MASTER

AN ASSESSMENT OF
THE POTENTIAL FOR DISTRICT HEATING
IN FOUR MAJOR EASTERN CITIES:

WASHINGTON, D.C.
PHILADELPHIA
BALTIMORE
BOSTON

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ENERGY AND ENVIRONMENTAL SYSTEMS

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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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Prepared by

Energy Systems Research Group, Inc.
Albany, New York

Principal Investigators: Stephen S. Bernow
Richard A. Rosen

Staff Assistants: Alice C. Israel
David R. McAnulty

for

Brookhaven National Laboratory
Upton, New York

and

Argonne National Laboratory
Argonne, Illinois

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ABSTRACT

This study assesses the potential functional and economic advantages of district heating systems for providing the heating, cooling, and hot water energy needs of Washington, D.C., Philadelphia, Baltimore, and Boston. Thermal energy demand, demand coefficients, and costs of thermal energy using conventional systems are considered. Finally, the design of district heating systems is discussed in terms of distribution networks, costs, and payback from fuel savings.

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

In this study the Energy Systems Research Group, Inc. offers an assessment of the potential functional and economic advantages of district heating systems for providing the heating, cooling, and hot water energy needs of the following four major metropolitan centers of the eastern United States:

Washington, D.C.,
Philadelphia,
Baltimore, and
Boston

In reviewing potential district heating system designs, it is necessary first to calculate, as accurately as possible with the information available, the several energy demands for each city. These demands have been derived for four categories of building type and include average, design, and maximum *daily* energy loads in Btu/ft² of floor space. Data on the square footage occupied by each of the four building types by 1-km grid squares were provided by Real Estate Research Corp. from 1970 Census Tract data and from various planning documents that were made available by the four city agencies.

Using these energy demand coefficients, district heating sections were designed for each city to allow the economically feasible potential to be under-

stood as a function of the differing levels of demand intensity in various areas of each city. Although actual street lengths were used to calculate total piping requirements, the distribution system was designed generically for each district heating section and then was geared to the average energy demands for the section as a whole. Cost estimates then were generated for the implementation and use of these district heating distribution systems, taking into account actual costs of labor, materials, and machinery, electric power plant retrofit costs, and user retrofit costs. The latter costs are generically estimated according to building type and present end-use technology. Finally, these cost estimates were compared with the costs of providing the heating energy needs through individual conventional space heating, water heating, and air-conditioning units using modern systems, based on the consumption of fossil fuels and electricity.

1.2 DISTRICT HEATING (D/H) SYSTEMS IN EXISTENCE

A review of the experience of those cities and nations that already have implemented district heating systems is appropriate to see if their experience lends support to this approach. Formerly, conditions in the United States have not encouraged establishment of district heating systems. Factors, such as low fuel costs (until recently), high labor costs for installation of D/H systems, inexperience of U.S. utilities with operating D/H systems, and lack of coherent regional planning tended to work against their implementation.¹ Turn-of-the-century businesses that housed steam-engine-driven electrical generators developed cogenerative thermal systems that utilized the waste steam, but these early efforts yielded to the economics and efficiency of large steam-electric condensing turbines and increasingly larger generating plants using advanced electrical transmission technologies to send power over longer distances.

In the next few decades, however, district heating systems are likely to gain wider acceptance and more extensive implementation in the United States, given rapidly rising fuel costs related to depletion of resources and increased public support of energy efficiency and environmental protection.

In Europe, meanwhile, the use of district heating systems has become increasingly widespread. An unpublished Argonne document² notes that:

The International Building Council...., founded in 1970 under the auspices of UNESCO, is an international success in development of district heating supported by 54 nations.

Argonne lists cities in almost all European countries where district heating systems have been installed. In Denmark, one of the western nation's leaders in implementing district heating, refuse incineration provides space heat in 27 cities; moreover, six power stations cogenerate heat and electricity for Copenhagen and other large cities. In Sweden, district heating provides about 20% of the Swedish demand for space heating and hot water.³ Although the use of waste heat and the cogeneration concept has not gained popular usage in England, district heating projects number 342, and at the *Third International District Heating Conference* in Warsaw, Poland, April 6-9, 1976, A.E. Hasder showed that, in England and Wales, the potential fuel savings resulting from the centralization of heat supply was 20 to 30%.

West Germany also is extensively involved in district heating plans, with 14 major cities already obtaining district heating from cogeneration or refuse incineration. A projected 25 to 30% of all dwellings will be using district heating by the year 2000.

Nations in eastern Europe and the U.S.S.R. use district heating extensively, particularly in the development of new housing, but also in the heating of existing structures. In these countries, legislation supporting total energy utilization, has served to expand use of waste heat from industry and electrical generation. By 1980, it is projected that in Poland, 75% of all buildings in the towns will be district heated. Hungary, Romania, Czechoslovakia, Bulgaria, Yugoslavia, and the GDR all use district heating to a substantial extent.

The facts and figures mentioned here are by no means comprehensive, but they do serve to emphasize that district heating systems have demonstrated increasing viability, particularly in northern European nations, and are presently in a state of rapidly advancing acceptance and implementation. The recent supportive research in using waste heat from fusion reactors² reinforces the concept of district heating in conjunction with the generation of electrical power. The experience of the few district heating systems, implemented on a small-scale basis in North America, also generally tends to be favorable in terms of economics and ability to meet energy demands.² Additional, favorable, studies of the utility and feasibility of district heating systems are available in Refs. 4-7.

The present state of the art in terms of large-scale district heating plans in the United States is still in the theoretical and projective research stages. Referring again to Ref. 1, these authors conclude that:

The results of regional studies indicated that the T and D unit costs (e.g., in $\$/10^6$ Btu) for the D/H systems were considerably lower than the fuel costs for oil heating (i.e., generally less than 50% of the oil heat costs).

This conclusion is reinforced here to the extent that the economics of implementation and use of district heating systems compare advantageously with the use of present heating systems using scarce fuels.

2 THERMAL ENERGY DEMAND*

2.1 BACKGROUND

To assess the costs of district heating systems in four pilot cities in the northeastern United States, it is necessary to obtain reasonable estimates of the thermal energy demand entailed by the space heating, hot water heating, and cooling requirements of these cities. The cities researched are:

Washington, D.C.,
Philadelphia,
Baltimore, and
Boston.

Thermal energy demand coefficients (measured in Btu/ft²/day) will be city-specific and will reflect differences in both climate (length and intensity of heating and cooling seasons) and building characteristics in the cities under study.

For purposes of accuracy and detail, the coefficients for each demand type in a given city will be obtained for each of four building categories designated and defined as follows:

- R₁ - Residential single-family and low density
(from 2 to 49 units per structure);
- R₂ - Residential high-density (multi-family
structures with 50 units or more);
- C/I - Commercial and institutional structures,
including primarily offices and banks,
retail businesses, schools, and hospitals;
and
- I - Industrial structures.

Furthermore, for greater accuracy, the space heating demand coefficients for each of these building categories will be derived from numbers reflecting both the mix and type of structures falling into each category (given in the above definitions) and the mix and demand characteristics of those types presently using different fuels. Finally, in addition to the detail obtained by keeping demand disaggregated by building category, floor space data for each category have been obtained in kilometer square grids spanning each city. This geographic and building category detail allows the analysis of district heating costs to be made for sections of the cities as well as for the cities, as a whole.

* Appendix A discusses thermal energy supply.

2.2 FLOOR SPACE DATA

For each of the four urban centers studied (with the exception of Washington, for which grid square residential floor space was provided on an aggregated basis for all residential building types) Real Estate Research Corporation (RERC) provided estimates of square footage of floor space totals for each category of structure type, i.e., R_1 ; R_2 ; C/I; and I, as defined in Section 2.1. The processes used to develop these figures were slightly different for residential, commercial, and industrial units.

2.2.1 Residential

Residential figures were based on census tract printouts from Table H-2 of the 1970 Census of Housing. They provide the number of year-round housing units in each tract, classified by the number of units per structure. Single-unit structures were converted on the basis of 1,500 ft² per unit; low-density structures, consisting of 2, 3, 4, and 5-49 units were covered at 1,300 ft² per unit. High-rise residential (50 units or more) were also assumed to contain 1,300 ft² per unit. After floor space had been estimated by census tract, these data were converted to a square kilometer basis and transferred to USGS topographical maps of each city. In this manner, the statistics on energy demand intensity could be related to the distribution of building type and floor space served in specific sectors of each city. This is true of the commercial/institutional and industrial sectors as well.

2.2.2 Commercial/Institutional and Industrial

The estimates of floor space in commercial/institutional and industrial buildings were derived from employment data provided by local regional planning commissions. From the number of employees in a given zone, RERC used Standard Industrial Classifications to convert floor space estimates, based on square-foot-per-employee factors indigenous to each city. These data were converted to a grid square basis and transferred to USGS topographical maps of each city, interfacing with the residential data. The floor space to be served in the four cities is listed in Table 2.1.

Table 2.1 Total Floor Space by Building Category in Each City ($10^8/\text{ft}^2$)

City	R ₁	R ₂	C/I	I
Washington, D.C.	3.47		1.80	.133
Philadelphia	7.32	.533	1.84	1.85
Baltimore	4.22	.179	.981	.867
Boston	1.04	1.96	1.00	.637

2.2.3 Fuel Mix

In aggregating final demand coefficients for the four cities, the fuel mix figures shown in Table 2.2 were used.

Except for Washington, D.C., these percentages were extrapolated from tabulations of all occupied housing units as listed in the 1970 Census of Housing. Washington, D.C. data were obtained from Ref. 8. Separate data on fuel mix of the commercial/institutional sector were not available; therefore, the fuel mix was assumed to be that of residential units. The industrial sector was assumed to be space heated predominantly by natural gas.

Table 2.2 Fuel Mix in Percent of Total Units Using Each Type

City		Gas %	Oil %	Electricity %
Washington, D.C.	R 1 & 2	54	40	6
	C/I	43.6	45.3	10.7
Philadelphia	R & C/I	58.4	35.6	2.0
Baltimore	R & C/I	45	51	2.8
Boston	R & C/I	31.1	64.5	3.4

2.3 THE DEMAND COEFFICIENTS

For each of the building categories in the four study cities, thermal energy demand coefficients have been derived for space heating, cooling, and hot water heating. Coefficients (in Btu/ft²/day) are obtained for: (1) the *average* space heating demand throughout the heating season, (2) the *design* space heating demand (average daily demand during the coldest month), and (3) the *maximum* space heating demand (demand incurred when the external temperature has a 1% probability of being exceeded). Similarly, coefficients for average cooling demand throughout the cooling season and maximum cooling demand also have been derived. Daily average hot water demand coefficients are derived assuming uniform requirements throughout the year. Tables 2.3, 2.4, and 2.5 provide annual and daily demand coefficients.

Table 2.3 Annual and Daily Heat Demands (Btu x 10³/ft²)

		Washington	Philadelphia	Baltimore	Boston
Annual Space Heat	(R ₁)	46	62.8	59.2	66.9
	(R ₂)		42.3	43.8	57
	(C/I)	47	59.7	55.7	66
	(I)	37	45	42	49.9
C ₀ : Ave. Space Heat/Day	(R ₁)	.212	.274	.263	.251
	(R ₂)		.185	.194	.214
	(C/I)	.217	.261	.248	.247
	(I)	.170	.197	.187	.187
C ₁ : Design Space Heat/Day	(R ₁)	.306	.402	.383	.416
	(R ₂)		.271	.284	.355
	(C/I)	.313	.383	.361	.410
	(I)	.245	.288	.272	.311
C ₂ : Maximum Space Heat/Day	(R ₁)	.536	.664	.622	.702
	(R ₂)		.448	.461	.598
	(C/I)	.549	.632	.586	.692
	(I)	.429	.475	.442	.523
Annual number of Heating Days		216.7	229	225	258
Annual number of Heating Degree Days		4,211	5,101	4,654	5,634
Design Degrees Below 65°F Reference*		28°	32.7°	30.2°	35°
Maximum Heating Degrees Below 65°F Reference*		49°	54°	49°	59°

*ASHRAE 99% values.

Table 2.4 Annual and Daily Cooling Demands (Btu x 10³/ft²)

		Washington	Philadelphia	Baltimore	Boston
Annual Cooling Demand	(R ₁)	12.54	7.49	8.5	1.67
	(R ₂)		8.09	10.88	2.36
	(C/I)	43.70	32.86	41.0	23.7
	(I)	48.02	36.48	44.75	26.4
C ₄ : Average Cooling Demand/Day, Saturation	(R ₁)	.087	.062	.068	.017
	(R ₂)		.067	.087	.024
	(C/I)	.303	.272	.328	.241
	(I)	.333	.302	.358	.269
C ₅ : Maximum Cooling Demand/Day, Saturation	(R ₁)	.226	.160	.259	.051
	(R ₂)		.176	.349	.073
	(C/I)	.786	.708	.870	.727
	(I)	.864	.785	.928	.808
C ₆ : Average Cooling Demand/Day, No Saturation	(R ₁)	.196	.163	.179	.057
	(R ₂)		.103	.134	.045
	(C/I)	.534	.576	.585	.502
	(I)	.584	.530	.628	.538
C ₇ : Maximum Cooling Demand/Day, No Saturation	(R ₁)	.509	.421	.681	.170
	(R ₂)		.270	.537	.138
	(C/I)	1.38	1.475	1.554	1.510
	(I)	1.52	1.377	1.628	1.616
Annual Number of Cooling Days		144.2	120.8	125	98.3
Annual Number of Cooling Degree Days		1,500	1,300	1,400	849
Maximum Cooling Degrees Above 65° Reference*		27°	28°	29°	26°
A/C Saturation	(R ₁)	.46	.30	.38	.30
	(R ₂)		.53	.65	.53
	(C/I)	.56	.48	.56	.48
	(I)	.57	.50	.57	.50

* ASHRAE, 1% values.

Table 2.5 Annual and Daily Hot Water Demands (Btu x 10³/ft²)

		Washington	Philadelphia	Baltimore	Boston
Annual Hot Water Demand	(R ₁)	12	20	13.6	12
	(R ₂)		13.9	10	10
	(C/I)	3.4	3.5	3.4	3.5
	(I)	2	2	2	2
C ₃ : Average Hot Water Daily	(R ₁)	.033	.038	.038	.033
	(R ₂)		.027	.027	.027
	(C/I)	.009	.0096	.009	.010
	(I)	.0055	.0055	.005	.005

2.3.1 Space Heating

The estimates of daily demand per square foot of floor space have been generated primarily from annual energy load figures provided by Arthur D. Little, Inc. (ADL).^{*} These figures were specified by building type, region, end-use category, and fuel used as shown in Table 2.6 for residential energy loads and in Table 2.7 for non-residential energy loads. Average daily demand estimates have been calculated by dividing by the number of heating days per year in each city. However, several intermediate steps were necessary. Because the ADL figures are region-specific, each demand figure has been made city-specific by assuming a linear relationship between annual space heating demand (per unit in the residential sector and per ft² in the non-residential sector) and the number of heating degree days per year.

When calculating the heat load demand for the cities of Washington, Philadelphia, and Baltimore, the demand figures for the northeast and south were first averaged. Then the number of heating degree days for these cities was divided by the average of heating degree days of the northeast and south. This yielded a numeric factor which was multiplied by the average heat load demands for the northeast and south to give reasonable estimates of heat load demands for each specific city.

^{*} These reports were an updated version of the ADL study done for the Project Independence Report. They were obtained from MOPPS study conducted for the Buildings and Community Systems Division of ERDA.

Table 2.6 Theoretical Building Energy Loads, Residential - Retrofit, 1975 Inventory

Building Type	Region	Heat			Cool	DHW	Light and Power	Aux.
		Gas	Oil	Electric				
Single-Family	NE	94	128	51	6	22	21	
	NC	118	114	64	19	22	23	
	S	43	79	31	63	22	21	NA
	W	57	102	44	74	22	23	
Low Density	NE	67	89	33	5	15	20	
	NC	87	84	45	11	15	21	
	S	30	54	21	36	15	20	NA
	W	37	65	30	54	15	20	
Multi-Family	NE	43	88	17	4	13	18	
	NC	50	49	24	9	13	18	
	S	16	29	10	34	13	17	NA
	W	20	35	14	33	13	18	
Mobile Homes	NE	44	59	24	6	10	17	
	NC	54	53	29	10	10	20	
	S	21	53	15	40	10	20	NA
	W	27	48	20	46	10	17	
All Figures in MMBtu/unit					Assumes the following firing efficiencies:			
					gas .6			
					oil .5			
					electric 1.0			
					a/c cop 2.1			

Table 2.7 Theoretical Building Energy Loads, Non-Residential - Retrofit, 1975 Inventory

Building Type	Region	Heat			Cool	DHW	Light and Power	Aux.
		Gas	Oil	Electric				
Office and Bank	NE	91	83	31	33	3	24	18
	NC	84	68	--	36	-	30	20
	S	64	60	19	87	3	30	22
	W	66	59	20	57	3	31	22
Retail	NE	50	47	14	37	2	62	22
	NC	46	37	--	41	-	67	27
	S	29	26	10	99	2	69	33
	W	35	32	13	68	2	72	33
Schools	NE	80	74	28	28	3	26	15
	NC	74	60	--	30	-	28	18
	S	50	44	14	70	3	28	20
	W	58	52	19	39	3	31	20
Hospitals	NE	97	89	33	42	16	60	32
	NC	90	73	--	45	--	74	32
	S	55	51	14	106	16	73	37
	W	68	61	20	76	16	86	37
Other	NE	49	45	16	37	2	34	22
	NC	46	37	--	41	-	38	27
	S	27	24	11	99	2	37	33
	W	33	30	13	68	2	39	33

All Figures in MMBtu/Square Foot

Assumes the following
firing efficiencies:

gas .6
oil .5
electric 1.0
a/c cop 2.1

A single number for annual space heating demand then was obtained for each building category (R_1 , R_2 , C/I, I) by aggregating the ADL-derived numbers (annual space heating in Table 2.3), by fuel mix (gas, oil, electric), and by building type within each category. The percentages of residential housing of each type (R_1 = single-family and low-density; R_2 = multi-family) were obtained from the 1970 census of housing for each city. Similarly, the fractions of all residential units using each fuel were obtained from housing census data. These numbers were for all residential units, and it was assumed that the same fuel mix was obtained for R_1 and R_2 . The mix of commercial/institutional (C/I) building types was obtained from the ADL regional figures taken from Table 2.8. The space heating fuel mix for the C/I category was assumed to be the same as that for the residential except for Washington, D.C., where the mix was obtained from estimates made by the Council of Governments.⁸

Table 2.8 Commercial Construction Inventory Forecasts (10^6 ft²)

	1975 Inventory	New Construction			Removals 1976-2000	2000 Inventory
		1976-1980	1981-1985	1986-2000		
Northeast Total	5,688	938	980	3,272	879	9,999
Office & Bank	1,321	193	203	660	198	2,179
Retail & Other	2,777	537	569	1,902	416	5,369
Schools	1,150	114	107	342	199	1,514
Hospitals	440	94	101	368	66	934
North Central Total	6,674	1,169	1,217	4,089	1,135	12,014
Office & Bank	1,317	198	207	675	224	2,173
Retail & Other	3,034	668	709	2,390	516	6,285
Schools	1,812	190	179	576	308	2,449
Hospitals	511	113	122	448	87	1,107
South Total	7,320	1,273	1,379	4,783	1,464	13,291
Office & Bank	1,650	265	288	975	330	2,848
Retail & Other	3,654	728	802	2,788	731	7,241
Schools	1,530	167	162	540	306	2,093
Hospitals	486	113	127	480	97	1,109
West Total	4,781	811	891	3,106	813	8,776
Office & Bank	1,146	185	203	690	195	2,029
Retail & Other	2,407	452	506	1,770	409	4,726
Schools	934	104	102	342	159	1,323
Hospitals	294	70	80	304	50	689
U.S. Total	24,463	4,191	4,467	15,250	4,291	44,080

To calculate the demand loads for the two residential categories, one initial step was required. The annual energy load data in the ADL source were given in Btu/units $\times 10^6$. These figures had to be divided by the average floor space (in ft^2) per unit to obtain annual space heating demand per ft^2 of floor space for each of the residential categories. This was necessary because these numbers would have to be multiplied by the floor space data, provided by Real Estate Research Corporation (RERC) to obtain demand on a km^2 grid basis in each city. The assumptions used by RERC in producing residential floor space data were:

single-family (SF) - 1,500 ft^2 /avg. unit
 multi-family (MF) and low-density (LD) - 1,300 ft^2 /avg. unit

The floor space of the R_2 unit, therefore, was taken as 1,300 ft^2 ; whereas, the floor space of the average R_1 unit was taken as an average of 1,300 ft^2 and 1,500 ft^2 weighted by the mix of SF and LD units in the R_1 category. The results are shown in Table 2.9.

Table 2.9 Average Unit Floor Space
in Residential Buildings

City	Mix in R_1 Category ^(a)		Average Unit Floor Space in R_1	Average Unit Floor Space in R_2
	SF(%)	LD		
Washington, D.C.	36.7	63	1,374	1,300
Philadelphia	66.6	27	1,442	1,300
Baltimore	61.3	34.1	1,430	1,300
Boston	14.7	80	1,331	1,300

(a) From 1970 housing census.

Given each of these initial calculations, to gain a total annual space heating demand by building category, appropriate to each city, the average daily heat demand is defined as follows:

$$C_o^i = \frac{D}{n_h} \quad (\text{Eq. 2.1})$$

where:

C_o = average space heating demand in Btu/ft²/day

i = building category: 1 = R_1 , Residential Low Density
 2 = R_2 , Residential High Density
 3 = C/I, Commercial/Institutional
 4 = I, Industrial

D = theoretical heating demand load per year in Btu/ft²

n_h = number of heating days per year for each city.*

The design space heat demand and maximum space heat demand calculations were generated by first deriving a demand-per-degree-day figure, or building factor (BF) for each building category. This building factor was formulated as follows:

$$BF_h = \frac{D}{n_h \text{ deg}} \quad (\text{in Btu/ft}^2/\text{heating degree day}) \quad (\text{Eq. 2.2})$$

where:

D and i are defined as above, and

$n_h \text{ deg}$ = heating degree days, the cumulative average daily variation below 65°F.

The sources of the heating degree days, as well as the cooling degree days in subsequent calculations, were data extrapolated from the Rand Corporation⁹ and *The Weather Handbook*.¹⁰

The design space heat demand then was calculated as follows:

$$C_1^i = BF_h (65^\circ - T_m) \quad (\text{Eq. 2.3})$$

where:

C_1 = design space heat demand load in Btu/ft²/day

i and BF are defined as above, and

T_m = average temperature in degrees Fahrenheit during the coldest month for each city.*

* These data are based on statistics provided by ASHRAE.

The *design* space heating demand (added to the hot water demand discussed below) is the demand for which the distribution pipe network is sized.

The maximum space heat demand was calculated as follows:

$$C_2^i = BF_{h_i} (65^\circ - T_d) \quad (\text{Eq. 2.4})$$

where:

C_2 = maximum space heat demand load in Btu/ft²/day

i and BF are defined as above, and

T_d = average temperature in degrees Fahrenheit on the coldest day of the year.*

2.3.2 Hot Water Heating

The energy demand for providing hot water was assumed to be constant throughout the year. Thus, the demand coefficient is directly obtained from the ADL numbers by dividing by 365.

Additional calculations initially required were:

- (a) The residential data were in Btu/unit and, as such, were converted by the factors of 1,500 ft²/unit for single-family units and 1,300 ft²/unit for multi-family and low-density units.
- (b) The energy demands for R_1 and C/I must be aggregated using the percentages of residential floor space by type of building provided in the ADL research.

2.3.3 Cooling

The calculation of energy demands for cooling follow similar principles to those of space heating. The base figures for annual building energy loads were derived from the ADL research. For Boston, energy demand figures for the northeast were considered appropriate. For the three mid-Atlantic cities, the averages of load figures for the northeast and south were multiplied by a factor created by comparing the number of cooling degree days for the northeast and south.^{9,10} This calculation yielded figures of cooling energy load more specifically appropriate to each city.

*ASHRAE 99% temperature for heating.

Each revised load demand then was multiplied by air conditioning (A/C) saturation factors, appropriate to each type of structure listed. The coefficients, therefore, do not represent cooling demand per square foot, as such. Rather, the A/C saturations are incorporated in the cooling because, in this study, the district heating systems are being compared with the present service of existing demand. The source of these A/C saturation factors, Arthur D. Little, Inc., lists these factors by region; entries for the northeast and south were averaged for use on the mid-Atlantic cities' data (see Table 2.4).

Then, the derived energy load figures for subcategories of R_1 (single-family and low-density) were weighted by the floor space mix percentages as provided in the ADL, Inc., research; the energy load figures for subcategories of C/I likewise were weighted to give representative load demand figures for each category.

Finally, the residential energy load figures appropriate to categories R_1 and R_2 , given in Btu/unit/year were divided by the average floor space per unit as given by RERC figures, to give energy load figures in Btu/ft²/year.

Thus, after revising the ADL, Inc., energy load figures to account for: (1) specific geographic area, (2) A/C saturation, (3) floor space mix, and (4) floor space per residential unit, the derived figures were used to calculate cooling demands. The yearly demand was divided by the number of cooling days per year for each city, as provided in statistics available from ASHRAE, and the resultant number was, in turn, divided by 0.7 (the coefficient of performance assumed for absorption air conditioners) to yield the average cooling energy demand per day:

$$C_4^i = \frac{C_4^i}{n_c} \div 0.7 \quad (\text{Eq. 2.5})$$

where:

C_4 = average cooling demand load in Btu/ft²/day

i = building category: 1 = R_1 , Residential 1

2 = R_2 , Residential 2

3 = C/I, Commercial/Institutional

4 = I, Industrial

C_4 = theoretical cooling demand load per year in Btu/ft², and

n_c = number of cooling days per year for each city.

The maximum cooling demand then was calculated as follows: the derived average cooling energy demand per year was divided by the number of cooling degree days per year (defined as the cumulative average daily variation above 65°).^{9,10} This yields a building factor for cooling (BF_c) expressed in units of Btu/ft²/degree day:

$$BF_c = \frac{C_4^i}{N_c \text{ deg}} \quad (\text{Eq. 2.6})$$

where:

C_4 and i are defined as above, and

$N_c \text{ deg}$ = the number of cooling degree days.

The maximum cooling demand then was derived using the formula:

$$C_5^i = BF_c (T_h - 65^\circ) \quad (\text{Eq. 2.7})$$

where:

C_5 = maximum cooling demand in Btu/ft²/day,

i and BF_c are defined as above, and

T_h = average temperature in degrees Fahrenheit on the hottest day of the year.*

The 100% saturation average cooling energy demand C_6 and 100% saturation maximum cooling energy demand C_7 were figures calculated using the above methodology with the exception that the saturation factors were not included in generating the final demand load figures.

2.4 SUMMARY

The coefficients for design space heat, average hot water, and average cooling demand (in Btu/ft²/day) are summarized in Table 2.10, and Figs. 2.1 through 2.4 show the average daily demands for each building category.

Tables 2.11 through 2.14 provide final annual demand figures for each city; first, by end-use and sector; then by end-use (with sectors aggregated); second for heating, space heat, and hot water combined; and finally for all end-use and sectors combined.

* ASHRAE 1% temperature for cooling.

Table 2.10 Average Daily Space Heat, Hot Water, and Cooling Demands (10^3 Btu/ft²/day)

	Washington	Philadelphia	Baltimore	Boston
R ₁ : Design Space Heat	.306	.402	.383	.416
Hot Water	.033	.038	.037	.033
Avg. Cooling (Sat.)	.087	.062	.068	.017
R ₂ : Design Space Heat	Combined	.271	.284	.355
Hot Water	into	.027	.027	.027
Avg. Cooling (Sat.)	R ₁ data	.067	.087	.024
C/I: Design Space Heat	.313	.383	.361	.410
Hot Water	.009	.0096	.009	.010
Avg. Cooling (Sat.)	.303	.272	.328	.241
I: Design Space Heat	.2450	.2880	.272	.311
Hot Water	.0055	.0055	.005	.005
Avg. Cooling (Sat.)	.3330	.3020	.358	.269

Fig. 2.1 Energy Demand, Residential (R₁) Units

Fig. 2.2 Energy Demand, Residential (R_2) Units

Fig. 2.3 Energy Demand, Commercial/Institutional (C/I) Units

Fig. 2.4 Energy Demand, Industrial (I) Units

Table 2.11 Final Annual Demand -
Washington, D.C.
(10^{12} Btu)

	Space Heat	Hot Water	Cooling
R	15.96	4.16	3.04
C/I	8.46	.61	5.51
I	<u>.49</u>	<u>.027</u>	<u>.45</u>
Total	24.91	4.80	9.00
Heating	<u>29.71</u>		
Heating & Cooling	<u>38.71</u>		

Table 2.12 Final Annual Demand -
Philadelphia
(10^{12} Btu)

	Space Heat	Hot Water	Cooling
R ₁	45.98	10.17	3.84
R ₂	2.27	.53	.30
C/I	10.76	.64	4.24
I	<u>8.32</u>	<u>.37</u>	<u>4.73</u>
Total	67.33	11.71	13.10
Heating	<u>79.04</u>		
Heating & Cooling	<u>92.14</u>		

Table 2.13 Final Annual Demand -
Baltimore (10^{12} Btu)

	Space Heat	Hot Water	Cooling
R ₁	24.99	5.74	2.51
R ₂	.78	.18	.13
C/I	5.46	.33	2.81
I	<u>3.64</u>	<u>.17</u>	<u>2.72</u>
Total	34.86	6.42	8.18
Heating	<u>41.28</u>		
Heating & Cooling	<u>49.46</u>		

Table 2.14 Final Annual Demand -
Boston (10^{12} Btu)

	Space Heat	Hot Water	Cooling
R ₁	6.96	1.25	.12
R ₂	11.17	1.96	.32
C/I	6.60	.35	1.66
I	<u>3.19</u>	<u>.13</u>	<u>1.18</u>
Total	27.92	3.69	3.28
Heating	<u>31.61</u>		
Heating & Cooling	<u>34.89</u>		

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3 COSTS OF THERMAL ENERGY USING CONVENTIONAL SYSTEMS

A primary factor in assessing the practicability of district heating systems is the potential economic advantage over conventional heating units. The following discussion provides comparative cost estimates in $\$/10^6$ Btu for meeting heating, cooling, and hot water needs by building type in the four cities under consideration. Table 3.1 provides the conventional system cost estimates generated.

3.1 METHOD OF ESTIMATION

The average price of space heating in a given city was computed using the most specific data available on the cost of each of the major fuel sources for each city, aggregated according to fuel mix, fuel-firing efficiency, and demand levels. The demand levels used below are the same as those derived in Tables 2.3 through 2.5.

Table 3.1 1977 Cost Estimates for Thermal Energy
Using Conventional Systems ($\$/10^6$ Btu)

Final Demand		Space Heat	Hot Water	Cooling
Washington, D.C.	(R)	5.02	5.39	5.23
	(C/I)	5.06	5.34	3.73
	(I)	4.22	4.75	2.20
Philadelphia	(R ₁)	4.93	6.79	9.94
	(R ₂)	5.03		
	(C/I)	4.61		
	(I)	4.22		
Baltimore	(R ₁)	5.05	5.22	7.05
	(R ₂)	5.14		
	(C/I)	4.87		
	(I)	4.22		
Boston	(R ₁)	6.18	6.56	9.14
	(R ₂)	5.64		
	(C/I)	5.70		
	(I)	5.69		

This calculation was derived using the following formula:

$$P_{sh} = \frac{\sum_{i=1}^3 \frac{D_i P_i f_i}{e_i}}{\sum_{i=1}^3 D_i f_i} \quad (\text{Eq. 3.1})$$

where:

P_{sh} = the price of space heating energy in \$/Btu x 10^6 , for each building category in each city,

i = fuel source; 1 = gas, 2 = oil, and 3 = electricity,

D_i = annual demand load figures for each fuel type,

P_i = price in \$/Btu x 10^6 for each fuel type,

f_i = fuel mix percentage (% of housing units using each fuel type), and

e_i = firing efficiency for each fuel type, taken to be 0.6 for gas heat, 0.5 for oil heat, and 1.0 for electric heat. These are the same assumptions used by ADL, Inc. in deriving its building energy loads.

3.2 SOURCES USED IN COST COMPUTATIONS

Throughout this study, energy demand data have been provided by Arthur D. Little, Inc. As described in Section 2, these annual demand figures have been revised to more specifically represent energy use figures in the cities studied and can be found in Tables 2.3, 2.4, and 2.5. The fuel firing efficiency factors are also taken from the ADL data. Fuel mix data are extrapolated from the *1970 Census of Housing; Detailed Housing Characteristics*.

The specific cost figures for each energy fuel type came from the following sources:

Natural Gas: "Energy Use and Conservation in the Residential Sector: A Regional Analysis," Stephen Dole, June 1975, The Rand Corporation, page 144.

Oil: "Distillate Fuel Oil Prices," the Energy Users News, Volume 2, No. 40, Fairchild Publications, October 10, 1977.

Electricity: Residential: The Directory of Electrical Utilities.

Commercial: Estimates and figures provided by local utilities, corroborated with page 49, "Sourcebook for Energy Assessment," M. Beller, Ed., Brookhaven National Laboratory, December 1975.

Industrial: "Sourcebook for Energy Assessment," loc. cit., "Energy User News," Volume 2, No. 36, Fairchild Publications, September 12, 1977, page 29.

The cost estimates used here were based on 1975 and 1977 statistics. Table 3.2 gives cost estimates for each fuel adjusted (assuming 10% annual inflation) to 1975 base figures. All subsequent calculations were based on 1975 demand and fuel cost figures; the final prices were inflated at a rate of 10% per year to approximate 1977 costs.

The computation of cooling energy demand costs was based strictly on the cost of electricity in each city, given usually in \$/kWh, then converted by the ratio $\frac{3413 \text{ Btu}}{1 \text{ kWh}}$. These figures were also inflated to approximate 1977 costs.

Table 3.2 1975 Cost Estimates of Fuel
for Each City (\$/10⁶ Btu)

City	Natural Gas	Oil	Electricity	
Washington, D.C.	1.76	2.71	R	9.58
			C/I	9.32
			I	5.50
Philadelphia	1.76	2.71	R	17.14
			C/I	14.82
			I	8.00
Baltimore	1.76	2.71	R	12.45
			C/I	12.47
			I	7.17
Boston	2.37	2.71	R	15.70
			C/I	11.72
			I	11.17

The cost of providing hot water was derived in essentially the same manner as space heat energy costs with one important difference. The demand levels for each fuel source were assumed to be equivalent and thus not a factor in aggregating the prices. Equation 3.1 thus was modified to:

$$P_{hw} = \sum_{i=1}^3 \frac{P_i f_i}{e_i} \quad (\text{Eq. 3.2})$$

where:

P_{hw} = the price of hot water in \$/Btu $\times 10^6$ for each building category in each city, and

P_i , f_i , and e_i are defined as previously in Section 3.1.

3.3 SUMMARY OF COST ESTIMATES BY END-USE AND CITY

Given the costs in Table 3.2, the cost of conventional space heating systems ranges from \$4-5 per MMBtu in mid-Atlantic cities and from \$5-6 in the northeast. District heating systems will have to be able to provide for equivalent demands of heat energy at lower cost to be considered a viable alternative to conventional systems. Furthermore, because the imposition of district heating production on existing processes generally decreases process efficiency or increases capital investment, the added cost of meeting process demands must be assessed. In the case of power plants, all increased costs to the utility will be absorbed into the waste heat charge for the hot water.

The cost of thermal energy in providing for hot water needs ranges from a low of \$4 in the industrial sector of Baltimore to \$6.62 in the residential sector of Philadelphia. In comparing the costs of cooling energy, the sector for which energy is provided is the major determining factor in cost ratios. Moreover, air-conditioning systems for the commercial/industrial sector show greater efficiencies; electricity costs (in \$/kWh) tend to be lower in the commercial/industrial sector because of the volume of usage. Cost estimates of cooling energy run from as low as \$2.20/MMBtu in industrial Washington, D.C. to as high as \$9.94/MMBtu in residential Philadelphia.

It is appropriate to further aggregate the data from Table 3.2 to provide direct comparisons of thermal energy costs by end-use and by city. Table 3.3 provides these comparisons: first, for each category of end-use; then

Table 3.3 Comparative Costs of Thermal Energy in
Four Cities, by End-Use (\$/10⁶ Btu)

<u>Total Demand and Cost by End-Use</u>						
City	Space Heat		Hot Water		Cooling	
	Demand*	Cost	Demand	Cost	Demand	Cost
Washington, D.C.	24.91	5.02	4.80	5.38	9.00	4.16
Philadelphia	67.53	4.79	11.71	6.72	13.10	6.21
Baltimore	34.86	4.94	6.42	5.21	8.18	4.95
Boston	27.92	5.79	3.69	6.51	3.28	5.24
<u>Total Demand and Cost, Space Heat, and Hot Water Combined</u>						
City	Space Heat and Hot Water			Cooling		
	Demand	Cost		Demand	Cost	
Washington, D.C.	29.71	5.08		9.00	4.16	
Philadelphia	79.24	5.08		13.10	6.21	
Baltimore	41.28	4.98		8.18	4.95	
Boston	31.61	5.87		3.28	5.24	
<u>Total Demand and Cost, End-Use Aggregated</u>						
City	Thermal Energy End-Use Aggregated					
	Demand		Cost			
Washington, D.C.	38.71		4.87			
Philadelphia	92.34		5.24			
Baltimore	49.46		4.98			
Boston	34.89		5.81			
Total	215.40		5.21			

* All tabled demand figures given in Btu x 10¹²/year.

with space heat and hot-water demand costs combined; and finally with all three end-uses combined, providing a cost-per-unit of thermal demand for each city. These figures are aggregated by weighting the cost data given in Table 3.2, by the annual final demands calculated for each sector for each end-use and city. The aggregated average costs for thermal energy in all four cities, all four sectors, and all three end uses is \$5.21 per 10⁶ Btu, meeting a total

final demand load of approximately 0.2 quads. The cost of energy generally runs higher in Boston than in the other three cities; however, the cost of cooling ran highest in Philadelphia. As might be expected, Washington and Baltimore showed comparable cost figures.

4 DESIGN OF DISTRICT HEATING SYSTEMS

4.1 BREAKDOWN OF CITIES INTO DISTRICT HEATING SECTIONS AND DISTRIBUTION NETWORKS

When the computer program that calculates the design level demand for space heating and hot water heating has determined each grid square of the city, the program then ranks the grid squares by design demand. These rankings are printed out in the form of a grid square map of the city. Natural boundaries, e.g., rivers and bays, were then drawn so that grid squares on opposite sides of such boundaries would not be included in the same "distribution section." A "distribution section" is defined as a small section of the city, generally composed of six contiguous grid squares, but ranging from 3 to 10 grid squares, depending on circumstances. The grid squares in distribution sections share a common pipe network for distributing the hot water from main transmission pipelines to the pipes that service individual blocks. The sections are designed to have as much uniformity in demand density as possible within each section because a subsequent analysis would analyze the system at the section level of aggregation. Sometimes the two criteria of geographical contiguity and rough uniformity of design demand density are not entirely compatible, when geographical and political boundaries make it difficult to satisfy the uniformity criterion. The four cities studied contained from about 20 to 50 such distribution sections each. Figures 4.1 through 4.4 show section maps of each city.

When sections are chosen in this way, it is relatively easy to design the piping system. This is done generically for different geometrical groupings of grid squares into sections. The additional design parameters that must be specified are the temperature changes the hot water would undergo at the point of end-use, and the outdoor temperature difference (and therefore demand) that is assumed for the design points; this includes hot tap water plus design space heating, as, for example:

1. water temperature into end-use device at design outdoor temperature - 200°F,
2. water temperature out of end-use device at design outdoor temperature - 110°F,
3. outdoor temperature; monthly average temperature of coldest month relative to 65°F base, and

Fig. 4.1 Washington, D.C. Section Map

Fig. 4.2 Philadelphia Section Map

Fig. 4.3 Baltimore Section Map

Fig. 4.4 Boston Section Map

4. optimal pipe flowrate as a function of pipe diameter and pressure drop (pumping energy); these were provided by Burns and Roe, Inc. -- see Appendix C.

To meet the peak heating requirements, then, both the hot water input temperature from the power plants and the hot water flowrate in the distribution system can be increased. Similarly, to meet peak cooling requirements the pressure must be greatly increased temporarily since the maximum useful temperature drop for cooling at the end-use device was assumed to be limited to 25°F, and the maximum coefficient of performance (COP) was assumed to be 0.7. Servicing peak demand for heating and cooling therefore requires an increased ratio of pumping energy requirements to district heating or cooling requirements for a small fraction of the year as compared with the pumping energy required to meet design conditions. Of course, this is more than offset by the larger fraction of the year when less hot water flow is required and therefore pumping energy requirements are relatively lower. Since pumping power is proportional to the velocity of flow squared (V^2), and district heating energy demand is proportional to V , the ratio of pumping energy to energy demand is proportional to V . Typical values of this ratio will be enumerated below once the section energy demands are derived. The hourly load curves for each city can be found in Appendix E. These were provided by J. Karkheck of Brookhaven National Laboratory.

For each section a "1 capacity" flowrate was defined as that flowrate that meets design demand of the average grid square in the section, i.e., total section demand divided by the number of grid squares in the section. All other distribution pipes were then sized by flowrate in integer multiples of the "1 capacity" pipe flowrate. The optimal relationship between flowrate (in gallons per minutes) and pipe diameter (in inches) was derived by Burns and Roe, Inc., assuming that the cost of heat from the utility is about \$1/MMBtu and the electricity charge for pumping energy is about \$.05 per kilowatt-hour. It is: Flowrate (in gallons/min.) = $14.32D^2$, where D is the pipe diameter in inches. The total length of pipe of each diameter optimally corresponding to the flowrate carried were then added up for each section. The most common section chosen was rectangular (2 x 3 grid squares). This provides the simplest illustration of the way the distribution pipe system was laid out and sized -- see Fig. 4.5.

* NUMBERS WITHIN THE FIGURE REPRESENT THE CAPACITY RATING OF THE PIPES WHICH ARE SHOWN AS DOTTED LINES.

Fig. 4.5 Distribution Pipe System for a Standard Six-Grid Section

Figure 4.5 shows a distribution pipe system for a standard six-grid section. The solid lines in Figure 4.5 are the grid square boundaries; the dotted lines are the pipes, and the X marks the point that the transmission system would connect to the distribution system. The numbers beside each pipe section indicate the capacity equivalent that pipe would carry to meet design demand. In each grid square, many 1/2-km street pipes (not shown) come off each "1 capacity" pipe (which runs through the center of each grid square) to service the individual blocks. A design calculation was performed, assuming that only streets running in one direction, i.e., in the longest block direction, would require pipes. The buildings on the end of the blocks could be served by a pipe running from the corner half-way down the block through the neighboring buildings. This assumption implies that each 1/2-km street pipe must be able to carry a capacity of 1/2 divided by the sectional average number of kilometers of streets per grid square. For example, if the grid squares in a section average 10 km of streets, then the 1/2 km street pipe will be rated at .05 capacity. If pipes are needed down each street in both directions, the district heating system would be more expensive than projected here. Cost sensitivity to this feature is examined later.

A more complicated pipe system for a section of an eight-grid square is shown in Fig. 4.6.

*NUMBERS WITHIN THE FIGURE REPRESENT THE CAPACITY RATING OF THE PIPES WHICH ARE SHOWN AS DOTTED LINES.

Fig. 4.6 Distribution Pipe System for an Irregularly Shaped Eight-Grid Section

4.2 COSTING THE DISTRICT HEATING SYSTEM

The capital costs of the district heating system include the costs of the distribution network within each section, the end-use retrofit and street connection costs (both for heating alone and for heating and cooling), the transmission costs, and power plant retrofit costs. For the purposes of this analysis, however, the transmission and power plant retrofit costs have been excluded from the capital costs and instead have been absorbed into the cost of the 200°F hot water supplied to the district heating system. These are treated separately. The capital costs (distribution and retrofit) can be calculated on a section-by-section basis, thereby permitting close scrutiny of the cost-effectiveness (marginal or system-wide) of adding each section in turn to the system.

4.2.1 Capital Costs

- *Distribution Network.* When the total length of pipes by diameter for each section has been obtained, the total distribution cost for the section is aggregated from parameterized pipe cost equations provided by Burns and Roe, Inc., for each of the four urban areas (see Table 4.1).

Table 4.1 Parameterized Pipe Costs for Distribution Networks

City	A	B
Washington, D.C.	78.38	13.83
Philadelphia	86.55	14.67
Baltimore	77.66	13.94
Boston	83.72	14.37

$$C = A + B \times D$$

where: C is the total cost of pipe laid
(in \$/ft.) for each pipe diameter
D (in inches).

Burns and Roe parameterized piping system cost estimates for urban, suburban, and rural, are provided in Appendix B. Given the calculation of yearly space heat, hot water, and cooling demand in each section, the capital cost (in \$/MMBtu) can be determined for the section distribution network alone. It might be useful to know this cost separately from the retrofit cost because ultimately it may be financed differently from the latter. However, from a systems point of view, i.e., one that measures energy conservation versus capital investment system-wide, it is more appropriate to aggregate the distribution network costs and end-use retrofit costs. These costs are given in Table 4.2.

Table 4.2 District Heating Capital Costs by City (\$/10⁹)

City	Distribution System	Heating Retrofit	Cooling Retrofit	Total Retrofit	Total Heating	Total System Cost
Washington, D.C.	.420	.281	.472	.753	.701	1.173
Philadelphia	1.115	.674	.681	1.355	1.789	2.460
Baltimore	.615	.368	.489	.857	.983	1.472
Boston	.424	.226	.377	.603	.650	1.027

• *End Use Retrofit.* The cost of retrofitting the existing end-use space heating, hot water heating, and cooling equipment to make them compatible with the district heating system is calculated for each section for space heating and hot water heating (total heating) and cooling separately. This allows the cost effectiveness of sections (and the entire system) to be evaluated for heating and heating-and-cooling separately. In this way, the marginal impact of adding cooling to the system's capability can be assessed. This may be important from several standpoints, as, for example, the relationship of the district heating systems to utility load factors and load management efforts.

Estimates for space heating/hot water and air conditioning retrofit costs were provided by Burns and Roe, Inc., based on building models and associated energy loads that they constructed. Separate costs were used for each of the four building categories for which floor space area was available at the grid square level of disaggregation (see Table 4.3).

The total cost for distribution and retrofit for both space heat and hot water, and then for adding air conditioning, was obtained by section for each city and then converted to a dollar per MMBtu of a final demand satisfied (see Tables 4.4 - 4.7). In Washington, D.C., the costs ranged from \$1.40/MMBtu to \$3.79/MMBtu for heating alone, and from \$1.71/MMBtu to \$4.22/MMBtu when air conditioning demand was included. These results assume an 8% fixed charge rate. To this, a charge of \$1.50/MMBtu to \$2/MMBtu is added to reflect the costs of the waste heat (200°F hot water) from the power plants. Because transmission costs, power plant retrofit costs, pumping costs, and the cost of extra power plant fuel have been included in the cost of the waste heat, it will be shown later that the choice of \$1.50 - \$2/MMBtu is reasonable.

Two points should be made here to put these results in proper perspective. First, although the upper limit of this range, i.e., \$4.22/MMBtu in Washington, D.C., which, with waste heat costs could reach \$6.22/MMBtu, appears somewhat high, this is the marginal cost for the least cost-effective section. Although generally the least cost-effective sections have the lowest demand density, the effect of adding these sections to the system does not substantially increase the system-wide average costs, which, as will be

Table 4.3 District Heating End-Use Retrofit, Case Study Descriptions and Cost Breakdowns^(a)

Building Type	Model Description	Gross Bldg. Area (Sq. ft.)	Capacity		Cost (\$)		Street Inter-Connection	Cost (\$/Ft ²)	
			HTG MMBtu/Hr	A/C Tons	HTG	A/C		HTG	A/C
R ₁ ^(b)	Apt. house unitary (window) A/C steam or hot water heat	30,000 30 apts.	--	--	18,000	70,000	--	0.60	2.33
R ₂	Apt. bldg. unitary (window) A/C hot water heat	200,000 200 apts.	16.5	350	63,600	489,000	14,000	0.32	2.45
C/I	Office bldg. 10 floors compression chiller one central fan room steam or hot water heat	200,000	17.5	520	152,200	176,900	14,000	0.76	0.83
I ^(c)	Office bldg. 10 floors steam absorption one central fan room steam or hot water heat	400,000	33.0	1,200	164,300	82,600	14,000	0.41	0.21

^(a) Model analysis supplied by Burns and Roe, Inc.

^(b) Private communication from Larry Davito of Burns and Roe, Inc., heating costs include street inter-connection.

^(c) This model was used to give estimates for the industrial sector.

Table 4.4 District Heating Capital Costs for Sections
of Washington, D.C.

Section Number	Cost at 8% FCR (\$/MMBtu)	Heating Demand (10 ¹² Btu)	Running Average (\$/MMBtu)	Cost with Cooling at 8% FCR (\$/MMBtu)	Demand with Cooling (10 ¹² Btu)	Running Average (\$/MMBtu)
2	1.38	2.98	1.38	2.31	3.63	2.31
1	1.40	5.24	1.393	1.71	7.49	1.906
4	1.64	2.14	1.444	2.22	3.80	1.969
9	1.70	1.50	1.476	2.70	1.77	2.052
11	1.71	1.17	1.497	2.66	1.40	2.101
10	1.85	1.23	1.528	2.53	1.55	2.137
3	1.88	2.55	1.581	1.87	3.82	2.092
8	1.89	1.45	1.606	2.41	1.90	2.116
5	1.90	1.75	1.631	2.61	2.20	2.157
7	2.03	1.46	1.658	3.00	1.72	2.209
6	2.05	1.69	1.687	2.47	2.25	2.228
13	2.07	1.04	1.704	3.00	2.23	2.258
14	2.31	.96	1.727	2.91	1.21	2.282
15	2.32	.61	1.741	3.09	.74	2.299
12	2.38	1.12	1.767	2.82	1.46	2.321
17	2.43	.57	1.781	3.21	.69	2.338
20	2.59	.42	1.793	3.48	.50	2.354
16	2.94	.57	1.816	3.01	.77	2.367
18	3.65	.48	1.847	4.23	.58	2.396
19	3.77	.41	1.874	3.89	.53	2.417
21	3.79	.27	1.891	3.54	.38	2.428

	Heating Demand (10 ¹² Btu)	Heating System Cost at 8% FCR (\$/MMBtu)	Demand with Cooling (10 ¹² Btu)	Heating and Cooling System Cost at 8% FCR (\$/MMBtu)
Citywide System	29.71	1.89	38.71	2.43

Table 4.5 District Heating Capital Costs for Sections of Philadelphia

Section Number	Cost at 8% FCR (\$/MMBtu)	Heating Demand (10^{12} Btu)	Running Average (\$/MMBtu)	Cost with Cooling at 8% FCR (\$/MMBtu)	Demand with Cooling (10^{12} Btu)	Running Average (\$/MMBtu)
1	1.23	4.51	1.23	1.76	4.98	1.76
2	1.26	4.03	1.24	1.64	4.67	1.70
7	1.36	4.34	1.28	1.69	5.36	1.70
3	1.39	3.72	1.31	1.94	4.11	1.75
6	1.39	4.98	1.33	1.79	5.80	1.76
8	1.40	4.41	1.34	1.36	6.01	1.68
5	1.42	3.90	1.35	1.79	4.63	1.70
9	1.43	2.61	1.36	1.73	3.10	1.70
4	1.44	2.71	1.36	1.79	3.15	1.71
10	1.51	2.55	1.37	1.87	3.01	1.72
12	1.52	2.16	1.38	1.98	2.45	1.73
13	1.52	2.36	1.39	2.02	2.61	1.75
11	1.53	2.01	1.39	1.89	2.33	1.75
20	1.60	2.64	1.41	2.10	2.91	1.77
19	1.69	1.33	1.41	2.19	1.53	1.78
14	1.70	1.48	1.42	2.17	1.64	1.79
15	1.70	1.68	1.43	2.23	1.90	1.81
16	1.78	1.29	1.44	1.87	1.60	1.81
22	1.79	2.22	1.45	2.16	2.54	1.82
21	1.81	2.04	1.47	2.25	2.27	1.84
28	1.89	1.18	1.48	2.38	1.31	1.85
17	1.95	1.48	1.49	2.48	1.62	1.86
27	1.95	1.53	1.50	2.42	1.68	1.87
23	1.97	1.76	1.51	2.30	2.02	1.89
35	2.00	.89	1.52	2.51	.98	1.89
18	2.01	1.48	1.53	2.45	1.64	1.91
56	2.03	.79	1.54	2.74	.90	1.92
29	2.17	1.07	1.55	2.07	1.32	1.92
31	2.17	.78	1.55	2.56	.88	1.93
24	2.19	1.34	1.57	2.65	1.48	1.94

Table 4.5 District Heating Capital Costs for Sections of Philadelphia (Contd.)

Section Number	Cost at 8% FCR (\$/MMBtu)	Heating Demand (10 ¹² Btu)	Running Average (\$/MMBtu)	Cost with Cooling at 8% FCR (\$/MMBtu)	Demand with Cooling (10 ¹² Btu)	Running Average (\$/MMBtu)
32	2.21	.78	1.57	2.63	.87	1.95
34	2.27	.98	1.58	2.69	1.09	1.96
39	2.29	.52	1.59	2.04	.72	1.96
38	2.40	.72	1.60	2.54	.86	1.99
25	2.41	.92	1.61	2.82	1.01	2.00
33	2.62	.94	1.62	2.84	1.07	2.01
26	2.63	.94	1.63	2.89	1.07	2.02
36	2.69	.58	1.64	3.04	.65	2.03
37	2.94	.54	1.65	3.25	.58	2.04
41	3.01	.34	1.65	3.48	.38	2.04
30	3.33	.56	1.67	2.94	.74	2.05
44	3.40	.33	1.67	3.01	.43	2.05
42	4.38	.29	1.68	4.39	.34	2.06
43	4.61	.21	1.69	4.28	.26	2.07
48	4.66	.14	1.70	3.29	.22	2.07
46	5.12	.15	1.70	5.29	.16	2.08
40	5.51	.26	1.72	4.17	.37	2.09
45	5.73	.19	1.73	4.14	.28	2.09
51	8.07	.09	1.73	5.94	.13	2.10
52	12.86	.07	1.74	9.42	.10	2.11
49	13.35	.08	1.76	11.14	.10	2.12
50	14.12	.09	1.77	9.73	.14	2.13
47	15.44	.06	1.78	10.71	.08	2.14
53	20.41	.05	1.79	14.94	.06	2.14
55	72.77	.001	1.79	53.71	.002	2.14
54	169.52	.004	1.80	119.32	.006	2.15
		Heating Demand (10 ¹² Btu)	Heating System Cost at 8% FCR (\$/MMBtu)	Demand with Cooling (10 ¹² Btu)	Heating and Cooling System Cost at 8% FCR (\$/MMBtu)	
Citywide System		79.1	1.80	92.2	2.15	

Table 4.6 District Heating Capital Costs for Sections of Baltimore

Section Number	Cost at 8% FCR (\$/MMBtu)	Heating Demand (10^{12} Btu)	Running Average (\$/MMBtu)	Cost with Cooling at 8% FCR (\$/MMBtu)	Demand with Cooling (10^{12} Btu)	Running Average (\$/MMBtu)
1	1.35	3.42	1.35	1.95	4.06	1.95
4	1.44	2.63	1.39	1.97	3.10	1.96
3	1.47	3.51	1.42	1.54	4.97	1.79
12	1.50	2.11	1.43	2.01	2.51	1.83
8	1.59	1.57	1.45	2.22	1.89	1.87
2	1.64	2.39	1.48	2.07	2.92	1.90
6	1.64	1.64	1.50	2.28	1.86	1.93
7	1.66	1.73	1.51	2.22	2.00	1.96
5	1.69	1.86	1.53	2.34	2.11	1.99
14	1.74	1.58	1.54	2.13	1.91	2.00
9	1.88	1.54	1.56	2.48	1.75	2.03
10	1.97	1.15	1.58	2.61	1.29	2.05
11	1.97	1.36	1.60	2.61	1.53	2.08
36	1.98	.44	1.61	2.14	.57	2.08
18	2.02	.80	1.62	2.40	.96	2.09
17	2.03	.78	1.63	2.39	.95	2.10
16	2.07	1.10	1.65	2.72	1.23	2.12
20	2.07	.84	1.66	2.70	.94	2.13
33	2.23	.41	1.67	2.67	.48	2.14
28	2.25	.77	1.68	2.80	.87	2.16
40	2.25	.59	1.69	2.80	.67	2.17
19	2.27	.54	1.70	2.36	.69	2.17
32	2.32	.60	1.71	2.65	.72	2.18
21	2.34	.54	1.72	2.75	.64	2.19
35	2.36	.69	1.73	2.79	.81	2.20
30	2.39	.39	1.74	3.05	.43	2.21
22	2.44	.54	1.75	3.03	.61	2.22
15	2.46	.94	1.77	3.06	1.05	2.24
13	2.47	.87	1.79	3.09	.97	2.26
37	2.47	.24	1.79	1.85	.38	2.26

Table 4.6 District Heating Capital Costs for Sections
of Baltimore (Contd.)

Section Number	Cost at 8% FCR (\$/MMBtu)	Heating Demand (10^{12} Btu)	Running Average (\$/MMBtu)	Cost with Cooling at 8% FCR (\$/MMBtu)	Demand with Cooling (10^{12} Btu)	Running Average (\$/MMBtu)
27	2.47	.49	1.80	3.03	.55	2.27
34	2.52	.47	1.81	2.46	.61	2.27
29	3.02	.49	1.82	3.47	.56	2.28
26	3.06	.37	1.84	3.56	.42	2.29
38	3.22	.32	1.85	2.27	.51	2.29
24	3.38	.41	1.86	3.65	.49	2.31
31	3.43	.20	1.87	2.83	.29	2.31
23	3.60	.30	1.88	3.91	.35	2.32
25	3.95	.22	1.89	4.08	.26	2.33
39	4.21	.16	1.90	3.14	.24	2.34
41	7.33	.04	1.91	4.94	.06	2.34
		Heating Demand (10^{12} Btu)	Heating System Cost at 8% FCR (\$/MMBtu)	Total Demand (10^{12} Btu)	Heating and Cooling System Costs at 8% FCR (\$/MMBtu)	
Citywide System		41.04	1.91	49.20	2.34	

Table 4.7 District Heating Capital Costs for Sections of Boston

Section Number	Cost at 8% FCR (\$/MMBtu)	Heating Demand (10^{12} Btu)	Running Average (\$/MMBtu)	Cost with Cooling at 8% FCR (\$/MMBtu)	Demand with Cooling (10^{12} Btu)	Running Average (\$/MMBtu)
5	1.22	2.21	1.22	2.33	2.39	2.33
3	1.24	3.29	1.23	1.96	3.76	2.10
1	1.28	5.97	1.26	1.56	7.24	1.81
4	1.31	2.77	1.27	2.39	2.98	1.92
12	1.49	.89	1.28	2.42	.99	1.94
7	1.63	1.62	1.31	2.65	1.69	2.01
2	1.68	2.85	1.37	2.60	3.01	2.09
6	1.68	1.88	1.39	2.48	2.05	2.12
8	1.90	1.25	1.42	2.74	1.29	2.15
13	1.90	1.00	1.44	2.73	2.06	2.18
20	1.93	.91	1.46	2.90	.95	2.20
10	1.94	1.07	1.48	2.61	1.20	2.22
14	1.96	.89	1.50	2.80	.91	2.24
21	2.21	.67	1.51	2.88	.69	2.25
17	2.24	.83	1.54	2.93	.85	2.27
11	2.29	.75	1.56	3.02	.79	2.29
15	2.33	.65	1.57	2.85	.69	2.30
18	2.46	.56	1.59	2.48	.70	2.30
9	2.50	.98	1.62	3.26	1.01	2.33
16	3.33	.39	1.64	3.78	.41	2.35
19	3.75	.17	1.65	4.49	.17	2.36
		Heating Demand (10^{12} Btu)	Heating System Costs at 8% FCR (\$/MMBtu)	Total Demand (10^{12} Btu)	Heating and Cooling System Costs at 8% FCR (\$/MMBtu)	
Citywide System		31.60	1.65	34.83	2.36	

shown, proves that the system, as a whole, is cost-effective. From an energy conservation standpoint, this is important. Similarly, from an energy conservation point of view, the cost in \$/MMBtu which measures total costs (capital investment and waste heat) against final demand served may not be as illuminating as measuring capital costs alone versus dollars saved from fuel conserved. These points, along with the results that reflect them, will be discussed further.

4.2.2 Waste Heat Costs

- *Design and Cost of the Transmission System.* The transmission lines were designed in a way that would interconnect the power plants providing waste heat and provide redundancy in heat delivery capability to each distribution section in the city. The costs were calculated on the assumption that all sections would be district heated. Table 4.8 lists the power plants and turbine capacities for each city; Table 4.9 compares available waste heat with demand; and Table 4.10 shows the transmission pipe requirements and the costs for each city. Figures 4.3 to 4.6 show the city-specific transmission systems. Total costs for laying transmission pipes of various diameters specific to urban, suburban, and rural environments were provided by Burns and Roe, Inc. Typical transmission costs range from \$.78/MMBtu to \$1.15/MMBtu at 10% fixed charge rate (see Table 4.10); these costs were absorbed into the waste heat costs.

Table 4.8 Availability of Power Plant Waste Heat

	Washington, D.C. Generating Stations			
	Benning	Buzzard	Potomac	Chalk Point
Turbine Capacities (MW)	52	28	86	330
	82	30	67	330
	275	50	102	330
	275	50	102	
		50	102	
		50		
Station Total (Steam)	684	258	459	1268
Available Capacity - 2669 MW				
Available Waste Heat - 159.6×10^{12} Btu/yr				

Table 4.8 Availability of Power Plant Waste Heat (Contd.)

	Philadelphia Generating Stations							
	Bar- badoes	Chester	Del- aware	Eddy- stone	Schyl- kill	South- wark	Edge- moor	Rich- mond
Turbine Capacities (MW)	136	130	128 128	321 343 380 380	175 54 34	188 188	70 70 82 167 412	175 115
Station Total (Steam)	136	130	256	1424	263	376	801	290
Available Capacity - Peach Bottom (1100 MW)								
W/O Peach Bottom -								3676
With Peach Bottom -								4776
Available Waste Heat - Without Peach Bottom -								219.8×10^{12} Btu/yr
With Peach Bottom -								285.6×10^{12} Btu/yr

	Baltimore Generating Stations				
	Riverside	Wagner	Peach Bottom	Dickerson	Bethlehem Steel Entitlement
Turbine Capacities (MW)	59	138	1100	182	169
	60	135		183	
	62	321		183	
	79	400			
	66				
Station Total (Steam)	326	994	1100	548	169
Available Capacity - 3137 MW					
Available Waste Heat - 187.6×10^{12} Btu/yr					

	Boston Generating Stations				
	New Boston	L Street	Edgar	Mystic	Pilgrim
Turbine Capacities (MW)	717	48	300	617 469	670
Station Total (Steam)	717	48	300	1086	670
Available Capacity - 2821 MW					
Available Waste Heat - 168.6×10^{12} Btu/yr					

Table 4.9 Power Plant Waste Heat Compared with District Heating Demand

	Maximum Available Waste Heat from Power Plant Steam Turbines (10^{12} Btu/hr)	Yearly Thermal Demand (10^{12} Btu/hr)		Maximum Available Waste Heat (10^{12} Btu/day)	Maximum Daily Thermal Demand (10^{12} Btu/day)	
		Heating	Heat. & Cooling		Heating	Cooling & Hot Water
Wash- ington	160	29.7	43.6	.438	.304	.244
Phil- adelphia	220 (286)*	79.0	97.8	.605 (.782)*	.744	.435
Balti- more	188	41.3	53.0	.515	.384	.260
Boston	169	31.6	36.2	.463	.342	.153

* Numbers in parenthesis are for inclusion of Peach Bottom.

Table 4.10 Transmission System Costs

	Km. of Pipeline (48-in. Diam.)		Approximate Cost \$/ft	Total Cost (\$/ 10^6)	Demand with Cooling (10^{12} Btu)	\$/ 10^6 Btu @ 10% FCR
	Urban	Rural & Suburban				
Wash- ington	53.3	48	1,000 800	175 126		
Total				301	38.7	.78
Phil- adelphia	136	59.7 (158)	1,000 800	446 157	(414)* 92.2	.65 (.93)*
Total				603 (860)*	92.2	.65 (.93)
Balti- more	68.3	130	1,000 800	224 341		
Total				565	49.2	1.15
Boston	57.7	80.5	1,000 800	189 211		
Total				400	34.9	1.15

* Numbers in parenthesis are for inclusion of Peach Bottom.

• *Utility Retrofit Costs.* The costs of retrofitting the power plants to produce 200°F hot water discharge to the district heating system have been estimated to be \$15 to \$20/kWe.¹¹ The total power plant capacities, available for the district heating systems in each city, are shown along with the final demand served and cost (in \$/MMBtu) at 10% fixed charge rate in Table 4.11. The contributions to the waste heat costs range from \$0.7/MMBtu to \$.18/MMBtu.

Table 4.11 Power Plant Retrofit Costs

	Total Capacity (MW)	Final Demand		Cost at 10% Fixed Charge	
		Heating (10 ¹² Btu)	Heating & Cooling Btu)	Heating (\$/MMBtu)	Heating & Cooling (\$/MMBtu)
Washington, D.C.	2669	29.71	38.71	.14-.18	.11-.14
Philadelphia	3676 (4776)*	79.04	92.14	.07-.09 (.09-.12)*	.06-.08 (.08-.11)*
Baltimore	3137	41.28	49.46	.12-.15	.09-.13
Boston	2821	31.61	34.89	.14-.18	.12-.16

* Numbers in parenthesis are for inclusion of Peach Bottom.

• *Pumping and Heat Losses.* Because the engineering designs provided by Burns and Roe, Inc., show that the optimal flowrate in the district heating network is related both to pressure drop and pipe diameter (see Appendix C), a simple expression can be derived for the ratio (R) of the pumping energy to the energy delivered at the design point. From above (Section 4.1):

$$\text{Flowrate} = 8.71 \times 10^5 / (\Delta p)^2$$

where:

flowrate is measured in gal/min

Δp (pressure drop) is measured in psi/mi

flowrate = 14.32 D², where D is the pipe diameter (in.)

the result is that:

$$R = 0.0103 (L/D), \text{ where } L \text{ is the length of pipe in km.}$$

This expression is valid only at the distribution system design point. Because R for higher flow velocities (V) is linearly proportional to V , and therefore demand,

$$R = .0103 (L/D) (Q/Q_0) \quad (\text{Eq. 4.1})$$

where:

Q = demand, and

Q_0 = demand at the design point.

Typical values of R in Washington, D.C., at the design point for the smallest pipes, the individual street pipes, range from .0010 to .0026 (.1% to .26%). The R 's are roughly additive from the power plant to the farthest point of any distribution section; however, as L increases for the largest distribution and transmission pipes, so does D , such that the ratio is approximately constant. Thus, for the transmission pipes with $L \approx 40$ km, and $D \approx 50$ in., $R \approx 1\%$. The sum of the pressure drops within the distribution sections would add about .5%, giving a total of about 1.5%. In Washington, D.C. at peak demand for heating or cooling, Q/Q_0 never exceeds 1.85, so that R would range to about 3% at maximum. The same results apply to the other cities as well.

Finally, because the design load is always set at a point greater than 50% of peak demand, from the hourly load curves (Appendix E), design demand for both heating and cooling is only exceeded about 20% of the year. This implies that the yearly average for R should fall well below the 1.5% for the design conditions. If 1% is used for purposes of estimating this contribution to waste heat costs, the resultant pumping energy costs are shown in Table 4.12. which includes the city specific electricity costs (for pumping energy).

Table 4.12 Pumping Energy Costs

City	Thermal Demand (10^{12} Btu)	Pumping Energy (10^{12} Btu)	Average Price of Electricity (\$/MMBtu)	Pumping Cost (\$/MMBtu)
Washington, D.C.	43.57	.44	6.66	.07
Philadelphia	97.75	.98	9.68	.10
Baltimore	52.97	.53	8.68	.09
Boston	36.30	.36	13.52	.14

System heat losses given in Appendix F, have been supplied by Burns and Roe, Inc., for supply line and return line, respectively. These results indicate that for typical water temperature differences of 100°F or less, a 4-in. street pipe 0.5 km long will lose about .7% in the supply line and 1.2% in the return line as measured against heat carried, with 3 in. and 2 in. of insulation, respectively. These numbers are for a section heat demand of 12×10^9 Btu/day. For large pipe sizes, the proportion of heat loss drops dramatically because, according to the Burns and Roe, Inc., figures, the slope for line #3 is less than 1, and the carrying capacity of pipes is proportioned to D^2 . Thus, total heat losses may be about 3% throughout the system.

• *Cost of Extra Fuel.* As will be demonstrated in Section 4.3 on fuel savings, the extra fuel required to maintain existing power plant generating capacity when the turbines are modified to produce 200°F hot water discharge is given by:

$$\Delta F = E/2.43 \quad (\text{Eq. 4.2})$$

where:

E = the demand for hot water in 10^{12} Btu/year, and

ΔF = extra fuel demand in the same units.

Thus, the cost of the extra fuel (in \$/MMBtu) is roughly 40% of the price of fuel paid by the utilities, which, for a mix of coal and oil is approximately \$1.50/MMBtu. This contributes about \$.60/MMBtu to the cost of waste heat.

While the total cost for waste heat supplied to the district heating system is estimated below (Table 4.13) to be between \$1.43 MMBtu and \$2.04/MMBtu, it should be noted that the transmission line costs which contribute about 50% of this are based upon highly inflated estimates. It, therefore, appears justified that the choices of \$2/MMBtu and \$1.50/MMBtu for the cost of waste heat have been made in order to evaluate the cost-effectiveness of the district heating systems.

Table 4.13 Waste Heat Costs (\$/MMBtu)

	Transmission	Utility Retrofit	Pumping	Fuel	Total
Washington, D.C.	.78	.15	.07	.60	1.60
Philadelphia	.65 (.93)	.08 (.10)	.10	.60	1.43 (1.73)
Baltimore	1.15	.12	.09	.60	1.96
Boston	1.15	.15	.14	.60	2.04

* Numbers in parenthesis are for inclusion of Peach Bottom.

4.2.3 System-Wide Costs

The system-wide costs of district heating in each city including both capital costs and waste heat costs, are summarized in Tables 4.14 to 4.17, which assume \$2/MMBtu or \$1.50/MMBtu waste heat costs and 8% or 10% annual fixed charge rate. The tables also show for comparison the costs of present service.

Table 4.14 District Heating Systems
Costs for Washington, D.C.
(\$/MMBtu)

Fixed Charges	Waste Heat Costs	Heating	Heating & Cooling
8%	\$1.50	3.39	3.92
8%	\$2.00	3.89	4.42
10%	\$1.50	3.86	4.53
Cost of present service:		5.08	4.87

Table 4.15 District Heating Systems
Costs for Philadelphia
(\$/MMBtu)

Fixed Charges	Waste Heat Costs	Heating	Heating & Cooling
8%	\$1.50	3.30	3.65
8%	\$2.00	3.80	4.15
10%	\$1.50	3.75	4.19
Cost of present service:		5.08	5.24

Table 4.16 District Heating Systems
Costs for Baltimore
(\$/MMBtu)

Fixed Charges	Waste Heat Costs	Heating	Heating & Cooling
8%	\$1.50	3.41	3.84
8%	\$2.00	3.91	4.34
10%	\$1.50	3.89	4.39
Cost of present service:		4.98	4.98

Table 4.17 District Heating Systems
Costs for Boston (\$/MMBtu)

Fixed Charges	Waste Heat Costs	Heating	Heating & Cooling
8%	\$1.50	3.15	3.86
8%	\$2.00	3.65	4.36
10%	\$1.50	3.56	4.45
Cost of present service:		5.87	5.81

4.2.4 Sensitivity of Results to Uni-Directional Street Pipe Assumptions

A check of ten randomly chosen distribution sections in Washington, D.C. shows that the total length of streets is, on the average, about twice (1.96) the length assigned to the smallest diameter pipes. If it is required that pipes be put down every street, new distribution costs can be calculated from the computer printouts of sectional costs obtained in this study. For instance, Washington, D.C., Table 4.18 compares new and old distribution and retrofit cost for heating only for Sections 1 to 10, and gives the ratio of new to old costs,

Table 4.18 Sensitivity of Results to Uni-Directional
Street Pipe Assumptions for Washington, D.C.

Section Number	Heating Distribution and Retrofit Costs (\$ x 10 ⁶)		Ratio New/Old	Cooling Retrofit Costs (\$ x 10 ⁶)	Ratio With Cooling
	Old	New			
1	91.9	113.5	1.24	128.3	1.10
2	51.6	71.5	1.39	77.4	1.15
3	59.8	76.9	1.29	62.0	1.14
4	43.8	58.4	1.33	54.7	1.15
5	41.7	58.1	1.39	45.3	1.19
6	43.5	62.4	1.43	43.0	1.22
7	37.1	53.6	1.44	38.1	1.22
8	34.3	48.5	1.41	37.1	1.20
9	31.8	44.9	1.41	39.1	1.18
10	28.3	40.4	1.43	31.2	1.20

The initial observation that can be made is that extending pipes to all streets would increase the capital costs for distribution and end-use retrofit by about 40% for a system supplying heating only. For a system supplying both heating and cooling, the costs would increase by only about 20% because cooling retrofit costs are quite high. These percentage increases would be even lower when the waste-heat charge is added (about 10% for cooling and heating, and about 20% for heating) and when they are weighted by section demand and averaged over the entire city.

4.3 DISCUSSION OF RESULTS

4.3.1 Cost Analysis and Energy Conservation

The two criteria generally used to assess new energy systems are improved energy (or fuel) efficiency and competitive system costs. Often these criteria cannot be satisfied simultaneously, especially when new and evolving technologies are involved. In district heating systems, however, system costs remain well below those of existing service. Furthermore, the substantial fuel savings resulting from replacing existing systems with district heating

systems entails an annual savings that offsets the large capital costs at reasonable fixed-charge rates.

4.3.2 Cost of Servicing Final Demand

When the capital costs of district heating have been determined on a section-by-section basis, then, assuming \$1.50/MMBtu or \$2.00/MMBtu for waste heat, the areas of the city that can be cost-effectively district heated can be determined for either of two options: (1) space-heating and hot-water heating (heating), or (2) heating and cooling. At least two criteria can be used to decide which sections are to be included when a cut-off cost per MMBtu has been established. It is possible to evaluate the cost-effectiveness of including sections in the system by examining either its marginal cost per MMBtu or its effect on the average system cost per MMBtu. Section maps (see Appendix D) of each city display the areas that would be included on the basis of marginal costs for each demand service option if those costs were lower than the costs of the comparable existing system. The system average cost criterion would allow even the marginally non-cost-effective sections to be included because generally these are sections that have low demand density and therefore do not substantially increase the system average costs which are considerably lower. From an energy conservation point of view, this is an important way of evaluating each district heating system because virtually the entire city's demand can be cost effectively satisfied using waste heat from existing central station power plants. The maps were based on the cut-off values given in Table 3.3 which represent the present-day mix of competing fuel costs to meet the same end-use demand, averaged over the whole city. The system-wide average cost for district heating all sections of each city is given in Tables 4.14 to 4.17. These tables show that each city can be district heated (heating or heating and cooling) at costs per million Btu that compete favorably with the present-day costs of servicing the same demand, assuming that capital costs can be paid at a fixed charge rate of 8 to 10%, and that the cost of waste heat is \$1.50 to \$2.00/MMBtu. Because the costs of fossil fuels are expected to rise faster than pipe system and end-use equipment costs, it is likely that, in the future, it will prove economical to district heat even those sections of the cities found to be marginally non-cost effective.

4.3.3 Estimates of Fuel Savings and Payback Due to District Heating Systems

From an energy conservation standpoint, it is interesting to examine the costs of the district heating systems in a somewhat different manner. Although district heating systems that use thermal discharge from central station power plants in major urban areas can be cheaper or at least cost competitive with existing decentralized systems, the extent to which primary fuels can be conserved as a result of these district heating systems is yet to be demonstrated. Individual systems for space heating and hot water heating (primarily gas, oil, and fossil-electric) and cooling (primarily fossil-electric) would be replaced by the district heating system (primarily fossil-hot water). As a result of this substitution, major fuel savings would result from the elimination of individual fuel-consuming units by replacing them with the district heating system. These savings would, in turn, result in substantial savings in fuel costs. Thus, the major capital investment entailed in establishing the district heating systems eventually is paid back in a savings process that begins immediately following operation of a district heating system.

- *End-Use Fuel Savings.* For each end use (space heating, hot water heating, cooling) the ADL-derived demand coefficients, disaggregated by building category (R_1 , R_2 , C/I, and I) and fuel mix (gas, oil, and electricity) were used to calculate demand for each fuel type by end use for the four cities. In deriving these numbers, it was assumed, consistent with earlier calculations, that the average conversion efficiencies for gas, oil, and electricity are 0.6, 0.5, and 1.0, respectively, at the end-use heating device, and that electrical generation has an average conversion efficiency of 33%. It was assumed further that A/C cooling has a COP of 3.0 for the commercial and industrial sectors, and approximately 2.0 in the residential sectors. The results for the four cities are summarized in the "End-Use Savings" portion of Tables 4.19 to 4.22, respectively.

- *Extra Fuel at Power Plant.* To estimate the amount of extra fuel at the power plant required to produce 200°F hot water for district heating, the relationship between capacity and fuel is taken initially as:

$$C = 0.330 F. \quad (\text{Eq. 4.3})$$

Table 4.19 Fuel Savings, Washington, D.C.

	Space Heat	Hot Water	Total Heating	Cooling	Heating & Cooling
<u>End-Use Savings (10^{12} Btu)</u>					
Gas	20.41	5.56	25.97	-	25.97
Oil	24.32	1.64	25.96	-	25.96
Electricity	1.28	1.90	3.18	10.11	13.29
Total	46.01	9.10	55.11	10.11	65.22
<u>Extra Fuel at Power Plant (10^{12} Btu)</u>					
Final Demand	24.91	4.80	29.71	9.0	38.71
Thermal Demand	24.91	4.80	29.71	13.86	43.57
Extra Fuel	10.24	1.98	12.23	5.70	17.57
Net Fuel Savings			42.88		47.65

Table 4.20 Fuel Savings, Philadelphia

	Space Heat	Hot Water	Total Heating	Cooling	Heating & Cooling
<u>End-Use Savings (10^{12} Btu)</u>					
Gas	69.39	12.42	81.81	-	81.81
Oil	50.30	5.20	55.50	-	55.50
Electricity	1.65	4.94	6.59	14.97	21.56
Total	121.34	22.56	143.90	14.97	158.87
<u>Extra Fuel at Power Plant (10^{12} Btu)</u>					
Final Demand	67.33	11.71	79.04	13.10	92.14
Thermal Demand	67.33	11.71	79.04	18.71	97.75
Extra Fuel	27.82	4.81	32.51	7.69	40.20
Net Fuel Savings			111.39		118.67

Table 4.21 Fuel Savings, Baltimore

	Space Heat	Hot Water	Total Heating	Cooling	Heating & Cooling
<u>End-Use Savings (10¹² Btu)</u>					
Gas	27.08	5.18	32.76	-	32.26
Oil	36.46	6.09	42.55	-	42.55
Electricity	3.05	.77	3.82	9.26	13.08
Total	66.59	12.04	78.63	9.26	87.89
<u>Extra Fuel at Power Plant (10¹² Btu)</u>					
Final Demand	34.86	6.42	41.28	8.18	49.46
Thermal Demand	34.86	6.42	41.28	11.69	52.97
Extra Fuel	14.33	2.63	16.99	4.81	21.77
Net Fuel Savings			61.64		66.12

Table 4.22 Fuel Savings, Boston

	Space Heat	Hot Water	Total Heating	Cooling	Heating & Cooling
Gas	15.67	2.42	18.09	-	18.09
Oil	36.84	3.90	40.74	-	40.74
Electricity	.82	.86	1.68	3.49	5.17
Total	53.33	7.18	60.51	3.49	64.00
<u>Extra Fuel at Power Plant (10¹² Btu)</u>					
Final Demand	27.92	3.69	31.61	3.28	34.89
Thermal Demand	27.92	3.69	31.61	4.69	36.30
Extra Fuel	11.48	1.51	13.00	1.93	14.93
Net Fuel Savings			47.51		49.07

To produce 200°F hot water, it is necessary to sacrifice power plant efficiency by about 25%. Thus, the extra fuel required to maintain capacity at pre-district heating level is:

$$C = 0.248 (F + \Delta F), \quad (\text{Eq. 4.4})$$

giving

$$\Delta F = 0.33 F. \quad (\text{Eq. 4.5})$$

Assuming that 15% of the energy content of power plant fuel is lost (stack losses, etc.),

$$C + E = 0.85 (F + \Delta F), \quad (\text{Eq. 4.6})$$

satisfying electrical generating requirements and district heating requirements, where E is the energy content of the hot water discharge to the district heating system. Then:

$$\Delta F = E/2.43 \quad (\text{Eq. 4.7})$$

In the cases of space heating and hot water heating, E is taken to be the final demand; whereas in the case of cooling, E is the final demand divided by the coefficient of performance of absorption air conditioners which is assumed to be 0.7. The results are summarized in Tables 4.19 through 4.22, along with the net fuel savings resulting from the district heating systems for heating alone and with cooling added. These savings range from about .043 quad for heating in Washington, D.C., to about .111 quad for heating in Philadelphia. For heating and cooling, they range from about .048 quad to about .119 quad in these cities respectively.

- *Payback from Fuel Savings.* The result of conversion to district heating service of final demand is a fuel savings at the user end that gives rise to a yearly costs savings. These appear in the second line of Tables 4.23 to 4.26. (These savings can be expected to be larger than given here because of increases in fuel costs over time.) The yearly waste heat costs (assuming \$1.50/MMBtu or \$2.00/MMBtu to meet the thermal energy demands) then are subtracted to obtain net yearly costs savings through the implementation of district heating. These payback numbers, which also appear in Tables 4.23 to 4.26, can then be directly compared with the system-wide capital costs to calculate the payback period for the capital costs (assuming that the service now in place does not become more costly during that period). The results shown in Tables

Table 4.23 Payback from Fuel Savings, Washington, D.C.

		Heating	Heating % Cooling
Final Demand (10^{12} Btu)		29.71	38.71
Cost (\$/MMBtu)		5.08	4.87
End-Use Savings (\$ x 10^6)		150.93	188.52
Waste Heat Cost (\$ x 10^6)	@ \$2/MMBtu	59.40	87.14
	@ \$1.50/MMBtu	44.55	65.36
Net Yearly Operating Cost	@ \$2/MMBtu	91.53	101.38
Savings (\$ x 10^6)	@ \$1.50/MMBtu	106.38	123.16
Total Capital Cost (\$ x 10^9)		.701	1.173
Payback Period (Years)	@ \$2/MMBtu	7.66	11.57
	@ \$1.50/MMBtu	6.59	9.52
Equivalent Fixed Charge Rate	@ \$2/MMBtu	13.1	8.64
on Capital Investment (%)	@ \$1.50/MMBtu	15.2	10.5

Table 4.24 Payback from Fuel Savings, Philadelphia

		Heating	Heating % Cooling
Final Demand (10^{12} Btu)		79.04	92.14
Cost (\$/MMBtu)		5.08	5.24
End-Use Savings (\$ x 10^6)		401.52	482.81
Waste Heat Cost (\$ x 10^6)	@ \$2/MMBtu	158.08	195.50
	@ \$1.50/MMBtu	118.56	146.63
Net Yearly Operating Cost	@ \$2/MMBtu	243.44	287.31
Savings (\$ x 10^6)	@ \$1.50/MMBtu	282.96	336.18
Total Capital Cost (\$ x 10^9)		1.789	2.460
Payback Period (Years)	@ \$2/MMBtu	7.35	8.56
	@ \$1.50/MMBtu	6.32	7.32
Equivalent Fixed Charge Rate	@ \$2/MMBtu	13.6	11.7
on Capital Investment (%)	@ \$1.50/MMBtu	15.8	13.7

Table 4.25 Payback from Fuel Savings, Baltimore

		Heating	Heating % Cooling
Final Demand (10^{12} Btu)		41.28	49.46
Cost (\$/MMBtu)		4.98	4.98
End-Use Savings (\$ x 10^6)		205.57	246.31
Waste Heat Costs (\$ x 10^6)	@ \$2/MMBtu	82.56	105.94
	@ \$1.50/MMBtu	61.92	79.46
Net Yearly Operating Cost	@ \$2/MMBtu	123.01	140.37
Savings (\$ x 10^6)	@ \$1.50/MMBtu	143.65	166.85
Total Capital Cost (\$ x 10^9)		.983	1.472
Payback Period (Years)	@ \$2/MMBtu	7.99	10.49
	@ \$1.50/MMBtu	6.84	8.82
Equivalent Fixed Charge Rate	@ \$2/MMBtu	12.5	9.5
on Capital Investment (%)	@ \$1.50/MMBtu	14.6	11.3

Table 4.26 Payback from Fuel Savings, Boston

		Heating	Heating % Cooling
Final Demand (10^{12} Btu)		31.61	34.89
Cost (\$/MMBtu)		5.87	5.81
End-Use Savings (\$ x 10^6)		185.55	202.71
Cost of Waste Heat (\$ x 10^6)	@ \$2/MMBtu	63.22	72.60
	@ \$1.50/MMBtu	47.42	54.45
Net Yearly Operating Cost	@ \$2/MMBtu	122.33	130.11
Savings (\$ x 10^6)	@ \$1.50/MMBtu	138.13	148.26
Capital Costs (\$ x 10^9)		.650	1.027
Payback Period (Years)	@ \$2/MMBtu	5.31	7.89
	@ \$1.50/MMBtu	4.71	6.93
Equivalent Fixed Charge Rate	@ \$2/MMBtu	18.8	12.7
on Capital Investment (%)	@ \$1.50/MMBtu	21.2	14.4

4.23 to 4.26 demonstrate that the savings from fuel conservation due to the district heating systems can pay back the capital costs in from four and one-half to eight years for heating alone and from seven to eleven and one-half years for heating and cooling. These correspond to equivalent annual fixed charges on capital investment of between 12% and 21% for heating alone and between 9% and 14% for heating and cooling (see Tables 4.23 to 4.26).

The above results show that the district heating capital costs can be paid back relatively quickly from the money that otherwise would be spent on fuels in the present system at present fuel prices. The costs of meeting demand thereafter would be considerably lower than present costs. However, one does not have to assume such high rates of return on capital investment shown at the bottom of Tables 4.23 to 4.26. If lower rates of return occur, the district heating payback period would be extended, and the costs of meeting demand would be lower than present costs.

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5 CONCLUSIONS

The results obtained on the cost competitiveness and costs-versus-savings for the district heating systems studied indicate the favorable economies of these systems. However, these results are only estimates based on the most readily available numbers for all the factors. In several areas further work could profitably be pursued beyond refining the results already obtained (e.g., more detailed analysis of power plant retrofit costs, including the savings associated with the possible elimination of cooling towers). Moreover, because district heating systems would not be in place for a period of several years, it would be necessary to examine the competing (and interacting) effects of demand charges, fuel price changes, and cost of capital on the economics of the district heating systems. The favorable economics of switching from the present system to district heating depends, in part, on high demand density. However, to the degree that other forms of energy conservation occur in the next decade, these would somewhat offset these results. Nonetheless, it can be expected that rising fuel prices would dominate this effect and result in still favorable economics. To obtain some order of magnitude estimates of the sensitivity of district heating economics, it would be useful to construct scenarios involving a range of fuel price and demand trajectories.

Additional work could be done to examine the interaction of district heating systems with utility load and generating capacity forecasts, load factors, and load management efforts. This too would have an impact on the economics of district heating. A modeling effort in this area could be usefully undertaken. Similarly the issues and economics of reliability, peaking capability, and redundancy in the district heating systems could be examined. Finally, the net environmental impact of replacing the existing systems with district heating systems is expected to be positive. A detailed examination of the environmental "credit" associated with district heating systems could be undertaken (for whole cities and for neighborhoods), and this result could be taken into account in assessing the costs and benefits of district heating.

In summary, the results of this study demonstrate that district heating systems in Washington, D.C., Philadelphia, Baltimore, and Boston would result in substantial fuel savings and have quite favorable economies, especially over the long run.

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APPENDICES

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APPENDIX A - THERMAL ENERGY SUPPLY

A.1 AVAILABILITY OF HEAT

The electric utilities which serve the four study cities have considerable modern capacity in place, and growth is expected. However, it is presumptuous to expect that sufficient new capacity would come on line in a time frame desirable for implementation of district heating, because this could require as much new capacity as is already available, to come on line in a span of 10-15 years. There is the possibility that, in some cases, district heat production could be incorporated into the design of new power plants, but the incremental capital investment might not appear justifiable unless the potential district heating market is well defined. In fact, this last point summarizes the attitude of many utilities, particularly those which currently district heat with steam; it also represents one of the many institutional factors implicit in the establishment of district heating service.

The availability of a heat and electric penalty, incurred for power plants designed for heat-electric production, is well studied (see Burns and Roe, Fig. A.1 and Table A.1). Nevertheless, in view of the above discussion, existing plant retrofit becomes an important consideration. Several features of this problem have taken shape on the basis of discussions with turbine manufacturers and utility representatives.

Most important is that retrofit strategies are power plant dependent and reflect factors, such as age, throttle conditions, capacity and number of stages, and the more subtle features of low-pressure turbine and condenser geometries and heat rate. Pursuit of these and related topics is beyond the scope of this study, and properly belongs in a detailed economic analysis of cost allocation strategies and load management consistent with existing local regulatory constraints.

To estimate the potential availability of heat, several case studies were analyzed with the cooperation of General Electric Co. Table 5.1 contains a summary of these analyses and upper boundary estimates of incremental capital costs of plant modification.

The first strategy is to extract steam at the crossover point between intermediate-pressure (I-P) and low-pressure (L-P) turbine units, and then to operate the L-P at maximum recommended condenser back pressure (typically 125mm

Table A.1 Technical and Economic Assessment of Power-Plant
Modification for Heat-Electric Coproduction

	New Design	First Retrofit Strategy	Second Retrofit Strategy
Turbine Modification \$/kWt	3	1	9
Balance of Plant Modification \$/kWt	8.7	7.5	8.3
Temperature of District Heating Water	100°C	57°C ^a 60°C ^b 63°C ^c	100°C
Heat Gained Electric Lost	10	12 ^a 9 ^b 7.8 ^c	9
Electric Production Efficiency	25%	30% ^a 28.5% ^b 26.7% ^c	25%
Energy Conversion Efficiency ^d	85%	70% ^a 70% ^b 69% ^c	79%

^a7% of throttle flow extracted at crossover.

^b12% of throttle flow extracted at crossover.

^c15% of throttle flow extracted at crossover.

^dWithout use of stack gas heat (nuclear plant yields 95%).

Hg, absolute). Additional equipment includes extra piping, a heat exchanger, and controls. Actual modifications could be effected in a short time and would not shut down the plant beyond the normal maintenance period.

A second strategy is radical redesign of the L-P unit which includes addition of two large-capacity extraction points and subsequent operation of the unit at 125mm Hg (absolute). This strategy is more costly than the first but yields hotter water. In this case, greater heat exchange area, more piping, and more complex control systems are required. The L-P case and rotor must be removed for extensive modification estimated to be almost as costly as a new unit. Moreover, a plant must be shown down longer than for the typical overhaul period. However, the loss in productivity is a relatively small, one time only, cost item.

Although both strategies allow operation of the turbine at full electric capacity, the first is best applied to small, older units, several of which generally comprise a plant. In this case, one unit could furnish a base load supply as indicated in Table A.1, while the others could supply crossover steam in series to drive the temperature up as needed. Utilization of stack gas heat would increase the heat rate and temperature and reduce the amount of extra fuel burned without affecting the generating efficiency. The second strategy is best applied to large, newer, single-unit plants which can furnish a spectrum of temperatures and heat rates by varying the relative amounts of extracted steam. For comparison, the new design incorporates a variable back-pressure operation and two large variable extractions. For summer use, operation of such a unit at the lower end of the back-pressure range could supply domestic hot water at one-third the electric penalty incurred at peak winter supply of 100°C. This analysis suggests that power-plant modification would cost between \$8 and \$20 per kWt, and considering the yearly temporal variation of district heat flowrate and temperature, would send out an average 10 units of heat per unit of electric lost. Thus, this modification represents a conservative basis by which to estimate extra fuel consumption.

Table A.2 contains estimates of the amount of heat that optimally could be obtained from each existing (or under construction) turbine generator at 100°C from retrofit according to Strategy No. 2. Table A.3 summarizes demand and estimated supply and shows the radial redesign according to Strategy No. 2 is not necessary in all cases, e.g., inclusion of Peach Bottom for Philadelphia introduces wide margin between supply and demand. Therefore, an approach similar to Strategy No. 1 when applied to older, multi-unit plants could permit them to function as intermediate-load and peaking plants.

A.2 COMPARISON OF COSTS

Independent of the retrofit strategy used, the power plant modification is by far the smallest cost component of a per-kilowatt basis of the four principal subsystems analyzed, shown in Table A.4.

Table A.2 Availability of Heat

City, Company, and Plants	Electric Rating (MW)	Heat Capability at 100 C (MW)	Reduced Electric Rating (MW)
<u>Washington, D.C.</u>			
Potomac Electric Power Company Benning Station			
Units 11, 12	58	138	38
Unit 13	52	99	37
Unit 14	24	48	17
Unit 15	275	459	221
Unit 16	275	459	221
Buzzards Point Station			
Unit 2	30	71	20
Units 3, 4, 5, 6	200	379	145
Potomac River Station			
Units 1, 2	153	261	122
Units 3, 4, 5	306	546	242
Dickerson Station			
Units 1, 2, 3	548	826	457
Chalk Point Station			
Units 1, 2	660	1078	541
Unit 3	608	1078	489
Morgantown Station			
Units 1, 2	1112	1426	995
Total	4301	6868	3505
<u>Philadelphia</u>			
Philadelphia Electric Company Barbadoes Station			
Units 3, 4	136	377	81
Chester Station			
Units 5, 6	130	396	73
Cromby Station			
Units 1, 2	370	612	303
Delaware Station			
Units 7, 8	256	444	204
Eddystone Station			
Units 1, 2	664	1043	549
Units 3, 4	760	1720	571

Table A.2 Availability of Heat (Contd.)

City, Company, and Plants	Electric Rating (MW)	Heat Capability at 100 C (MW)	Reduced Electric Rating (MW)
<u>Philadelphia (Contd.)</u>			
Richmond Station			
Unit 9 *	175	308	139
Unit 12 *	115	312	78
Schuylkill Station			
Unit 1	175	292	141
Unit 3, + 9	88	-	-
Southwark Station			
Unit 1, 2	376	1000	259
Limerick Nuclear Station			
Unit 1, 2 (under construction)	(2110) ++	(3800)	(1635)
Total	3245	6504	2398
Total Including Stations Under Construction	(5152)	(9992)	(3995)
<u>Baltimore</u>			
Baltimore Gas and Electric Calvert Cliffs Station*			
Unit 1	883	1514	694
Unit 2	878	1505	690
Charles P. Grave Station			
Unit 1	183	250	154
Unit 2	183	248	154
Herbert A. Wagner Station			
Unit 1	139	195	116
Unit 2	125	175	104
Unit 3	330	417	284
Unit 4	393	643	322
Gould St. Station			
Unit 3	103	237	75

* Retirement in 1982

+ Unit 3 passes out steam for district heating

++ On line in early 1980's

** Nuclear Power Station

Table A.2 Availability of Heat (Contd.)

City, Company, and Plants	Electric Rating (MW)	Heat Capability at 100 C (MW)	Reduced Electric Rating (MW)
<u>Baltimore (Contd.)</u>			
Riverside Station			
Units 1, 2	117	223	85
Unit 3	61	118	44
Unit 4	78	151	56
Unit 5	65	126	47
Westport Station			
Units 1, 13, 14*	51	118	34
Unit 3	58	138	38
Unit 4	68	154	46
Brandon Shores			
Units 1, 2 (under construction) ⁺	1200	1590	1025
Total	3664	6094	2909
Total Including Stations Under Construction	(4864)	(7684)	(3934)
<u>Boston</u>			
Boston Edison Company			
New Boston Station			
Unit 1	380	504	324
Unit 2	380	528	322
Mystic Station			
Unit 4	135	189	113
Unit 5	135	189	113
Unit 6	150	210	125
Unit 7	565	823	474
Edgar Station			
Units 1, 2, 3	255	547	176
Pilgrim Station			
Unit 1	670	1238	515
Unit 2 (under construction)	1180	2125	914
Total	2670	4228	2162
Total Including Stations Under Construction	(3850)	(6353)	(3076)

* Retirement in 1982

⁺ On line in 1981 and 1983

Table A.3 Comparison of Projected Heat Demand and Estimated Availability through Turbine Modification

City	Average Demand (MW)	Peak Demand (MW)	Heat Available (MW)
Washington, D.C.	2200	3800	6868
Philadelphia	5900	9300	(9992)* 6504
Baltimore	3000	4800	(7684)* 6094
Boston	2300	3800	(6353)* 4228

* Includes stations under construction.

Table A.4 Capital Cost Summary

City	Transmission \$/kWt	Distribution \$/kWt	Heating Retrofit \$/kWt	Power Plant Retrofit \$/kWt
Washington, D.C.	79	111	74	8-20
Philadelphia	65	120	72	8-20
Baltimore	119	129	77	8-20
Boston	105	111	61	8-20

APPENDIX B - PIPING SYSTEM COSTS

Table B.1 Piping System Cost Estimate
 (\$ Per Foot of System)*
 Washington, D.C.
 Rural Area
 Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
NO STREET				
1. Wooden Forms	31.68	36.69	41.69	51.70
2. Excavation by Machine, 25% Hauled, Sides Sloped 1:1	7.02	8.55	10.20	13.99
3. Concrete Fill and Reinforce- ment	29.06	39.21	47.29	65.36
4. Backfill - Excavated Material, Spread by Machine, Not Hauled, Not Compacted	4.59	5.37	6.19	7.98
5. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves, X-Ray Equipment	25.84	38.38	50.57	102.32
Labor (Installation & Welding)				
- Pipes, Insulation & Coating	66.53	76.77	90.60	114.09
- Valves and Fittings	4.15	4.99	5.90	7.73
6. Expansion Loops - Excess Piping	45.55	50.83	60.95	96.08
7. Manholes	1.17	1.17	1.17	1.17
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	331.21	388.50	467.80	730.66

*Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.2 Piping System Cost Estimate
(\$ Per Foot of System)*
Washington, D.C.
Suburban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
1. Street Removal - 6" Asphalt	5.51	6.50	7.35	9.05
2. Timber Sheeting	53.30	56.38	59.44	65.60
3. Excavation - Medium Soil, by Machine	7.75	10.18	12.41	17.43
4. Concrete Fill and Reinforce- ment	29.06	39.21	47.29	65.36
5. Backfill - Sandfill, Spread by Machine	7.01	8.27	9.35	11.50
6. Street Replacement	5.40	6.37	7.20	8.87
7. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves, Expansion Joints, & X-Ray Equipment	51.42	68.84	89.75	167.94
Labor (Installation & Welding)				
- Pipes, Insulation & Coating	74.17	85.18	100.15	125.55
- Fittings, Valves & Expansion Joints	8.27	9.90	11.58	15.03
8. Manholes	9.00	9.00	9.00	9.00
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	366.51	426.37	506.76	765.57

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.3 Piping System Cost Estimate
(\$ Per Foot of System)*
Washington, D.C.
Urban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)				
	4	8	12	20	30
1. Street Removal - 2" Asphalt, 8" Concrete (Non-Reinforced)	3.70	4.62	5.54	7.18	9.45
2. Timber Sheeting - Place & Remove	44.50	46.60	48.77	52.96	58.30
3. Excavation - Medium Weight Soil, 50% by Hand, 50% by Machine	9.53	13.12	17.24	25.44	39.52
4. Concrete Fill & Reinforcement	8.39	12.43	17.09	25.33	40.35
5. Backfill - Sand Fill, Spread by Hand	4.38	5.47	6.56	8.51	11.18
6. Street Replacement	4.90	6.12	7.34	9.51	12.52
7. Piping					
Material & Equipment					
- Pipes	9.62	23.82	44.88	69.72	82.14
- Insulation & Coating	8.56	13.26	18.70	28.60	43.22
- Fittings, Valves, Expansion Joints & X-Ray Equipment	9.90	15.35	20.99	43.68	80.27
Labor (Installation & Welding)					
- Pipes, Insulation & Coating	23.25	44.85	58.80	75.06	95.81
- Fittings, Valves & Expansion Joints	2.61	4.13	6.37	8.33	11.22
8. Manholes	4.35	4.35	7.34	9.23	9.23
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	133.69	194.12	259.62	363.55	493.21
ADJUSTED TOTAL FOR URBAN AREA (\$/FT)	260.69	378.52	477.69	734.36	1030.81

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.4 Piping System Cost Estimate
(\$ Per Foot of System)*
Philadelphia
Rural Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
NO STREET				
1. Wooden Forms	37.27	43.16	49.05	60.82
2. Excavation - By Machine, 25% Hauled, Sides Sloped 1:1	7.16	8.72	10.41	14.27
3. Concrete Fill & Reinforcement	30.14	40.65	49.03	67.76
4. Backfill - Excavated Material, Spread by Machine, Not Hauled, Not Compacted	4.84	5.66	6.52	8.41
5. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves & X-Ray Equipment	25.84	38.38	50.57	102.32
Labor				
- Pipes, Insulation & Coating	78.73	90.80	107.69	135.86
- Fittings & Valves	4.76	5.72	6.77	8.87
6. Expansion Loops - Excess Piping	48.60	54.33	65.23	101.53
7. Manholes	1.27	1.27	1.27	1.27
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	354.23	415.23	499.78	771.35

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.5 Piping System Cost Estimate
(\$ Per Foot of System)*
Philadelphia
Suburban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
1. Street Removal - 6" Asphalt	5.88	6.94	7.85	9.66
2. Timber Sheeting	57.69	61.02	64.35	71.00
3. Excavation - By Machine	7.90	10.39	12.67	17.79
4. Concrete Fill & Reinforcement	30.14	40.65	49.03	67.76
5. Backfill - Sandfill, Spread by Machine	7.21	8.51	9.62	11.83
6. Street Replacement	5.48	6.47	7.31	9.00
7. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves, Expansion Joints & X-Ray Equipment	51.42	68.84	89.75	167.94
Labor				
- Pipes, Insulation & Coating	87.50	100.45	118.65	149.01
- Fittings, Valves, Expansion Joints	9.49	11.37	13.30	17.26
8. Manholes	9.55	9.55	9.55	9.55
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	387.88	450.73	535.22	801.04

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.6 Piping System Cost Estimate
(\$ Per Foot of System)*
Philadelphia
Urban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)				
	4	8	12	20	30
1. Street Removal - 3" Asphalt, 9" Concrete (Non-Reinforced)	4.80	6.00	7.20	9.33	12.27
2. Timber Sheeting	48.30	50.58	52.92	57.48	63.27
3. Excavation - Medium Weight Soil, 50% by Hand, 50% by Machine	10.15	13.99	18.37	27.11	42.13
4. Concrete Fill & Reinforcement	8.16	12.75	17.58	25.99	41.41
5. Backfill - Sand Fill, Spread by Hand	4.58	5.72	6.86	8.89	11.69
6. Street Replacement	5.85	7.31	8.78	11.37	14.96
7. Piping					
Materials & Equipment					
- Pipes	9.62	23.82	44.88	69.72	82.14
- Insulation & Coating	8.56	13.26	18.70	28.60	43.22
- Fittings, Valves, Expansion Joints & X-Ray Equipment	9.90	15.35	20.99	43.68	80.27
Labor (Installation & Welding)					
- Pipes, Insulation, & Coating	27.33	52.42	68.77	88.30	112.79
- Fittings, Valves, & Expan- sion Joints	2.99	4.74	7.32	9.57	12.89
8. Manholes	4.54	4.54	7.66	9.63	9.63
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	145.23	210.48	279.99	389.67	526.67
ADJUSTED TOTAL FOR URBAN AREA (\$/FT)	283.20	410.44	515.18	787.13	1100.75

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.7 Piping System Cost Estimate
(\$ Per Foot of System)*
Baltimore
Rural Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
NO STREET				
1. Wooden Forms	30.19	34.96	39.73	49.27
2. Excavation - By Machine, 25% Hauled, Sides Sloped 1:1	7.10	8.65	10.32	14.15
3. Concrete Fill & Reinforcement	28.36	38.26	46.15	63.78
4. Backfill - Excavated Material, Spread by Machine, Not Hauled, Not Compacted	4.24	4.96	5.71	7.37
5. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves & X-Ray Equip.	25.84	38.38	50.57	102.32
Labor				
- Pipes, Insulation & Coating	70.13	80.90	95.79	120.77
- Fittings & Valves	4.28	5.15	6.09	7.98
6. Expansion Loops - Excess Piping	46.45	57.85	62.25	97.75
7. Manholes	1.09	1.09	1.09	1.09
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	333.30	390.74	470.94	734.72

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.8 Piping System Cost Estimate
(\$ Per Foot of System)*
Baltimore
Suburban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
1. Street Removal - 6" Asphalt	4.99	5.89	6.66	8.20
2. Timber Sheeting	50.63	53.55	56.47	62.31
3. Excavation - By Machine	8.12	10.67	13.01	18.26
4. Concrete Fill & Reinforcement	28.36	38.26	46.15	63.78
5. Backfill - Sandfill, Spread by Machine	7.01	8.27	9.35	11.50
6. Street Replacement	5.29	6.24	7.06	8.69
7. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves, Expansion Joints, & X-Ray Equipment	51.42	68.84	89.75	167.94
Labor (Installation & Welding)				
- Pipes, Insulation & Coating	78.02	89.58	105.65	132.60
- Fittings, Valves, & Expansion Joints	8.54	10.23	11.97	15.53
8. Manholes	8.88	8.88	8.88	8.88
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	366.88	426.95	508.19	767.93

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.9 Piping System Cost Estimate
(\$ Per Foot of System)*
Baltimore
Urban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)				
	4	8	12	20	30
1. Street Removal - 4" Asphalt, 9" Concrete Non-Reinforced	4.48	5.60	6.72	8.70	11.45
2. Timber Sheeting	42.18	44.17	46.22	50.20	55.26
3. Excavation - Medium Weight Soil, 50% by Hand, 50% by Machine	8.86	12.21	16.04	23.66	36.77
4. Concrete Fill & Reinforcement	8.09	11.98	16.48	24.41	38.90
5. Backfill - Sandfill, Spread by Hand	4.24	5.30	6.35	8.24	10.83
6. Street Replacement	6.18	7.73	9.27	12.01	15.80
7. Piping					
Material & Equipment					
- Pipes	9.62	23.82	44.88	69.72	82.14
- Insulation & Coating	8.56	13.26	18.70	28.60	43.22
- Fittings, Valves, Expansion Joints, & X-Ray Equipment	9.90	15.35	20.99	43.68	80.27
Labor (Instillation & Welding)					
- Pipes, Insulation & Coating	24.40	46.89	61.51	78.81	100.64
- Fittings, Valves, & Expansion Joints	2.69	4.26	6.59	8.61	11.60
8. Manholes	4.21	4.21	7.10	8.93	8.93
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	133.41	194.78	260.85	365.57	495.81
ADJUSTED TOTAL FOR URBAN AREA (\$/FT)	260.15	379.81	479.95	738.46	1036.24

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.10 Piping System Cost Estimate
(\$ Per Foot of System)*
Boston
Rural Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
NO STREET				
1. Wooden Forms	36.07	41.77	47.46	58.86
2. Excavation - By Machine, 25% Hauled, Sides Sloped 1:1	7.18	8.74	10.43	14.31
3. Concrete Fill & Reinforcement	29.19	39.39	47.49	65.64
4. Backfill - Excavated Material, Spread by Machine, Not Hauled, Not Compacted	4.59	5.37	6.19	7.98
5. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves, & X-Ray Equipment	25.84	38.38	50.57	102.32
Labor				
- Pipes, Insulation & Coating	76.91	88.67	105.46	133.18
- Fittings & Valves	4.57	5.49	6.50	8.52
6. Expansion Loops - Excess Piping	48.13	53.83	64.68	100.85
7. Manholes	1.25	1.25	1.25	1.25
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	349.35	409.40	493.27	763.15

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.11 Piping System Cost Estimate
(\$ Per Foot of System)*

Boston
Suburban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)			
	24	30	36	48
1. Street Removal - 6" Asphalt	5.44	6.42	7.26	8.93
2. Timber sheeting	56.05	59.28	62.51	68.98
3. Excavation - By Machine	7.90	10.39	12.66	17.79
4. Concrete Fill & Reinforcement	29.19	39.39	47.49	65.64
5. Backfill - Sandfill, Spread by Machine	7.03	8.29	9.38	11.53
6. Street Replacement	5.39	6.39	7.19	8.85
7. Piping				
Material & Equipment				
- Pipes	82.40	83.32	99.82	168.92
- Insulation & Coating	33.22	43.22	53.42	101.32
- Fittings, Valves, Expansion Joints, & X-Ray Equipment	51.42	68.84	89.75	167.94
Labor				
- Pipes, Insulation & Coating	85.32	97.94	115.98	145.81
- Fittings, Valves, & Expansion Joints	9.12	10.92	12.77	16.57
8. Manholes	9.46	9.46	9.46	9.46
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	381.94	443.83	527.69	791.74

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Table B.12 Piping System Cost Estimate
(\$ Per Foot of System)*
Boston
Urban Area
Poured Concrete Fill Design

ITEM OR PROCESS	PIPE OD (IN.)				
	4	8	12	20	30
1. Street Removal - 3" Asphalt, 9" Concrete, Non-Reinforced	4.42	5.52	6.63	8.59	11.30
2. Timber Sheeting	46.90	49.11	51.39	55.81	61.44
3. Excavation - Medium Weight Soil, 50% by Hand, 50% by Machine	9.29	12.80	16.81	24.80	38.54
4. Concrete Fill & Reinforcement	8.33	12.34	16.98	25.15	40.08
5. Backfill - Sandfill, Spread by Hand	4.32	5.39	6.47	8.39	11.03
6. Street Replacement	5.82	7.27	8.73	11.30	14.87
7. Piping					
Material & Equipment					
- Pipes	9.62	23.82	44.88	69.72	82.14
- Insulation & Coating	8.56	13.26	18.70	28.60	43.22
- Fittings, Valves, Expansion Joints, and X-Ray Equipment	9.90	15.35	20.99	43.68	80.27
Labor (Installation & Welding)					
- Pipes, Insulation & Coating	26.60	50.86	66.75	85.98	109.87
- Fittings, Valves & Expansion Joints	2.87	4.55	7.03	9.19	12.38
8. Manholes	4.57	4.57	7.72	9.70	9.70
TOTAL COST PER FOOT OF SYSTEM (\$/FT)	141.20	204.84	273.08	380.91	514.84
ADJUSTED TOTAL FOR URBAN AREA (\$/FT)	275.34	399.44	502.46	769.44	1076.01

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

Figure B.1

PIPING SYSTEM COST ESTIMATE
INSTALLED COST* VS. PIPE DIAMETERWASHINGTON, D.C.
POURED CONCRETE FILL DESIGN

*Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

PIPING SYSTEM COST ESTIMATES
INSTALLED COST* VS. PIPE DIAMETER

Figure B.2

WASHINGTON, D.C.
CONDUIT SUPPLY PIPE DESIGN

*Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

PIPING SYSTEM COST ESTIMATE
INSTALLED COST* VS. PIPE DIAMETER
PHILADELPHIA
POURED CONCRETE FILL DESIGN

Figure B.3

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

PIPING SYSTEM COST ESTIMATE
INSTALLED COST* VS. PIPE DIAMETERBOSTON
POURED CONCRETE FILL DESIGN

* Cost includes one foot of insulated supply pipe and one foot of insulated return pipe.

AVERAGE PERCENTAGE BREAKDOWN OF PIPING SYSTEM COSTS

POURED CONCRETE FILL DESIGN

	PIPE DIAMETER (IN.)												
	URBAN					SUBURBAN				RURAL			
	4	8	12	20	30	24	30	36	48	24	30	36	48
Excavation and Street Work	25.7	20.1	17.9	14.2	12.8	21.3	20.4	18.7	14.6	13.3	13.3	12.6	10.3
Pipe, Fittings, Valves and Expansion Joints, etc. - Materials	11.2	13.9	17.9	19.4	19.8	45.7	45.8	47.6	56.6	50.0	49.2	50.3	58.8
Pipe, Fittings, Valves and Expansion Joints, etc. - Labor	11.3	14.1	15.0	12.6	11.4	25.2	24.8	24.5	20.4	28.1	27.7	27.3	22.2
Concrete Fill & Reinforcement	3.1	3.2	3.5	3.3	3.8	7.8	9.0	9.2	8.4	8.6	9.8	9.8	8.7
Add on Cost for Urban Area	48.7	48.7	45.7	50.5	52.2	-	-	-	-	-	-	-	-
TOTAL PIPING SYSTEM COST	100	100	100	100	100	100	100	100	100	100	100	100	100

APPENDIX C - OPTIMAL PRESSURE DROP VS. FLOWRATE AND
OPTIMAL PIPE DIAMETER VS. FLOWRATE

Fig. C.1 Optimal Pressure Drop vs. Flowrate

Fig. C.2 Optimal Pipe Diameter vs. Flowrate

APPENDIX D - MARGINALLY COST EFFECTIVE SECTIONS FOR DISTRICT HEATING

Washington, D.C. - 8% Fixed Charge Rate
Heat Charge = \$1.50

Washington, D.C. - 10% Fixed Charge Rate
Heat Charge = \$1.00

Washington, D.C. - 10% Fixed Charge Rate
Heat Charge = \$1.50

Philadelphia - 8% Fixed Charge Rate
Heat Charge = \$1.50

Philadelphia - 10% Fixed Charge Rate
Heat Charge = \$1.00

Philadelphia - 10% Fixed Charge Rate
Heat Charge = \$1.50

TO PEACH BOTTOM
(58 km)

DICKERSON
(75 km)

Light shading indicates sections that are marginally non-cost-effective for heating.

Dark shading indicates sections that are marginally non-cost-effective for heating and cooling.

Baltimore - 8% Fixed Charge Rate
Heat Charge = \$1.50

TO PEACH BOTTOM
(58 km)

TO DICKERSON
(75 km)

Baltimore - 10% Fixed Charge Rate
Heat Charge = \$1.50

Light shading indicates sections that are marginally non-cost-effective for heating.

Dark shading indicates sections that are marginally non-cost-effective for heating and cooling.

Boston - 8% Fixed Charge Rate
Heat Charge = \$1.50

Boston - 10% Fixed Charge Rate
Heat Charge = \$1.00

Boston - 10% Fixed Charge Rate
Heat Charge = \$1.50

Fig. E.1 Hourly Load Curve - Washington, D.C.

Fig. E.2 Hourly Load Curve - Philadelphia

Fig. E.3 Hourly Load Curve - Baltimore

Fig. E.4 Hourly Load Curve - Boston

APPENDIX F - HEAT LOSSES

Fig. F.1 Heat Loss for Underground Pipe with 3" Calcium Silicate Insulation Supply Line

Fig. F.2 Heat Loss for Underground Pipe with 2" Calcium Silicate Insulation Return Line