3-16. Transmission, Distribution Installation Classes Used for Each Load Case

Building density		Building peak load (kW)			
buildings/ block	(buildings/ acre)	10	100	1000	5000
1	(.15)	---	3,3	3,2	1,1
5	(.74)	3,3	2,2	2,1	---
20	(3.0)	2,2	2,1	---	---
50	(7.4)	2,1	1,0	---	---

Transmission and Distribution Subsystems. A negligible length transmission subsystem was used in all 20 load cases for the initial 32 characterization runs. Nonzero lengths were used in some of the sensitivity runs.

There were eight different distribution subsystems: two different DHC system sizes each with four different building densities. The larger distribution subsystem, serving the 15 block district, is shown in Figure 3-2. The smaller distribution subsystem, serving the 3 block district, is shown in Figure 3-3. Each block is 420 ft x 700 ft (about 7 acres) for both districts.

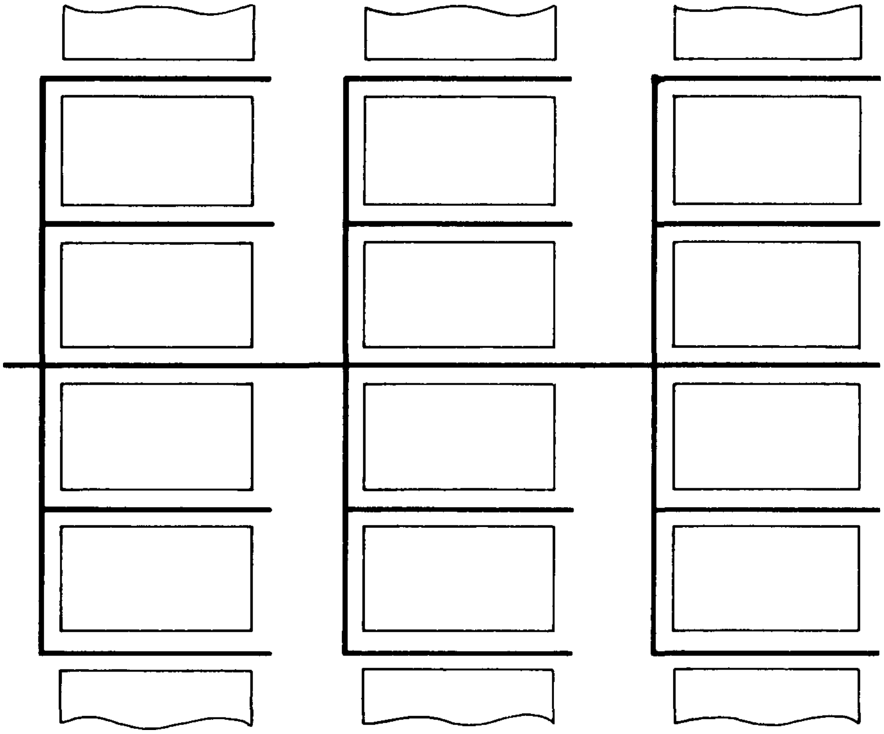

Figure 3-2. Distribution Subsystem for 15 Block Case

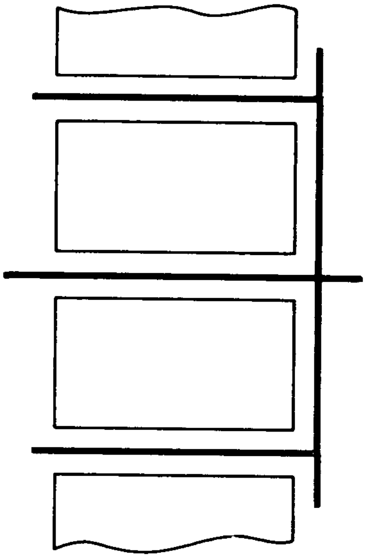

Figure 3-3. Distribution Subsystem for 3 Block Case

Method of Comparison

The systems listed in Tables 3-2 and 3-3 were each run for all ten load cases shown in Table 3-13 and both district sizes. The resulting annualized delivered energy cost for each case was compared to the delivered energy cost of the nondistrict baseline--gas boilers for heating and electric air conditioners for cooling. The allocation of costs within the system was examined to identify the main cost factors. Additional sensitivity runs were performed on some system types to answer "what if" questions, e.g., would the system compete with reduced distribution costs or higher electricity revenues. All systems have negligible transmission lengths unless otherwise noted.

Nondistrict Baseline Systems

Heating. The baseline heating system is 85% efficient individual gas boilers. The delivered energy cost for this system, shown in Table 3-17, averages roughly 3 cents/kWh (about $9 million Btu). Since almost all the delivered energy cost is due to fuel used, economies of scale are modest.

Cooling. The baseline cooling system is individual electric air conditioners with a COP of 2.5 (seasonal performance factor = 8.5) for small units and 3.0 (SPF = 10.2) for large units. Delivered energy cost ranges from about 9 cents/kWh for small buildings to 4 cents/kWh for the largest. Capital cost plays a large role due to the comparatively small number of hours/year of cooling over which to amortize this cost.

Table 3-17. Baseline Systems Delivered Energy Costs (¢/kWh)

		Peak load (kW)			
Service	System type	10	100	1000	5000
Heating	Individual gas boiler	3.62	2.62	2.54	2.58
Cooling	Individual electric AC	8.78	7.90	6.71	4.16

Urban Oil-Fired Cogenerator Retrofit

Heating. Tables 3-18a and 3-18b compare the delivered energy cost of the urban oil-fired cogenerator for steam versus hot water distribution for the 15 block district. The delivered energy costs for the 3 block district are somewhat higher, but similar. Although the steam system requires only one pipe (i.e., no condensate return), the hot water system using insulated fiberglass-reinforced polyester (FRP) pipe has a lower delivered energy cost in all load cases.

Table 3-18a. Heating Delivered Energy Cost (¢/kWh) Urban Oil-Fired Cogenerator Retrofit Steam Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		10.21	2.30	1.91
5	20.56	3.43	1.69	
20	8.15	2.15		
50	5.63	2.13		

Table 3-18b. Heating Delivered Energy Cost (¢/kWh) Urban Oil-Fired Cogenerator Hot Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		7.92	1.85	1.67
5	15.31	2.69	1.51	
20	5.87	1.73		
50	4.28	1.76		

A large variation in delivered energy cost exists for both system variations, mainly related to total system load, due to the large minimum size set for the primary energy converter. For those load cases that are large enough, this delivered energy cost is significantly lower than the nondistrict baseline. For these cases the largest cost contributor is purchased thermal energy, followed by retrofit capital cost and distribution cost (see Figures II-1A through II-1D).

The competitiveness of this system is due first to its efficient use of energy via cogeneration. The steam version, though, is competitive with individual gas boilers in only a few of the largest load cases. The hot water version is competitive in several more cases because the cost of the FRP piping system, which is comparable to modern direct-burial steel systems, is lower than the cost of the steam piping system with its much greater thermal expansion problems.

Cooling. The urban oil-fired cogenerator system uses distributed absorption chillers for space cooling. Such a stand-alone cooling system is not competitive with the nondistrict baseline in any load case due to high capital costs.

However, as shown in Table 3-19, the incremental delivered energy cost of adding cooling to an existing heating system is competitive--albeit marginally--in a number of larger building cases. This is due to sharing the

Table 3-19. Incremental Cooling Delivered Energy Cost (¢/kWh) Combined System Urban Oil-Fired Cogenerator Retrofit, Hot Water Distribution 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		7.66	6.24	3.06
5	11.95	7.18	6.18	
20	11.08	7.09		
50	10.96	7.07		

cogenerator and distribution costs with heating service and the economy of scale in absorption chiller capital cost.

Coal Boiler

Heating. Despite the low cost of coal, as shown in Table 3-20, the coal boiler is not competitive with individual gas boilers for any load case. Like the urban oil cogenerator retrofit, primary converter-related costs dominate (see Figs. II-2A and II-2B). Reducing the primary converter cost from $340 to $140/kW output makes this system competitive for some of the larger load cases.

Table 3-20. Heating Delivered Energy Cost (¢/kWh), Coal Boiler Steam Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		20.18	3.11	3.43
5	40.70	5.15	2.69	
20	12.85	3.16		
50	7.25	3.14		

Table 3-21. Incremental Cooling Delivered Energy Cost (¢/kWh) Combined System Coal Boiler, Steam Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		7.67	6.97	3.12
5	12.58	6.87	6.89	
20	11.06	6.71		
50	10.77	6.68		

Cooling. Stand-alone cooling costs using distributed absorption chillers were much higher than the cost of electric air conditioners (see Fig. II-2B). Incremental cooling costs for the combined system were marginally competitive, as shown in Table 3-21. As before, the problem is the absorption chiller cost (see Fig. II-2C).

Diesel Cogeneration

Heating. Table 3-22 presents the heating delivered energy costs for this system assuming cogenerated electricity can be sold for 5¢/kWh, a rate which is typical today. In most cases the delivered cost is moderately higher than the baseline. Far less cost variation is seen because of the small scale economy of the primary converter (see Fig. II-3A).

What is important, as Table 3-23 shows, is the selling price--or avoided purchase price--of the cogenerated electricity. With this price at 10¢/kWh, the district heating delivered energy cost is far lower than for individual gas boilers. In fact, for buildings with peak thermal loads of 100 kW or more, the heating delivered energy cost is negative! That is, the electricity sales revenue outweighs all costs associated with the district system. Thus the competitiveness of the diesel cogenerator is extremely sensitive to the selling price of cogenerated electricity.

Table 3-22. Heating Delivered Energy Cost (¢/kWh), Diesel Cogenerator, Hot Water Distribution, 5¢/kWh Electricity Sales, 15 Block District

	---------------Peak load (kW)---------------			
Bldg/blk	10	100	1000	5000
1		3.72	2.58	3.01
5	5.66	2.88	2.46	
20	4.43	2.69		
50	4.49	2.72		

Table 3-23. Heating Delivered Energy Cost (¢/kWh), Diesel Cogenerator, Hot Water Distribution, 10¢/kWh Electricity Sales, 15 Block District

	---------------Peak load (kW)---------------			
Bldg/blk	10	100	1000	5000
1		-0.32	-0.73	-0.26
5	0.53	-0.56	-0.82	
20	0.44	-0.63		
50	0.71	-0.60		

Cooling. Both central and distributed absorption chillers were examined for use with the diesel cogenerator. The central chiller can take advantage of high temperature exhaust reject heat to boost efficiency. Tables 3-24 and 3-25 show the scale economy of the central chiller leads to a competitive cooling delivered energy cost for this variation in all load cases.

Figures II-3D and II-3E show that, although there is an additional chilled water distribution cost for the central system, this is outweighed by the lower chiller cost.

Table 3-24. Incremental Cooling Delivered Energy Cost (¢/kWh) Combined System Diesel Cogenerator, Hot Water Distribution, Distributed Absorption Chillers, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		7.40	6.11	2.96
5	11.42	7.04	6.08	
20	10.79	6.97		
50	10.66	6.96		

Table 3-25. Incremental Cooling Delivered Energy Cost (¢/kWh) Combined System Diesel Cogenerator, Hot/Chilled Water Distribution, Central Absorption Chiller, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		5.41	4.72	2.87
5	7.17	4.55	3.91	
20	4.88	4.25		
50	4.56	3.82		

Coal-Fired Cogenerator

Heating. Table 3-26 presents the heating delivered energy cost results for this system. Like the urban oil-fired cogenerator retrofit, a large variation in delivered energy cost is seen, mainly related to total system load. Again this variation is due to the large minimum size of the primary converter, the coal-fired cogenerator, whose capital cost dominates the cost of delivered energy (see Fig. II-4A). The cost of fuel is lower than the revenue from electricity sales.

The coal-fired cogenerator is competitive with individual gas boilers in almost precisely those load cases--i.e. with annual heating load density above

3 kWh/ft^2 land area·yr--which the Swedish rule of thumb would predict (see Table 3-14). This competitiveness is attributed to efficient energy use via cogeneration and the modern FRP hot water piping system.

Table 3-26. Heating Delivered Energy Cost (¢/kWh), Coal-Fired Cogenerator, Hot Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		13.58	1.90	2.57
5	27.76	2.76	1.79	
20	7.86	1.99		
50	4.17	2.03		

Table 3-27. Incremental Cooling Delivered Energy Cost (¢/kWh) Combined System Coal-Fired Generator, Hot Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		5.06	4.37	1.27
5	8.24	5.21	4.39	
20	8.53	5.23		
50	8.64	5.24		

Cooling. Cooling is performed with distributed absorption chillers. Stand-alone cooling costs were not competitive with the nondistrict baseline. However, for the combined system, the incremental cooling cost is lower than the baseline for all load cases. As before, chiller capital cost dominates, making cooling cost strongly sensitive to building size (see Figs. II-4B and II-4C).

Low-Backpressure Central Cogenerator

Heating. Tables 3-28 and 3-29 compare the delivered energy cost of the low-backpressure central cogenerator using insulated FRP versus uninsulated polyethylene (PE) pipe. Because the PE piping is less expensive, it has lower delivered energy cost. The difference is quite small as the uninsulated PE system has much higher thermal losses which necessitate larger piping and energy converters (see Figs. II-5A and II-5D).

A large variation in delivered energy cost is found, related to total system load, due to the extreme economy of scale of the primary converter capital cost--the main cost factor. For those loads which are large enough, the delivered energy cost is extremely low, far below the individual gas boilers.

Table 3-28. Heating Delivered Energy Cost (¢/kWh), Low Backpressure Central Cogenerator, Warm Water Distribution, Insulated FRP Piping, 15 Block District

Buildings/ block	(Buildings/ acre)	Building peak load (kW)			
		10	100	1000	5000
1	(.15)	---	4.15	0.93	0.66
5	(.74)	8.37	1.43	0.57	---
20	(3.0)	3.55	0.88	---	---
50	(7.4)	2.91	0.81	---	---

Table 3-29. Heating Delivered Energy Cost (¢/kWh), Low Backpressure Central Cogenerator, Warm Water Distribution, Uninsulated Polyethylene Pipe, 15 Block District

Buildings/ block	(Buildings/ acre)	Building peak load (kW)			
		10	100	1000	5000
1	(.15)	---	3.98	0.75	0.58
5	(.74)	7.98	1.18	0.51	---
20	(3.0)	2.84	0.79	---	---
50	(7.4)	2.90	0.73	---	---

Table 3-30 presents "worst case" sensitivity results for this system. Since electric generating stations are frequently located far from high-density building areas, a 5-mile transmission subsystem is used. The cost of thermal energy is 1¢/kWh instead of 0.25¢/kWh. A temperature drop of 20°F is used instead of 30°F. The resulting delivered energy cost is above the baseline is all load cases.

Hence, the competitiveness of the low-backpressure central cogenerator is highly sensitive to the assumptions made, particularly with regard to plant location.

Cooling. The low-backpressure central cogenerator is a heating-only system. Cooling is added by pumping cold water from the body of water used to cool the generating station through the distribution subsystem to distributed water-source electric heat pumps. The resultant incremental cooling costs are lower than the baseline in all load cases, as shown in Table 3-31, mainly because of this dual use of the distribution subsystem (see Fig. II-5C).

Table 3-30. Heating Delivered Energy Cost (¢/kWh), Low-Backpressure Central Cogenerator, Warm Water Distribution, Insulated FRP Piping, 5 mile transmission line, 1¢/kWh Thermal Energy Cost, 20°F ΔT, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		8.53	3.40	3.09
5	14.70	5.04	2.80	
20	8.89	2.99		
50	6.59	3.16		

Table 3-31. Incremental Cooling Delivered Energy Cost (¢/kWh) Combined System Low-Backpressure Central Cogenerator, Insulated FRP Pipe, Cold Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		4.64	4.43	2.93
5	6.70	4.53	4.43	
20	6.65	4.53		
50	6.65	4.66		

Distributed Water-Source Heat Pumps

Heating. As shown in Table 3-32, heating costs vary from slightly better to slightly worse than the baseline. The main cost contributor is purchased electricity (see Fig. II-6A).

Table 3-32. Heating Delivered Energy Cost (¢/kWh), Distributed Water-Source Heat Pumps, Uninsulated Polyethylene Piping, Ambient Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		2.93	2.79	2.72
5	3.32	2.86	2.78	
20	3.30	2.97		
50	4.39	2.98		

Delivered energy cost will be quite sensitive to electricity purchase price. Because polyethylene pipe is inexpensive to install in an uncongested site, distribution costs rise sharply with site congestion. As a result, this system is most competitive in low density load cases, unlike any other system studied.

Cooling. Stand-alone cooling costs are competitive with the electric air conditioner non-district baseline in all load cases but one, as shown in Table 3-33. The benefit of increased heat pump efficiency due to the use of the cool ambient water heat sink outweights distribution subsystem costs (see Figs. II-5B, II-5E, and II-6B).

Table 3-33. Stand-Alone Cooling Delivered Energy Cost (¢/kWh), Distributed Water-Source Heat Pumps, Uninsulated Polyethylene Pipe, Ambient Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		5.61	4.65	3.04
5	7.35	5.33	4.67	
20	7.28	5.80		
50	12.09	5.87		

The incremental cooling delivered energy cost for the combined system is 1.71 cents/kWh for all load cases--far below the baseline. The incremental cost is just the electrical energy required for cooling, since the distribution and heat pump capital costs are attributed to heating (see Fig. II-6C).

Fuel-Driven Heat Pump

Heating. Heating delivered energy costs for the fuel-driven heat pump, shown in Table 3-34, vary from slightly worse to somewhat better than the baseline heating system. Because little scale economy exists for the fuel-driven heat pump itself, delivered energy cost is most sensitive to distribution subsystem capital costs (see Fig. II-7A). As a result delivered energy costs are lowest for load cases with large buildings where distribution costs are lowest. Even so, the overall scale economies are small and, unlike some of the large cogenerators, this sytem is competitive in several of the intermediate size load cases.

Cooling. Stand-alone cooling costs for the fuel-driven heat pump system were not competitive in any load case due to high capital costs (see Fig. II-7B). However, the incremental cost of adding cooling to an existing heating system is very low, as seen in Table 3-35, despite the need to increase the distribution subsystem size (see Fig. II-7C).

Table 3-34. Heating Delivered Energy Cost (¢/kWh), Fuel-Driven Heat Pump, Hot Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		2.87	1.88	2.14
5	4.58	2.15	1.76	
20	3.58	1.99		
50	3.68	2.02		

Table 3-35. Incremental Cooling Delivered Energy Cost (¢/kWh), Fuel-Driven Heat Pump, Combined System, Chilled Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		1.10	1.43	1.26
5	1.10	1.41	1.10	
20	1.26	1.37		
50	1.48	1.07		

Ice Pile

The ice pile is a cooling-only system. Delivered energy costs were not competitive with the baseline for any load case. As with all stand-alone cooling systems, except the distributed water source heat pumps, capital costs were simply too high--given the number of cooling operating hours (see Fig. II-9). Distribution costs were high due to the small temperature rise permitted for chilled water. The capital cost of the ice pile itself was a major cost contributor in all load cases.

Municipal Waste Incinerator/Cogenerator

Heating. The municipal waste system is very competitive with the baseline system in most of the larger load cases, as shown in Table 3-36. Although the capital cost of the incinerator is high, this is outweighed by revenue from electricity sales (at 5¢/kWh) and waste tipping fees ($10/ton after handling expenses) (see Fig. II-11A).

Cooling. Cooling is performed with distributed absorption chillers. Because of plant revenues, cooling costs are quite competitive, as Table -37 which presents the incremental cooling costs of a combined system indicates (see Figs. II-11B and II-11C).

Table 3-36. Heating Delivered Energy Cost (¢/kWh), Municipal Waste Incinerator/Cogenerator, Hot Water Distribution, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		23.90	1.18	2.71
5	50.81	2.59	1.11	
20	11.25	1.27		
50	3.63	1.33		

Table 3-37. Incremental Cooling Delivered Energy Cost (¢/kWh), Municipal Waste Incinerator/Cogenerator Combined System, 15 Block District

	Peak load (kW)			
Bldg/blk	10	100	1000	5000
1		1.10	1.43	1.26
5	1.10	1.41	1.10	
20	1.26	1.37		
50	1.48	1.07		

3.5 Summary of Results and Conclusions

Heating

For a new space conditioning system to compete with a well-established technology such as gas boilers, it must have a significant cost advantage. Table 3-38 ranks the district heating system types studied in terms of the number of load cases in which each is "very competitive" -- delivered energy cost more than 25% below the baseline, or "competitive" -- delivered energy cost 0 to 25% below the baseline. Important sensitivity factors and the nature of scale economies are also identified. Tables 3-39 and 3-40 summarize these results for all system types by load case.

The top-ranked system--the diesel cogenerator with an electricity sales price of 10¢/kWh--is very competitive in all ten land cases. The low-backpressure cogenerator is very competitive in six load cases, the urban oil-fired cogenerator in five, and the municipal waste incinerator/cogenerator in four. The diesel cogenerator with 5¢ electricity is competitive in only one load case, and the coal boiler--the lowest ranked heating system--in none.

Table 3-38. Ranking of District Heating System Competitiveness for 15 Block District

Rank	System	Load Cases Where Delivered Energy Cost Is Very Competitive (More than 25% Below Baseline)	Load Cases Where Delivered Energy Cost Is Very Competitive (0-25% Below Baseline)	Important Sensitivity Factors	Nature of Scale Economy
1	Diesel Cogenerator Elec. Sales Price 10¢/kWh	10 Cases (All)	0 Cases	Extremely Sensitive to Electric Sales (or Avoided PUrchase) Price	Small
2	Low-Backpressure Cogenerator	6 Cases (Large Bldg, High Density)	2 Cases (Large-Bldg, High Density)	Total System Load, Transmission Distance, Temperature Drop (and Piping Size)	Large
3	Urban Oil-Fired Cogenerator Retrofit*	5 Cases (High-Density, Large Bldg)	0 Cases	Total System Load, Purchased Thermal Energy Cost	Large
4	Municipal Waste Incinerator/Cogenerator	4 Cases (100, 1000 kW Peak; High Density)	1 Case (100 kW Peak, 5 Bldg/Block)	All Primary Costs (Capital, Tipping Fees, Handling Expenses, Electricity Revenues)	Large
5	Fuel-Driven Heat Pump	2 Cases (1000 kW Peak)	5 Cases (10, 100, 5000 kW Peak)	Distribution Capital Cost	Small
6	Coal-Fired Cogenerator	2 Cases (1000 kW Peak)	3 Cases (Large-Bldg, High Density)	Total System Load	Large
7	Distributed Water-Source Electric Heat Pumps	0 Cases	2 Cases (Small Bldg, Low Density)	Purchased Electricity Cost	Small, Negative
8	Diesel Cogenerator Electricity Sales Price 5¢/kWh	0 Cases	1 Case (1000 kW Peak, 5 Bldg/Block)	Extremely sensitive to Electricity Sales or Avoided Purchase) Rice	Small
9	Coal Boiler	0 Cases	0 Cases	Boiler Capital Cost	Large

*Hot Water Distribution

Table 3-39. District Heating Systems with Delivered Energy Costs More than 25% Below Baseline for 15 Block District

Building density		Building peak load (kW)			
Buildings/ block	(Buildings/ acre)	10	100	1000	5000
1	(.15)	---	3*	1,3*,4,5,7,11	1,3*,5
5	(.74)	3*	3*,5	1,3*,4,5,7,11	---
20	(3.0)	3*	1,3*,5,11	---	---
50	(7.4)	3*	1,3*,5,11	---	---

System Type Key

Number	System Type	Distributed fluid
1	Urban oil generator retrofit	Water
2	Coal boiler	Steam
3	Oil-fired diesel cogenerator (5¢/kWh electricity sales)	Water
3*	Oil-fired diesel cogenerator (10¢/kWh electricity sales)	Water
4	Coal-fired cogenerator	Water
5	Low-backpressure central cogenerator	Water
6	Distributed water-source electric heat pumps	Water
7	Central gas-fired heat pumps	Water
11	Municipal waste incinerator/cogenerator	Water

Several general conclusions are clear from these results:

o A revenue-producing coproduct is essential.

Except for the fuel-driven heat pump, all of the most competitive district heating systems have a revenue-producing coproduct--either electricity sales or waste incineration.

o Most competitive systems have large-scale economies.

As a result, the competitiveness of these systems (urban oil-fired cogenerator retrofit, coal-fired generator, low-backpressure cogenerator, municipal waste incinerator/cogenerator) depends mainly on total system load.

o Some competitive systems have small-scale economies.

Table 3-40. District Heating Systems with Delivered Energy Costs 0-25% Below Baseline

Building density		Building peak load (kW)			
Buildings/ block	(Buildings/ acre)	10	100	1000	5000
1	(.15)	---	None	None	4,7
5	(.74)	6	7,11	3	---
20	(3.0)	5,6,7	4,7	---	---
50	(7.4)	5	4,7	---	---

System Type Key

Number	System Type	Distributed fluid
1	Urban oil generator retrofit	Water
2	Coal boiler	Steam
3	Oil-fired diesel cogenerator (5¢/kWh electricity sales)	Water
4	Coal-fired cogenerator	Water
5	Low-backpressure central cogenerator	Water
6	Distributed water-source electric heat pumps	Water
7	Central gas-fired heat pumps	Water
11	Municipal waste incinerator/cogenerator	Water

The competitiveness of these systems (diesel cogenerator, distributed water-source heat pumps, and fuel-fired heat pump) is less sensitive to building size and density. However, it is very sensitive to other factors (e.g., electricity sales price or purchase cost, fuel cost, distribution capital cost).

o Optimal distribution systems are important.

Use of the lowest-cost suitable piping option was essential to competitiveness of most systems.

o Low-temperature transmission/distribution systems and internal building distribution systems deserve attention.

Several of the most competitive systems (diesel cogenerator, low-backpressure cogenerator, distributed water-source heat pumps, and fuel-driven heat pump) operated at 200°F or lower. Suitable optimal thermal transmission and building internal distribution systems--especially in retrofit--are needed.

- Piping thermal capacity enhancement is desirable.

Systems using lower temperature fluid (and this includes district cooling) have smaller temperature ranges available, leading to increased flow rates and piping sizes. The sensitivity run for the low-backpressure cogenerator demonstrates this problem. Methods to enhance piping thermal capacity are essential to foster the competitiveness of these lower-temperature systems.

Several conclusions emerge regarding specific systems:

- The urban oil-fired cogenerator retrofit is surprisingly competitive.
- Stand-alone central boilers cannot compete with modern distributed boilers.
- The competitiveness of small diesel cogenerators is <u>extremely</u> sensitive to electricity sales (or avoided purchase) price. These systems are very competitive even in small load cases if electricity prices are high.
- The coal-fired cogenerator is competitive where Scandinavian experience would indicate.
- The low-backpressure cogenerator is competitive in a wide range of load cases.
- Distributed water-source heat pumps are competitive for small buildings, especially if electricity costs are low compared to gas.
- The fuel-fired heat pump competitiveness would be enhanced by reduced distribution costs.
- The municipal waste system can be very competitive if tipping fees are high.

Cooling

Stand-alone cooling costs are competitive only for the distributed water-source heat pump system. In pathological cases, e.g., very high electricity sales price or waste tipping fee, other stand-alone systems might be competitive. The small number of annual cooling hours in the climate studied makes it difficult to amortize the capital cost of a district cooling system.

Combined heating/cooling systems--which share capital equipment--are very competitive, even in this northern climate. The incremental cooling costs of combined heating/cooling systems are at least competitive for almost all cases. In fact, all system types, except the urban oil-fired cogenerator retrofit and the diesel cogenerator with distributed absorption chillers, are very competitive (more than 25% below the baseline) in almost all load cases.

4.0 RECOMMENDATIONS

DOE should work to implement the most competitive DHC systems because they further DOE goals and benefit system users and owners economically. This has different meanings for each system.

Conventional Technology

Some of the most competitive DHC systems (urban oil-fired cogenerator retrofit, coal-fired cogenerator) use existing technology. Indeed, the coal-fired cogenerator is common throughout Europe. It must be recognized that technoeconomics is not the problem for these systems. Instead, DOE should focus on the other problems which limit the implementation of these systems—institutional impediments and market wants, needs, and preferences, to determine if and under what circumstances these systems will "make it" in the U.S.

Innovative Technology

Some DHC systems require new technology to be competitive. The incremental cooling cost of combined heating/cooling systems as a class appears highly competitive, even for the northern U.S. climate studied. These systems deserve deeper investigation.

Other system types are at various developmental stages. A detailed analysis and--if warranted--test of the low-backpressure cogenerator is recommended. Fuel-driven heat pumps, too, can be competitive in DHC systems. R&D to develop these systems--particularly compressors and refrigerants suitable for the 120-180°F condensing range--for application to DHC is needed.

Several of the most competitive systems studied operate at low temperature. More R&D support is recommended for components used in low temperature DHC systems, specifically:

- optimized low-temperature transmission/distribution piping systems;
- piping thermal capacity enhancement (e.g., higher energy-density fluids, drag reduction);
- Low-temperature building distribution system heat transfer enhancement--especially in retrofit.

Contingent Technology

The competitiveness of several of the DHC technologies studied is sensitive to "uncontrollables." It is first recommended that DOE, through its analytical activities, identify likely future scenarios (e.g., energy prices, new technology, etc.). Then, R&D should be targeted to those DHC systems which will be most competitive in these likely environments.

For example, diesel cogeneration packages are now at or near mark feasibility. This study concludes that in regions of the U.S. with expensi electricity, these systems are very competitive and may proliferate. Howeve the applications of these systems to district heating and cooling poses maj unresolved problems--and opportunities. DOE should address these problems n to capture the greatest benefits for district heating--and DOE goals--fr these systems.

Similar opportunities exist for competitive DHC systems tied to municip waste incinerators if tipping fees are high, distributed water-source he pumps if electricity prices are low, and fuel-driven heat pumps if distrib tion capital costs are low.

New DHC Markets

Several of the DHC systems studied are competitive in small load cases:

- diesel cogenerator,
- distributed water-source heat pumps,
- fuel-driven heat pump.

In fact, the overall top-ranked system type is the diesel cogenerat with 10¢/kWh electricity sales price. DOE should investigate these small systems to illuminate the district concept in small load cases whe institutional impediments are likely to be smaller. It is also recommend that attempts be made to "break" the scale economies of those systems n competitive only for large system loads (e.g., via energy storage, new prima energy converters, or systems which can be switched on and off). Through su innovative approaches the future markets for district heating may be qui different from those of the past.

District Cooling

This study showed that in a Philadelphia-New York City climate, stan alone district cooling systems are almost uniformly noncompetitive, while t incremental cooling cost in a combined heating/cooling system is almost alwa competitive. It is recommended that combined systems be given greater atte tion. The finer cooling systems issues have not been fully addressed, a should be investigated in a study of a southern U.S. climate.

Revenue-Producing Coproducts

Because the most competitive DHC systems also have a revenue-produci coproduct (e.g., electricity or waste incineration), DHC systems cann sensibly be studied in a vacuum. DHC R&D must address the issues and proble associated with these coproducts as well.

APPENDIX I

CHARACTERIZATION COMPUTER PROGRAM DESCRIPTION

APPENDIX I. CHARACTERIZATION COMPUTER PROGRAM DESCRIPTION

This appendix is a detailed description of the technology characterization computer program. Appendix IA presents an overview of the program calculations and subroutines. Appendix IB describes the program subroutines and data files in detail. In Appendix IC, the operation and use of the program is described.

IA. Technology Characterization Program Overview

Characterization Program Flow

The characterization program actually consists of two programs, one which does all the energy calculations, called "DISTHT," and one which performs the economic calculations, called "OUTPUT."

The flowchart in Figure I-1 shows the sequence of calculations followed by the characterization program. Each box in the flow chart refers to a single subroutine. Each box gives the name of the subroutine and identifies the calculations done by it.

As the flowchart shows, the program first calls READFL which inputs all the data pertaining to the components: the converters, economic assumptions, and pipe costs. None of the information pertaining to the loads is read in at this point. Next GETPAR is called to input the information describing the specific system to be run. This information comes either from a batch file or from the keyboard. Among these inputs are the configuration of the system, temperatures and temperature drops, and pipe materials.

The program runs through calculations for a set of load cases for each system inputted by GETPAR. The next subroutine, ITERAT, and those that follow are called once for each load case. ITERAT reads the data from the transmission and distribution configuration files and the load-duration data files as specified by the load case file.

The next set of subroutines is called once for each subsystem. ANCOST calls the pipe-sizing and heat loss subroutines after it calculates the input energy, in turn, for each converter. To calculate the input energy, ANCOST first looks at the individual loads for each building in the load-duration data. By doing an energy balance on the user converter, it calculates an input load for each bin. The new load data together with the original duration data this becomes the load-duration data specifying the output for the next subsystem upstream of the user converter, the distribution system. ANCOST then calls either OPTPIP or OPTSTM, depending on whether water or steam is used, to size the piping. THRMLS is then called to calculate the heat exchanged between the pipe and the ground. The loop returns to ANCOST for the second iteration where the fuel and thermal inputs to the secondary converter are calculated. Again, the thermal input of the secondary converter becomes the thermal output of the transmission subsystem. The appropriate pipe-sizing routine is called and then THRMLS for the transmission subsytstem. In the

Characterization Program Flow

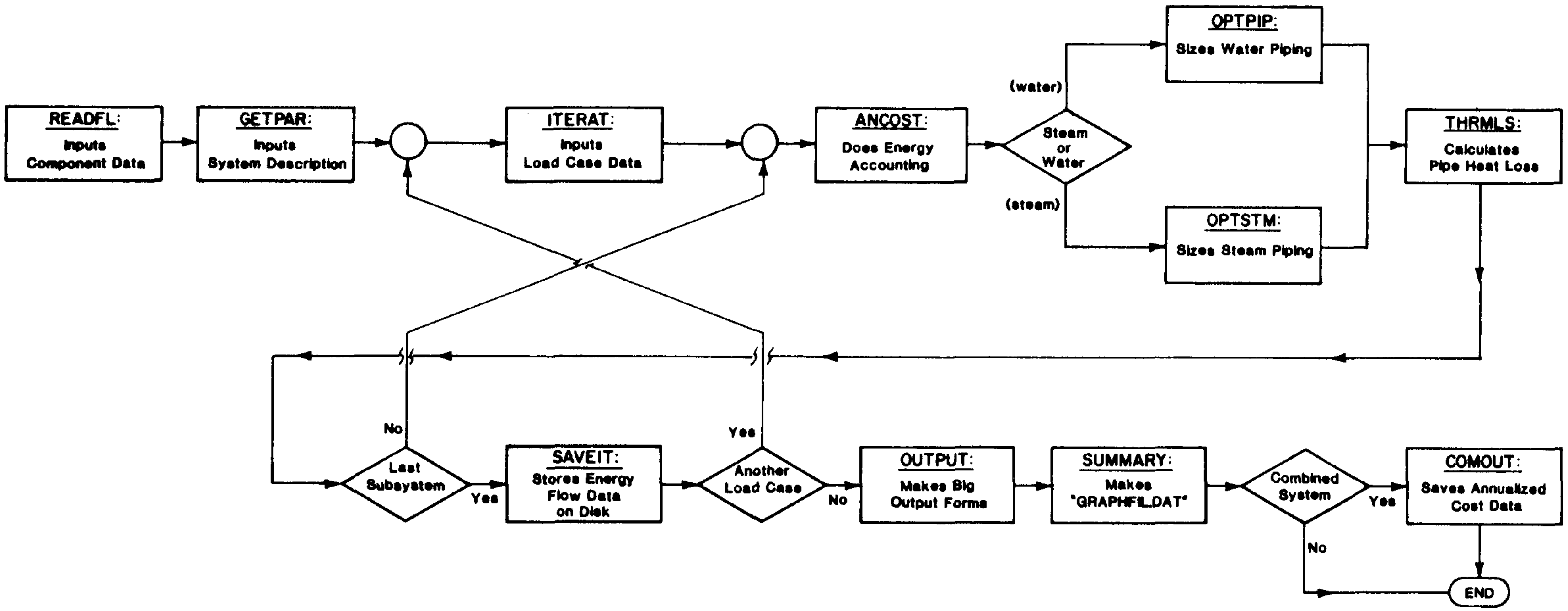

FIGURE I-1

third and last iteration ANCOST calculates the fuel and thermal inputs to the primary.

After the third iteration of the ANCOST loop the subroutine SAVEIT saves all the energy flow data on a disk file called "SAVEFILE.DAT" and returns to ITERAT to get the inputs for another load case. The energy-balance calculations are repeated and again saved for each load case. After all the load cases have been run, the second program, OUTPUT, is automatically run.

The program OUTPUT first calls the subroutine READIT which reads in all the data saved by SAVEIT. It does a large number of straightforward economic and energy calculations and prints them out (See Section 3.3). OUTPUT then calls SUMMARY which stores the annualized cost data appearing in "GRAPHFIL.-DAT" (See Section 3.3.4). If the program is being run in the batch mode for combined heating and cooling systems, COMOUT will be called to save the annualized cost data. This can then be used in the scheme discussed below to calculate the corresponding figures for combined heating and cooling systems. What follows is a supplement to Section 3.2 that gives a little more detail on the program's approach. Additional information is given in the Appendix I-B.

The Energy Input Factors

The way the program steps through the generic system model from the load to the primary converter, doing energy balances along the way, was explained in Section 3.3. As stated the program uses coefficients from which the ratios of input energy of a given type to the output thermal energy of a converter are calculated. These ratios are called energy input factors (EIF) and may warrant a bit more explanation than that given in Section 3.3.

An example of an EIF is the inverse of the COP of a heat pump (since the COP is defined as the ratio of thermal output to electric input), which represents the EIF for electricity. Thus the EIF's for an electric heat pump would be zero for all the other types of fuel and one minus the electricity EIF for thermal (since the sum of thermal and electrical EIF's must be unity for conservation of energy). The COP of a heat pump is sensitive to both input temperature (assuming the output temperature is fixed) and load factor. The dependence of the EIF's on these parameters can be represented adequately by two curves, one for source temperature, and one for load factor. The coefficients of the linear approximation of these curves are stored in a file that is used by the program to calculate the electrical and thermal inputs from the output, the load factor, and the input temperature.

The EIF's represent the ratios of instantaneous energy flow, so the program has to use the load duration data to obtain an inventory of fuel consumption by the susbsystems as it steps through the system. The program calculates the instantaneous energy flows for each load bin in the load/duration data, multiplies the associated inputs by the corresponding duration, and sums. It saves the instantaneous thermal inputs for each load bin so it can do the same for the subsystem upstream of it.

Sizing of Water Piping

The water piping is sized by picking the pipe diameter corresponding to the lowest total annualized cost. The procedure is as follows:

1. The description of the piping subsystems gives a list of pipe lengths with a corresponding number of blocks served by that length. The total length of pipe characterized by the number of blocks it serves is called a level of the piping subsystem. The optimal pipe diameter is chosen independently for each level. For each level, the subroutine OPTPIP:

1. starts with the smallest pipe diameter;
2. calculates the pumping power for each load bin from the number of blocks served by the level, the number of buildings per block, and the load of each building;
3. multiplies by the corrsponding duration to get the pumping energy;
4. adds the annualized capital cost of the length of pipe for the level to the annual pumping energy to obtain the total annualized cost;
5. steps 2 to 4 are repeated for each pipe diameter until a minimum total cost is found;
6. steps 1 through 5 are repeated for all the levels in the piping subsystem.

Sizing of Steam Piping

The system characterization program sizes steam piping via a simple set of rules that are appropriate for low velocity systems. The application of the rules requires more information about the distribution system configuration than that for sizing water piping. The program always reads this additional information from the distribution system data files, but does not use it for water systems.

The two rules used for sizing are: a limitation of the pressure change between any two points in the system, and a maximum pressure change per unit length of pipe. The values of these limits depend on the initial pressure and follow from a number of design considerations such as the avoidance of near-sonic velocities. The user inputs values for these limits from the console at the start of each run. The values used in the following derivation are arbitrary. The values used in the study were taken from the ASHRAE Fundamentals handbook, reference.[1]

The fifteen block distribution system used in the Potential study is shown below in Figure I-2 with pressure drops per hundred feet of pipe and number of blocks served indicated on each section of pipe. These pressure drops were derived by limiting the pressure drop between any two points in the system to 20 psi, an arbitrary value taken due to the 100 psi steam used in the systems studied. The procedure involved is as follows.

1. The pressure is assumed to drop linearly with distance along the path connecting the source of the steam with the most remote point in the system,

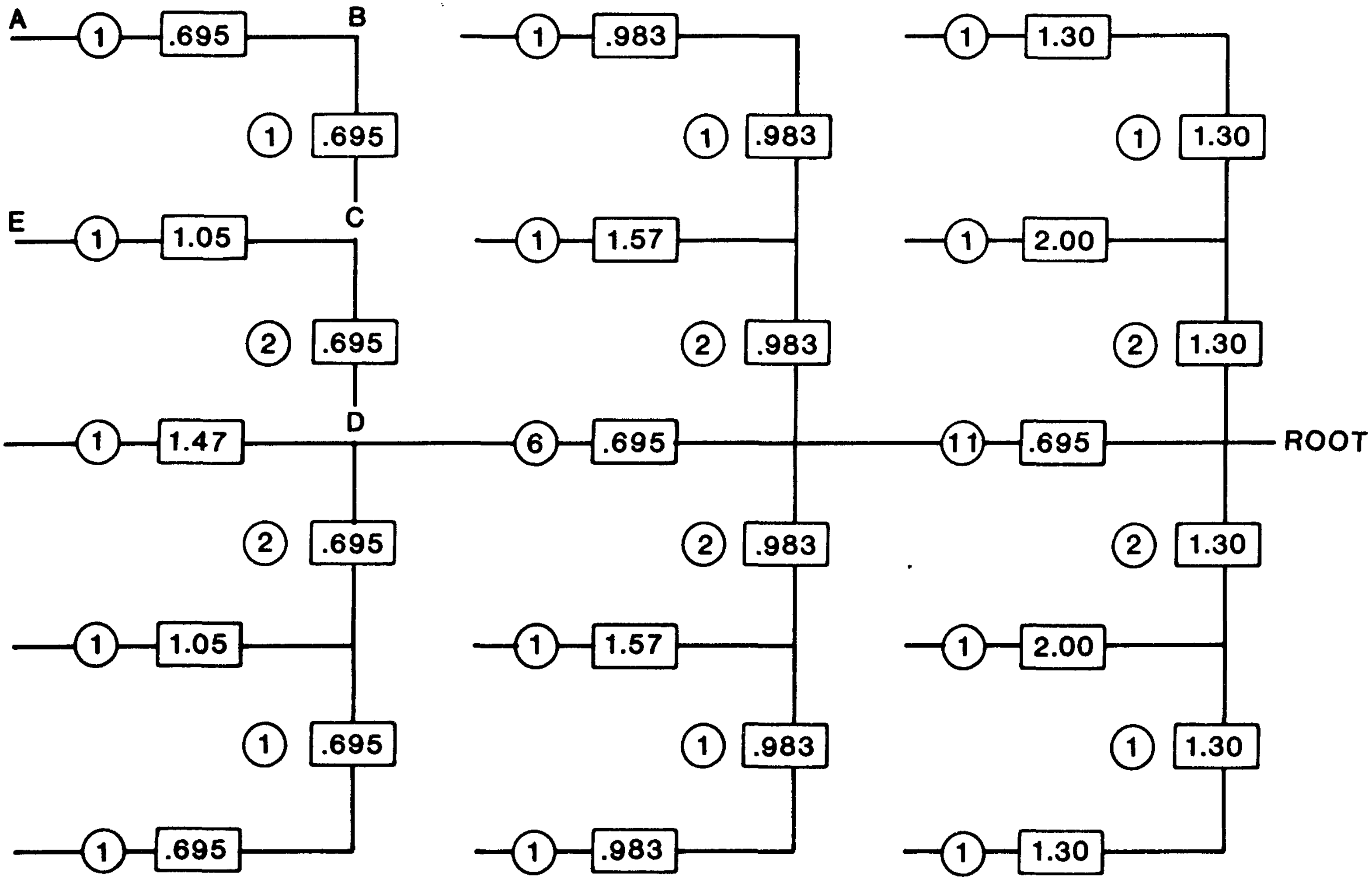
A
1
.695
B
1
.983
1
1.30
1
.695
1
.983
1
1.30
E
1
1.05
C
1
1.57
1
2.00
2
.695
2
.983
2
1.30
1
1.47
D
6
.695
11
.695
ROOT
2
.695
2
.983
2
1.30
1
1.05
1
1.57
1
2.00
1
.695
1
.983
1
1.30
1
.695
1
.983
1
1.30

FIGURE I-2

A-B-C-D-ROOT. The pressure difference, 20 psi, is divided by the length of A-B-C-D-ROOT, 2940 feet (A-B is 700 ft. typ., B-C is 420 ft. typ.).

2. The pressures at points B, C, and D can then be calculated by subtracting the respective total pressure drops from the pressure at ROOT.

3. To obtain the pressure drop along E-C, the final pressure at C, is subtracted from the pressure at E, ROOT pressure minus 20.

4. This is done for the rest of the junctures in the system noting that the pressure where every pipe dead ends is equal to the ROOT pressure minus 20.

This pressure drop information, along with the other information used for sizing the water piping, and the limit of the pressure drop per hundred feet of pipe are needed to size the steam pipe. The procedure followed by the program is to take a given section of pipe, determine the mass flow of steam required in it, compute the pressure drop for each pipe diameter, and choose the smallest pipe for which the calculated pressure drop is lower than the allowed maximum value for that segment of pipe. To determine the mass flow of steam from the thermal load carried by the pipe, the maximum load of the system is assumed to prevail. The enthalpy change used to calculate the mass flow of steam is an input to the program. For the Potential study the value used for phase change and a 200 F sensible temperature change of the condensate at 338 F initial steam temperature was 1091 Btu/lb.

To put the data in the form required by the distribtuion configuration file the following adjustments are required.

Each section of pipe is characterized by its length, the number of blocks it serves, and its allowed pressure drop. A table was constructed with the allowed pressure drops going across and the number of blocks served going down. The table for the above distribution system looks like this.

No. Blks	Pressure drop/100 ft. (psi),length (ft) (L=52.0 x No. Bldgs/blk)						
1	1.0,L						
1	.695,2240	.983,2240	1.05,1400	1.30,2240	1.47,700	1.57,1400	2.0,1400
2	.695,840	.983,840	1.30,840				
6	.695,700						
11	.695,700						

The pressure drop for the links between the buildings and the street mains are assumed to be 1.0 psi, or 5 percent of the maximum pressure drop. The seven different pressure drops in the second level can be grouped into five if .983 and 1.05 are both taken to be 1.0, and 1.47 and 1.57 are both taken to be 1.5. If the lengths of the pipe sections are also indicated as a fraction of the total length of the level, and the length in the level indicated in the table then the result is:

No. Blks	Length (ft.)	Pressure drop/100 ft.,length (section/total)				
1	L	1.0,1.0				
1	11620	.695,.193	1.0,.313	1.3,.193	1.5,.181	2.0,.12
2	2520	.695,.333	.983,.333	1.30,.333		
6	700	.695,1.0				
11	700	.695,1.0				

Combined Heating/Cooling Systems

Most of the heating systems marked for further study have a cooling system counterpart, and vice versa. In a combined system--one that supplies both heating and cooling--it is possible that the heating and cooling functions can share parts of the same system. For example the same distribution system may be used to distribute both hot water in the winter and chilled water in the summer. In combined systems it is useful to think of the capital cost of a cooling system as the incremental cost of the additional equipment and upgrading of the shared resources of a heating system.

From appropriate figures taken from the output of both the cooling system and the corresponding heating-alone system one may calculate the incremental cost of adding cooling capability to a heating system. A procedure for doing this is outlined below.

The first step is to identify the system configuration representing the combined heating/cooling system corresponding to a given heating system. If the two modes of a system will share a subsystem, then the system's operation in one of the two modes will determine the minimum size of the subsystem. For example, the flowrates in the distribution subsystem will probably require different pipe diameters. To be exact, the heating and cooling systems should be run separately, the minimum size requirements of each shared subsystem determined to obtain a combined system configuration, and the combined system run in both the heating and cooling modes. Then the outputs can be further digested to yield a profile of the incremental costs associated with adding cooling capability to a heating system. Some approximations were adopted in the foregoing procedure to simplify this process.

The combined system's capital and operating costs can be assembled from the data on the corresponding system's optimized and simulated separately. This combined cost information will not be exact, but the inaccuracies are minor. The pertinent information measured are the capital and operating costs for the subsystems: the converters: Primary, Secondary, and User, and the piping: Distribution and Transmission. We start with these numbers for the heating system, run the corresponding cooling system and obtain the combined numbers as follows:

Take the larger of:	See note:
- The capital costs of the shared converters	(1)
- The capital costs of the shared piping systems	(1)

Take the sum of:

- The energy costs for the shared converters (2)
- The energy costs for the unshared converters (2)
- The capital costs of the unshared converters (3)

Take the piping energy cost for the piping susbsystem with the larger capital cost. (4)

Rationales:

(1) The capital costs of the subsystems in the combined system will be determined by whichever mode demands a greater capacity of that subsystem.

(2) If the operating energy is independent of the ratio of load to converter capacity, the operating energies, for the mode for which the converter may be undersized, are the same as for the modes optimized independently.

(3) If a subsystem is needed by one mode then it must be present in the combined system.

(4) The pumping power for the mode for which the piping will be oversized, will be close to zero since pumping power drops off precipitously as the pipe diameter increases.

This strategy was applied for the following combined heating/cooling systems:

1. Primary: Urban Oil Cogenerator
   Secondary: Nothing
   User: Heat Exchanger/Double-Effect Absorption Chiller
   Distribution Pipe: RICWIL Hi Pressure Steel
   Pipe Fluid: Steam

2. Primary: Urban Oil Cogenerator
   Secondary: Nothing
   User: Heat Exchanger/Single Effect Absorption Chiller
   Distribution Pipe: RICWIL F.R.P.
   Pipe Fluid: Water

3. Primary: Coal Boiler
   Secondary: Nothing
   User: Heat Exchanger/Double Effect Absorption Chiller
   Distribution Pipe: RICWIL Hi Pressure Steel
   Pipe Fluid: Steam

4. Primary: Diesel Cogenerator
   Secondary: Nothing
   User: Heat Exchanger/Single Effect Absorption Chiller
   Distribution Pipe: RICWIL F.R.P.
   Pipe Fluid: Water

5. Primary: Diesel Cogenerator
Secondary: Single Effect Absorption Chiller
User: Heat Exchanger
Distribution Pipe: RICWIL F.R.P.
Pipe Fluid: Water

7. Primary: Coal Cogenerator
Secondary: Nothing
User: Heat Exchanger/Single Effect Absorption Chiller
Distribution Pipe: RICWIL F.R.P.
Pipe Fluid: Water

8. Primary: Low Backpressure Cogenerator
Secondary: Nothing
User: Heat Exchanger/Electric Heat Pump
Distribution Pipe: RICWIL F.R.P.
Pipe Fluid: Water

9. Primary: Low Temperature Source
Secondary: Nothing
User: Electric Heat Pump
Distribution Pipe: Polyethylene pipe
Pipe Fluid: Water

10. Primary: Low Temperature Source
Secondary: Fuel-Driven Heat Pump
User: Heat Exchanger

IB. Program Details

Content and Format of the Detailed Program Description

The following is a detailed description of each of the subroutines making up the characterization program. For each subroutine, the following information is given:

Subroutine Name - the identifier used in the Fortran source code.

Purpose - the purpose of the subroutine; calculations, input, output, etc.

Overview - a discussion of the routine's logic,

Inputs - a key to the variables recieved by the subroutine from other subroutines.

Outputs - a key to the variables transmitted to other subroutines by the subroutine.

Other Variables - a key to the variables which play a role in the subroutines calculations.

Engineering the important equations, if any, used by the subroutine to do calculations.

Detailed descriptions of the default data and the formats of the respective files are given following the subroutine descriptions. A user's guide to the program completes this section.

The Subroutines

DISTHT

Purpose: This is the main program that calls, directly or indirectly, all of other subroutines in the program.

Overview: Within this routine the program iterates on the load cases. Via calls to READFL and GETPAR, it reads all the data not pertaining to a particular load case. This includes both data read from the console by the user and data from the default files. The loop which iterates on the load cases contains one call each to ITERAT, ANCOST, and SAVEIT which must be called for each load case.

Inputs: none

Outputs: none

Other Variables:

Engineering Equations: none

READFL

Purpose: Inputs data which does not pertain to a particular load case from the default data files.

Overview: READFL reads the default data for the pipes and the energy converters as well as miscellaneous economic and physical data such as earth temperature and fuel prices. These data are contained in the files named CONVER.DAT and PIPES.DAT.

Inputs: none

Outputs: All of the data read is fed to the other routines via COMMON blocks.

PTYPES - number of pipe types.
PIPSIZ(I) - number of pipe diameters of type I.
NPS(I) - number of pipes in trench for pipe type I .
PIPNAM(I) - name of Ith pipe type.
IDIAM(I,J) - inner diameter of Ith size of Jth pipe type.
ODIAM(I,J) - outer diameter of Ith size of Jth pipe type.
PIPCST(I,J) - unit length cost of Ith size of Jth pipe type.
PIPCON(I,J) - effective wall conductivity of Ith size of Jth pipe type.
PDEPTH(I,J) - burial depth of Ith size of Jth pipe type.
CONTOT - number of energy converters types.
CONTYP(I) - name of Ith energy converter.
CAPSLP(I) - slope of capital cost line fit for Ith converter.
CAPCON(I) - constant of capital cost line fit for Ith converter.
FIXCST(I) - fixed annual operating costs for Ith converter.
MINCAP(I) - minimum allowed size for the Ith converter.
BIGPTR(I) - points to the index of the converter which has the next higher capacity.
CQ(I,J,K) - load factor-dependent part of EIF. K is order of coefficient in the straight line fit of the EIF for the Jth energy type, for Ith converter type.
CT(I,J,K) - temperature-dependent part of EIF. K is order of coefficient in the straight line fit of the EIF for the Jth energy type, for Ith converter type.
OILCP6 - Wholesale price of no. 6 oil
OILRP6 - retail price of no. 6 oil
OILCP2 - wholesale price of no. 2 oil

OILRP2 - retail price of no. 2 oil
GASCP - wholesale price of natural gas
GASRP - retail price of natural gas
RATTYP(I) - name of Ith input energy form (eg. oil, gas, thermal).
RATE(I) - price of Ith input energy form
PTHERM(I) - if Ith converter inputs thermal energy which has to be payed for, like a fuel, then PTHERM(I) takes the name of the Ith converter
TRATE(I) - rate associated with PTHERM(I)
EARTHT - average yearly earth temperature
ERTHCN - earth thermal conductivity

Other Variables: none

Engineering Equations: none

GETPAR

Purpose: This routine inputs the description - all non-default information - on the system from the console or data file.

Overview: This routine prompts the user for choices of options from the default data sets.

Inputs:
SYSTYP(I) - index pointing to the type of the Ith converter 1=primary, 2=secondary, 3=user
PMATER(I) - index pointing to the type of the Ith pipe material
T(I) - temperature of heat transfer fluid in: 1=distribution, 2=transmission
DELTAT(I) - temperature difference between supply and return legs of of non-steam system piping 1=distribution, 2=transmission
RESP1 - character indicating two options: 1) whether to use retail or wholesale fuel prices, 2) the choice of steam or water in the transmission and distribution systems
RESP2 - character indicating whether to use No. 2 or No. 6 fuel oil prices
RESP3 - character indicating two options 1) whether it is desired to have pipe diameters chosen by the program, 2) whether the system is doing heating or cooling
CFAC - ratio of cooling to heating load

Outputs:
SYSTYP(I)
PMATER(I)
T(I)
DELTAT(I)
CFAC
RATE(1) - price of oil
RATE(2) - price of gas
STEAM(1) - logical variable indicating whether transmission uses steam
STEAM(2) - logical variable indicating whether distribution uses steam
LOG2 - logical variable indicating whether system is for cooling

Other Variables: none

Engineering Equations: none

ITERAT

Purpose: This routine reads the data files pertaining to the load case

Overview: ITERAT is the beginning of the control loop that is executed, once for each load case. It reads the transmission and distribution configuration files and the load-duration data files the combination of which determines each load case.

Inputs:
PCLASS(I) - installation class index 1 = distribution, 2 = transmission.
PMATER(I) - piping material for 1 = distribution, 2 = transmission
* DISNOM - descriptive name of distribution system
* FLWDIS - number of buildings served by distribution
* DISLEV - number of levels in the distribution system
* DISLNG(I) - length of Ith distribution level
* DISFLW(I) - number of users on the Ith level
* NSTMDS(I) - number of different allowed pressure drops for steam service for pipe level I
* DISDPS(I,J) - Jth allowed steam pressure drop for Ith level
* DISFSM(I,J) - Jth fraction of length of level to which Jth allowed pressure drop applies for Ith level
* TRNNOM - descriptive name of transmission sysem
* FLWTRN - number of terminals served by transmission system
* TRNLEV - number of levels in the transmission system
* TRNLNG(I) - length of Ith transmission level
* TRNFLW(I) - number of users in the Ith level
* NSTMTR(I) - number of different allowed pressure drops for steam service for pipe level I

* TRNDPS(I,J) - Jth allowed steam pressure drop for Ith level
* TRNFSM(I,J) - Jth fraction of length of level to which Jth allowed pressure drop applies for Ith level
* NUMBIN - number of load-duration bins
* ENDLOD(I) - building load for Ith bin
* DURAT(I) - duration for Ith bin

Outputs: * all input variables marked by asterisk are transmitted to other subroutines without modification

PIPTYP(I) - identifies type of pipe for: 2=distribution, 2=transmission

Other Variables:
LFNAME - name of load duration data file
DNAME - name of distribution configuration data file
TNAME - name of transmission configuration data file

Engineering Equations: none

ANCOST

Purpose: Calculates energy flows between subsystems and between subsystems and the outside world. ANCOST also determines the converter sizes required.

Overview: ANCOST marches backward through the system from the user to the primary converter, calculating the energy inputs from the outputs for each subsystem in turn. At each step it keeps track of fuel and thermal inputs and outputs to/from the system environment.

Inputs:
CAPCON(I)
CAPSLP(I)
ENDLOD(I)
MINCAP(I)
SYSTYP(I)
STEAM(I)
CQ(I,J,K)
CT(I,J,K)
FLWDIS
FLWTRN
LSSDIS - annual thermal loss from distribution
LSSTRN - annual thermal loss from transmission

Outputs:
CAPCST(I) - capital cost for converter I
PSTP(I) - pumping power
ANEN(I,J) - annual energy consumption of energy type I by converter J

MAXCAP(I)
INSTEN - instantaneous energy consumption for a given converter, a given energy type, and a given load bin. Values are stored on a file and differentiated by position in file
LSSTRN
Q(I) - instantaneous thermal input to converter for load bin I

Other Variables:
EFFIC(I,J) - ratio of input energy of Ith type to the converter thermal output corresponding to the Jth bin.
Q(I) - The converter thermal output corresponding to the Ith bin.

Engineering Equations: The thermal inputs to the energy converters are calculated from the coefficients CQ and CT as follows

$$Q_{ij} = [IK_{ij1}+K_{ijo}][TL_{ij1}+L_{ijo}]Q_o \text{ if } K_{ijk} \text{ and } L_{ijk} \text{ are both nonzero}$$

$$Q_{ij} = [IK_{ij1}+K_{ijo}]+[TL_{ij1}+L_{ijo}]\ Q_o \text{ if } K_{ijk} \text{ or } L_{ijk} \text{ is zero}$$

where:
$K_{i\ j\ k}$ = Kth coefficient for load factor dependence of the Jth energy type of the Ith converter, CQ(I,J,K)
$L_{i\ j\ k}$ = kth coefficient for the temperature dependence of the Jth energy type of the Ith converter, CT(I,J,K)
Q_o = output thermal energy, Q(J)
$Q_{i\ j}$ = input thermal energy of type J
I = load factor = output load, Q(J), divided by converter capacity, MAXCAP(L)
T = input fluid temperature

OPTPIP

Purpose: This subroutine chooses the pipe diameters for each level in the distribution and transmission systems

Overview: Pipe diameters are chosen on the basis of lowest annualized cost for each level of the piping system. The annualized cost is the sum of the pumping energy and the product of the capital cost and the capital recovery factor

Inputs:
LENGTH - local name for DISLNG or TRNLNG
FLOW - local name for DISFLW or TRNFLW
NUMLEV - local name for DISLEV or TRNLEV
LOAD - local name for Q

PIPLEV - =1 for distribution, =2 for transmission

Outputs:
HICOST(I,J,K) - annualized cost of pipe for level I, pipe size J, and piping system K
LOPIPE(I,J) - points to pipe size corresponding to lowest annualized cost for level I and piping system J
PANEN(I) - annual pumping energy for piping system I
PSTP(I)

Other Variables:
PIPLOD - load carried by level of pipe
ROUGH - relative roughness of pipe wall
VOLFLO - volume flowrate of water
AREA - cross sectional area of pipe
VELOC - mean flow velocity
NU - kinematic viscosity
REYNLD - Reynolds number
FRICT - friction factor
NWFRIC - new friction factor (calcualated by iterative equation)
ANLCST - annualized cost for pipe level

Engineering Equations: Friction factor:

$$\frac{1}{\sqrt{f}} = -2 \log_{10}\left(\frac{E/D}{3.7} + \frac{2.51}{R\sqrt{f^*}}\right)$$

where:
f^* = old value of friction factor
f = new value of friction factor
R = Reynolds number
E = relative roughness
D = inner diameter of pipe

Pumping power:

$$Q_p = K \frac{f}{D} v^2 V/2g$$

where:
Q_p = pumping power
V = volume flowrate
v = mean flow velocity
g = gravitational constant
k = conversion constant for appropriate units

OPTSTM

Purpose: Chooses pipe diameters for each level of the piping system when steam is the working fluid

Overview: The piping systems are broken into more levels by OPTSTM because the piping lengths must be characterized by both the number of users served and the allowed pressure drop per unit length. OPTSTM chooses the smallest pipe diameter for which the calculated pressure drop does not exceed the allowed pressure drop.

Inputs:
LENGTH
FLOW
NUMLEV
LOAD
PIPLEV
NSTM - NSTMDS for distribution, NSTMTR for transmission (see definition of NSTMTR)
STMDP - DISDPS for distribution, TRNDPS for transmission (see definition of TRNDPS)
FSTM - DISFSM for distribution, TRNFSM for transmission (see definition of TRNFSM)

Outputs:
HICOST(I,J,K) - for steam systems HICOST carries the pressure drops for each pipe tested by OPTSTM
LOPIPE(I,J)

Other Variables:
PIPLOD
SPVOL
LBPS
PSIPHF

Engineering Equations: Friction factor:

$$f = .0027\ (1+36/d)$$

where:
f = friction factor
d = pipe inner diameter

Pressure drop:

$$\Delta P = 174.2\ Lfm^2\ V/d^2$$

where:
ΔP = pressure drop in pounds per square inch per hundred feet
$\dot{m}$ = mass flow in pound per second
L = length of pipe in hundreds of feet
V = specific volume of steam (assumed constant)
d = inner diameter pipe

THRMLS

Purpose: THRMLS calculates the heat loss to the ground from the transmission and distribution systems.

Overview: Heat loss is calculated from an approximate equation for heat loss from a single pipe to a constant temperature surface in a semi infinite homogeneous medium. Interaction between the pipes is neglected and a constant effective pipe wall conductivity is used for both the pipe wall and surrounding insulation. Thus the pipe outer diameter is that of the pipe, insulation, and jacket.

Inputs:
T(I)
DORT
LENGTH

Outputs:
LSSDIS - rate of heat loss from entire distribution system in Btu/hr
LSSTRN - rate of heat loss from entire transmission in Btu/hr
LOSS - rate of heat loss from pipe in Btu/hr

Other Variables:

Engineering Equations: $Q_1 = P(T_f - T_e)L$

where:
T_f = pipe fluid temperature
T_e = earth temperature at burial depth
L = length of pipe

$$P = \left[\frac{1}{2\pi K_p / \ln(od/id)} + \frac{\ln(2D)(.159)}{K_e} \right]^{-1}$$

where:
K_p = pipe wall conductivity
id = pipe inner diameter
od = pipe outer diameter
D = burial depth
K_e = earth conductivity

SAVEIT

Purpose: Writes all energy flow data to a file to be used by the output program.

Overview: Dumps all the data to an intermediate data file for each load case. It is called once for each load case.

Inputs: All outputs from above

Outputs: All outputs from above

Other Variables: none

Engineering Equations: none

READIT

Purpose: Reads the energy flow data written by SAVEIT.

Overview: This subroutine is called by OUTPUT.

Inputs: All energy flow data written by SAVEIT.

Outputs: " " " " " " "

Other Variables: none

Engineering Equations: none

OUTPUT

Purpose: OUTPUT calculates all the economic results and generates tabular and graphical summaries of this and thermal information.

Overview:

Inputs: All energy flow data from READIT, energy flow rate data from ANCOST.

Outputs: Printed output

SPEL1 - revenues corresponding to electrical generation divided by annual thermal production for primary converter
SPEL2 - revenues corresponding to electrical generation divided by annual thermal production for secondary converter
SPEL3 - revenues corresponding to electrical generation divided by annual thermal production for user converter
SPCAP1 - capital cost multiplied by capital recovery factor divided by annual thermal production for primary converter
SPCAP2 - capital cost multiplied by capital recovery factor divided by annual thermal production for secondary converter

SPCAP3 - capital cost multiplied by capital recovery factor divided by annual thermal production for user converter
SPTOT(I) - energy costs divided by annual thermal production; I points to subsystem 1=primary, 2=transmission, etc.
SPFCST - fixed costs for the converters divided by annual thermal production
SPTTRN - sum of operating and annualized capital cost for transmission
SPTDIS - sum of operating and annualized capital cost for distribution
TRNNOM
DISNOM
LODNOM
TOTAL(I) - annual cost of fuel or electricity for subystem I
EL1 - annual revenues from electrical generation by primary converter
EL2 - annual revenues from electrical generation by secondary converter
EL3 - annual revenues from electrical generation by user converter
CAP1 - capital cost of primary converter multiplied by capital recovery factor
CAP2 - capital cost of secondary converter multiplied by capital recovery factor
CAP3 - capital cost of user converter multiplied by capital recovery factor
FTCC - capital cost of transmission subsystem multiplied by capital recovery factor
FDCC - capital cost of distribution subsystem multiplied by capital recovery factor
UO - annual thermal production by system

Other Variables: (too numerous to list, see source listing)

Engineering Equations: none

SUMMRY

Purpose: Saves figure-of-merit data in a compact and readable format for a system run under a complete set of load cases.

Overview: SUMMRY produces a data file which consists of a table of costs divided by system annual thermal production interspersed with histogram plots of these data. The file can be used as is or digested by a BASIC program called TABLE that reorganises the data into a more readable summary.

Inputs: SPEL1
SPEL2
SPEL3
SPCAP1
SPCAP2
SPCAP3
SPTOT
SPFCST
SPTTRN
SPTDIS
TRNNOM
DISNOM
LODNOM

Outputs: none

Other Variables: none

Engineering Equations: none

COMOUT

Purpose: Produces a data file for use in calculating economics on combined heating and cooling systems.

Overview: COMOUT simply writes the input variables to a data file which can then be used by a BASIC program which "combines" the data from a number of pairs of heating and cooling systems

TOTAL(I) - Annual cost of fuel or electricity for subsystem I
EL1
EL2
EL3
CAP1
FTCC
CAP2
FDCC
CAP3
UO

Outputs: none

Other Variables: none

Engineering Equations: none

THE DATA FILES

The program makes use of a number of data files, all of which may be modified by the user to alter the default inputs. Not all of the data files are used for a given run, and not all need be present to run the program. The original set of defaults should, however, be retained as an example of the formats of the files. This section gives the format of each type of data file and some information about their use not contained in the user guide.

The following is a list of the data file types and their purposes. Some of them are named outside the code of the program so that the name has no significance, Default Names. Others need to be given specific names, Required Names, because the name is contained in the executable program. In addition the input data files there are several data files which are used by the program which the user needn't bother with except to be sure they are present.

Data Files Used by DH/C Characterization Program

Data File Type	(Default) or Required Name	Purpose		
Converter Data	CONVER.DAT	Gives performance and economics for each type of energy converter, thermal and fuel prices, electricity buy and sell rates, average earth temperature and conductivity, and capital recovery factor.		
Pipe Data	PIPES.DAT	Gives pipe dimensions, wall thermal conductivity, installed cost per unit length, for each type of pipe material and class.		
Heating Load Cases	HLODCAS.DAT	Gives the names of the files containing the heating load case data.		
Cooling Load Cases	CLODCAS.DAT	Gives the names of the files containing the cooling load case data.		
		Peak Load	Cool/Heat	Resid/Commer
Load-Duration Data	(TEN.DAT)	10 KW	Heating	Residential
	(HUND.DAT)	100 KW	"	"
	(THOU.DAT)	1000 KW	"	"
	(FTHOU.DAT)	5000 KW	"	Commercial
	(RCTEN.DAT)	10 KW	Cooling	Residential
	(RCHUND.DAT)	100 KW	"	"
	(RCTHOU.DAT)	1000 KW	"	"
	(CFTHOU.DAT)	5000 KW	"	Commercial
Transmission Configuration	(TZERO.DAT)	Gives the transmission system layout.		

Distribution Configuration		Gives the distribution system layout.	
		No. Blocks	No. Bldgs/Block
	(DLOW.DAT)	15	1
	(DMED.DAT)	"	5
	(DHI.DAT)	"	20
	(DRHI.DAT)	"	50
	(DSLOW.DAT)	3	1
	(DSMED.DAT)	"	5
	(DSHI.DAT)	"	20
	(DSRHI.DAT)	"	50
Output Device	OUTDEV.DAT	Names the output device or file that the output form is written to.	
Load Case Counter	ITER.DAT	Holds the number of load cases that have been run for a given system.	
Batch Run	RUN.DAT	Holds the number of systems to be run and the number which have been run.	

Data File Formats

This section gives details pertaining to the data files that should give a user with a knowledge of Fortran enough information to modify or create data files for the characterization program. The exact input descriptors used for each data field are not listed in this appendix. Since most of the default and example data files supplied with the program themselves use very readable formats, it should be easy to modify them with an editor without using inappopriate fields. The less readable files are small and use list-directed inputs, so that all that is needed is the order of the data on each line, which are given below.

Converter Data

This file's structure is evident from a listing of the default file. The first line contains the number of converter types. Starting at the seventh line is a list of converter names with several corresponding data, one per line as follows:

Datum	Variable Name
1) Name of converter	CONTYP
2) Slope of capital cost curve	CAPSLP
3) Constant of capital cost curve	CAPCON
4) Fixed annual operating costs	FIXCST
5) Minimum capacity	MINCAP
6) Pointer to converter next higher in capacity	BIGPTR
7) Unused	

Four lines down from the above list is a list which contains the rates for fuel, electricity, thermal energy (unused; vestigal), and selling rate for electricity. Each line contains an identifying name for the type of energy and a rate in dollars. The order should not be altered. There are four prices for oil: 1) Wholesale - No. 6, 2) Wholesale - No. 2, 3) Retail - No. 6, and 4) Reatil - No. 2. For gas there are two prices, the first for wholesale and the second for retail.

The costs for thermal energy come from the next set of lines, the number of which is given in the first line of this set. The first datum in each line gives the identifying number of a converter which is not owned by the district heating system and for which there is a cost associated with thermal energy input. A descriptive name is the second datum in each line and the third is the cost of thermal energy.

The second line after the above list contains the number of converters which is a redundant vestige and is not used. Beginning at the eighth line from the thermal rate list is a set of tables which give the CQ and CT arrays for each converter. The first line in each table gives the number of the pertinent converter. The first two numbers in each line are for CQ and the second two for CT, all in free format fields. Each line is for a different energy type in the following order: oil, gas, coal, electricity, thermal. The following shows the format for a typical format.

```
CONVERTER=N
-----------------
CQ(N,1,1) CQ(N,1,2) CT(N,1,1) CT(N,1,2)
CQ(N,2,1) CQ(N,2,2) CT(N,2,1) CT(N,2,2)
CQ(N,3,1) CQ(N,3,2) CT(N,3,1) CT(N,3,2)
CQ(N,4,1) CQ(N,4,2) CT(N,4,1) CT(N,4,2)
CQ(N,5,1) CQ(N,5,2) CT(N,5,1) CT(N,5,2)
-----------------
```

where in CQ(N,I,J) N=number of the converter
I=number of the energy type
J=order of the straight line fit coefficient

At the end of the file the capital recovery factor, earth temperature, and earth conductivity are given. These data are free formatted and their locations are obvious from the example file supplied.

Origin and Validity of Converter Data

The program has 25 converter types in the default converter file. Since the program actually calculates the energy flows for the heating mode and cooling mode separately, the converters that supply both heat and "cold" are split into two converters. This section contains a brief technical description of each. Below is a list of the converters, which is followed by a detailed description of each converter.

The Default Converters

1 NOTHING
2 SMALL ELECTRIC HEAT PUMP - HEATING MODE
3 LARGE ELECTRIC HEAT PUMP - HEATING MODE
4 SMALL ELECTRIC HEAT PUMP - COOLING MODE
5 LARGE ELECTRIC HEAT PUMP - COOLING MODE
6 RESIDENTIAL CAST IRON OIL BOILER
7 COMMMERCIAL CAST IRON OIL BOILER
8 SCOTCH-MARINE OIL BOILER
9 DIESEL COGENERATOR
10 URBAN OIL COGENERATOR
11 COAL BOILER
12 SMALL SINGLE EFFECT ABSORPTION CHILLER
13 LARGE SINGLE EFFECT ABSORPTION CHILLER
14 SMALL DOUBLE EFFECT ABSORPTION CHILLER
15 LARGE DOUBLE EFFECT ABSORPTION CHILLER
16 COAL-FIRED COGENERATOR
17 LOW BACKPRESSURE COGENERATOR
18 LOW TEMPERATURE SOURCE
19 ICE PILE
20 FUEL-DRIVEN HEAT PUMP - HEATING MODE
21 FUEL-DRIVEN HEAT PUMP - COOLING MODE
22 WATER-WATER HEAT EXCHANGER
23 GAS-FIRED HOT WATER BOILER
24 SMALL ELECTRIC AIR CONDITIONER
25 LARGE ELECTRIC AIR CONDITIONER
26 MUNICIPAL WASTE COGENERATOR

Converter Detailed Descriptions

In this section the information given in the converter data file is presented a little less prosaically along with a brief explanation of the origins and validity of the data. The ratio of output to input for the various energy types are given as a function of temperature in the tables included in the discussions of each component. The capital cost, which is represented as a linear function of the converter capacity, is given in the following format:

Capital Cost = Greater of : [\$M X Capacity + \$B or \$X]

where \$M and \$B are the slope and intercept of the linear capital cost function of capacity and \$X is the cost given by the minimum capacity for that type of converter. The sources used in deriving the capital cost functions are cited below and in each case, at least a spot check from a second source is indicated.

Converter Descriptions

1 NOTHING

This subsystem is put in converter positions when no conversion takes place. The ratio of input thermal energy to output thermal energy is a constant 1.0 and zero for all other types energy.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.00	1.00	1.00	1.00

Capital Cost = $0.00

2 SMALL ELECTRIC HEAT PUMP - HEATING MODE

This subsystem inputs both heat and electricity. The output is the sum of the two; i.e., no losses. The output temperature, that of the condenser coolant, was taken to be a constant 130 F. Performance was estimated from data from tests of water-source heat pump at Brookhaven National Lab.

Ratio of Thermal Output to Electricity Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	3.13	3.72	4.59	5.99

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.47	1.37	1.28	1.20

Capital Cost = Greater of : [$90.00 X Capacity + $270.00 or $1170.00]

3 LARGE ELECTRIC HEAT PUMP - HEATING MODE

Same performance as above. The capital cost of this heat pump is based on multiple cyclinder reciprocating compressor chillers.

Ratio of Thermal Output to Electricity Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	3.13	3.72	4.59	5.99

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.47	1.37	1.28	1.20

Capital Cost = Greater of : [$42.50 X Capacity + $53,000.00 or $104,000.00]

4 SMALL ELECTRIC HEAT PUMP - COOLING MODE

The cost and performance of the heat pump in the cooling mode is the same as that in the heating mode except that the COP is given as a function of the condenser coolant temperature. The output temperature of chilled water was taken to be 40 F.

Ratio of Thermal Output to Electricity Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-7.00	-4.38	-3.18	-2.50

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.88	0.81	0.76	0.71

Capital Cost = Greater of : [$127.00 X Capacity + $270.00 or $1160.00]

5 LARGE ELECTRIC HEAT PUMP - COOLING MODE

Essentially the same machine as the heating mode but with COP a function of condenser coolant temperature. The chilled water supply temperature was taken to be 40 F.

Ratio of Thermal Output to Electricity Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-7.00	-4.38	-3.18	-2.50

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.88	0.81	0.76	0.71

Capital Cost = Greater of : [$59.60 X Capacity + $53,000.00 or $104,000.00]

6 RESIDENTIAL CAST IRON OIL BOILER

This small-capacity boiler has a constant efficiency of 75%. The installed cost was obtained from an expert on fossil fired heaters.

Ratio of Thermal Output to Oil Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.75	0.75	0.75	0.75

Capital Cost = Greater of : [$25.35 X Capacity + $1,050.00 or $1,643.00]

The capital cost curve for the residential cast iron boiler was verified using cost data pertaining to boilers with retention-head burners and an insulated jacket taken from Means Mechanical Cost Data. Data from a Means were within 20% of our cost curve.

7 COMMMERCIAL CAST IRON OIL BOILER

The larger oil boilers are assumed to have a constant efficiency of 80%. The installed costs for this type of converter were derived from the Means Mechanical Cost Data handbook.

Ratio of Thermal Output to Oil Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.80	0.80	0.80	0.80

Capital Cost = Greater of : [$18.25 X Capacity + $3,300.00 or $6,585.00]

8 SCOTCH-MARINE OIL BOILER

This is the largest oil boiler. The capital cost function was derived from Means Mechanical Cost Data for boilers in the capacity range of 900 to 10,000 KW. The efficiency is assumed constant and equal to 80%.

Ratio of Thermal Output to Oil Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.80	0.80	0.80	0.80

Capital Cost = Greater of : [$13.34 X Capacity + $23,000.00 or $35,000.00]

9 DIESEL COGENERATOR

Diesel Cogenerator performance was based on specifications for Caterpillar diesel generators. The electrical generation efficiency is assumed constant at 32%, the thermal recovery from the jacket and stack gas at 74%. Eighteen precent of the fuel consumed by the generator is dissipated. Price and performance were derived from information supplied by two manufacturers of generator sets: Fairbanks-Morris and Caterpillar.

Ratio of Thermal Output to Oil Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.50	0.50	0.50	0.50

Ratio of Thermal Output to Electricity Output vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.54	1.54	1.54	1.54

Capital Cost = Greater of : [$272.00 X Capacity + $0.00 or $27,200.00]

10 URBAN OIL COGENERATOR

The capital costs are for the conversion of an existing oil-fired generating station. The cogenerator itself is not considered to be part of the district heating system and thermal energy is bought from the utility. The capital-cost function is based on data from several Public Service Electric and Gas reports. Retrofit costs for two 1978 installations were used as a basis for the estimates of cost per unit generating capacity. Although a wide variation in the ratio of thermal output to lost generating capacity (coefficient of performance; COP) results from varying the load, we used a constant cost for the thermal energy which was based on lost generating capacity and a likely load/supply scenario.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.00	1.00	1.00	1.00

Capital Cost = Greater of : [$68.30 X Capacity + $0.00 or $1,700,000.00]

The urban oil cogenerator retrofit cost was spot checked using costs for two cognererating power plants. The cost model predicted costs which were approximately 40% above for one and approximately 5% below for the other.

11 COAL BOILER

The coal boiler efficiency is taken to be a constant 85%. The first capital cost function given below is for a boiler suitable for steam generation at pressures needed for electrical power generation. The costs include solid fuel handling equipment and pollution control. The second cost estimate is for a lower quality boiler and is based on the data in the Means Mechanical Equipment Costs Handbook with additional costs of 40% for coal handling equipment and 80% for pollution control equipment.

Ratio of Thermal Output to Coal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.85	0.85	0.85	0.85

Capital Cost = Greater of : [$340.00 X Capacity + $0.00 or $5,000,000.00]

Revised Lower Cost Estimate:

Capital Cost = Greater of : [$140.00 X Capacity + $0.00 or $2,050,000.00]

12 SMALL SINGLE EFFECT ABSORPTION CHILLER

The performance of the small single-effect chiller is based on input temperature of 230 F, with a chilled water supply temperature of 45 F. The capital cost function was derived from data for an installed solar absorption chiller and a cooling tower in the Means Mechanical Costs handbook.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Output/Input:	-0.73	-0.73	-0.73	-0.73

Capital Cost = Greater of : [$279.50 X Capacity - $654.00 or $2,136.00]

13 LARGE SINGLE EFFECT ABSORPTION CHILLER

The performance (COP and capacity) estimates are based on input temperatures between 200 and 250 F with 90 F condensing temperature and 45 F chilled water. The costs from which the capital-cost curve was derived were obtained from data in reference ++_[Jim Saunders and Dick Leigh for GRI].

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-0.73	-0.73	-0.73	-0.73

Capital Cost = Greater of : [$110.00 X Capacity + $58,000.00 or $96,170.00]

The capital cost function for the large single-effect chiller was checked using data from Means Mechanical Cost Data. The slope of the cost curve derived from the Means data was within 6% of our cost function.

14 SMALL DOUBLE EFFECT ABSORPTION CHILLER

The small double-effect chiller is identical to the small single-effect chiller.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-0.73	-0.73	-0.73	-0.73

Capital Cost = Greater of : [$279.50 X Capacity - $654.00 or $2,136.00]

15 LARGE DOUBLE EFFECT ABSORPTION CHILLER

The COP and capacity esimates for the large double effect chillers are based on input temperatures of approximately 340 F (steam at 100 psi). The capital cost function was derived from data in reference ++.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-1.04	-1.04	-1.04	-1.04

The capital cost function for the large double-effect chiller was verified using data from Means Mechanical Cost Data. The slope of the cost curve derived from the Means data was within 9% of our cost function.

Capital Cost = Greater of : [$156.00 X Capacity + $91,300.00 or $208,000.00]

16 COAL-FIRED COGENERATOR

The electrical generating efficiency of the coal-fired cogenerator was taken to be constant at 16% with a thermal generation efficiency of 69%, with a total of 15% losses. The cost function was derived from published costs for four individual projects in the 22 to 64 MW power range.

Ratio of Thermal Output to Coal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.69	0.69	0.69	0.69

Ratio of Thermal Output to Electricity Output vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	4.35	4.35	4.35	4.35

Capital Cost = Greater of : [$156.00 X Capacity + $91,300.00 or $208,000.00]

17 LOW BACKPRESSURE COGENERATOR

The low backpressure cogenerator is a minor retrofit to an existing generating station. The cogenerator is not considered to be part of the DH/C system and thermal energy is, therefore, purchased by the DH/C system. The performance and costs were derived by the inventor of the low backpressure cogeneration concept.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.00	1.00	1.00	1.00

Capital Cost = Greater of : [$17.00 X Capacity + $0.00 or $850,000.00]

18 LOW TEMPERATURE SOURCE

The low temperature source represents any source of water at any desired temperature as long as it is free. The capital and energy costs for this type of converter are zero.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.00	1.00	1.00	1.00

Capital Cost = $0.00

19 ICE PILE

The ice-pile performance and cost were based on a study for Atlantic City by R. W. Timmerman. The water consumption is 6.67 tons of water per ton of ice produced. Water pumping pressure, nozzle pressure included, taken to be 255 psi with the total ice-making operating time of 420 hours per year. The minimum size was taken to be 730 KW.

Ratio of Thermal Output to Electricity Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-65	-65	-65	-65

Capital Cost = Greater of : [$284.00 X Capacity + $0.00 or $2,840,000.00]

20 FUEL-DRIVEN HEAT PUMP - HEATING MODE

The performance of a fuel driven heat pump was derived from the following approximations:

- diesel motor mechanical efficiency of 0.3

- 86% efficiency of recovery of waste heat from the engine cooling jacket water and stack gas
- a mechanical COP of 3.5 at 30 F and 7.0 at 120 F.

The cost model was derived from data obtained from reference 3.

Ratio of Thermal Output to Gas Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.64	1.88	2.19	2.64

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	2.34	2.00	1.75	1.55

Capital Cost = Greater of : [$180.00 X Capacity + $8760.00 or $26,800.00]

The cost of a fuel driven heat pump should not be as great as but not very much less than the sum of the costs for a diesel generator and electric chiller. Since electric motors and generators are fairly inexpensive compared to diesel engines and heat pumps of the same size, the contribution of these components to the total cost can be taken to be minor. The cost function for the fuel-driven heat pump was verified by this approximate method in that the combined costs for the generator set and heat pump satisfied the above-stated condition.

21 FUEL-DRIVEN HEAT PUMP - COOLING MODE

The cooling mode performance was derived using the same assumptions as for the heating mode.

Ratio of Thermal Output to Gas Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-1.40	-1.40	-1.40	-1.40

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.61	0.61	0.61	0.61

Capital Cost = Greater of : [$232.00 X Capacity + $8760.00 or $26,800.00]

22 WATER-WATER HEAT EXCHANGER

The slope of the capital cost curve was obtained by averaging quoted costs for heat exchangers in the capacity range of 300 to 7000 KW at 10 F log mean temperature difference. The quotes were originally obtained in 1980 and were multiplied by 1.34 to account for price escalation between 1980 and 1985.

Ratio of Thermal Output to Thermal Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	1.00	1.00	1.00	1.00

Capital Cost = Greater of : [$10.24 X Capacity]

23 GAS-FIRED HOT WATER BOILER

The performance and cost function for the gas-fired water heater were obtained from an expert in the field of fossil fueled heaters. The cost model was estimated from data obtained from numerous published costs and quotes.

Ratio of Thermal Output to Gas Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	0.85	0.85	0.85	0.85

Capital Cost = Greater of : [$25.00 X Capacity + $1915.00 or $2,500.00]

24 SMALL ELECTRIC AIR CONDITIONER

The performance and cost function for the small air conditioner were calculated using data in Means Mechanical Costs handbook.

Ratio of Thermal Output to Electricity Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-2.50	-2.50	-2.50	-2.50

Capital Cost = Greater of : [$216.00 X Capacity + $459.00 or $1,971.00]

25 LARGE ELECTRIC AIR CONDITIONER

See above

Ratio of Thermal Output to Electricity Input vs. Input Temperature

Input Temp:	30	60	90	120
Output/Input:	-3.03	-3.03	-3.03	-3.03

Capital Cost = Greater of : [$101.30 X Capacity + $90,100.00 or $177,000.00]

26 MUNICIPAL WASTE-FIRED COGENERATOR

The performance of the municipal waste-fired cogenerator is the same as that of the coal-fired cogenerator except that the boiler efficiency was assumed to be 70%.

Ratio of Fuel Input to Thermal Output vs Temperature

Input Temp:	30	60	90	120
Output/Input:	1.85	1.85	1.85	1.85

Ratio of Electrical Output to Thermal Output vs Temperature

Input Temp.	30	60	90	120
Output/Input:	.333	.333	.333	.333

Pipe Data

The pipe data are given in a simply formatted file that is nearly self-explanatory. The first line gives the number of different types of pipe. There must be four pipe types for every construction or material type, one for each class. If there is not a multiple of four pipe types an error will occur. Beginning at the third line a list containing descriptive names for the pipe types is given. The first four columns in each line of the list contain the number of sizes for each pipe type and the number of pipes per trench respectively. The last column is unused.

Following the first list are five tables giving various properties of the pipe for each pipe size. Each line in each table pertains to a pipe type. Each successive column gives data pertaining to successively greater pipe sizes. The tables are read with free format read statements so exact column placement is immaterial. The tables are labeled in the default file supplied with the program. The definitions are:

Inner Diameter - pipe inner diameter in feet
Outer Diameter - pipe outer diameter including insulation and jacket
Pipe Cost - cost of pipe on a unit trench length basis. Note that some pipe types include two pipes per trench.
Pipe Conductivity - the effective thermal conductivity of the pipe wall and insulation material combination
Pipe Burial Depth - centerline depth of installed pipe in feet.

Origins and Validity of Pipe Data

The costs per unit length of trench for installed pipe were generated from fairly detailed unit costs for site work and material. We considered three types of piping materials: uninsulated polyethylene, fiberglass-reinforced polyester, and insulated schedule 40 steel pipe (RICWIL). The costs corresponded to two pipes per trench for each type of pipe and, for the RICWIL steel pipe, for one pipe per trench as well. For each type of pipe we considered different construction situations. The precise definitions of these "classes" are given below, but they can be identified with the different levels of "urbanization" corresponding to: 1) downtown Minneapolis, 2) downtown Des Moines, 3) suburbia, and 4) rural.

The assumptions associated with the "urbanization" class and the type of pipe are correlated in the following table. Afterwards a somewhat detailed breakdown of the costs for each type of pipe and glass are given.

Table I-1. Pipe Cost Assumptions - Differences Between Classes

	Class			
Work Item	0 (Downtown Mineapolis)	1 (Downtown Des Moines)	2 (Suburbia)	3 (Rural)
Surface	8" concrete + 2" asphalt	6" concrete + 2" asphalt	4" asphalt + 2" asphalt	no pavement
Excavation	60 % machine 40 % hand	80 % machine 20 % hand	90 % machine 10 % hand	100 % machine
Excavation Equipment	backhoe	backhoe	backhoe	backhoe or chain trencher
Hauling of soil	4 mi. R/T incl. reload	4 mi. R/T incl. reload	N/A	N/A
P.E. PIPE (2/TRENCH)				

(continued)

Table I-1. cont.

	Class			
trench depth X width (ft)	0	1	2	3
dia. = 3 "	3.25 X 2.3	3.25 X 2.3	3.25 X 1.5	3.00 X 1.5
4	3.50 X 2.3	3.50 X 2.3	3.50 X 1.5	3.00 X 1.5
6	3.50 X 3.0	3.50 X 3.0	3.50 X 2.3	3.00 X 1.5
8	3.75 X 3.0	3.75 X 3.0	3.75 X 2.6	3.00 X 1.5
10	4.00 X 3.8	4.00 X 3.8	4.00 X 3.0	4.00 X 2.3
12	4.00 X 4.5	4.00 X 4.5	4.00 X 3.0	4.00 X 3.0
14	4.25 X 4.5	4.25 X 4.5	4.25 X 3.4	4.25 X 3.4
16	4.50 X 5.3	4.50 X 5.3	4.50 X 3.8	4.50 X 3.8
18	4.50 X 5.3	4.50 X 5.3	4.50 X 4.5	4.50 X 4.5
------------				
trench depth X width (ft)				
dia. = 4 "	3.75 X 3.0	3.75 X 3.0	3.75 X 3.0	3.75 X 3.0
6	4.00 X 3.4	4.00 X 3.4	4.00 X 3.4	4.00 X 3.4
8	4.00 X 3.8	4.00 X 3.8	4.00 X 3.8	4.00 X 3.8
10	4.25 X 4.5	4.25 X 4.5	4.25 X 4.5	4.25 X 4.5
STEEL PIPE (1/TRENCH)				
------------				
trench depth X width (ft)				
dia. = 6 "	4.50 X 4.0	4.50 X 4.0	4.50 X 4.0	4.50 X 4.0
8	4.75 X 4.3	4.75 X 4.3	4.75 X 4.3	4.75 X 4.3
10	5.00 X 4.5	4.00 X 4.5	5.00 X 4.5	5.00 X 4.5
12	5.50 X 5.0	5.50 X 4.0	5.50 X 4.0	5.50 X 4.0
STEEL PIPE (2/TRENCH)				
------------				
trench depth X width (ft)				
dia. = 6 "	4.50 X 6.0	4.50 X 6.0	4.50 X 6.0	4.50 X 6.0
8	4.75 X 6.4	4.75 X 6.4	4.75 X 6.4	4.75 X 6.4
10	5.00 X 6.8	4.00 X 6.8	5.00 X 6.8	5.00 X 6.8
12	5.50 X 7.5	5.50 X 7.5	5.50 X 7.5	5.50 X 7.5
labor productivity factor	0.5	0.75	0.85	0.95
Shoring	yes	yes	yes	no

Pipe Costs - Factors Pertaining to Pipe Material

Uninsulated Polyethylene

The following is a high level breakdown of projected installed costs for polyethylene pipe. Unit costs for site construction, some materials, and joining were obtained from the appropriate Means handbooks. For pipe sizes outside the range of 3 to 18 inches, a straight line-of-best-fit was used to extrapolate the unit costs.

Assumptions:

1. Pipe and fittings are directly buried
2. Joining by heat bonding
3. no manholes
4. chain driven trenching tool for class 3

Cost Breakdown for Polyethylene Pipe - 2 Pipes per Trench

	Nominal	Cost ($/ft. trench)			
Work Item	I.D.(in.)	Class 0	Class 1	Class 2	Class 3
Surface Demolition and Reinstatement	3	21.71	12.49	3.29	0.
	4	21.71	12.49	3.29	0.
	6	28.94	16.65	4.92	0.
	8	28.94	16.65	5.75	0.
	10	36.18	20.82	6.57	0.
	12	43.41	24.98	6.57	0.
	14	43.41	24.98	7.38	0.
	16	50.66	29.15	8.21	0.
	18	50.66	29.15	9.84	0.
Excavation, Backfill, Soil Transport, Shoring	3	41.11	24.41	2.51	.90
	4	44.28	26.28	2.70	.90
	6	51.06	29.72	4.04	.90
	8	56.88	31.83	5.06	.90
	10	66.09	37.91	5.17	2.01
	12	73.85	41.84	6.17	2.68
	14	78.47	44.43	7.37	3.21
	16	91.79	51.48	8.66	3.78
	18	91.79	51.48	10.40	4.53
Pipe	3	3.70	3.70	3.70	3.70
	4	6.00	6.00	6.00	6.00
	6	8.30	8.30	8.30	8.30
	8	14.00	14.00	14.00	14.00
	10	21.80	21.80	21.80	21.80
	12	31.00	31.00	31.00	31.00
	14	37.00	37.00	37.00	37.00
	16	48.30	48.30	48.30	48.30
	18	64.00	64.00	64.00	64.00

Pipe Joining	3	2.80	1.88	1.66	1.48
	4	3.06	2.04	1.80	1.62
	6	3.44	2.30	2.02	1.82
	8	7.70	5.14	4.52	4.06
	10	8.96	5.98	5.26	4.72
	12	10.42	6.94	6.12	5.48
	14	12.50	8.34	7.36	6.58
	16	12.50	8.34	7.36	6.58
	18	13.54	9.02	7.96	7.12
Unladen and Set and Trench	3	.54	.36	.32	.
	4	.54	.36	.32	.
	6	.80	.54	.48	.
	8	.98	.66	.58	.
	10	1.82	1.12	1.08	.
	12	2.10	1.40	1.40	.
	14	2.52	1.68	1.68	.
	16	3.08	2.06	2.06	.
	18	3.22	2.16	2.16	.

Fiberglass Reinforced Polyester

The following is a high level breakdown of projected installed costs for fibergalss reinforced polyester pipe. Unit costs for site construction, some materials, and joining were obtained from the appropriate Means handbooks. For pipe sizes outside the range of 4 to 10 inches, a linear straight line of best fit was used to extrapolate the unit costs.

Assumptions:

1. Pipe and fittings are directly buried
2. no manholes

Cost Breakdown for Fiberglas Reinforced Polyester - 2 Pipes Per Trench

Work Item	Nominal I.D.(in.)	Cost ($/ft. trench)			
		Class 0	Class 1	Class 2	Class 3
Surface Removal and Reinstatement	4	28.94	18.23	4.95	0
	6	32.57	20.51	5.57	0
	8	36.18	22.78	6.19	0
	10	43.41	27.33	7.43	0
Excavation, Backfill, Soil Transport, Shoring, Compaction	4	54.71	31.83	20.85	2.52
	6	62.22	35.94	23.01	3.02
	8	56.09	37.89	23.78	3.30
	10	78.35	44.43	26.91	4.28
Manholes and Anchors	4	0	0	0	0
	6	0	0	0	0
	8	0	0	0	0
	10	0	0	0	0
Pipe	4	34.90	34.90	34.90	17.45
	6	50.66	50.66	50.60	25.33
	8	74.00	74.00	74.00	74.00
	10	105.26	105.26	105.26	105.26
Joining	4	2.14	1.44	1.26	1.12
	6	3.22	2.14	1.90	1.70
	8	4.30	4.30	2.52	2.26
	10	5.36	5.36	3.16	1.82
Fittings		0	0	0	0
Unladen and set in trench	4	10.08	6.72	5.92	5.30
	6	12.86	8.58	7.56	6.78
	8	15.72	12.86	9.24	8.26
	10	20.14	15.72	11.86	10.60

Insulated Schedule 40 Steel

The following is a high level breakdown of projected installed costs for insulated schedule 40 steel pipe. Unit costs for site construction, some materials, and joining were obtained from the appropriate Means handbooks. For pipe sizes outside the range of 6 to 12 inches, a straight line-of-best-fit was used to extrapolate the unit costs.
Insulated Schedule 40 Steel - 2 pipes per trench

Insulated Schedule 40 Steel - 2 pipes per trench

Assumptions:

1. Manholes are used.
2. Fittings are encased in manholes.

Cost Breakdown for Schedule 40 Steel Pipe - 2 Pipes per Trench

Work Item	Nominal I.D.(in.)	Cost ($/ft. trench) Class 0	Class 1	Class 2	Class 3
Surface Removal and Reinstatement	6	57.90	36.45	9.90	0
	8	61.44	38.73	10.52	0
	10	65.13	41.01	11.14	0
	12	72.36	45.56	12.38	0
Excavation, Backfill, Soil Transport, Shoring	6	100.52	55.91	31.98	9.06
	8	110.70	61.32	34.65	11.16
	10	121.35	88.65	37.46	13.43
	12	144.17	79.13	43.31	16.62
Manholes and Anchors	6	65.69	47.13	39.54	59.87
	8	72.28	52.86	45.07	67.90
	10	79.07	58.79	50.79	76.20
	12	88.44	66.45	58.04	86.67
Pipe	6	127.92	127.92	127.92	127.92
	8	177.78	177.78	177.78	177.78
	10	210.70	210.70	210.70	210.70
	12	250.00	250.00	250.00	250.00
Joining	6	57.96	38.64	34.10	30.50
	8	83.08	55.38	48.86	43.70
	10	107.22	71.48	63.08	58.49
	12	131.38	87.58	77.28	69.10
Fittings	6	41.56	27.72	24.46	21.88
	8	53.52	35.68	31.48	28.16
Unladen and set in trench	10	65.46	43.64	38.52	34.46
	12	77.42	51.62	45.54	40.74

Insulated Scheduled 40 Steel - 1 pipe per trench

Assumptions:

1. No return pipe, for steam.
2. Two manholes contain fittings.

Cost Breakdown for Schedule 40 Steel Pipe - 1 Pipe per Trench

	Nominal	Cost ($/ft. trench)			
Work Item	I.D.(in.)	Class 0	Class 1	Class 2	Class 3
Surface Removal and Reinstatement	6	38.60	24.30	6.60	0
	8	40.96	25.82	7.01	0
	10	43.42	27.34	7.43	0
	12	48.24	30.37	8.25	0
Excavation, Backfill, Soil Transport, Shoring	6	67.01	37.27	21.32	6.04
	8	73.80	40.88	23.10	7.44
	10	80.90	59.12	24.97	8.95
	12	96.11	52.75	28.87	11.08
Manholes and Anchors	6	65.69	47.13	39.54	39.91
	8	72.28	52.86	45.07	45.28
	10	79.07	58.79	50.79	50.85
	12	88.44	66.45	58.04	57.78
Pipe	6	63.96	63.96	63.96	63.96
	8	88.89	88.89	88.89	88.89
	10	105.35	105.35	105.35	105.35
	12	125.00	125.00	125.00	125.00
Joining	6	28.98	19.32	17.05	15.25
	8	41.54	27.69	24.43	21.86
	10	53.61	35.74	31.54	28.22
	12	65.69	43.79	38.64	34.57
Fittings Unladen and set in trench	6	20.78	13.86	12.23	10.94
	8	26.76	17.84	15.74	14.08
	10	32.73	21.82	19.26	17.23
	12	38.71	25.81	22.77	20.37

Heating and Cooling Load Cases

The load case file is a list of data file names which define the load cases which are run for each system. The first line gives the number of load cases. Each line following the first contains the names, in this order, of a transmission configuration file, a distribution configuration file, and a load-duration data file. At the end of each line a pair of digits gives the class of the transmission and distribution systems for each load case.

Load/Duration Data File

The first line in this type of file contains an identifying name for the load-duration data contained within the file. The second line gives the number of load bins. The list beginning at line three gives the load-duration data, one bin per line. The first number in each line is the load, the second, the duration.

Transmission and Distribution Configuration Files

The first line in this type of file consists of a descriptive name. The second gives the number of terminals served by the piping system. The third line gives the number of levels in the distribution or transmission system. Starting at the fourth line is a table of numbers giving, among other things, the length of each level and the number of terminals served by each level, in that order, one level per line. On each line, after the number of terminals, stretching out to the right, is a list of numbers used in steam calculations. The first number is the number of different allowed pressure drops there are within a level. The rest of the numbers are paired, one per allowed pressure drop. The first number of each pair is the allowed pressure drop in psi/100 ft. The second number is the fraction of the total length of the level to which this allowed pressure drop applies. For more information on the allowed pressure drops, the section on steam pipe sizing.

Output Device

This file has two lines. The first has a logical input, "T" or "F", to tell the program, if it is running a batch of systems, whether to store the data used by the BASIC program that "combines" heating and cooling systems. This usually set to "F". The second line names the output device or file; usually "LPT1:" for the printer.

Load Case Counter

This file contains one number which is automatically set to zero by the batch program "DH.BAT". This number tells the program how many load cases have been run. It should be set to zero if the batch file is not used to run the program.

Batch Run Counter

This file contains two numbers on one line. The first is the number of systems which have been run when running systems in the batch mode. The second is the number of systems which are to be run in the batch mode. If the first number is set to zero, the program operates in the interactive mode, i.e., non-batch.

Batch Inputs

The batch inputs file contains all the inputs which are entered through the keyboard in the interactive mode. The inputs are free formatted numbers, some of which are integers, and single letters. The format follows exactly, the inputs from the keyboard when the program is run interactively. The format is as follows (no lines ending with blanks--carriage returns only, commas or blank separators between characters are allowed--see list directed inputting discussion in any Fortran 77 manual).

The first line consists of three integers giving the identifying number for the converters in each position of the system. The second line contains the identifying numbers of the pipe materials for the transmission and distribution subsystems. The next line contains the input temperatures to the converters starting with the primary. The next line gives the transmission and distribution subsystems. The next line contains the answer to the question of whether to use wholesale or retail oil or gas prices. The line should have a capital W or R if the question is pertinent, otherwise any other character will tell the program the question is not relevant. If the above question had a W or R then the next question must be responeded to with a 1 or 6 telling the program whether to use number 6 or number 2 oil prices. If the wholesale/ retail question is not relevant this next line is skipped. The next line contains a Y or N to tell the program whether to size the piping by itself or read the sizes from an external file. The option is not implemented yet so this line should contain a Y. The next line contains an H or C indicating that this is a heating or cooling run. The last two lines identify the heat transfer fluid for the transmission and distribution subsystems as steam or water using W or S.

IC. User Guide for District Heating/Cooling Technology Characterization Program

This section describes the procedure for running the DHC Technology Characterization Program (TCP). At present, the program will run only on an IBM PC XT or compatible. It relies heavily on batch command files and other idiosyncracies for this computer. As mentioned earlier, the program can be run in a batch mode, where all of the inputs are in files, or in a direct mode, where some of the inputs are entered via the keyboard. In order to run combined heating/cooling systems, the program must be run in the batch mode. Whichever way it is run the user must acquaint himself with certain fiels which control the batch operation. In the direct mode there are only two files to be concerned about and once set up, they can usually be ignored for all subsequent uses of the models in the direct mode.

The program first looks at the contents of a file called "RUN.DAT" to determine if the program is being run in the batch mode or in the direct mode. The "RUN.DAT" file is very simple. It contains two integer numerals in a free format, meaning they can be anywhere on a single line with either a space or comma separating them, and there can't be any decimals. If the first numeral is a zero then the program runs in the direct mode. If the first numeral is a one then it runs in the batch mode. The second numeral represents the number of systems that will be run in the batch mode.

The program also looks at a file called "OUTDEV.DAT" when it is ready to do the final calculations and output. This file tells the program two things: 1) whether the run is for a combined heating/cooling set of systems, and 2) what output device or file to print the output forms to. The file has two lines. The first line contains a "1" to indicate that the run if for combined set. This is only true for batch operation. An "F" indicates the program is not for combined systems. The first line should contain an "F" if the program is being run in the direct mode. The "1" or "F" should be in the first column of the first line. The second line holds the name of a file or device to which the program output is sent. If the output is to be sent to the printer then the second line would usually have "LPT1".

Direct Mode Operation

The following is a list of steps that are followed when the program is set up and run in the direct mode. In the following section the symbol "(cr)" represents the carriage return key.

1. Make sure file "RUN.DAT" has two integer numerals, the first, a zero. Make sure the "OUTDEV.DAT" file has an "F" in the first column of line 1 and "LPT1" or a file name on line 2.

2. Make sure there is at least 120K of free disk space and that all the default files listed in Appendix IB are present on the local directory or disk.

3. Type: DH (cr)

4. A menu will appear after the better part of a minute showing the converter options. Enter three numerals, separated by blanks or commas, which represent the converters for the system you want to run. As indicated on the screen, put the primary first, the secondary, second, and the user, third, followed by (cr).

5. Another menu will appear on the screen giving the pipe type options for the transmission and distribution systems. Enter the choices for the transmission subsystem and the distribution subsystem in that order, again, separated by a blank or comma and followed by (cr).

6. The program then asks for the input temperatures for the primary, secondary, and user converters. The latter two of these are the transmission and distribution temperatures respectively. The input to the primary rarely has to be specified, only when the primary converter accepts heat from an upstream source, for example, if the primary converter were a heat pump. Enter the temperatures in the same order as in step 3 followed by (cr).

7. Next, the program asks for the transmission and distribution temperature drops. If the system uses steam then any temperature drop can be entered. Enter two numerals, separated by comma or blank, and followed by (cr).

8. The program asks whether, if the system uses gas or oil, it should use wholesale or retail prices for the fuel. Answer with a "W" for wholesale or "R" for retail or nothing if the system uses neither gas nor oil. Use capitals. If the response to this question is "W" or "R" then the next question is whether the oil type is No. 6 or No. 2. If the system uses gas, not oil, respond with either, otherwise, respond accordingly. Just hit the appropriate numeral key and then a (cr) immediately afterward; i.e., no leading or trailing blanks.

9. For the next question, hit a "Y" then a (cr). No other option is implemented.

10. Answer the next question with an "H" if the run is for a heating system or a "C" if it is for a cooling system. Follow the one-capital-letter response with a (cr) immediately after typing the letter key; i.e., no leading or trailing blanks. If you answer with a "C" the program will ask you to input a factor to be multiplied by all the loads which determines the ratio of cooling to heating load.

11. The next two questions ask for the heat transfer fluids used in the transmission and distribution subsystems. Enter an "S" for steam or a "W" for water. One capital letter only and no leading or trailing blanks.

12. Make sure there is at least 120K of free disk space and that all the default files are present on the local directory or disk.

The program will run for several minutes after the last datum is entered and the output sent to whatever output file or device was identified in step 1.

Batch Mode Operation

In the batch mode of operation, the answers to all the above questions for any number of systems are contained in a file and the program runs without any keyboard input. To use the program in the batch mode, the user must acquaint hinself with a few more files. The first, called "BATCH.DAT" is the one that contains the answers to all the input questions delineated in the section on the direct mode above. The structure of this file is in exact accord with the input format shown for direct mode operation. An example if contained in the file "COMBATCH.DAT" which contains the inputs for 18 systems.

There is a batch command file that contains a set of instructions, mostly redundant, which essentially tell the computer to run the program over and over again, the correct number of times; i.e., the number of systems being run. An example of one of these files is "DHBC18.BAT". This example batch file refers to a file called "BCHIN18.DAT" which contains the "RUN.DAT" file which corresponds with the batch command file which iteratively runs the program. The current method of running the program in batch mode is awkward and will probably be simplified in the near future. For the present, the following instructions should allow a person, who is familiar with batch command files and facile with a file editor, to run the program in batch mode.

1. Set up a file called "BATCH.DAT" with the inputs for each system you want to run. Use the direct-mode instructions as a guide and refer to "COMBATCH.DAT" as an example of a "BATCH.DAT" file.

2. Set up a batch command file to do the following:
   - Copy an appropriate contents of "RUN.DAT" to this file
   - The following instructions as many times as there are systems to be run

   ```
   COPY NUMONE.DAT ITER.DAT
   DHR
   OUTR
   COPY GRAPHFIL.DAT %OUT%
   BASIC TABLE
   ```

   The last two are optional. The first prints the histogram summary of the annualized costs and the second prints the tabular summary of the annualized costs. The latter, BASIC program, will work only with the original load default load cases. The symbol %OUT% represents the name of an output device or file, usually "LPT1" for the printer.

3. Put the appropriate data in OUTDEV.DAT (see above).

4. Make sure BASIC can be called, either by putting it in the local directory or by executing the appropriate PATH command.

5. Make sure there is at least 120K of free disk space and that all the default files are present on the local directory or disk.

6. Type in the name of the batch command file constructed in step 2 above to begin.

Other Output

In addition to the output described in Section 3.3, the program outputs a file called "GRAPHFIL.DAT" which contains a histogram plot of the annualized cost data for each load case. A BASIC program, called "TABLE.BAS" may be run, for the original default load cases, which outputs tabular summaries of the same data. The following is a description of the "GRAPHFIL.DAT" output.

In the output file, "GRAPHFIL.DAT", a breakdown of the annualized costs of the system divided by the useful thermal production for each load case are displayed in the form of a stacked histogram. The breakdown for each load case, and the way the corresponding segments of the histogram look, are as follows:

1. Annualized capital cost of primary converter

2. Annual input energy cost for primary converter

3. Total cost of the transmission subsystem (annualized capital plus energy)

4. Annualized capital cost of secondary converter

5. Annual input energy cost for secondary converter

6. Total cost of the distribution subsystem (annualized capital plus energy)

7. Annualized capital cost of user converter

8. Annual input energy cost for user converter

The parts of the histogram corresponding to each of the above costs are shown below in the same order as they appear in the list above.

```
111111*111111*TTTTTT*222222*222222*DDDDDD*333333*333333*
   C      E      T      C      E      D      C      E
   C      E      T      C      E      D      C      E
111111*111111*TTTTTT*222222*222222*DDDDDD*333333*333333*
```

For each load case the "GRAPHFIL.DAT" file shows the names appearing at the top of the transmission and distribution configuration data files and the one appearing at the top of the load duration data file. Then the histogram is plotted with a scale graduated in cents/kWh.

APPENDIX I

REFERENCES

1. Marks' Standard Handbook for Mechanical Engineers, McGraw-Hill, Inc., New York (1978).

2. Cost Reductions in Absorption Chillers - Final Report. Prepared for Gas Research Institute, Chicago, IL, by R. W. Leigh. March 1986.

3. Andrews, J. W., Catan, M. A., and LeDoux, P. Solar Energy and Heat Pumps: Evaluation of Combined Systems for Heating and Cooling Buildings. BNL 51603.

APPENDIX II

TECHNOLOGY CHARACTERIZATION COMPUTER ANALYSIS RESULTS

APPENDIX II

TECHNOLOGY CHARACTERIZATION COMPUTER ANALYSIS RESULTS

Guide:

The figure numbers in this appendix correspond to the "run identifier" numbers in Tables 3-2, 3-3, 3-6, 3-7, 3-8, 3-9, 3-10, and 3-11. Refer to these tables for detailed system descriptions.

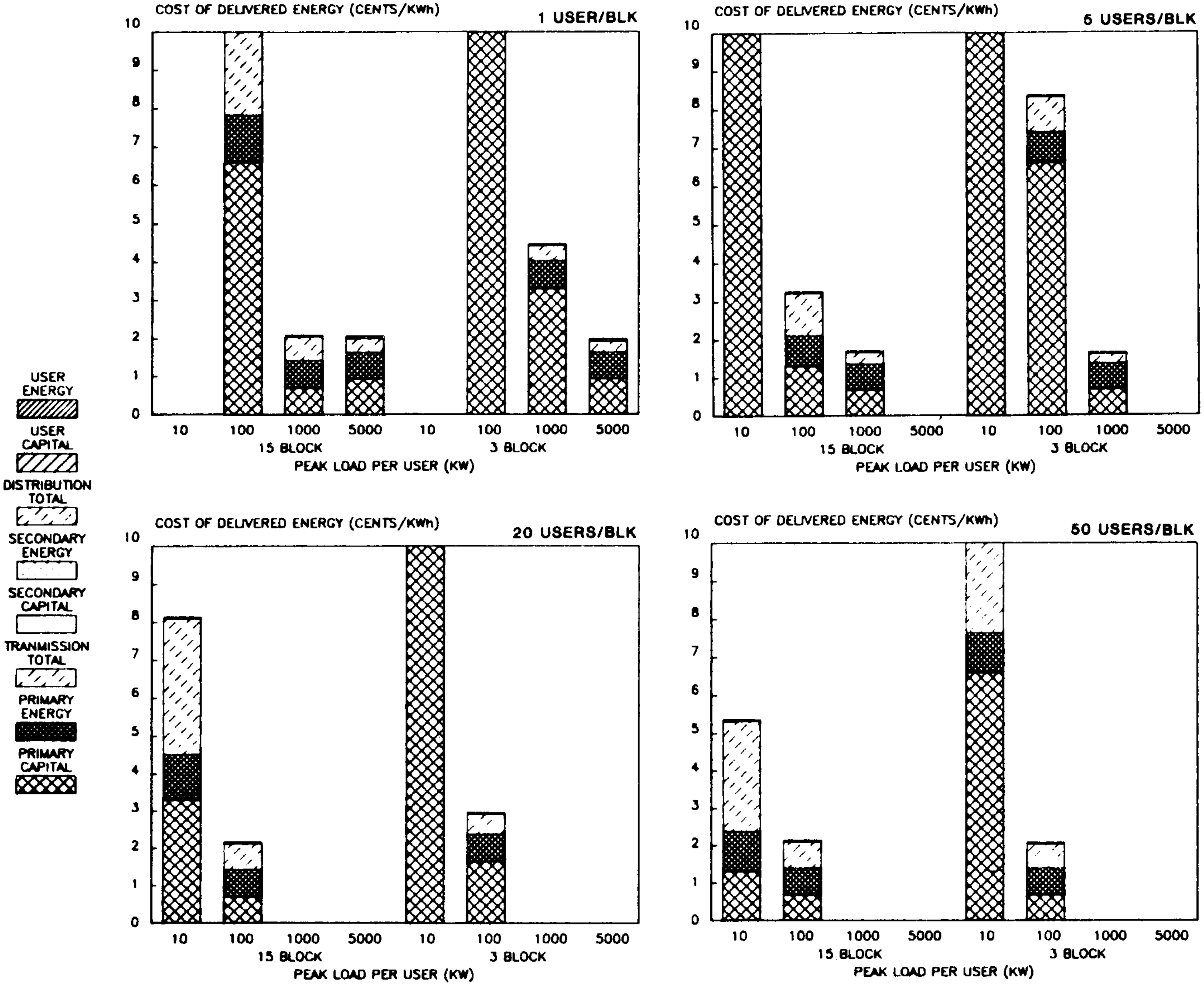

FIGURE II-1A. Urban Oil Cogenerator Retrofit - Heating - Steam Distribution

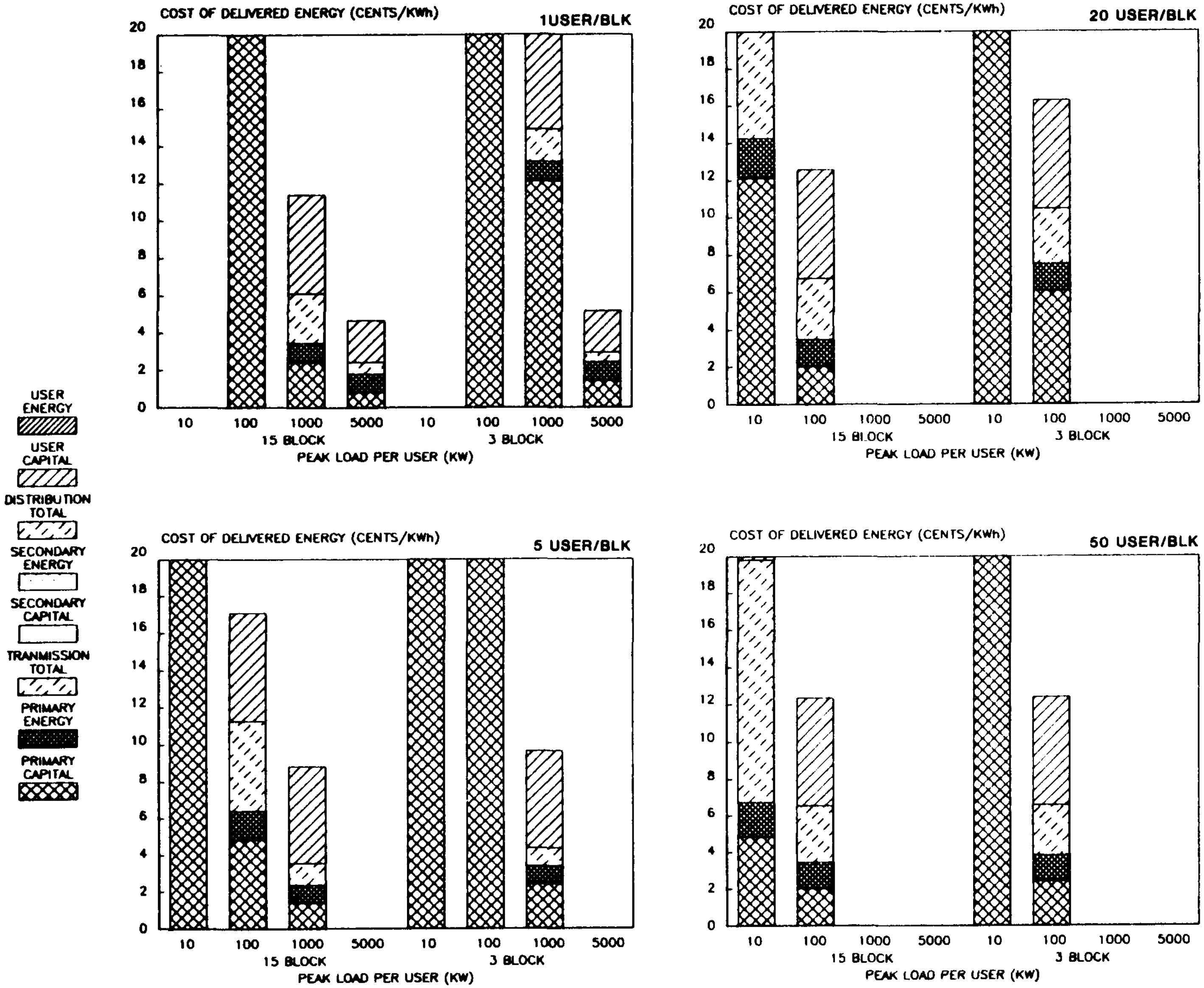

FIGURE II-1B. Urban Oil Cogenerator Retrofit - Cooling - Steam Distribution

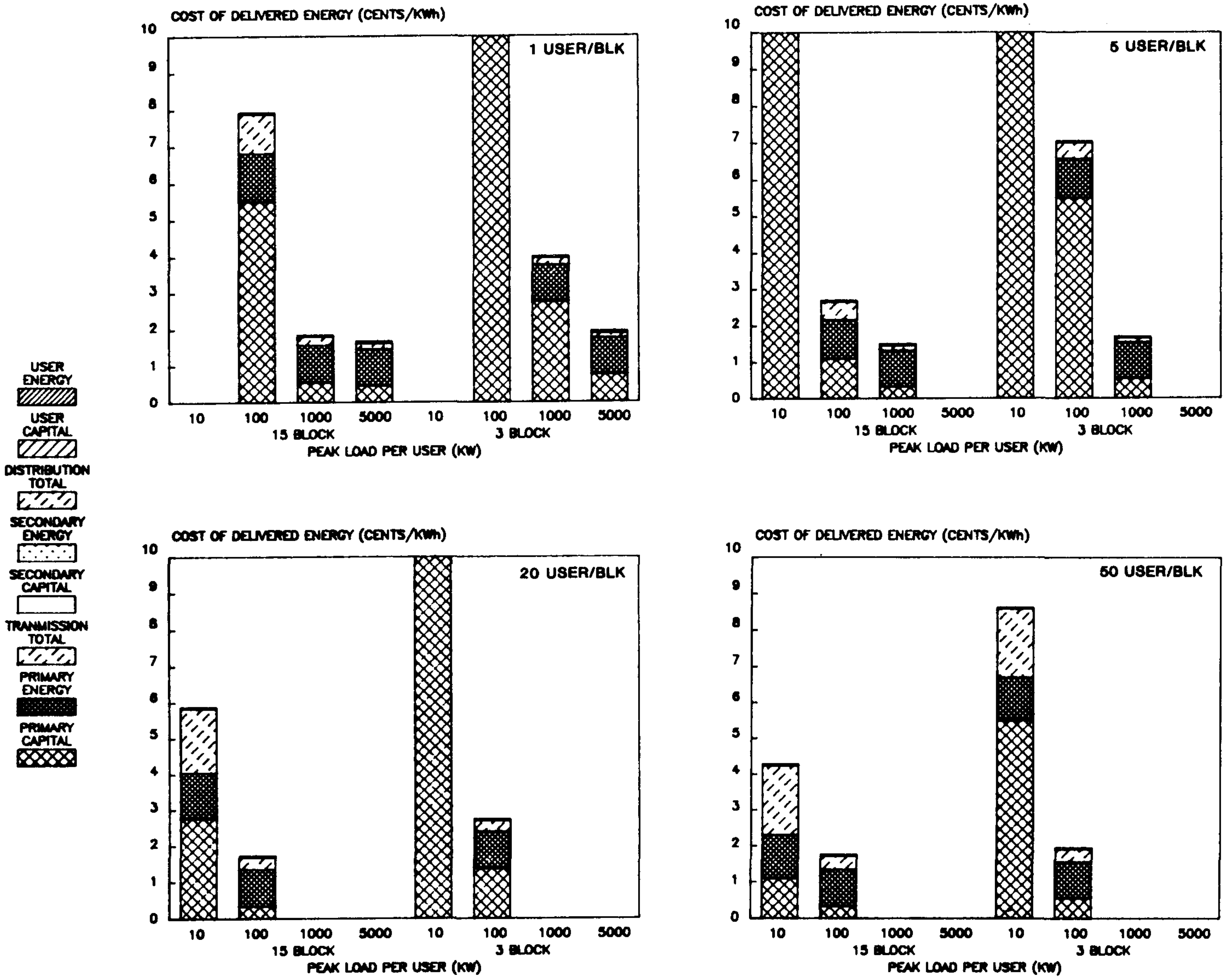

FIGURE II-1C. Urban Oil Cogenerator Retrofit - Heating - Water Distribution

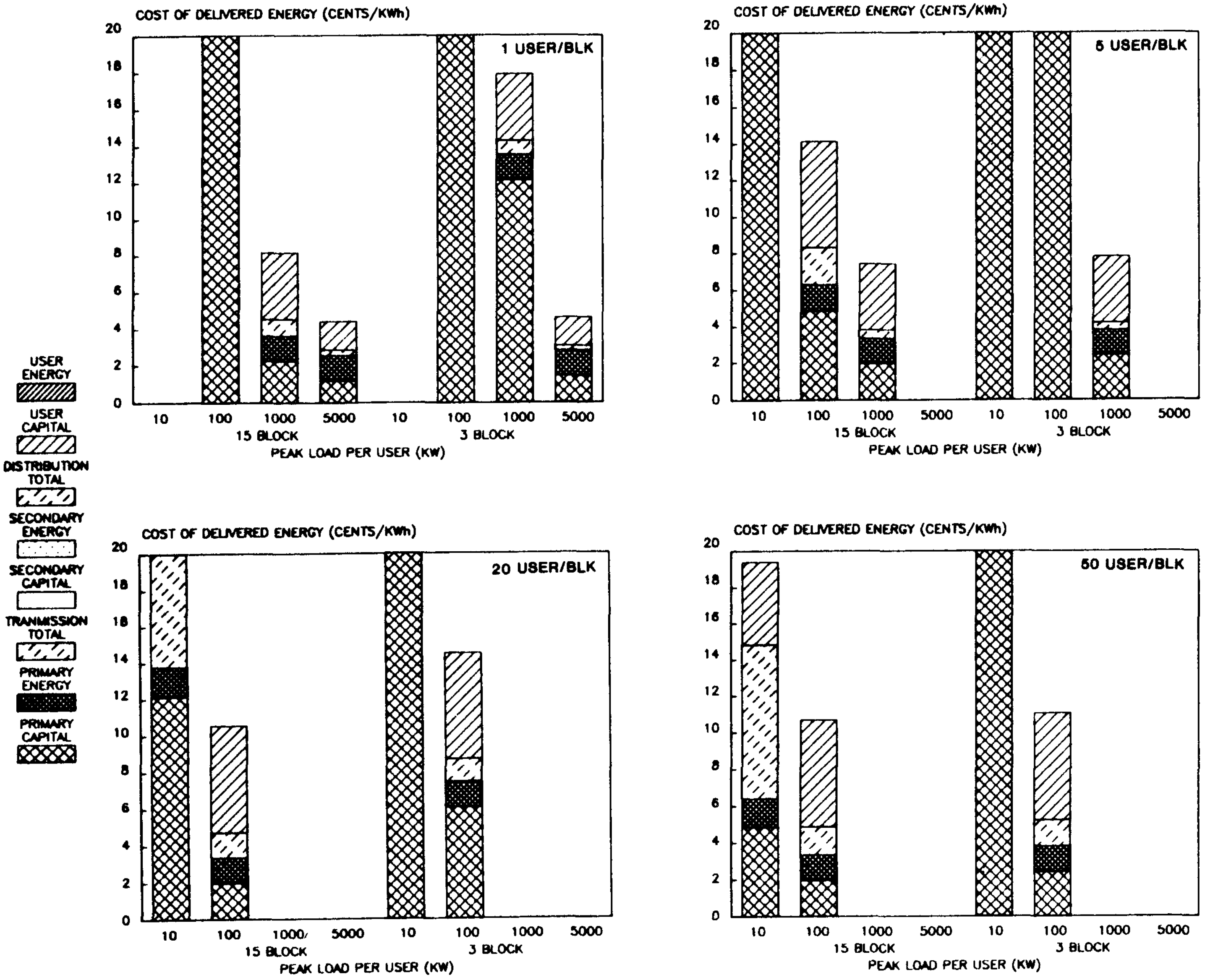

FIGURE II-1D. Urban Oil Cogenerator Retrofit - Cooling - Water Distribution

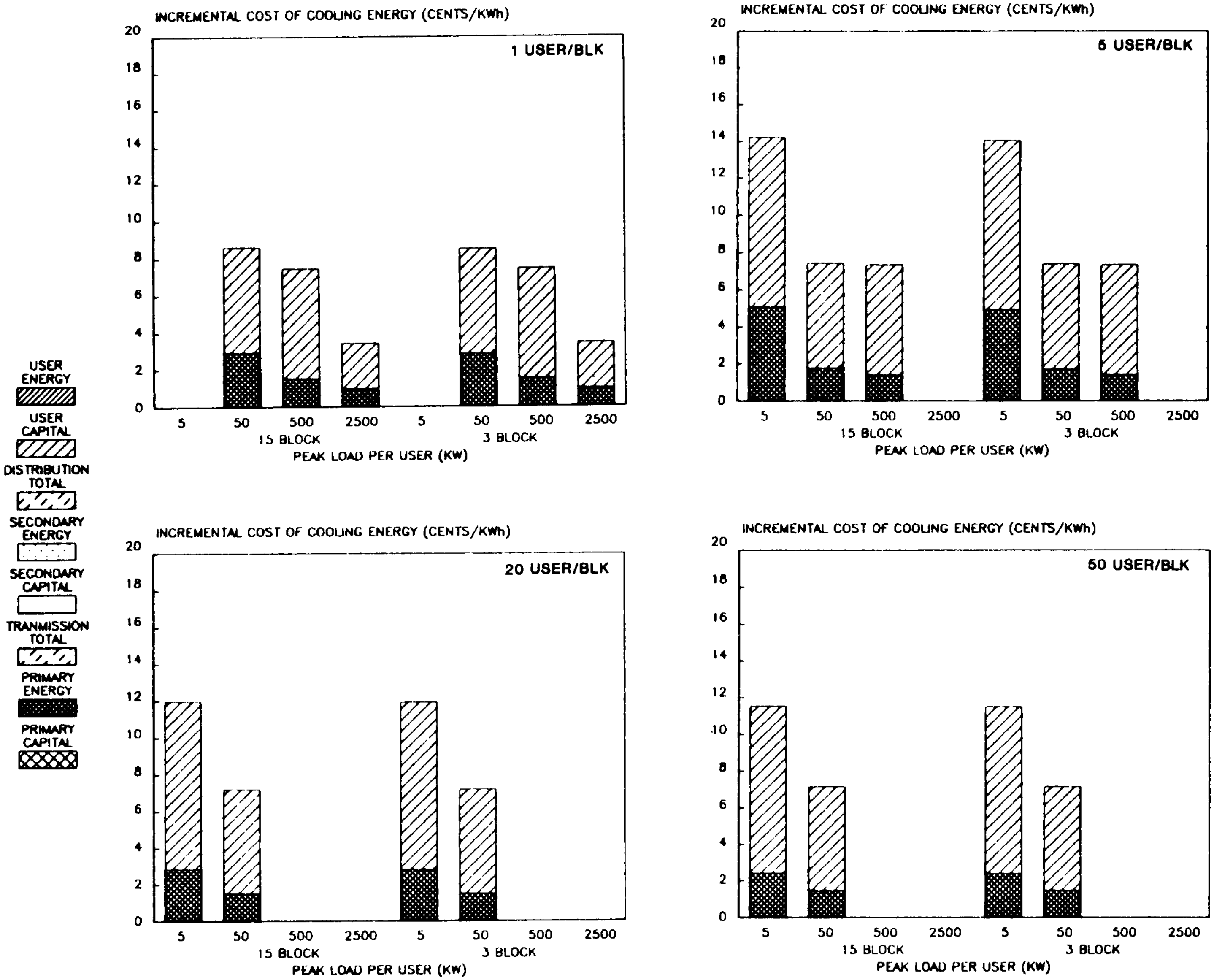

FIGURE II-1E. Urban Oil Cogenerator Retrofit - Combined - Steam Distribution

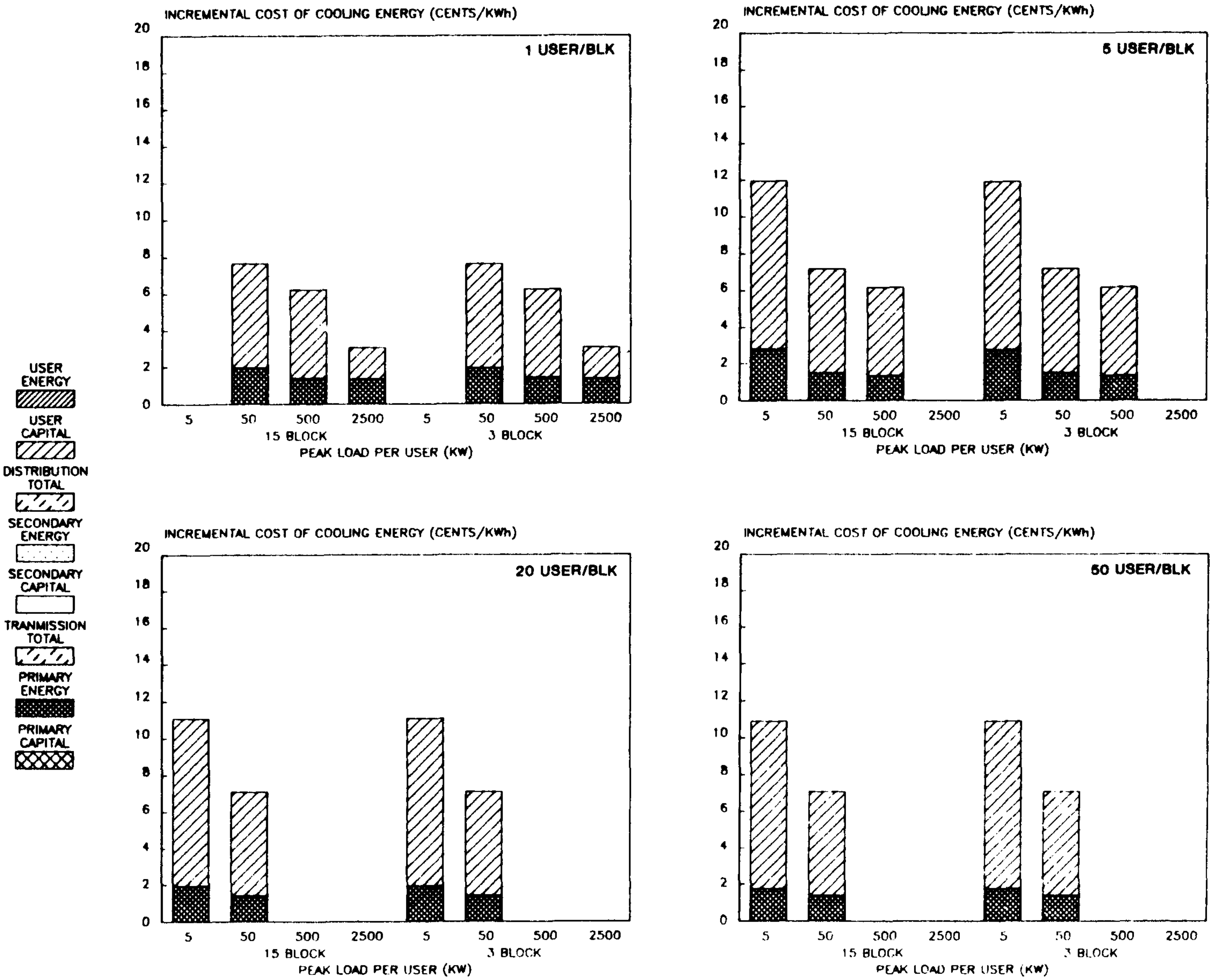

FIGURE II-1F. Urban Oil Cogenerator Retrofit - Combined - Water Distribution

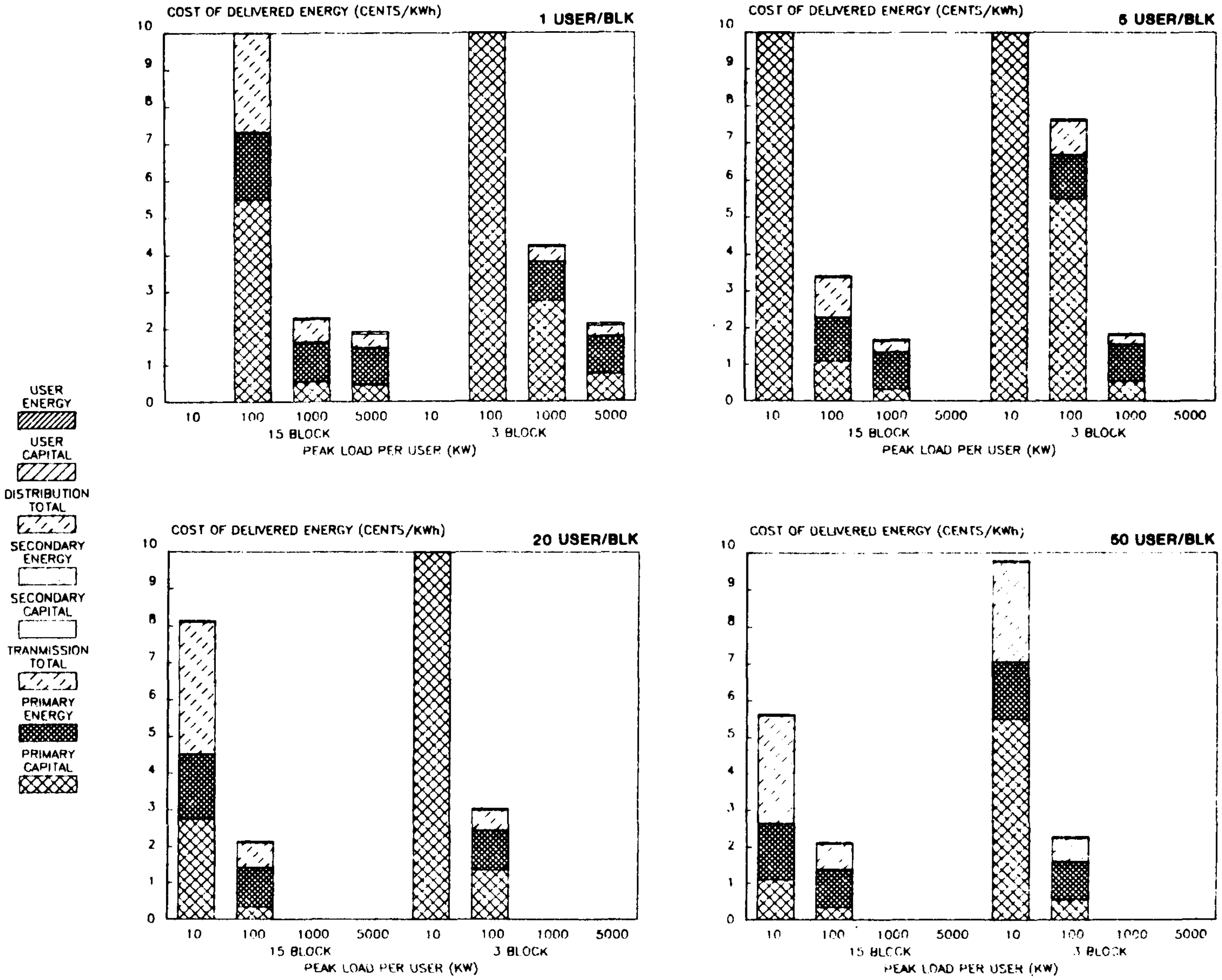

FIGURE II-1G. Urban Oil Cogenerator Retrofit - Heating - Water Distribution

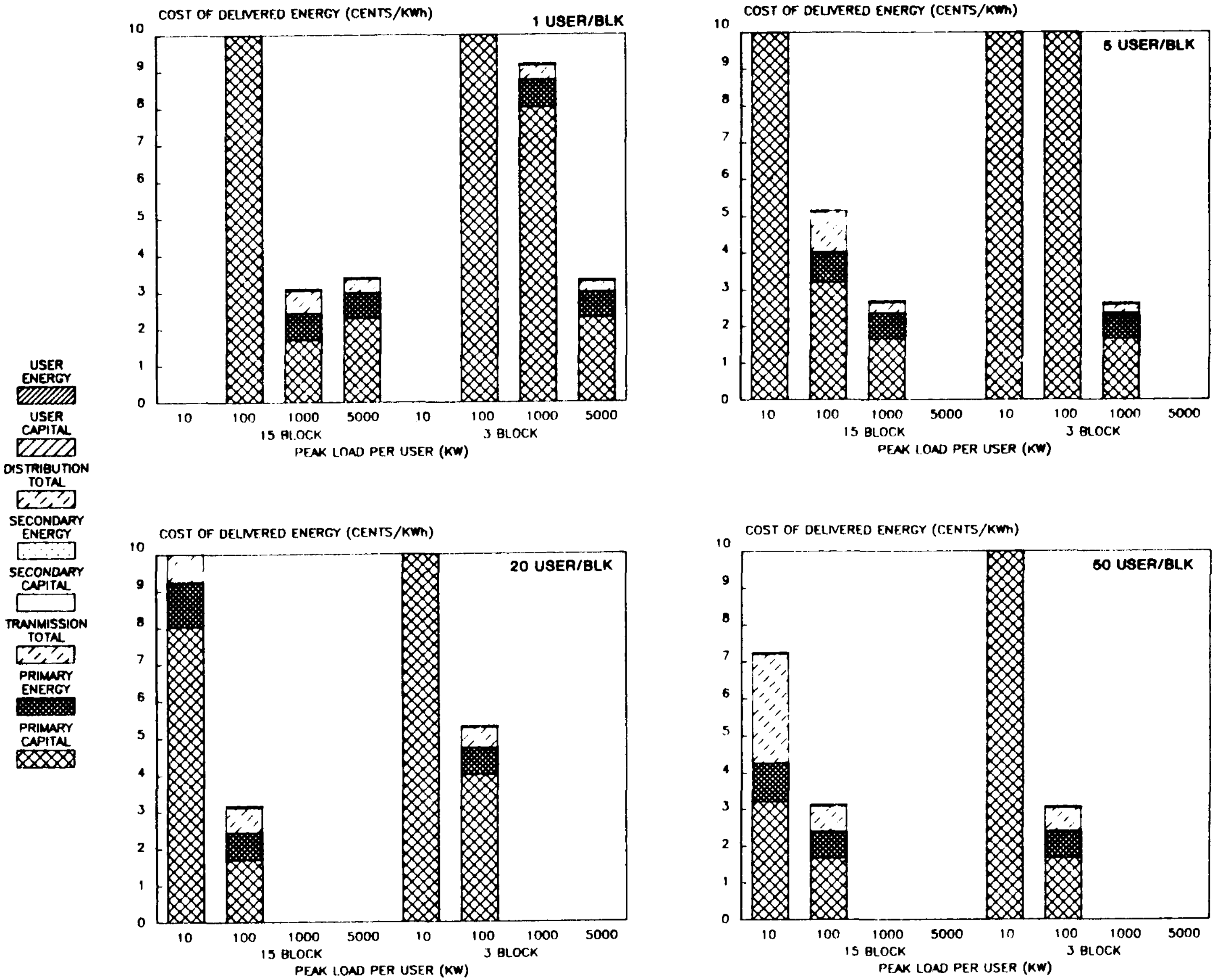

FIGURE II-2A. Coal Boiler - Heating - Steam Distribution

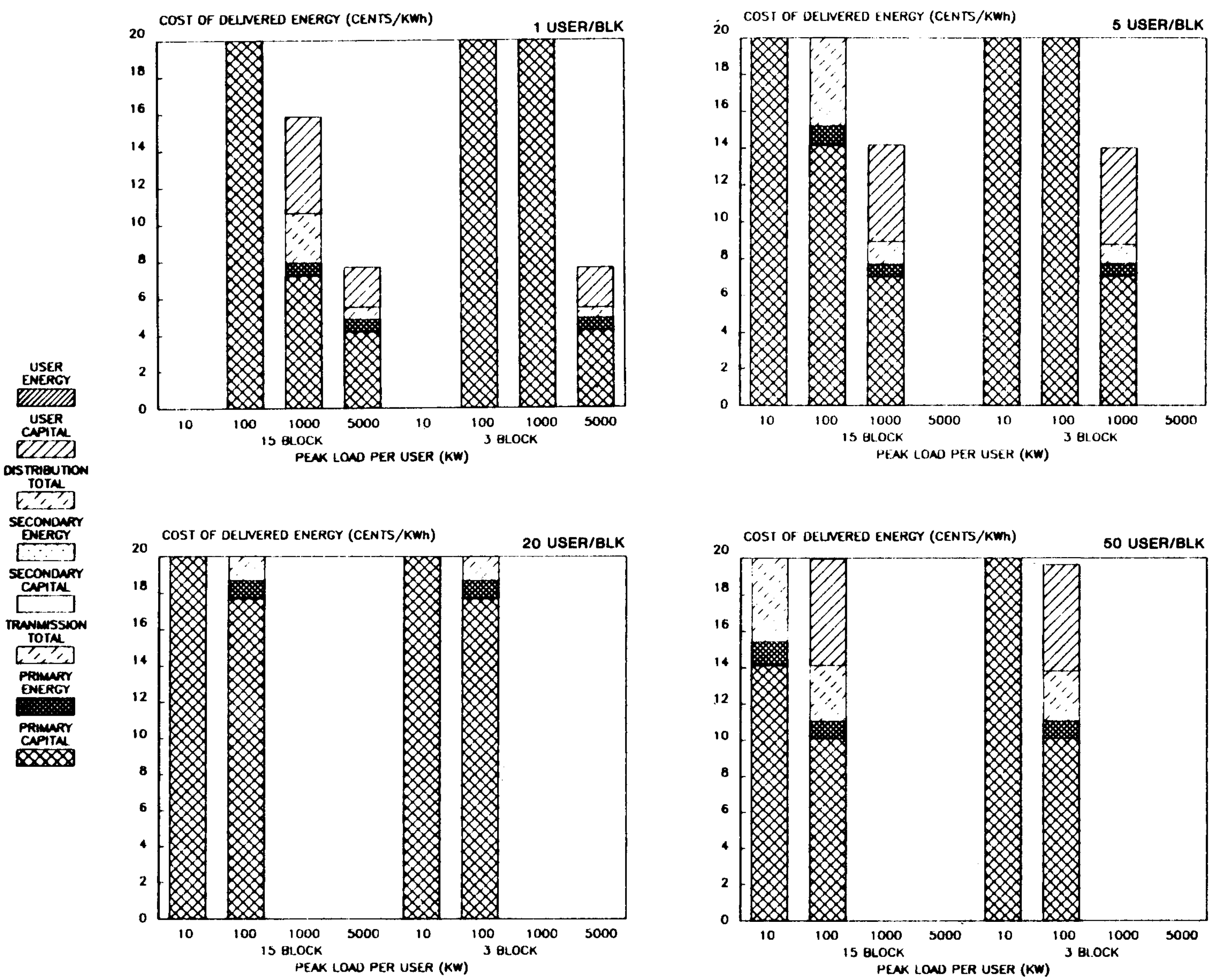

FIGURE II-2B. Coal Boiler - Cooling - Steam Distribution

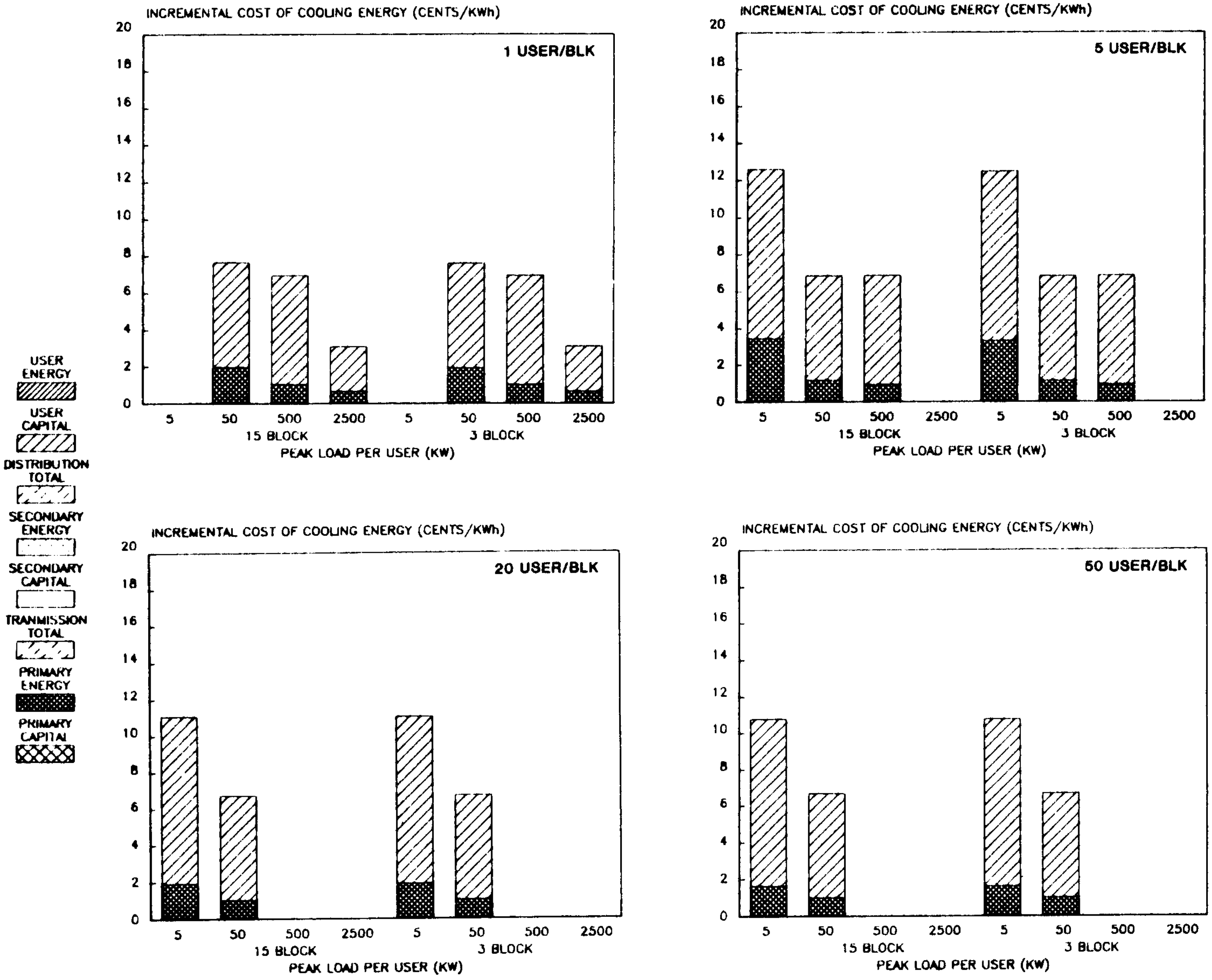

FIGURE II-2C. Coal Boiler - Combined - Steam Distribution

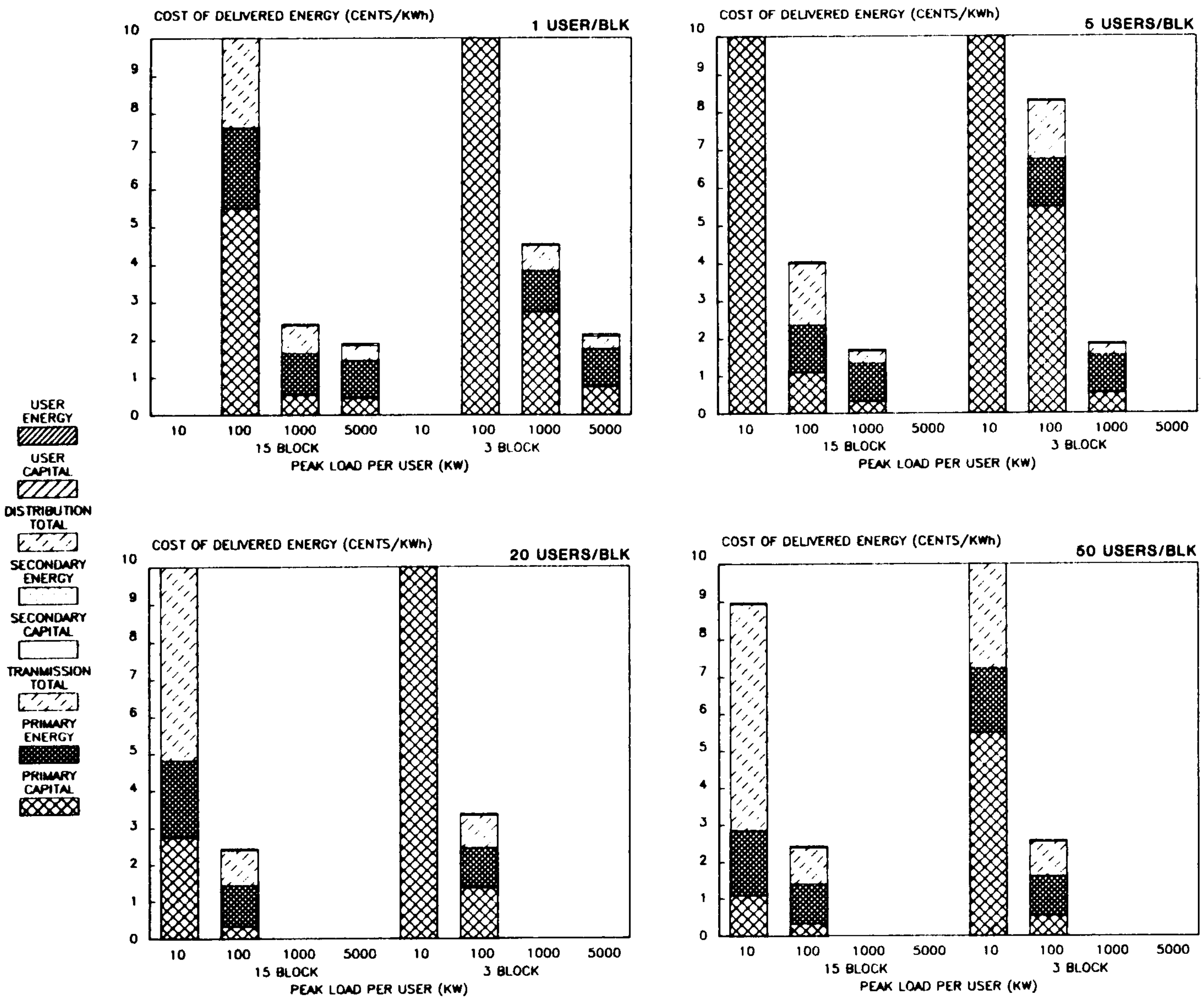

FIGURE II-2D. Coal Boiler - Heating - Steam Distribution

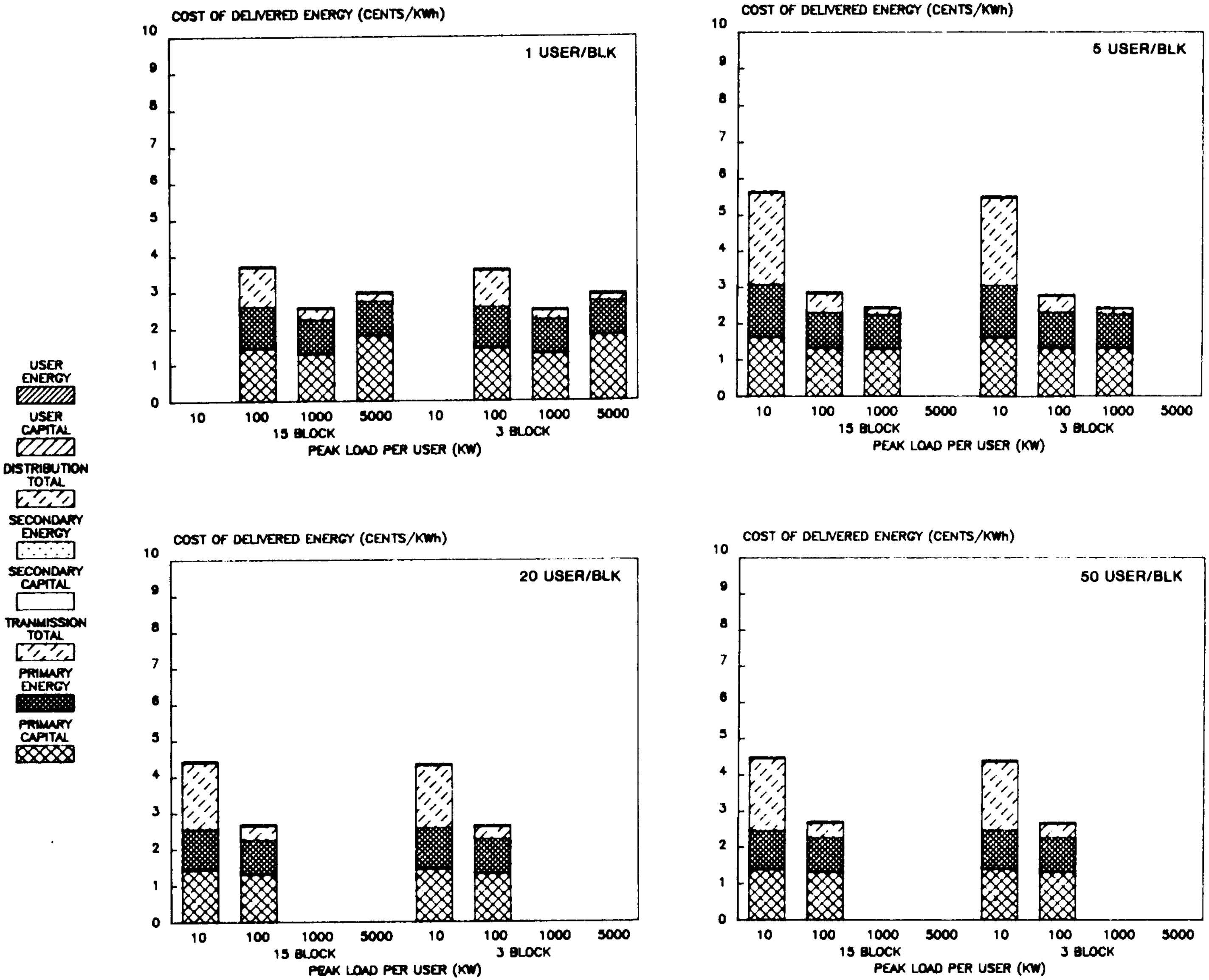

FIGURE II-3A. Diesel Cogenerator - Heating - Water Distribution

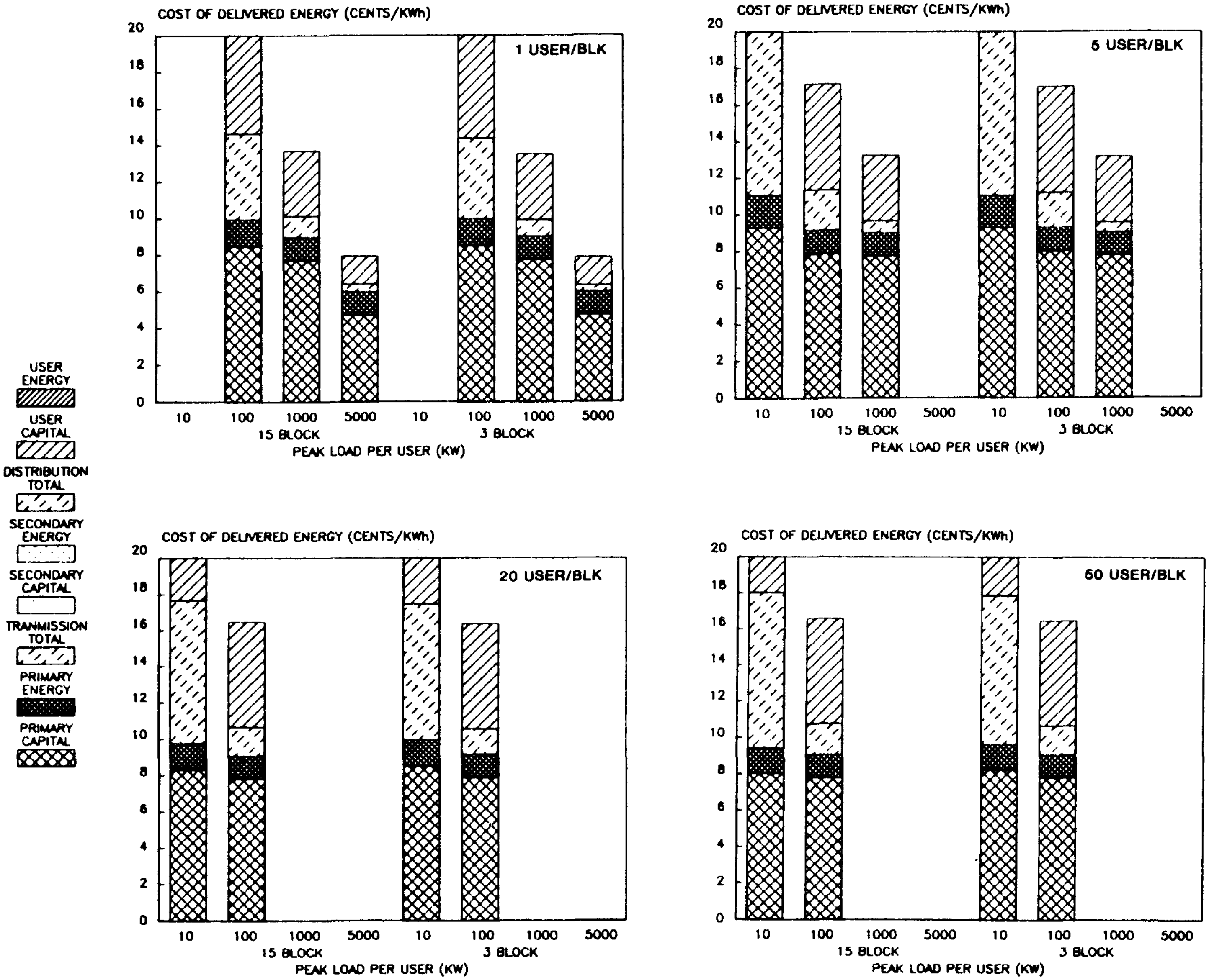

FIGURE II-3B. Diesel Cogenerator With Remote Chillers - Cooling - Water Distribution

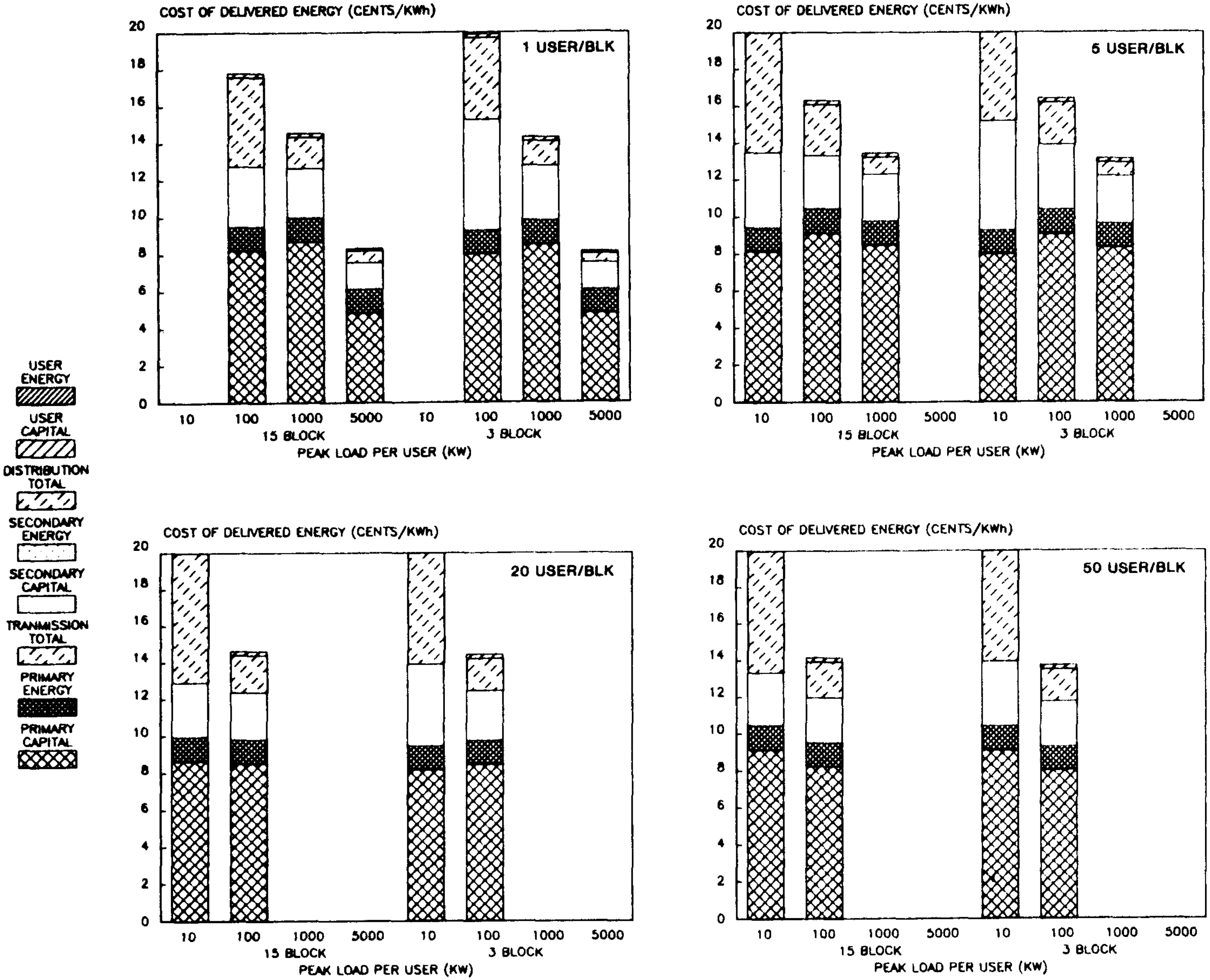

FIGURE II-3C. Diesel Cogenerator With Central Chiller - Cooling - Water Distribution

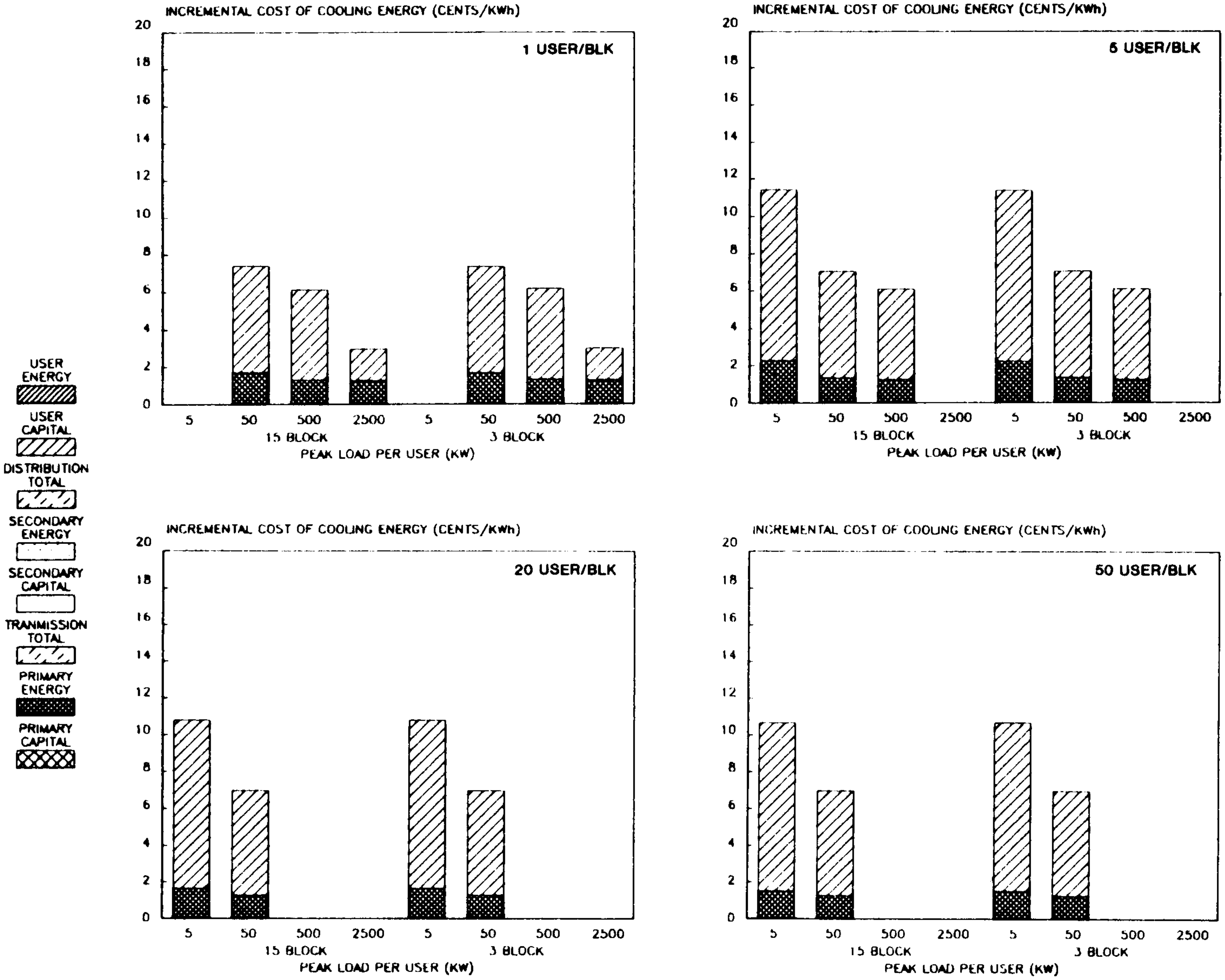

FIGURE II-3D. Diesel Cogenerator With Distributed Chillers
- Combined
- Water Distribution

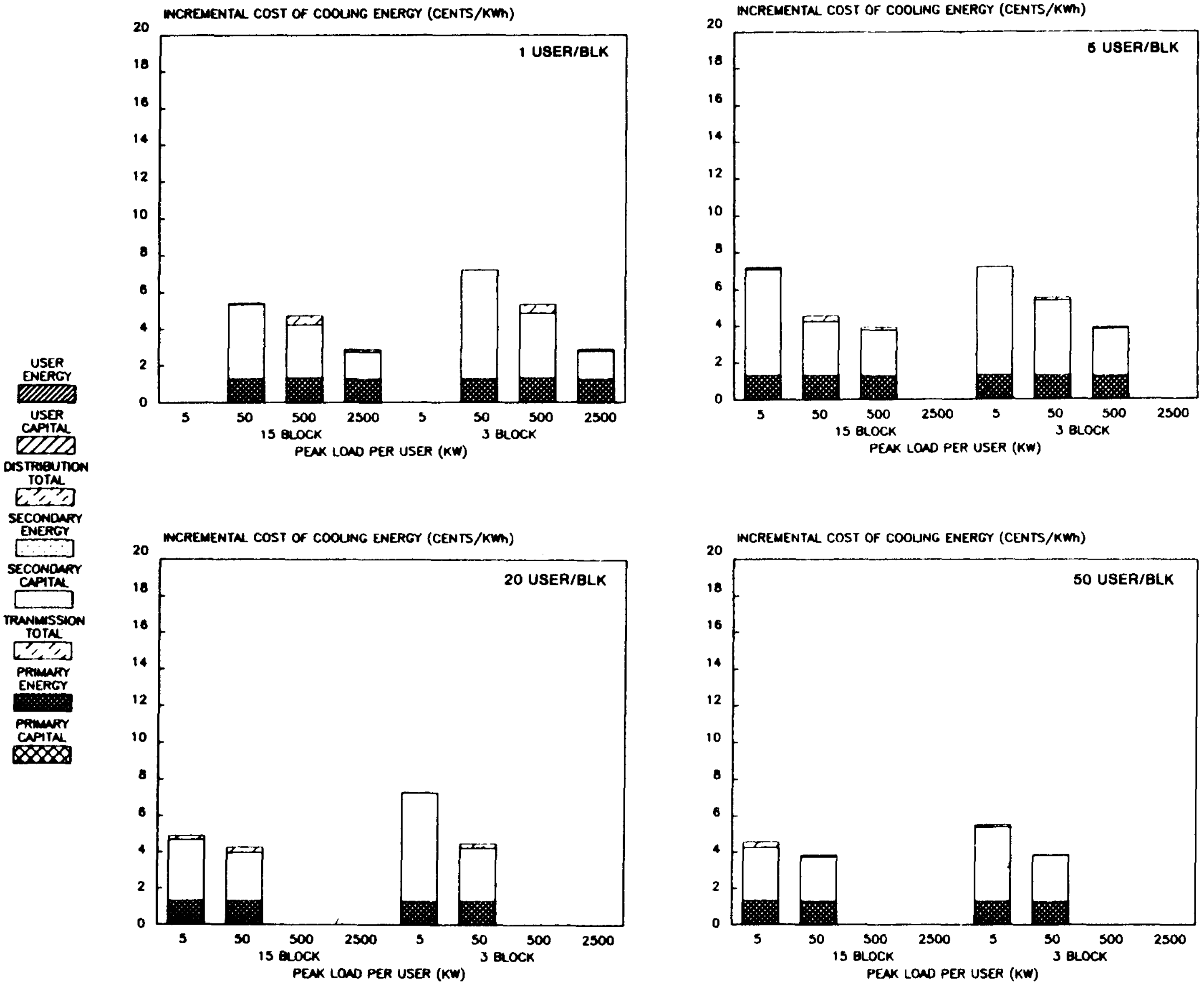

FIGURE II-3E. Diesel Cogenerator With Central Chiller - Combined

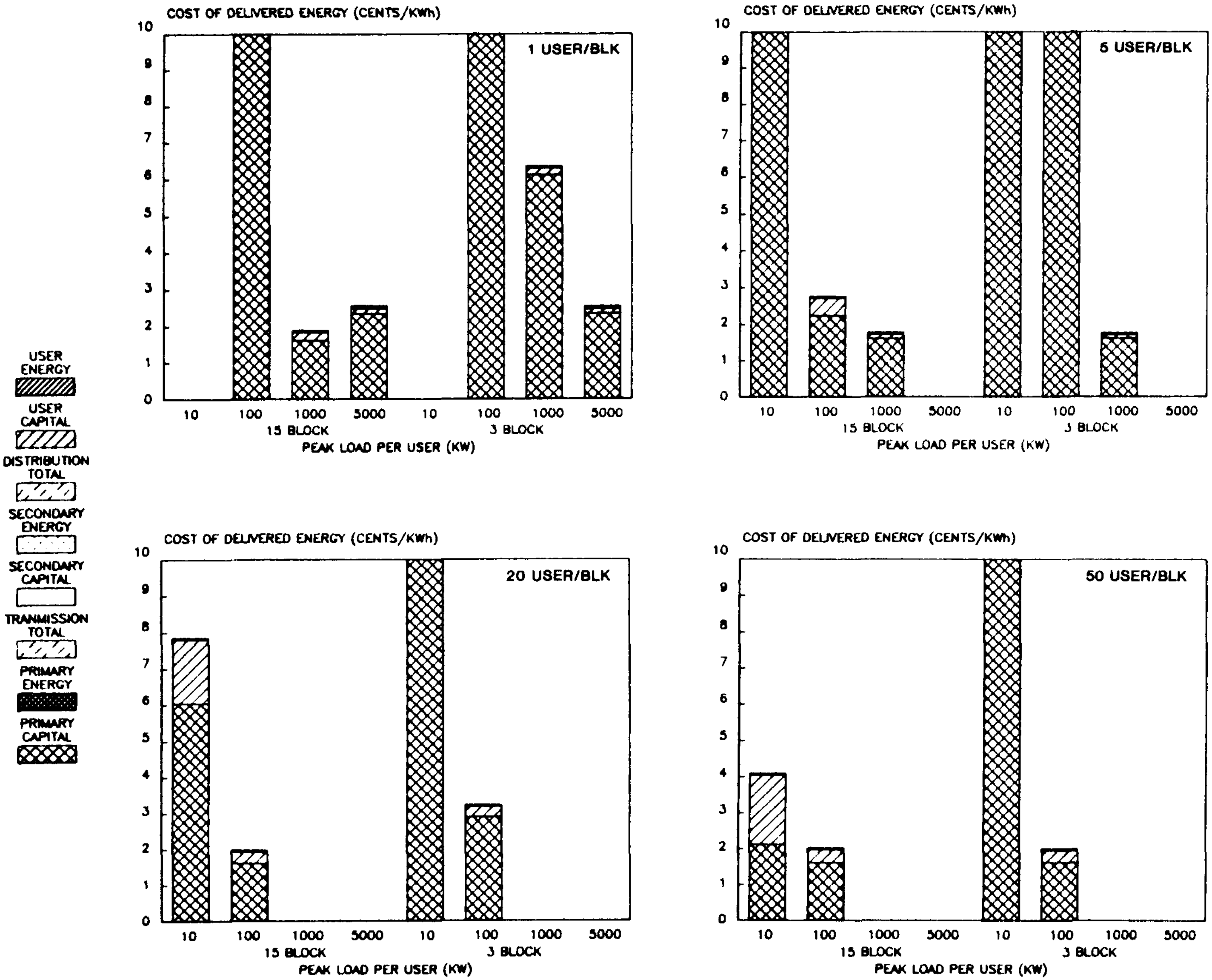

FIGURE II-4A. Coal-Fired Cogenerator - Heating - Water Distribution

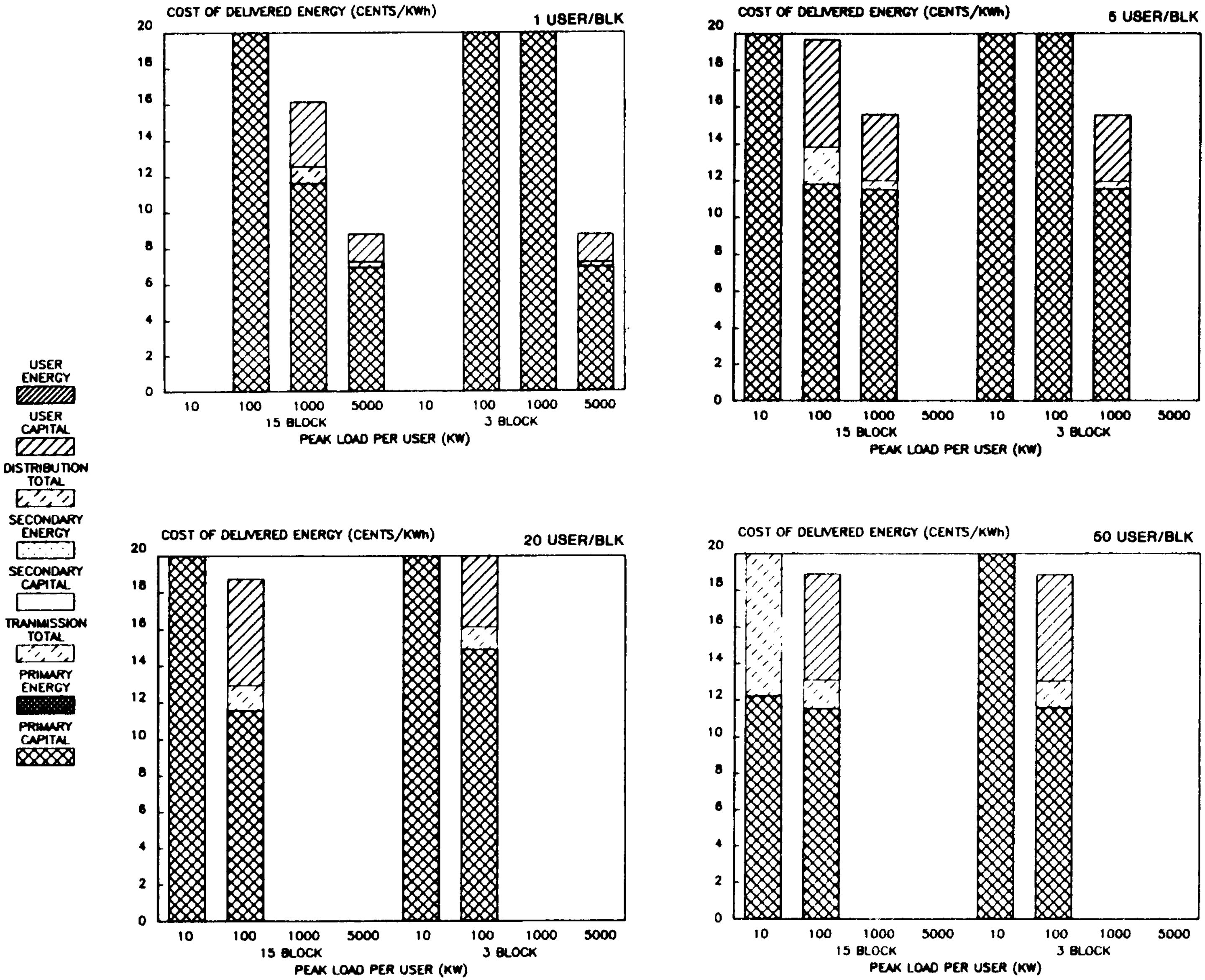

FIGURE II-4B. Coal-Fired Cogenerator - Cooling - Water Distribution

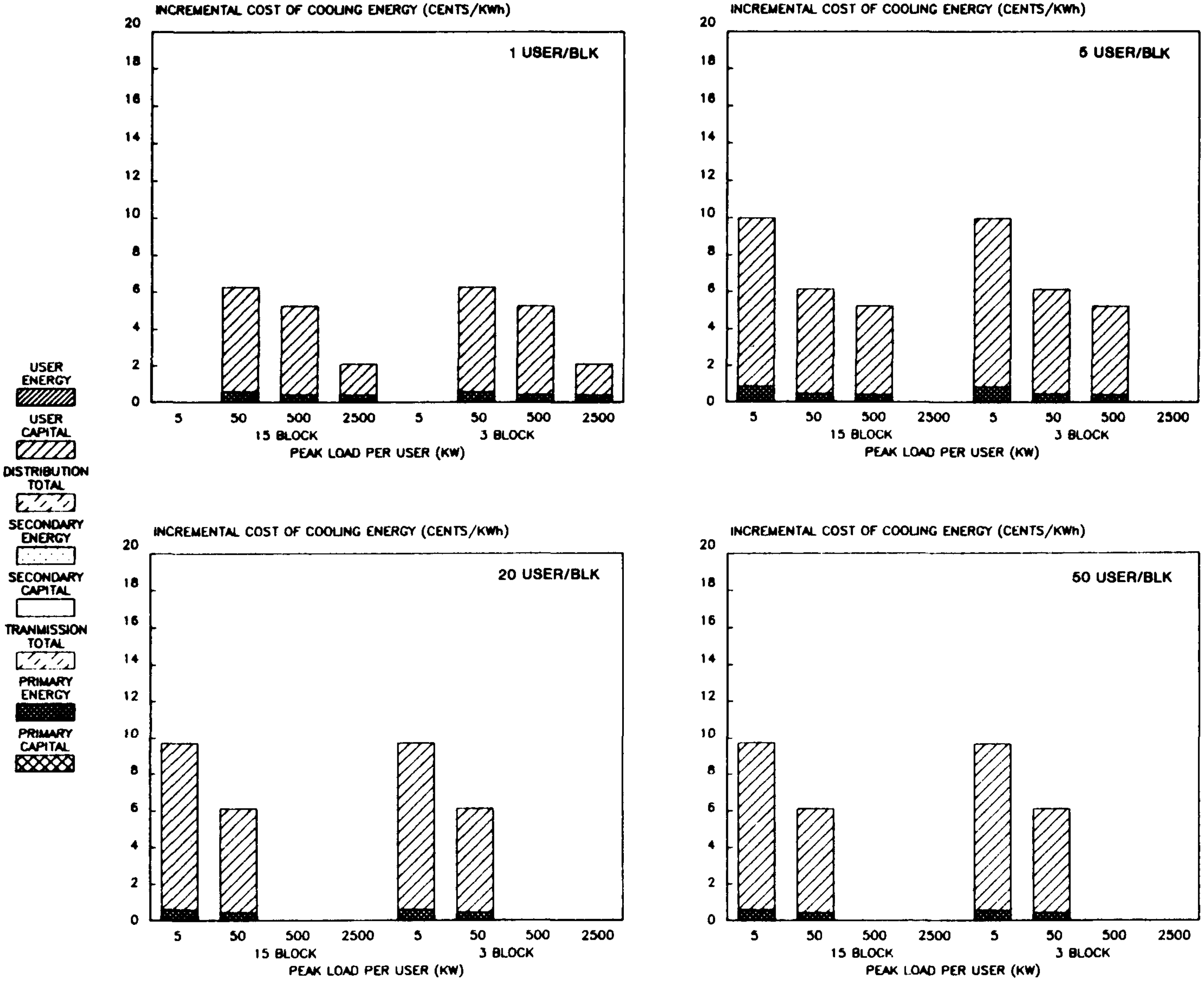

FIGURE II-4C. Coal Cogenerator - Combined - Water Distribution

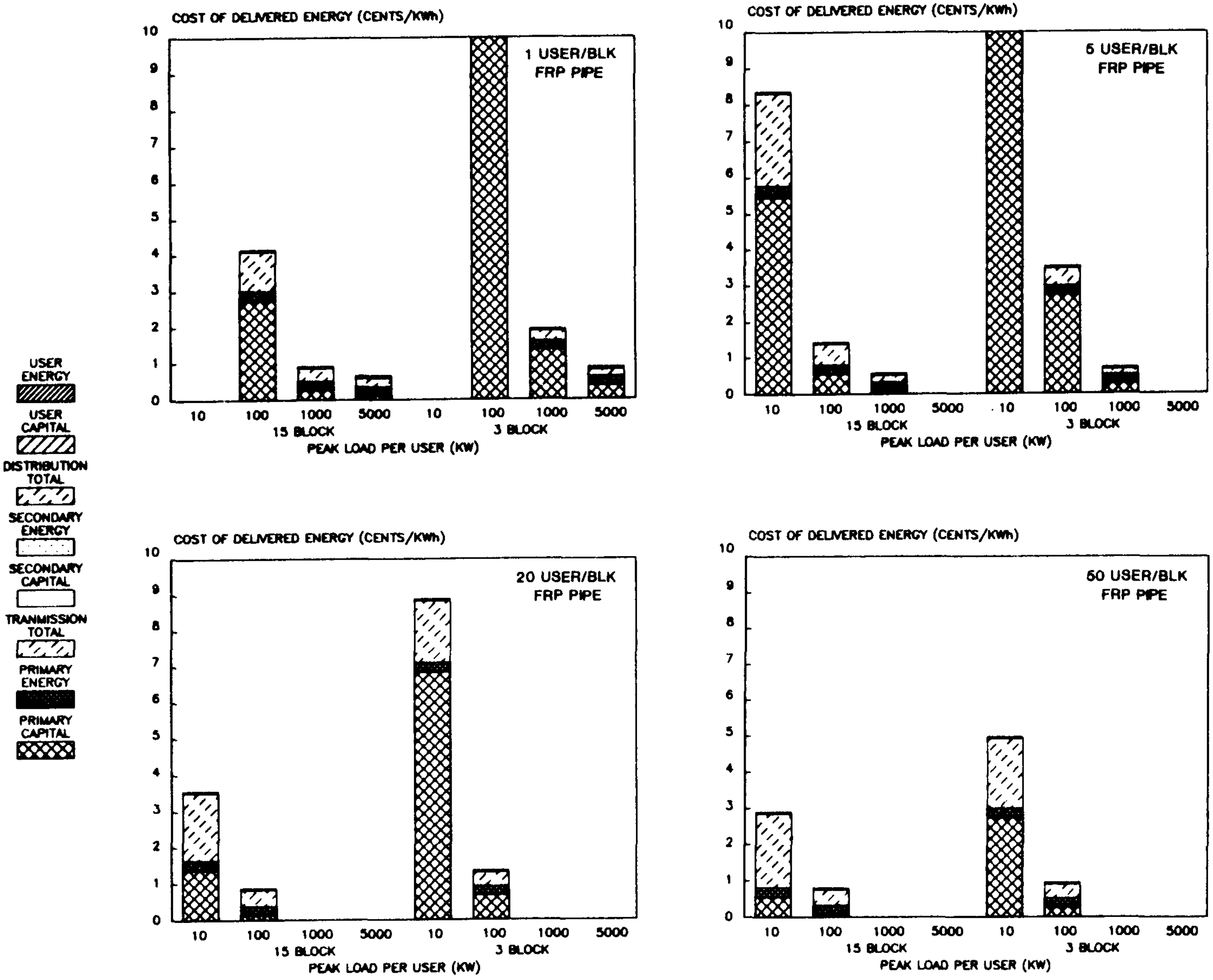

FIGURE II-5A. Low Backpressure Cogenerator - Heating - Water Distribution - FRP Pipe

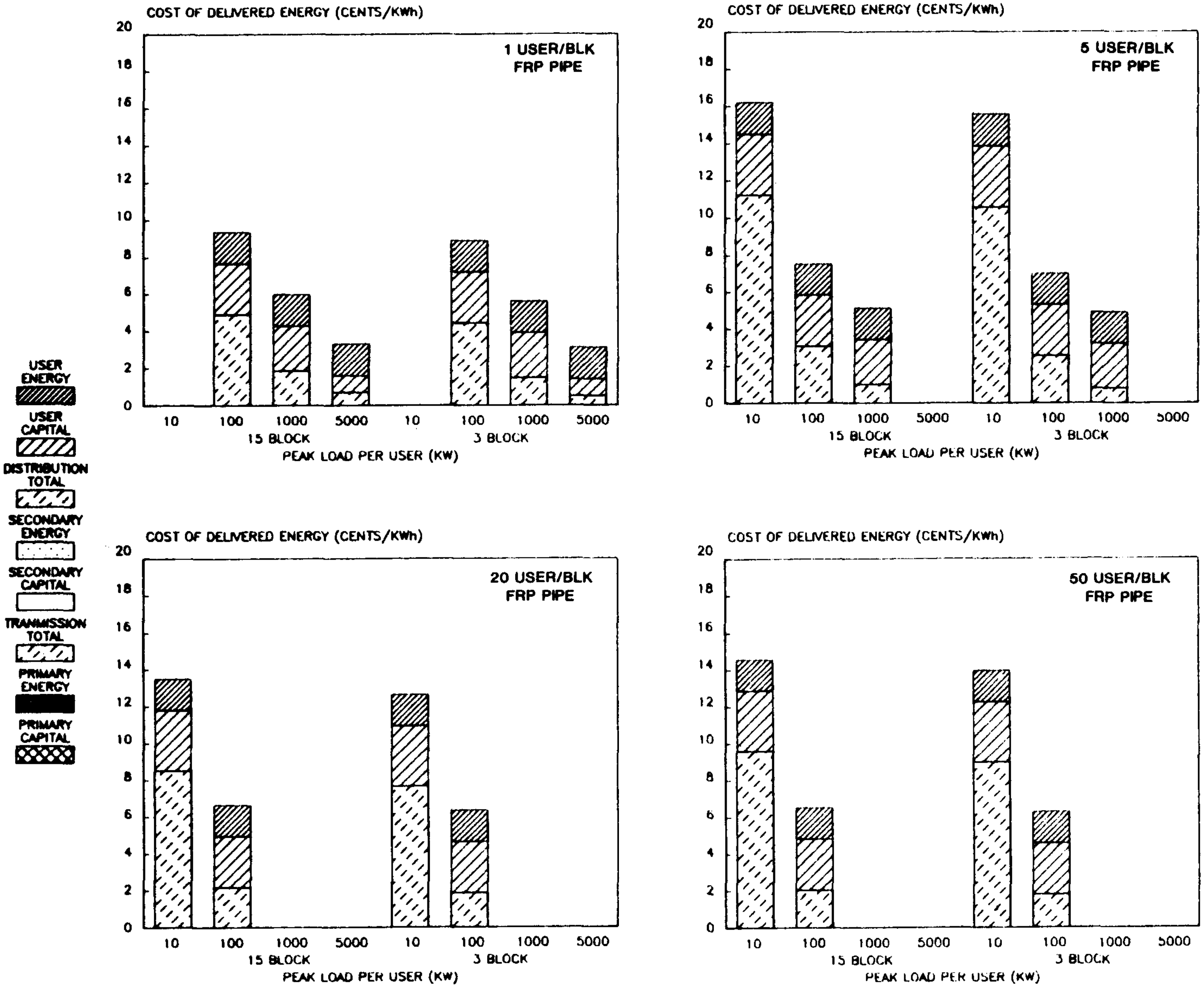

FIGURE II-5B. Distributed Electric Heat Pumps - Cooling - FRP Pipe

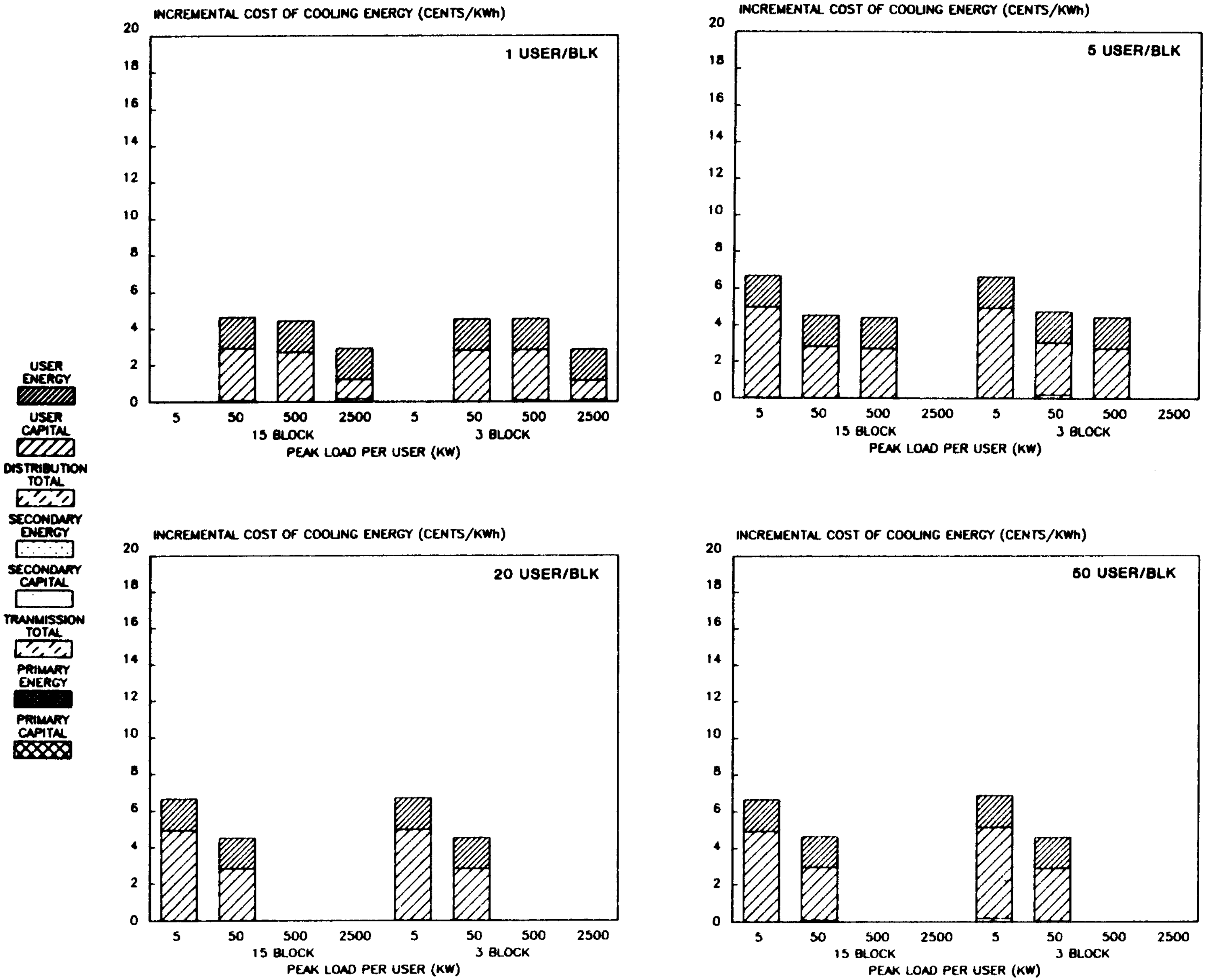

FIGURE II-5C. Low Backpressure Cogenerator Plus Water Source Heat Pumps
- Combined System
- Water Distribution

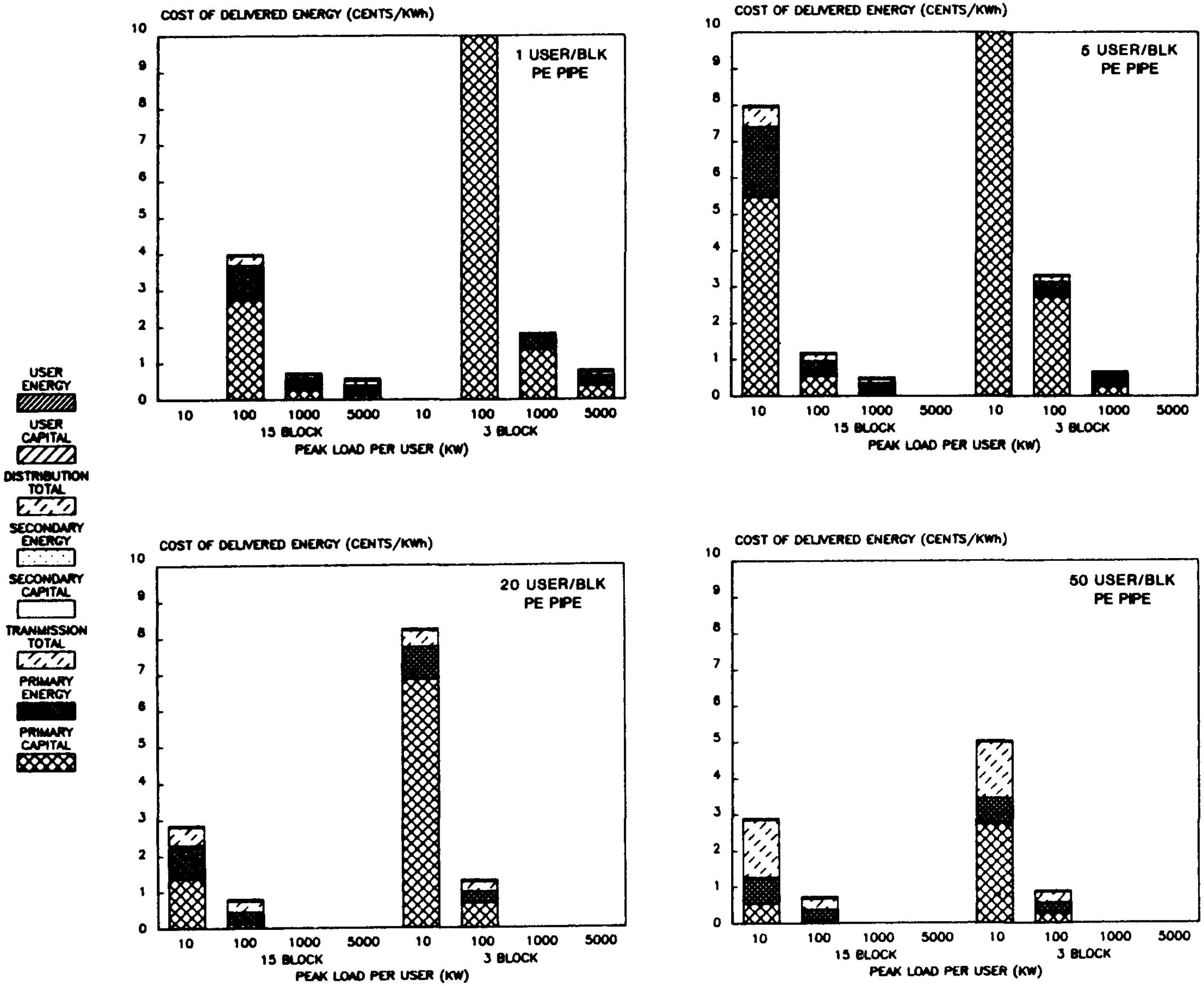

FIGURE II-5D. Low Backpressure Cogenerator - Heating - Water Distribution - PE Pipe

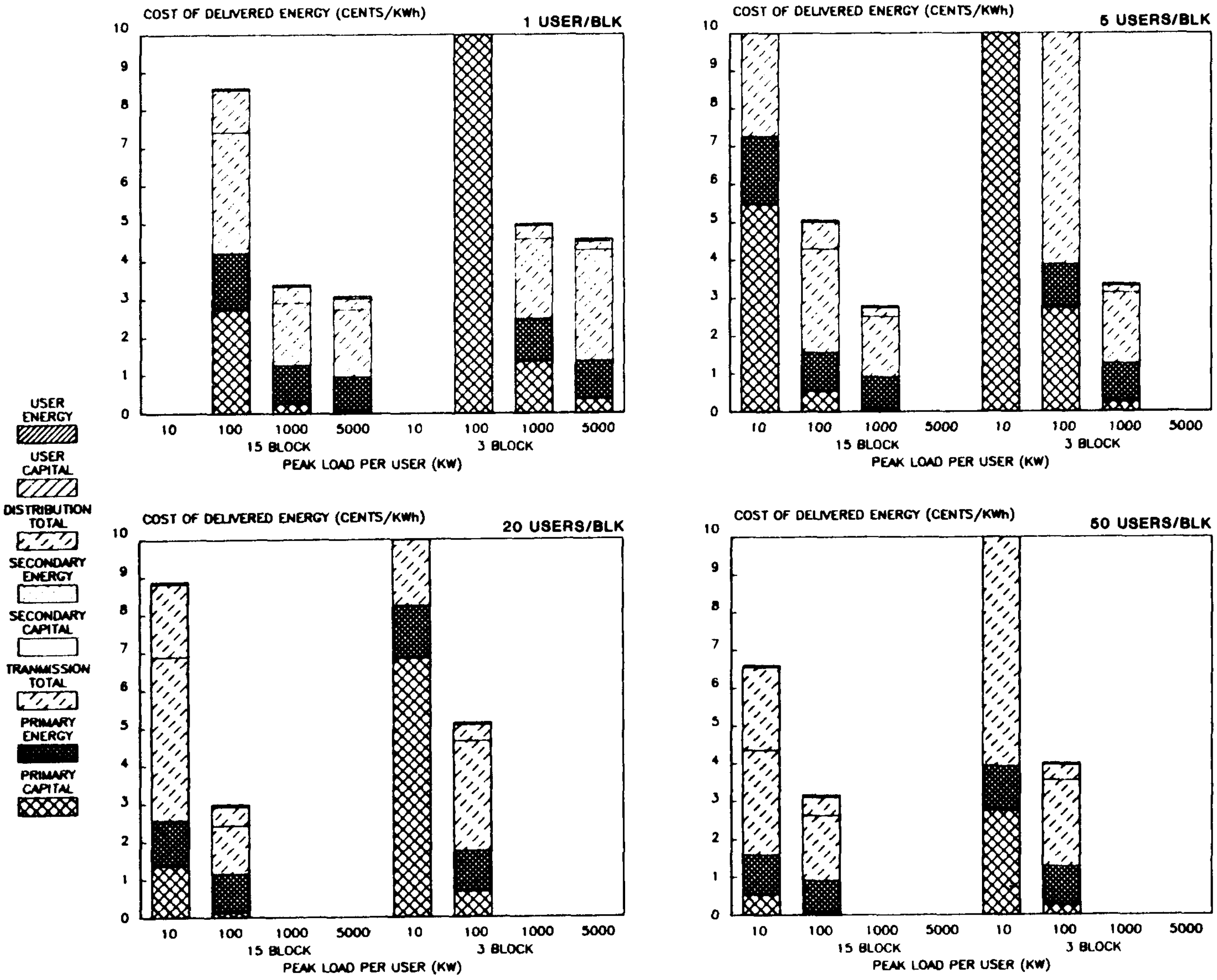

FIGURE II-5F. Low Backpressure Cogenerator - Heating - Water Distribution

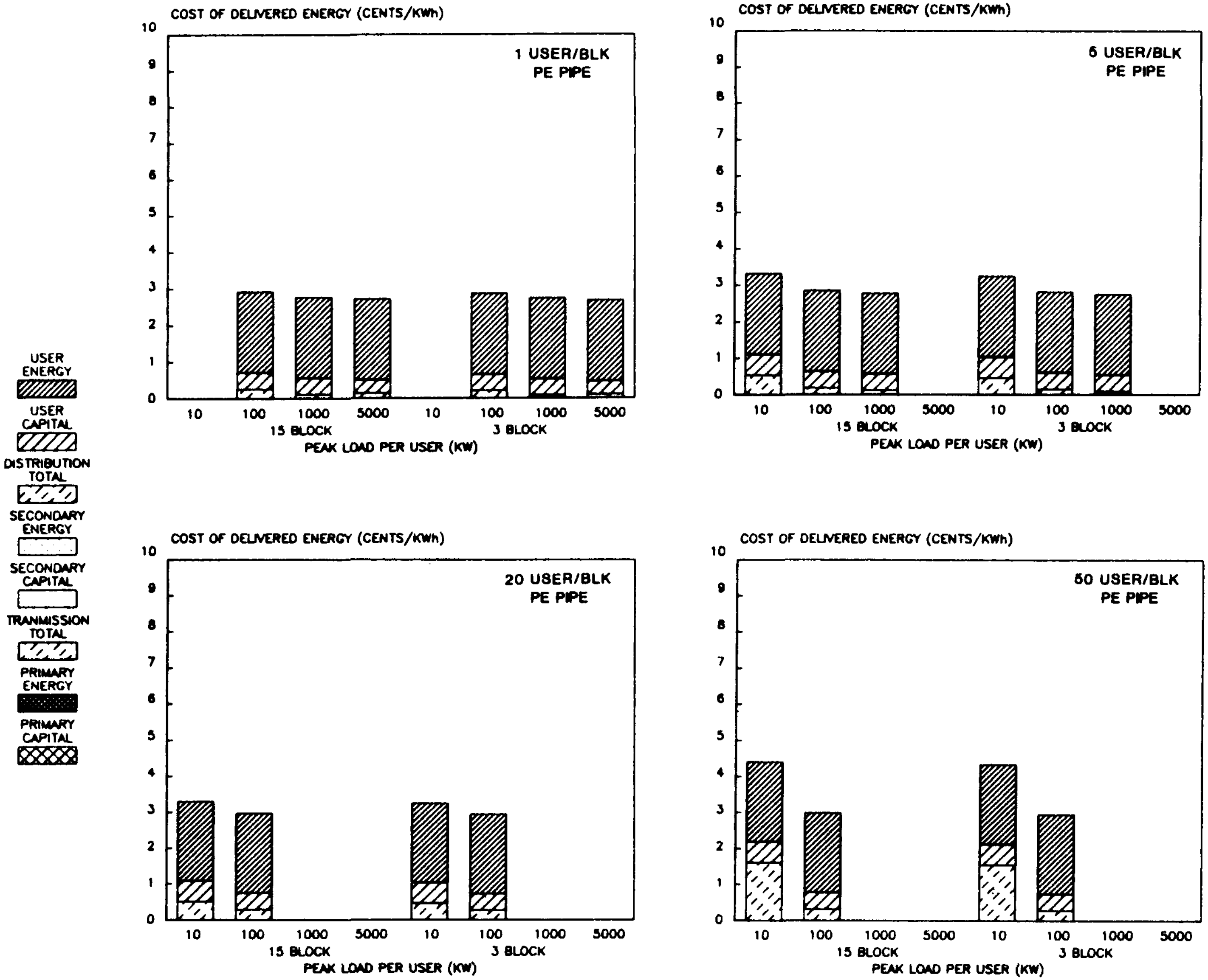

FIGURE II-6A. Distributed Water Source Heat Pumps - Heating
- Water Distribution
- PE Pipe

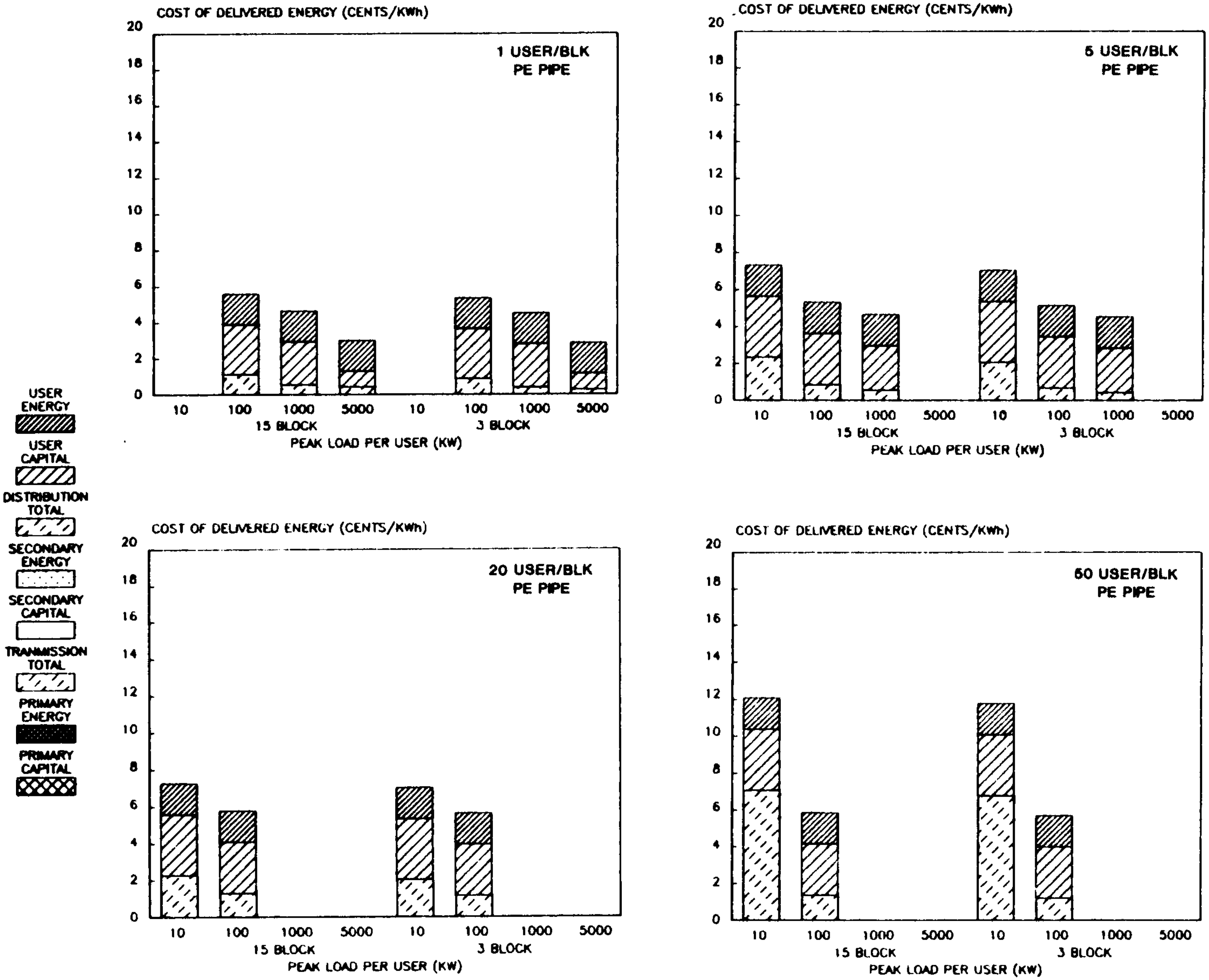

FIGURE II-6B. Distributed Electric Heat Pumps - Cooling - PE Pipe

DISTRIBUTED ELECTRIC HEAT PUMP — COOLING

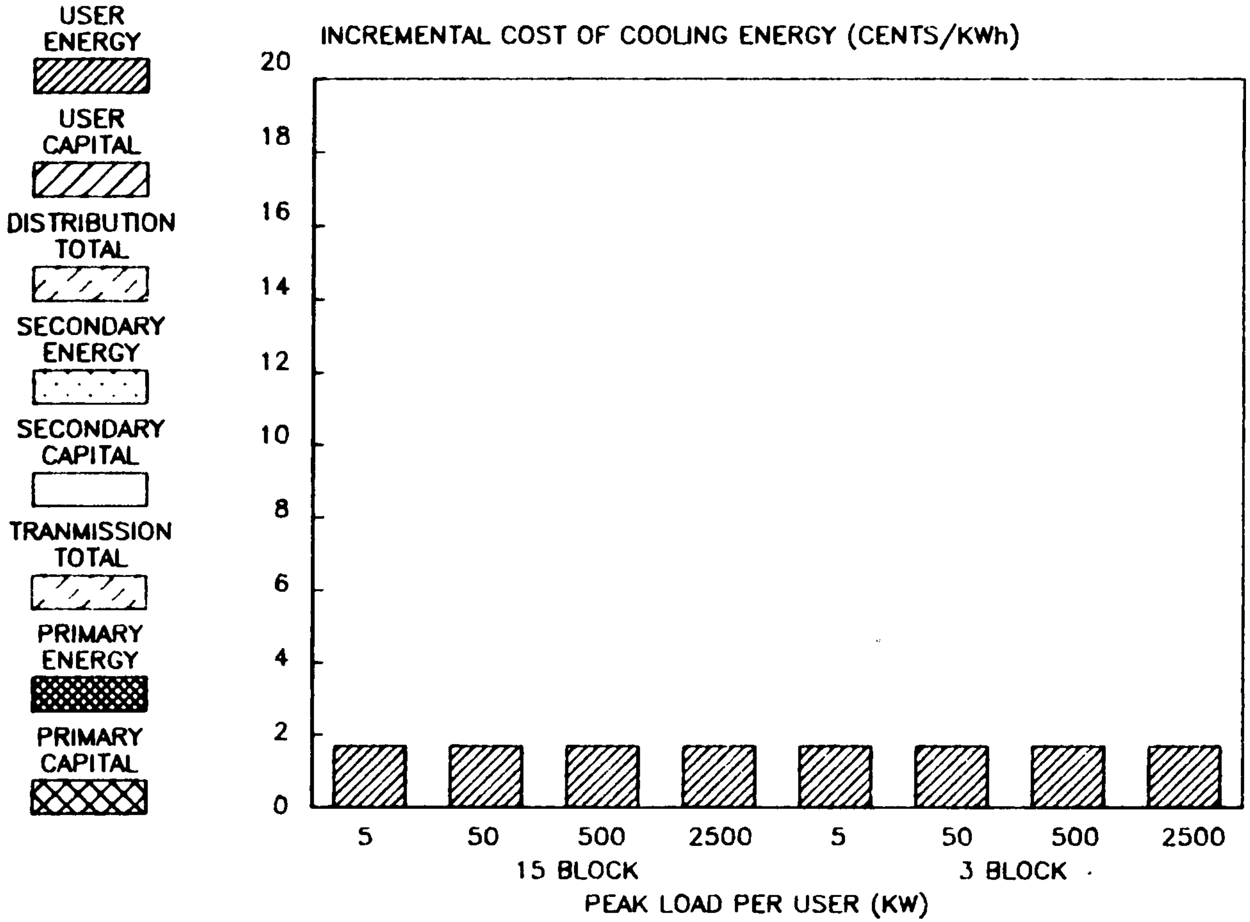

FIGURE II-6C

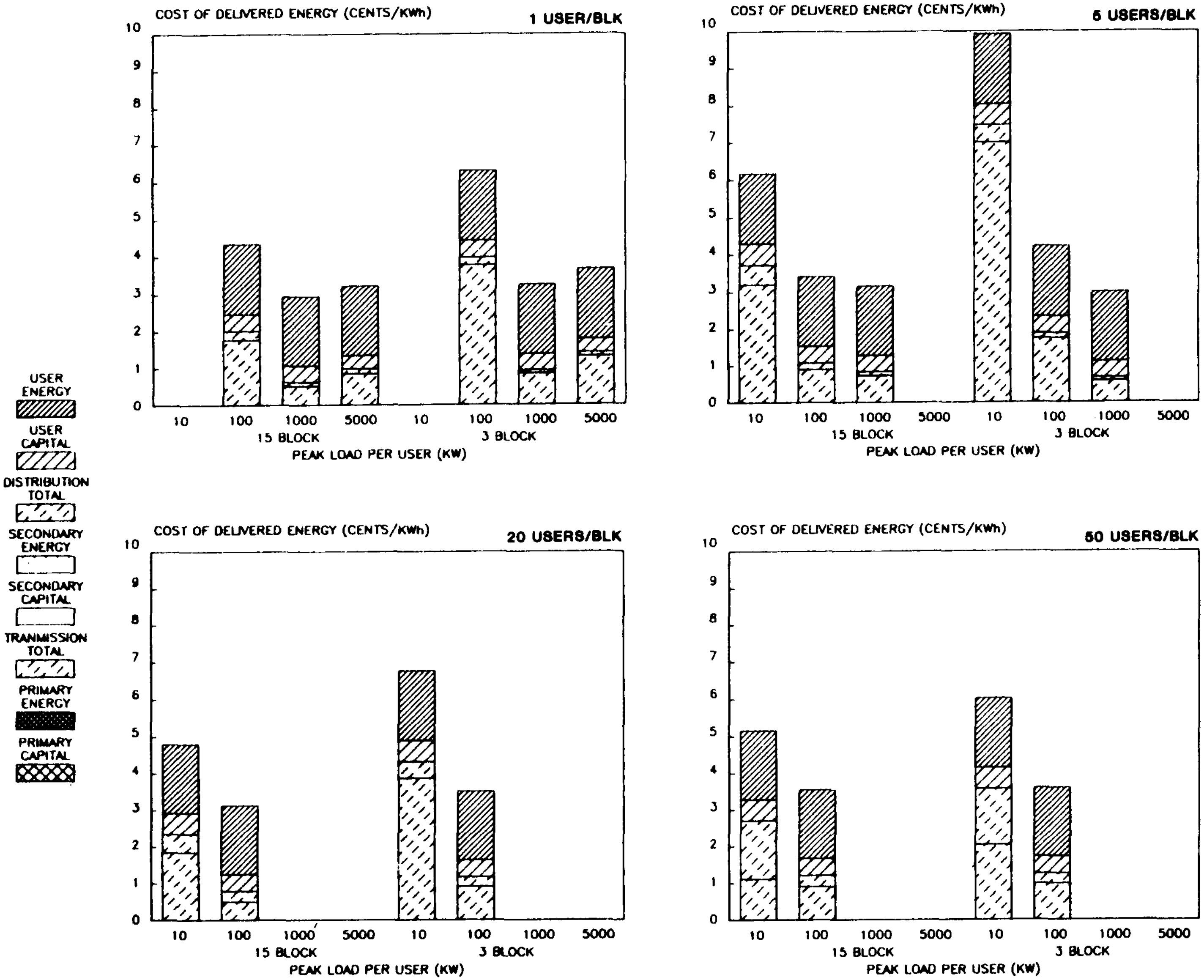

FIGURE II-6D. Distributed Water Source Heat Pumps - Heating - Water Distribution

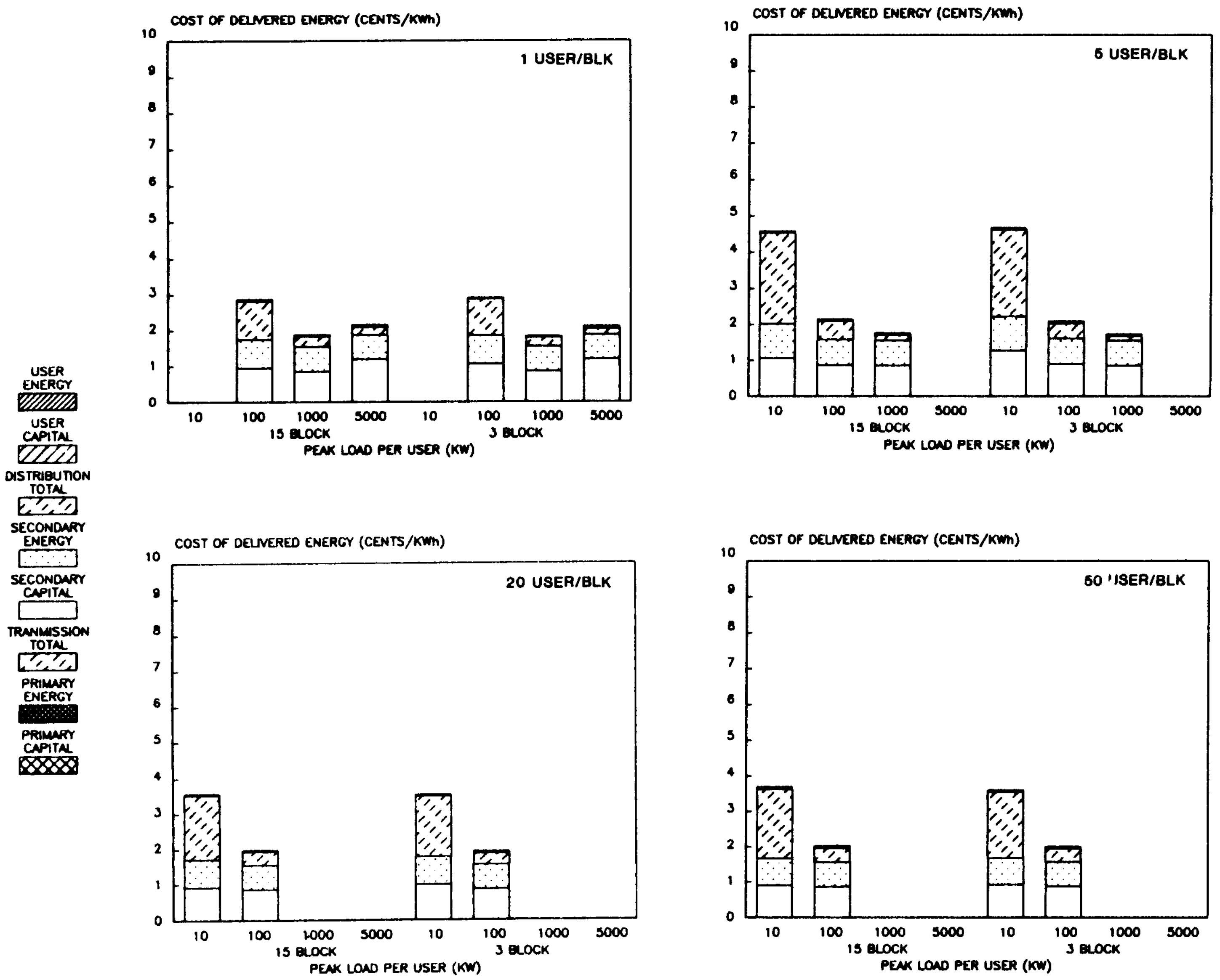

FIGURE II-7A. Central Fuel-Driven Heat Pump - Heating - Water Distribution

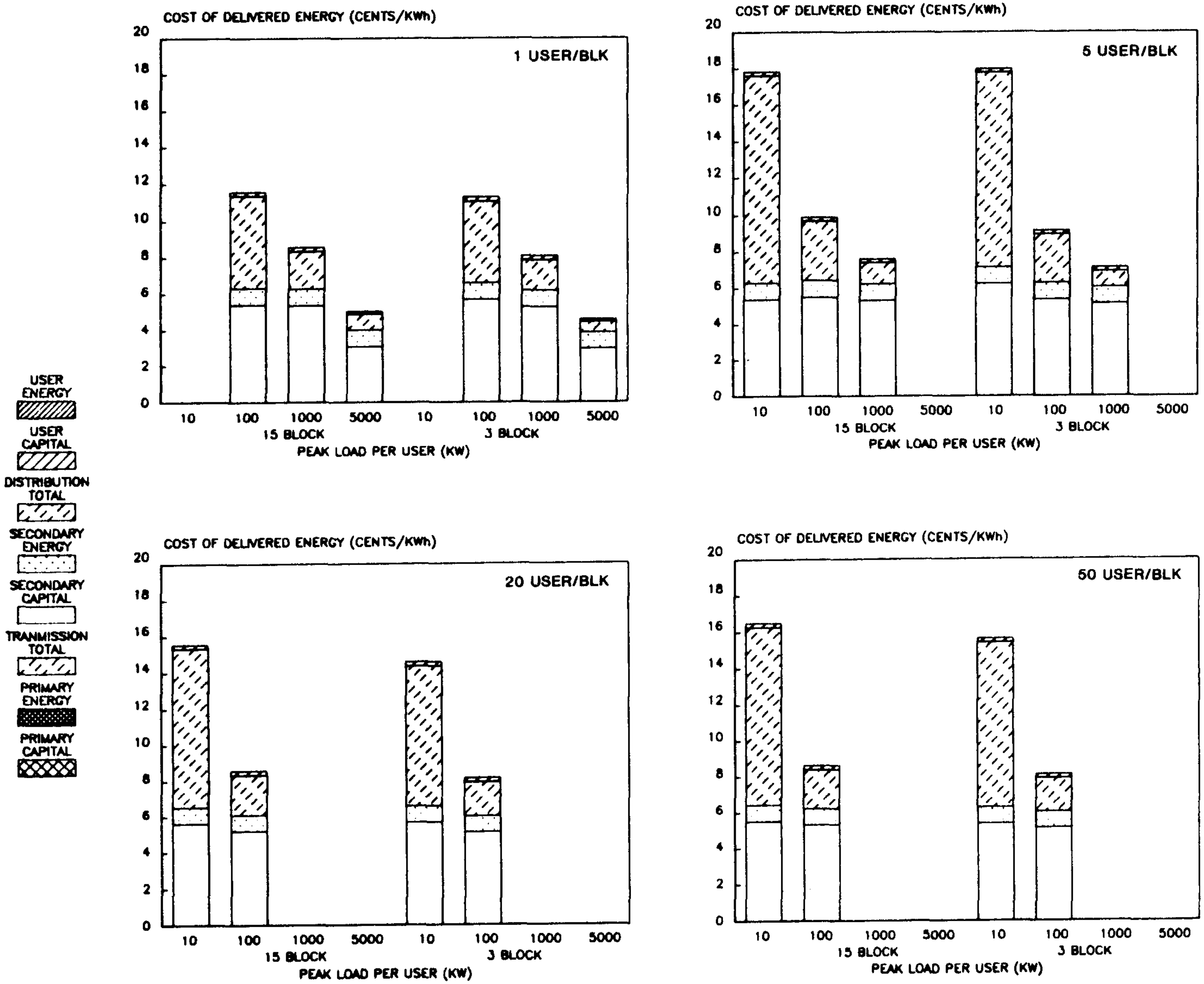

FIGURE II-7B. Central Fuel-Driven Heat Pump - Cooling - Water Distribution

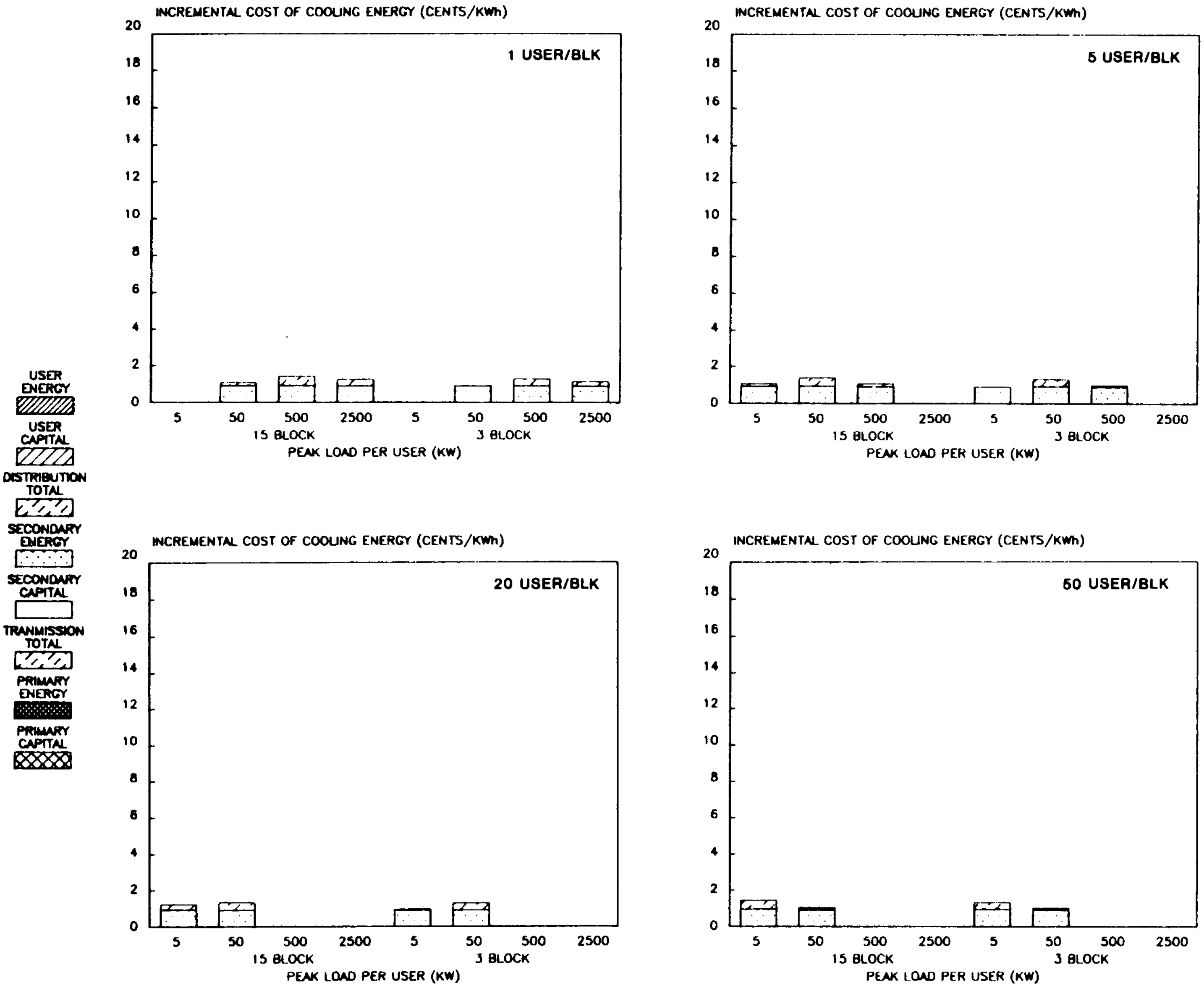

FIGURE II-7C. Fuel-Driven Heat Pump - Combined - Water Distribution

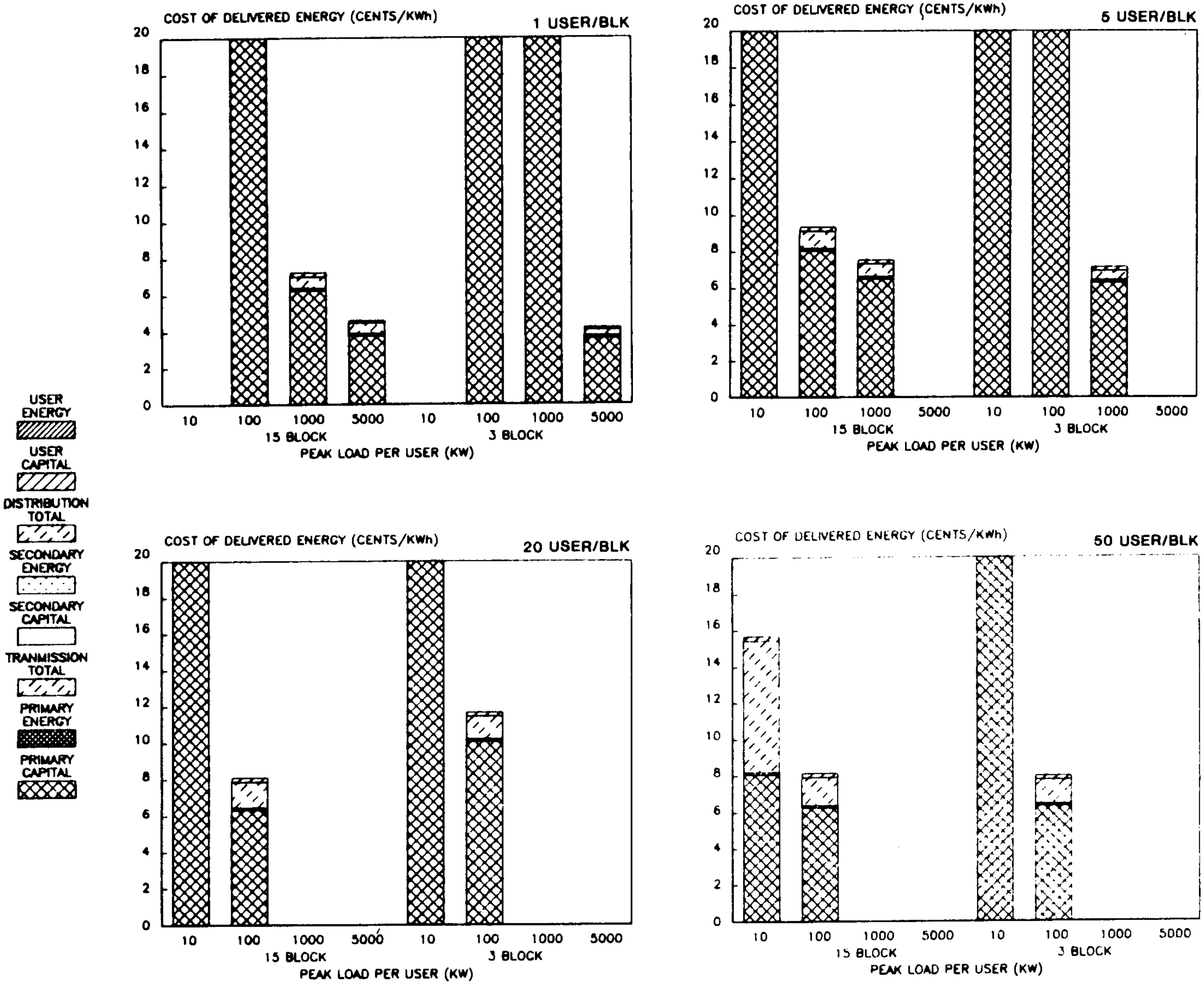

FIGURE II-9. Ice Pile - Cooling - Water Distribution

DISTRIBUTED GAS BOILER – HEATING

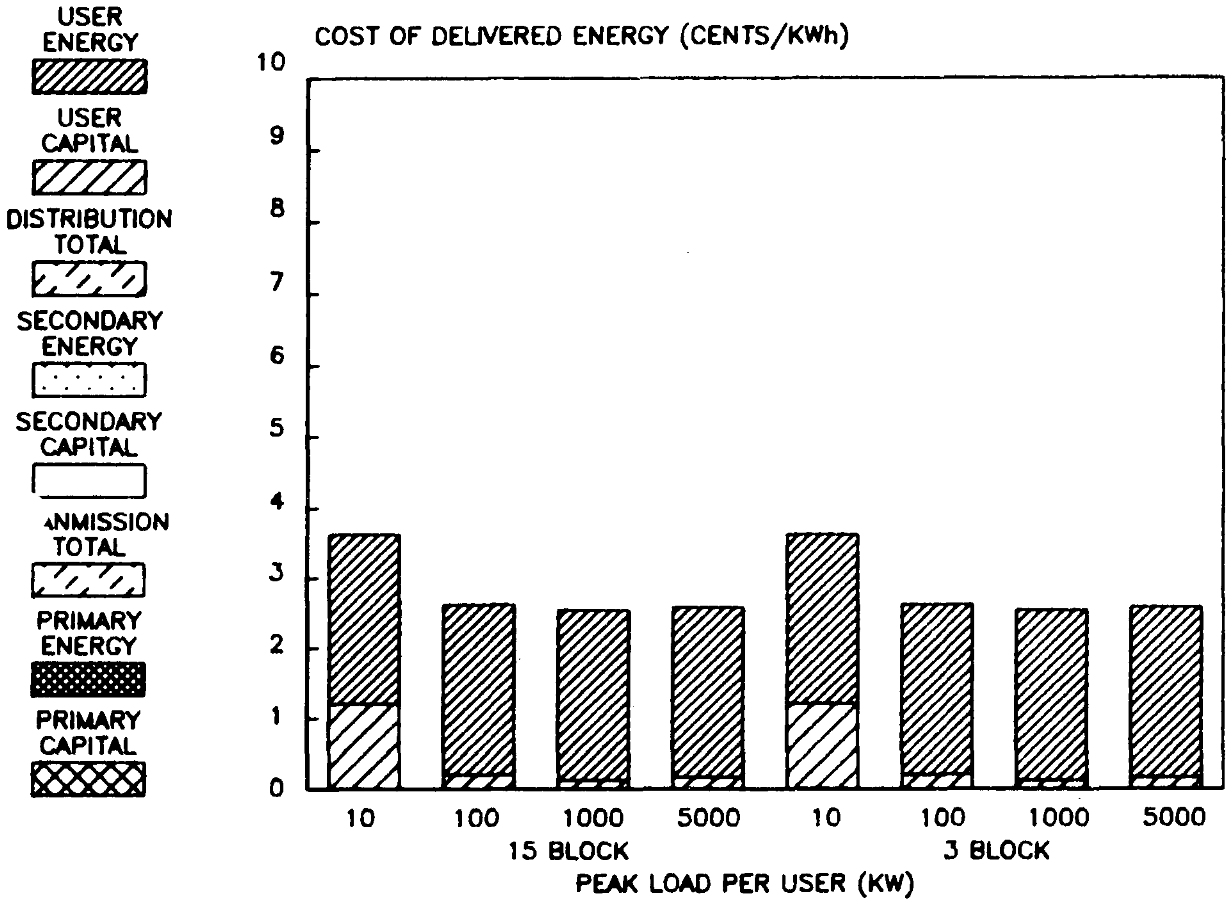

FIGURE II-10

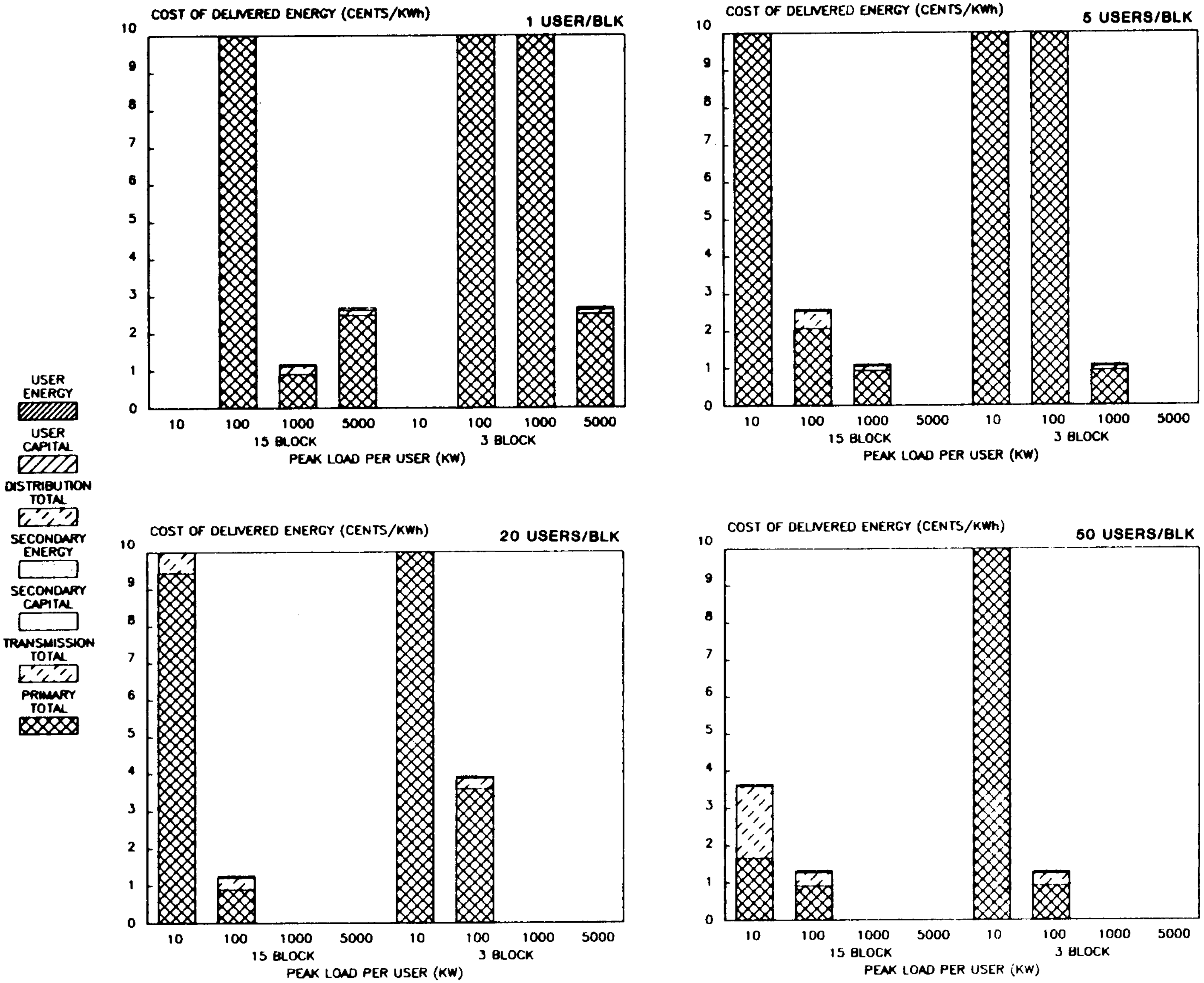

FIGURE II-11A. Municipal Waste Cogenerator - Heating - Water Distribution

SMALL ELECTRIC AIR CONDITIONER

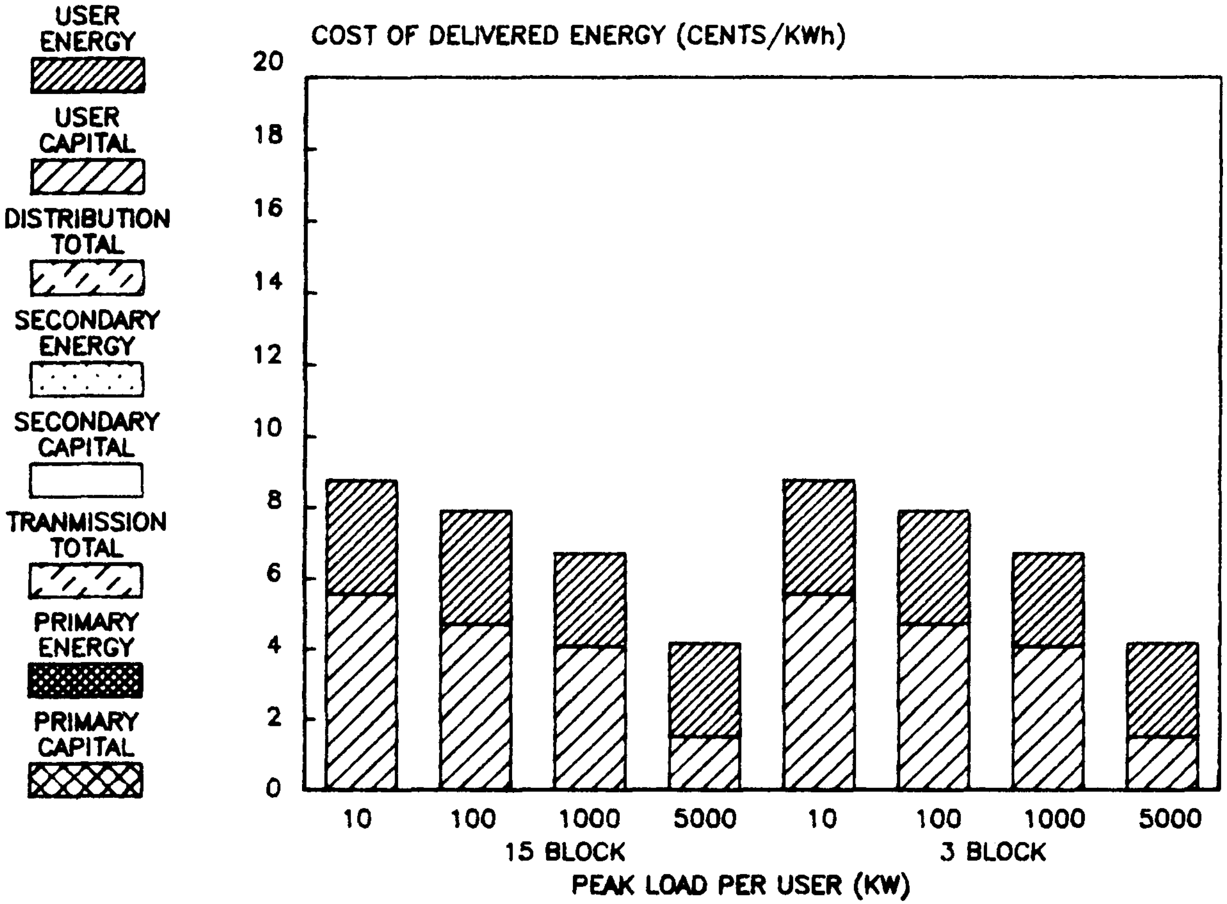

FIGURE II-12