ASSESSMENT OF INTEGRATED URBAN ENERGY OPTIONS

by

Gerald D. Pine

MIT Energy Laboratory Report No. MIT-EL 79-021
February 1979

Energy Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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ABSTRACT

An initial comparison is carried out for the following residential space and water heating options: electric resistance heating, electrically-driven heat pumps, distribution of condenser temperature water combined with heat pumps to extract heat at the point of use, district heating via hot water from a combined heat-electric utility energy source, and individual gas furnaces. This comparison indicates that district heating is potentially competitive with conventional technologies for new urban areas.

A more detailed analysis of the district heating option is undertaken to clarify its economics. Base case urban models, economic assumptions and distribution networks are defined and a computer program is developed to select optimum pipe sizes for the networks and to calculate life cycle costs. Cost optimization is carried out by considering thermal energy production costs as well as thermal conveyance costs.

Because of the large number of variables entering into the cost determination, sensitivity analyses are performed to examine the effects of variations from base case assumptions. Variations in the installed pipe cost, interest rate, maintenance costs and degree of market penetration are shown to have the greatest effect on energy cost. Pumping power and heat loss are found to be relatively insignificant cost items.

Proper phasing of system inplementation with urban growth is shown to be very important. Initial use of temporary heat sources located near the loads coupled with implementation of only local piping networks is advantageous for present gas and oil prices if the urban growth occurs over a period of 15-30 years. There is shown to be an economically optimum time for conversion to a large centralized thermal energy source.

Several potential institutional barriers to district heating system implementation are identified. These barriers will be more difficult to overcome than any technical or economic barriers, and success in overcoming them will determine the national significance of district heating. Given positive government efforts to overcome the institutional barriers, district heating can play a major role in the U.S.

ACKNOWLEDGEMENTS

The author is deeply indebted to Professors David J. Rose and Leon R. Glicksman. Both have given generously of their time in spite of very busy schedules, and their guidance has been invaluable in completing this work. More importantly, working with them has been a pleasure, and the personal and professional examples they set will be remembered by the author long after the thesis has been forgotten.

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CHAPTER I

INTRODUCTION

1.1 Introduction

With the prospect of steadily increasing oil and natural gas prices and of inadequate supplies of these fuels in the near future (1), the energy supply for heating buildings in the future becomes uncertain. Most of the U.S. population live in urban areas, and the trend is toward increasing urbanization (2). The high population density of cities offers the opportunity to apply special energy supply techniques not applicable in rural areas; this study focuses on some of these special techniques.

A large source of free or very low cost energy is generally available near cities, namely, an electricity generating plant. A modern nuclear plant, for example, discharges about 2.1 units of thermal energy into the environment for each unit of electrical energy produced. This thermal energy is discharged at the lowest possible temperature, usually less than 100F, to maximize electricity generation efficiency. This temperature is rather low for direct use in space or water heating applications. Two remedies appear for this problem, both of them quite expensive to implement. First, by sacrificing some electricity generation capacity, the temperature can be increased to a more useful level and the thermal energy distributed to the users by hot water or steam. Second, low temperature water can be distributed and used as a heat source for heat pumps located at the points of use. A heat pump, with the addition of some electricity, extracts energy at a low temperature and supplies energy at a higher temperature. To assess the practicality of these scenarios, one most compare them economically with the conventional energy supply options relying on electricity, heat pumps and resistance heating, and with the fossil furnace option.

This study is in reality a series of increasingly detailed analyses which focus on increasingly specific problems. First, an overall comparison of the above energy supply options is undertaken to identify the most appropriate areas for detailed analysis. Second, one of the options, district heating with high temperature water, is identified as the prime target and analyzed using reasonable economic assumptions and idealized new city urban models. Finally, sensitivity analyses are performed to demonstrate the effects of variations in the economic parameters, urban characteristics, and system implementation pattern. Some of the institutional problems associated with district heating are also identified.

1.2 District Heating Outside the U.S.

District heating has been used in the U.S., Europe, and the U.S.S.R. throughout most of the twentieth century, though only to a relatively small extent. Partially because of the large amount of reconstruction following World War II, district heating has become very popular in Europe and the U.S.S.R. and is recognized as an important energy conservation measure. Strong government encouragement, particularly in the U.S.S.R., Finland, Sweden, Denmark, and Western Germany, has aided rapid system growth (5). Western Germany has at least 22 large combined heat-electric systems. In the U.S.S.R., more than half of all domestic thermal demands are supplied by combined heat-electric stations (7). District heating penetrations of 78% and 98%, respectively, have been achieved in the new Swedish towns of Malmo and Vasteras (8). By 1980, it is projected that 50% of all Danish demand, 70% of all Swedish demand, and 50-60% of all Finnish demand will be supplied by district heating. District heating is favored by a longer heating season in the Scandinavian countries, but this alone is insufficient to explain its relatively greater success than in the U.S.

Much of the success of district heating in these countries can be attributed to favorable government policies. All new thermal plants in Sweden must be combined heat-electric rather than electric only. Sweden has some advantage in that the energy supply industry is semi-public, and that a greater degree of planning and government control has been accepted in the past than in the U.S. Similarly, Finland has succeeded in rapidly implementing district heating because a single authority is responsible for both heat and electricity. Denmark approves potential district heating schemes and then guarantees them economically and technically. Scandinavian utilities are not allowed to show profits or losses, which helps to hold down consumer costs; surplus income is normally used to finance extensions or modifications of existing systems.

The government commitments to district heating in the U.S.S.R. and Western Germany are illustrated by news of tentative plans for regional district heating grids (7, 9). Regional grids would cause energy costs and heat losses to be slightly greater than for unconnected local systems, but would increase load diversity and system energy storage capacity and would allow the use of a greater variety of fuels. Oil and natural gas could be eliminated as fuels in utilities in this way.

1.3 District Heating Studies for the U.S.

Recent increases in oil and natural gas prices have rekindled interest in district heating in the U.S. Analytical efforts to date have not matched the sophistication of the European efforts, notably Swedish research (10,11), which has addressed the problems of growth, improved distribution and end use technologies, and use of large nuclear plants as energy sources.

Most U.S. studies have focused on district heating for new towns or on smaller scale (1000 dwelling units) total energy systems. The best known study of the first type was done at Oak Ridge National Laboratory in 1971 (12). It focused on district heating with high temperature water for a new city of 389,000 people and a Philadelphia climate. The energy source was assumed to be a nuclear reactor. Cost estimates were based on accepted engineering practice, but the economic optimization of the system was not considered in detail, nor were the problems of urban growth or end use equipment.

Because new cities experienced many problems in the 1960s, the Department of Housing and Urban Development now emphasizes smaller developments of 300-1000 dwelling units. The Modular Integrated Utility System (MIUS) program thus emphasizes integrated utility systems for these small developments. Many problems characteristic of small systems will differ slightly from those of large scale district heating systems, but many problems are common to large and small systems. Consequently, much of the MIUS research is useful to district heating studies (13, 14, 15, 16, 17, 18, 19). Besides providing useful technical information, the MIUS developments may serve as an interim step toward large integrated district heating systems.

Military bases are attractive targets for total energy systems because they will have few political problems associated with system implementation or thermal plant siting. Total energy systems for Army bases (Fort Bragg and Fort Knox) have been considered in detail by Stetkar (20) and by Best et. al. (32).

The transmission of thermal energy from the plant to the users will contribute significantly to energy cost, especially if electricity generating plants remotely sited from cities supply thermal energy for district heating. However, the economics of scale are important in thermal energy transmission (21), and at least one study presents results indicating that long distance (30-60 kilometers) energy transmission is economically feasible (22). As shown in Appendix A (Figure B.2), the costs used in that study favor large diameters, however, and have a functional dependence on diameter that is strikingly different than costs obtained from other sources.

Several studies of district heating systems have been restricted to specific locations. The studies were generally done by utilities proposing to expand existing systems (23,24,25). Such studies suffer the handicap of containing little innovation because of the constraints imposed by the need to be compatible with existing systems.

Large scale district heating studies have just begun at several national laboratories (26,27,28,29,30,31). Interest appears to be growing rapidly among government officials and funding agencies (See, for example Reference 32), indicating that district heating may finally be taken seriously in the U.S.

1.4 Structure of Report and Significant Accomplishments

As mentioned above, this study is a series of increasingly detailed and specific analyses. In Chapter II an initial comparison is made for electric resistance heating, heat pumps, the combination of distribution of power plant condenser temperature water and heat pump, district heating, and gas furnaces. This initial comparison serves the purpose of identifying the best prospect for further, more detailed work.

In Chapter III a detailed examination of the district heating option begins. Urban models and piping network structures are chosen. Given a set of assumptions concerning economics and urban characteristics, base case costs for district heating for each urban model are obtained. A computer program is used to select pipe sizes for the networks based on minimization of life cycle costs.

Several studies mentioned above and listed in the references have obtained results comparable to the base case cost estimates, and it is really the remainder of the thesis that contains significant additions to published literature concerning district heating. The final sections of Chapter III contain sensitivity analyses showing the effect on the base case costs of variations in key economic and urban parameters. These analyses show areas where uncertainities in costs are more important and define areas needing further study.

In Chapter IV one of these areas, the effect of urban growth and finite system implementation times, is analyzed in more detail. This topic has been neglected in other published studies, but is shown to be very important to system economics. As shown from the U.S.'s experience in developing new cities, urban growth is very difficult to predict, and deviations from planned growth patterns are the rule rather than the exception. Thus, it is quite important that potential developers be aware of the flexibility or lack of it available in successfully implementing a district heating system. The material presented in this chapter, or similar results for a specific site obtained by using the approach developed, should prove quite helpful for this purpose.

Chapter V describes briefly some of the potential institutional obstacles to district heating implementation. The need to limit the scope of the study to a manageable thesis curtailed the work done in this area greatly, but this chapter contains ideas which the author hopes may serve as seeds for further work. If nothing else, this chapter is significant because it illustrates the meager amount of knowledge concerning institutional impacts of and on district heating in the U.S.

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CHAPTER II

INITIAL COMPARISON OF ALTERNATIVES

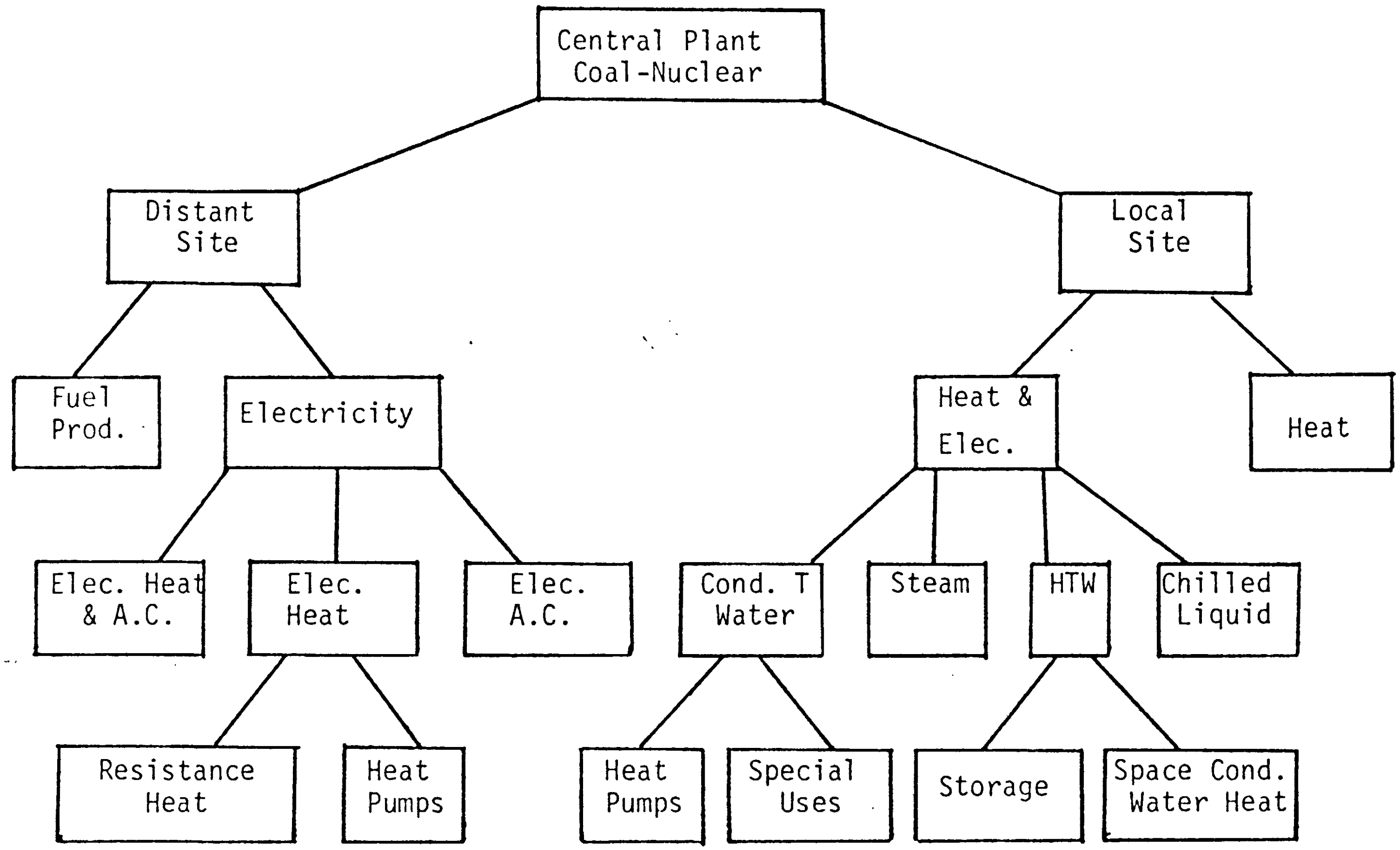
2.1 Introduction

The material presented in this chapter is an initial comparison of selected alternatives for providing the energy requirements for space heating and water heating in new urban areas. This comparison serves to identify the best target of opportunity for further, more detailed analysis through the remainder of the report. Figure 2.1 shows possible options for supplying space conditioning and water heating demands with electrical or thermal energy from a large utility heat source. From these options the following were chosen for this initial comparison: electric resistance heating, air-to-air heat pumps, the condenser temperature water-heat pump combination option, and the hot water district heating option. The gas furnace option is also included to provide a benchmark figure.

All options compared are based on available technologies; changes in the state-of-the-art of any of the technologies (e.g., piping installation) could reorder their relative economics, but commercial acceptance of new technologies has always been a slow process, requiring ten to twenty years. The centralized options also allow efficient effluent control, which will produce a cleaner environment than possible for individual fossil furnaces. Other options, such as solar heating and synthetic fuels, are not considered below, primarily to limit the scope of the study, but synthetic fuels can be included in part by choosing an appropriate fuel cost for the gas furnace option.

Figure 2.1

Technology Options



Two urban models are considered for each option (except resistance heating), a 100% single family house model and a 100% low-rise apartment building model. Mixtures of the housing types are found in practice, but consideration of such mixtures would add little to the analysis because of the difficulty in constructing meaningful urban models. In any case, these two models will identify the cost extremes, particularly for the options relying on water distribution.

Consistent assumptions about economic and energy use parameters are used to ensure comparable results for the various options. The results illustrate the wide range of variation among options, from highly fuel intensive (gas furnaces and resistance heating) to highly capital intensive (district heating). These differences will influence policy decisions, depending on the relative weights given the different variables. The remainder of the chapter is devoted to elaborating on the quantitative details.

2.2 Fossil Furnace Option

As the fossil furnace is now the lowest cost option, it is an appropriate reference for comparing alternative heating methods. Also, because it is the lowest cost option, its cost will be the primary determinant of when new options become economically attractive (insofar as fuel prices reflect scarcity rather than being fixed at artificially low values).

The costs shown below are based on data obtained by Yee (1) for the Boston area. Equipment costs will be about the same for other locations, but fuel costs will vary. The interest rate, maintenance cost, etc., are listed in Tables 2.1 and 2.2. A fuel heating value of 1022 Btu per cubic foot, a furnace efficiency of 65%, and an average gas cost of $0.403 per 100 cubic feet are used to estimate fuel costs. The gas cost is only ephemerally valid as it rises substantially year by year. Furnace efficiencies are poorly documented, and values ranging from 50-75% are claimed.

This option differs from some options presented below in that it is fuel rather than capital intensive. If fuel oil were used rather than gas, the fuel intensiveness would be even more marked, because oil prices in the Boston area are about 20% higher than gas prices for equal heating values, and gas furnaces are generally more efficient than oil furnaces. The fuel intensiveness will increase as fossil fuel prices continue to rise as shown in Appendix G.

2.3 All-Electric Options

Electricity can be used for either resistance heating or heat pumps. These options differ primarily in that resistance heating is an energy intensive option, while the heat pump is capital intensive. High cost electricity favors the heat pump, while high capital cost favors resistance heating.

The basic principles of heat pump operation are discussed briefly here and in more detail in Reference 2. Figure 2.2 shows the basic components of a heat pump system. The device absorbs an energy Q_L at a low temperature T_L and discharges energy Q_H at the higher temperature T_H, requiring a work input W_C to accomplish the job. An energy balance on the heat pump system requires that

$$Q_H = Q_L + W_C$$

TABLE 2.1

GAS FURNACE OPTION (SINGLE FAMILY HOUSES)

ASSUMPTIONS

1. Urban Model: 100% single family houses; density and population irrelevant.
2. Heat Demand: peak, 48,800 Btu/hour; annual load 110 X 10^6 Btu.
3. End Use Equipment: gas furnace, capacity 49,000 Btu/hour; efficiency 65%; initial cost, $1800.
4. Interest Rate: 9%
5. Fuel Cost: $0.403 per 100 cubic feet; heat value 1022 Btu/cubic foot.
6. Maintenance Cost: 2%/year of initial cost.
7. Capital Costs: use capital recovery factor; furnace lifetime, 20 years.

COST DATA

	PER UNIT ANNUAL	 INITIAL
Capital:	$197	$1800
Maintenance:	36	-
Fuel:	667	-
TOTAL	$900 or $8.18/$10^6$ Btu	$1800

TABLE 2.2

GAS FURNACE OPTION (LOW-RISE APARTMENTS)

ASSUMPTIONS

1. Urban Model: 100% low-rise apartment buildings; population and density irrelevant here; 18 units/bldg., 1000 sq. ft./unit.
2. Heat Demand: peak, 416,000 Btu/hour; annual load 920×10^6 Btu.
3. End Use Equipment: gas furnace, capacity, 400,000 Btu/hour; efficiency, 65%; initial cost, $3500.
4. Interest Rate: 9%.
5. Fuel Cost: $0.403 per 100 cubic feet; heating value, 1022 Btu/cubic foot.
6. Maintenance Cost: 2%/year of initial cost.
7. Capital Costs: use capital recovery factor; furnace lifetime, 20 years.

COST DATA

	Per Bldg.	
	Annual	Initial
Capital:	$383	$3500
Maintenance:	70	-
Fuel:	5581	-
TOTALS	$6034 or $\$6.56/10^6$ Btu	$3500

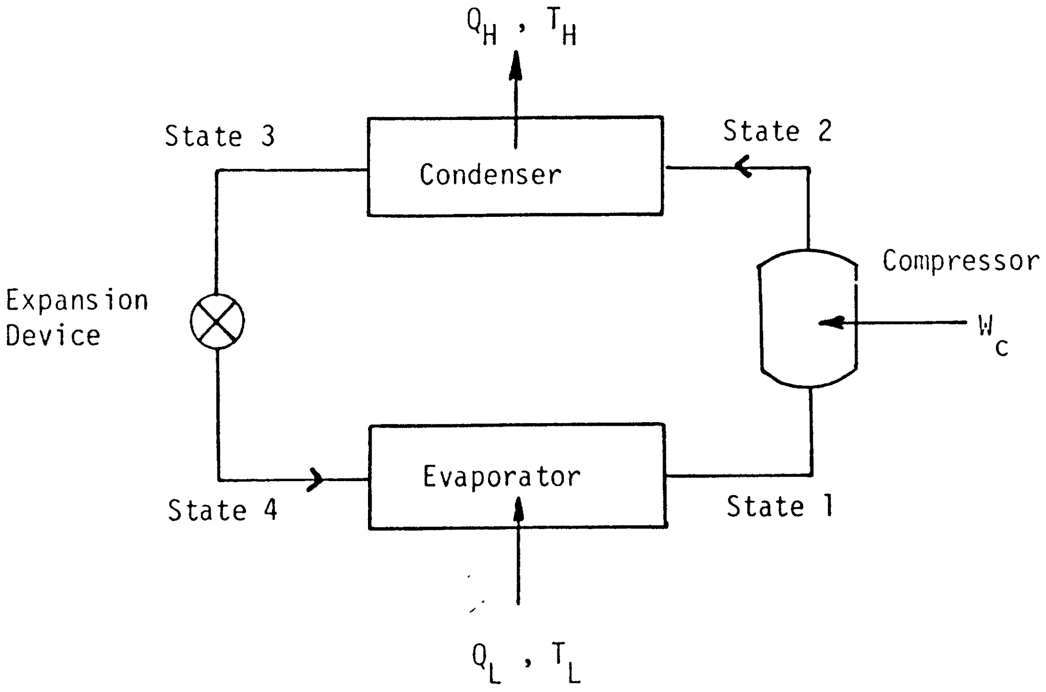


Figure 2.2
(from Hiller (2))

Basic Heat Pump Components

A useful figure of merit for the heat pump is the coefficient of performance (COP), defined as the ratio of the heat output to the work input.

$$COP = Q_H/W_c = 1 + Q_L/W_c$$

The COP of a heat pump is always greater than one; that is, the heat pump always produces more heat energy than the work energy input.

Since the heat pump is a reverse heat engine, the maximum theoretical value of COP is the Carnot cycle COP.

$$COP_{Carnot} = 1/(1 - T_L/T_H)$$

where T_L = lower temperature of the cycle, and

T_H = higher temperature of the cycle.

The actually achieved COP of a heat pump is lower than the Carnot value because of system irreversibilities (discussed further in Appendix A). Figure 2.3 is a plot of the temperature variations of COP_{Carnot} and of the COP of a typical air-to-air heat pump. Next generation heat pumps are likely to have COPs 20-30% higher than indicated. The high temperature is fixed at 70F, and the low temperature is varied across the normal range of outdoor air temperatures. Fan powers are not included in the COP calculations, but would significantly lower the COP if included (by 20-30%).

Unfortunately, the COP does not tell the whole story. To maintain acceptable temperatures and humidities during summer air conditioning use, present day heat pumps are usually sized smaller than the ideal size for winter heating in the northern U.S. Consequently, below some outdoor air temperature, the balance point, the building thermal demand

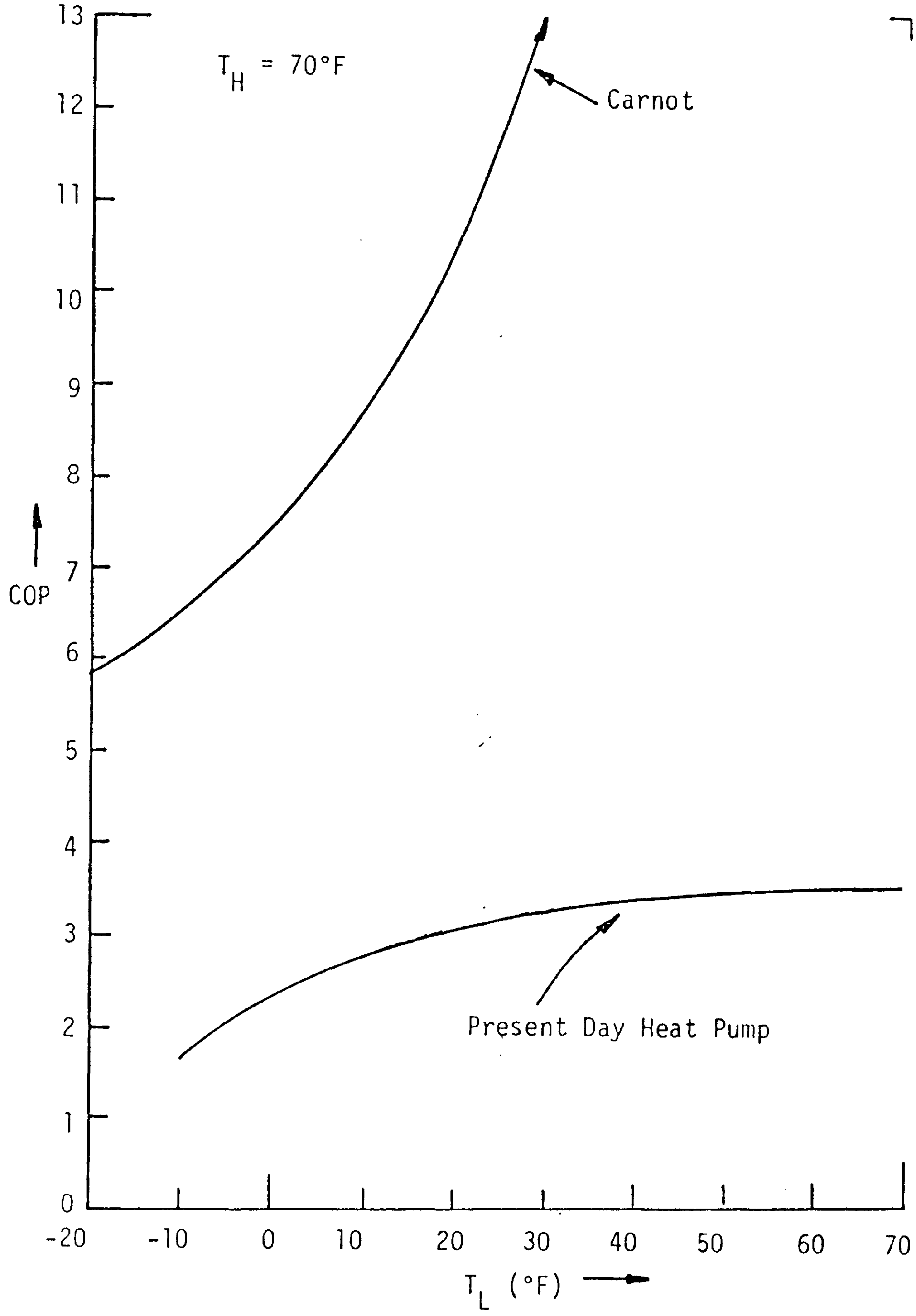


Figure 2.3
(from Hiller (2))

Actual vs Carnot COP's

is larger than the heat pump capacity. Auxiliary resistance heaters augment the heat pump capacity during these periods. For this reason, the seasonal average COP, often called the seasonal performance factor (SPF), is lower than the COP versus temperature curve might indicate.

With present air-to-air heat pumps, resistance heating must supply the entire load on days when the temperature is below about 10F. (A fossil furnace backup was not considered in this study.) Therefore, while the annual use of electricity is about two times more for resistance heating than for the heat pump, the peak electrical requirements are equal. Thus heat pumps do not reduce the required installed electricity generation capacity and, in fact, lower the utility load factor.

2.3.1 Electric Resistance Heating

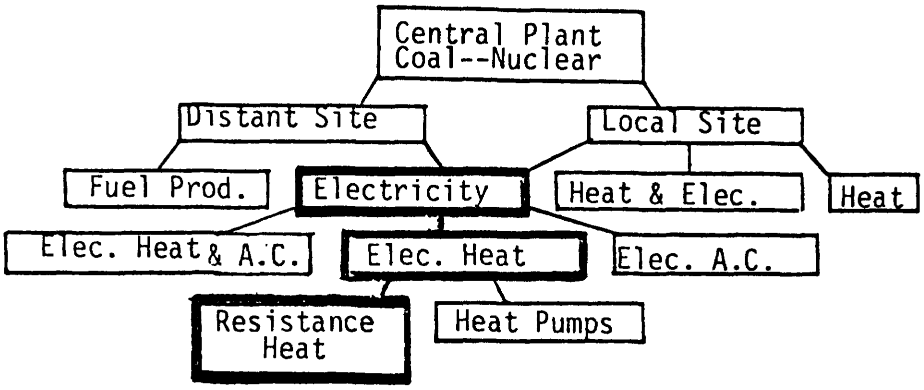
Results for resistance heating are obtained by using cost data presented in a Westinghouse study (3). The results and assumptions used are shown in Table 2.3 along with a sketch illustrating the position of this option in the technology option space.

2.3.2 Electrically-Driven Heat Pumps

The heat pump competes with resistance heating in space conditioning applications because it supplies more than one unit of heat per unit of electrical energy used, as explained above. However, the initial cost of a heat pump is quite high compared to resistance heating systems, and the reliability of heat pumps has been poor. Therefore, the heat pump penetration into the residential and commercial markets has been slow, but it is now increasing.

Air-to-air heat pumps accounted for most of the small unit (less than 50,000 Btu/hour) sales in 1976. Cost and performance data for this

TABLE 2.3 - Resistance Heating Option. House Model.



ASSUMPTIONS

1. Urban Model: 100% single family houses; model independent of population or land area.
2. Heat Demand: 38,000 Btu/hr peak, 35,000 kw-hrs annually (includes space heating and water heating).
3. End Use Equipment: Baseboard heaters; lifetime 20 years; associated equipment lifetime 40 years.
4. Interest Rate: 9.% (average Mass. mortgage rate, Nov. 1975).
5. Electricity Cost: 4.0¢ per kw-hr.
6. Maintenance Cost: 2% of capital equipment cost per year (excluding heating element costs).
7. Capital Cost Procedure: 1973 data updated to May 1975 via *Chemical Engineering* Plant Cost Index.

COST DATA

Item		Annual Cost Per Dwelling Unit
Capital Charges:		
heating elements		68
assoc. equipment		48
Maintenance:		
assoc. equipment		10
Electricity:	35000 x .04	1400
Cost of Energy at Plant:		included above
Energy Distribution Cost::		included above
Total Cost		$\$1526$ or $\$12.8/10^6$ Btu

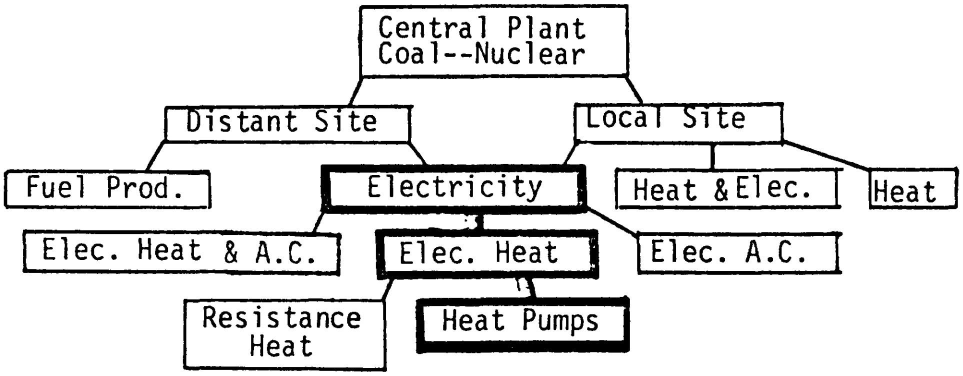
type of heat pump are readily available (3,4,5), but the data apply to units suitable for both heating and air conditioning. To adjust the cost to be consistent with the costs of alternative systems, the capital and maintenance costs were reduced to reflect costs for a heat pump used only for space heating. The adjustments include reductions of 25% in the initial cost and 15% in annual maintenance costs. The assumptions and results of the analysis are summarized in Table 2.4.

The heat pump lifetime is uncertain; some studies use a lifetime of 20 years (this one included), but ten years may be more realistic. Using ten rather than twenty years in this analysis increases the annual cost from $1086 to $1172. The interest rate and electricity cost realized in practice will vary; the sensitivity of annual cost to changes in these numbers is illustrated in Table 2.5, all other assumptions being the same as in Table 2.4.

2.4 Condenser Temperature Water-Heat Pump Option

Large quantities of low temperature (80-100F) heat are produced as a by-product of electricity generation. Most of this energy is discharged into the environment (via cooling towers or water bodies) and is consequently considered a nuisance. In northern regions of the U.S., the quantity of energy discharged at peak electrical output is about equal to the peak space and water heating load of residential and commercial buildings using the electricity generated. Therefore, the question arises "Can this wasted energy be used to supply the space and water heating demands of a city using the electricity?" The answer is, of course, that some of it might be used if the costs of distributing and using the energy are not prohibitive. Unfortunately, since thermal

TABLE 2.4 - Heat Pump Options. House Model.



ASSUMPTIONS

1. Urban Model: 100% single family houses; model independent of population or land area.
2. Heat Demand: 38,000 Btu/hr peak; 35,000 kw-hrs annually (includes space heating and water heating).
3. End Use Equipment: Air-to-air heat pumps, COP = 2.0, capacity, 36,000 Btu/hr nominal, lifetime 20 years; ductwork lifetime 40 years.
4. Interest Rate: 9 %.
5. Electricity Cost: 4.0¢ per kw-hr.
6. Maintenance Cost: $51/yr.
7. Capital Cost Procedure: 1973 costs updated to May 1975 via <u>Chemical Engineering</u> Plant Cost Index.

COST DATA

Item	Annual Cost Per Dwelling Unit
Capital Charges:	
heat pump	191
ductwork and install.	144
Maintenance:	51
Electricity: (35000/2.0) x .04	700
Cost of Energy at Plant:	included above
Distribution Costs:	included above
TOTAL COST	$1086 or $9.1/ 10^6 Btu

Table 2.5

Sensitivity of Annual Heat Pump Costs to Electricity and Interest Rates ($/house);

20 Year Lifetime

	cents/kilowatt-hour				
interest (%)	3.0	3.4	4.0	5.0	6.0
7.0	852	922	1032	1202	1372
9.5	927	997	1102	1277	1452
12.0	992	1062	1172	1342	1522

storage costs are very high, most of this energy must still be discharged into the environment during low demand periods for thermal energy.

The heat pump extracts thermal energy from an otherwise unuseable low-temperature source by using external energy (generally in the form of electricity). The most common energy source for a heat pump is air, but a heat pump using water as the energy source should be somewhat cheaper because of the reduced heat exchanger size. If the water temperature is constant, the output is independent of ambient air temperatures. The capacity and coefficient of performance of a heat pump both increase with source temperature, resulting in lower electricity and capital costs for the end use equipment. For this system to compete economically with the air-to-air heat pump, the cost reductions must at least compensate for the water distribution cost. It is shown below that this does not occur.

The economics of this scenario was considered in an approximate way in the initial stages of this study, and motivated by these early results, the analysis was redone more completely by Yee (1). Some selected results from his work are presented below in a slightly modified form to make all assumptions about electricity costs, etc., agree within this chapter.

Although Yee considered three housing types (1-, 4-, and 12-unit buildings) and a range of densities for each, only two housing types (1- and 12-unit buildings) and one density for each type are presented here. These are directly comparable to the hot water distribution system results presented in the following section. None of the omitted data alter the conclusion about this option, namely, that it does not appear economically competitive.

The urban models considered are (a) all single family houses at a density of 2000 per square mile, and (b) all 12-unit low-rise apartment buildings at a density of 4000 per square mile. Yee's models and the present models for the hot water distribution system case differ in that the present model populations are 54,000 for each model, while Yee used total populations of about 250,000 and 500,000 for the 1-unit and 12-unit models, respectively. As will be shown in the next chapter, however, the energy costs are only weakly sensitive to total urban population. For other housing models (excepting high-rise) the energy cost will fall between the values for these models. The cost variation arises from two chief sources, the service line costs, which decrease with increasing numbers of dwelling units per building, and the distribution costs (other than service lines), which decrease with increasing thermal load density until competition for underground space among various utilities begins to drive costs up at high densities.

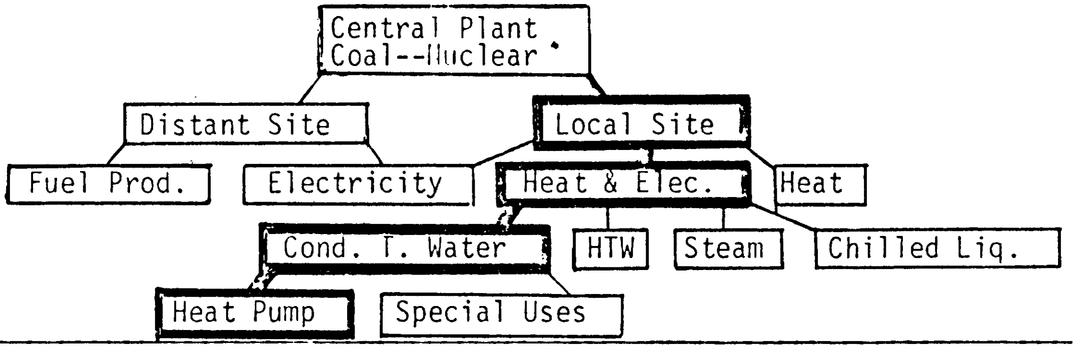
The Boston climate is used in Yee's analysis, and the annual heat loads for the two building types are 920 and 110 x 10^6 Btu for the 12- and 1-unit buildings, respectively, while the respective peak loads are 416,000 and 48,800 Btu/hour. These loads differ somewhat from those used in the hot water system analysis, but the differences insignificantly affect the results.

The original idea was to distribute condenser temperature water, but Yee's analyses showed that increasing the sendout temperature at the expense of some electricity generation capacity is economically advantageous. The results presented below assume a sendout temperature of 125F and a 40F drop across the system. Higher sendout temperatures were not considered. The main economic advantage to higher sendout temperatures and associated larger temperature drops is the reduced cost of water distribution because of the smaller required flow rates.

One significant item ignored by Yee is the cost of remote plant siting; his data imply that the plant is located at the edge of the 36 square mile city. For larger plant-city separation distances, large additional costs will be incurred. The hot water system option (summarized in the next section and analyzed in detail in Chapter III) assumes a separation distance of ten miles. Increasing the separation distance significantly increases the energy costs. The omission of this effect does not alter any of the conclusions about this option in this study, but the omission should be noted for future studies.

The assumptions and results of Yee's studies are presented in Tables 2.6 and 2.7. The dominant cost items for both urban models are the capital and maintenance costs. The latter costs are uncertain because of the lack of good data. An annual maintenance cost of 5% of initial costs is accurate for a steam distribution system, and is considered somewhat high for a high temperature water system. No data is available for low temperature water systems, but it should be remembered that the quantity of water circulated is large compared to a high temperature system, and that corrosion problems are often more severe for low temperature systems than for high temperature systems. The electricity costs for driving the heat pumps are also large, but much reduced from the air-to-air heat pump case. Unfortunately, the capital costs of the distribution system exceed the savings in the heat pump costs, making this option economically unattractive compared to the air-to-air heat

TABLE 2.6 - CTW-Heat Pump Option. House Model.



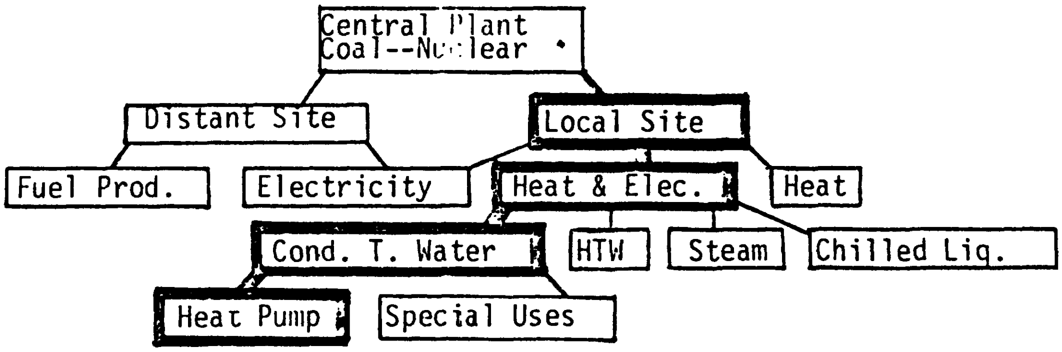
ASSUMPTIONS

1. Urban Model: 100% single family houses; 2000 units per square mile; 250,000 people total in city.
2. Heat Demand: 48,800 Btu/hr peak per house; 110 X 10^6 Btu annually (Including space and water heating).
3. End Use Equipment: Water-to-air heat pumps; SPF=2.5; capacity (nominal), 39,000 Btu/hr.
4. Interest Rate: 9%
5. Electricity Costs: $0.04/kw/hr for all except lost power cost and $0.024/kwh for that.
6. Maintenance Costs: heat pump, $15/ton (one ton equals 12,000 Btu/hr), distribution system 5%/year of initial system cost.
7. Capital Costs: levelized costs via capital recovery factor; equipment lifetimes: heat pump, 15 yrs; piping network, 50 yrs; heat pump ductwork, 40 yrs; allowance for distribution system engineering costs, 15% of material costs.

COST DATA

	PER UNIT	
	ANNUAL	INITIAL
Capital:		
Heat pump and ductwork:	$385	$3640
distribution system:	427	4680
Maintenance:		
Heat pump:	49	
Distribution system:	203	
Electricity:		
Heat pump:	476	
pumping power	28	
Energy at plant: (lost power)	28	
TOTAL COST	$1596 or $14.5/ 10^6 Btu	$8320

TABLE 2.7 - CTW-Heat Pump Option. Apartment Model.



ASSUMPTIONS

1. Urban Model: 100% low-rise apartment buildings; 12 units per building; 4000 buildings per square mile; total city population 500,000.
2. Heat Demand: 416,000 Btu/hr peak load, 920 X 10^6 Btu annual load per building (12 units), including space and water heating.
3. End Use Equipment: Water-to-air heat pumps, SPF=3, capacity nominal 200,000 Btu/hr (two units).
4. Interest Rate: 9%
5. Electricity Costs: \$0.04 for all except lost power, and \$0.024/kwh for that.
6. Maintenance Costs: heat pump, \$15/ton; distribution system, 5%/yr of initial cost.
7. Capital Costs: Use capital recovery factor to levelize cost; equipment lifetimes: heat pump, 15 yrs; piping network, 50 yrs; heat pump ductwork, 40 yrs; distribution system engineering costs, 15% of material costs.

COST DATA

	PER BUILDING	
	ANNUAL	INITIAL
Capital:		
heat pump and ductwork:	\$ 3000	\$ 28000
distribution system:	1404	13400
Maintenance:		
heat pump	252	
distribution system:	672	
Electricity:		
heat pump:	3600	
distribution system: (pumping power)	216	
Energy Cost at Plant: (lost power)	228	
TOTALS	\$9370 or \$10.2/10^6 Btu	\$41400

pump. If more realistic plant sites were considered, the difference would be even greater. For this option to compete with the heat pump, the initial capital costs of the distribution systems must be reduced by an order of magnitude, a very unlikely possibility. The only probable source of cost reductions is the heat pump. Available water-to-air heat pumps are not significantly less expensive than air-to-air heat pumps of equal capacity nor are they significantly more efficient. It has been suggested that the cost of a water-to-air heat pump might be reduced by 30% from the cost of an equal-sized air-to-air heat pump because smaller heat exchangers are needed (5), but such a cost reduction does not alter the above conclusion.

The conclusion that the condenser temperature water-heat pump option is not economically attractive does not eliminate the possibility of using this energy without the heat pump. Low cost end use equipment, for example, cheap plastic heat exchangers being developed in Sweden, might still allow economic use of this energy.

The gas furnace energy cost was shown to be $8.18/10^6$ Btu for a single family house and $6.56/10^6$ Btu for a 12-unit low-rise apartment building (see Section 2.2). The delivered cost of energy in the form of 125F water (with a temperature drop of 40F) is summarized in Table 2.8. The total costs are $6.24 and $2.74/10^6$ Btu for single family houses and apartment buildings, respectively. Thus, for condenser temperature water to compete economically with gas as an energy source, the allowable costs for end use equipment are $1.94 and $3.82/10^6$ Btu, respectively, for the two building types.

Using the annual thermal loads of 110×10^6 Btu for the house and 920×10^6 Btu for the apartment building, the allowable annual equipment

Table 2.8 - Costs of Delivered Heat from a 125° F Water Distribution System; $\Delta T = 40$ F; No Heat Pump

ITEM	HOUSE	APT. BUILDING
Capital Charge	\$427	\$117
Maintenance	203	56
Electricity	28	18
Energy at Plant *	28	19
TOTAL COSTS	\$686 or \$6.24/ 10^6Btu	\$210 or \$2.74/ 10^6 Btu

*Busbar cost of electricity sacrificed because of 125F discharge temperature rather than 90F.

costs are $213 for the house and $3510 for the apartment building. Using a nine per cent interest rate, a 30-year lifetime for equipment, and two per cent of initial costs for annual maintenance costs, one obtains a maximum initial equipment cost of $1820 for the house and $29,900 for the apartment building if total energy costs are to compete with gas furnace energy costs.

Using fan coil unit costs from Building Construction Cost Data 1976, by Robert S. Means, together with an estimate of one dollar per square foot for ducting yields initial equipment costs of $2250 for a house and $21,400 for an apartment building. The low temperature water option is still unattractive for the single family house in comparison to either the gas furnace or district heating. However, this option is now competitive with the gas furnace option but not with district heating for low rise apartment buildings. Lower cost end use equipment could make this option economically attractive, but this is a topic for another study.

2.5 District Heating Option

Condenser temperature water and heat pumps do not make an attractive option because two high-capital-cost items are combined. Since the economics of the air-to-air heat pump option was presented earlier, it seems quite natural that a system relying on higher temperature water without need of a heat pump should be analyzed. This turned out to be the best scheme of all.

Water and steam are currently the only widely accepted heat carriers for district heating. Steam is commonly used in the U.S., largely for historical reasons, while hot water is commonly used in the rest of the world. Hot water was selected for the purposes of this study because it has been shown to be the more economical of the two in most instances (6,7).

Though some effort is aimed toward development of low cost space heating equipment which uses low temperature water (80-120F), equipment now available requires higher water temperatures, generally in the range 140-220F. Since the premise of this study is that only available technologies be considered, the analysis is based on the higher sendout temperatures. Sendout and return temperatures of 220F and 160F, respectively, were chosen for the distribution system analysis.

Details are presented in Chapter III, which is devoted to an analysis of this option, but a few comments facilitate a comparison of this option to the other options. Similar urban models are used for the condenser temperature water-heat pump option and the district heating option, namely, 100% single family houses and 100% low-rise apartment buildings. The populations and thermal loads are different, but this has no significant effect on the results. Part of the thermal load difference arises from the different choice of climates; Yee (1) used a Boston climate, while this study assumes a New York City climate. But most of the difference arises from building model differences. Yee used heat load data for existing buildings, while this study assumes that buildings meet ASHRAE 90/75 guidelines. For the single family house, ASHRAE 90/75 standards make little difference, and the load structures are similar for the two studies. For apartment buildings, the hot water load is more important in this study than in Yee's, and as a result, the load factor is significantly higher. The probable result is a slight favoring of district heating for low-rise apartment buildings, but little effect for the single family house model.

End use equipment costs are estimated from data obtained by Yee (1). For single family houses, his costs are used directly, but for low-rise apartment buildings, the data must be adjusted to reflect lower peak loads. It is assumed that half of the equipment cost is constant, independent of the capacity, and the other half scales linearly with capacity. The costs obtained this way are:

single family house:	\$2120
apartment building :	\$12100

For an equipment lifetime of 30 years and an annual maintenance cost equal to two per cent of initial cost, the annual equipment costs are:

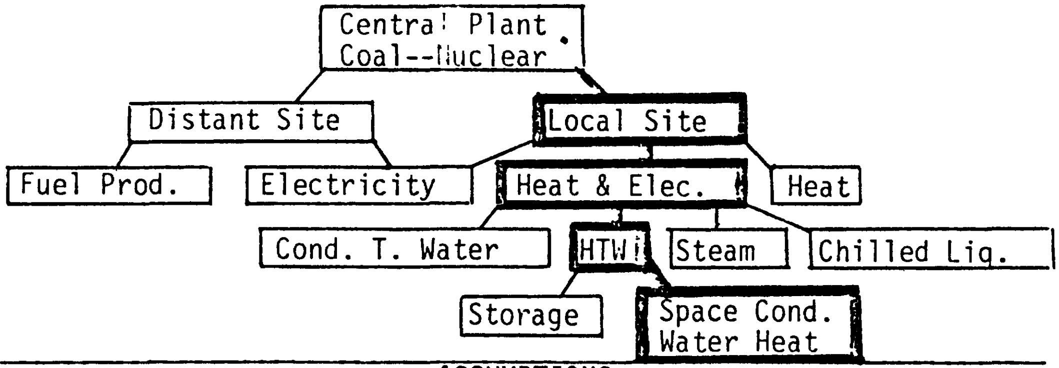
single family house:	\$250 or \$2.1/10^6 Btu
apartment building :	\$1420 or \$1.3/10^6 Btu

The plant location is assumed to be ten miles from the city for these calculations. Varying this distance will have a large, though not dominant, effect on energy costs as shown in the next chapter. The larger is the total thermal energy demand, the weaker the effect.

The piping network costs for the hot water distribution system apply to the new city case. For an existing city, pipe costs would be higher, and consequently, energy costs would be higher. This cost dependence is considered in Chapter III.

Costs and assumptions for the district heating analysis are presented in Tables 2.9 and 2.10. The economic analysis gives reason for optimism regarding the district heating system. This optimism is tempered

TABLE 2.9 - District Heating Option. House Model.



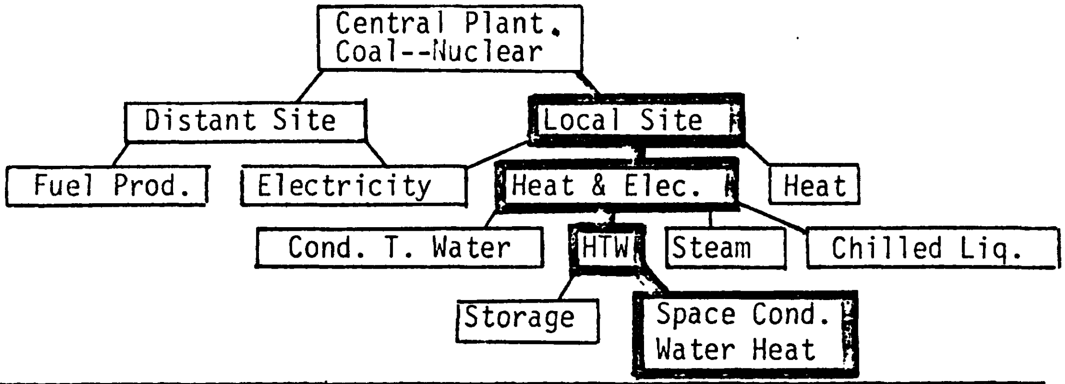
ASSUMPTIONS

1. Urban Model: 100% single family houses; 1700 units per square mile total city population, 54,000.
2. Heat Demand: peak load, 45,000 Btu/hr; 120 X 10^6 Btu annual load (includes space and water heating).
3. End Use Equipment: Hydronic heaters (e.g. Beacon-Morris Co., Inc. equipment), several units per house chosen to meet peak load; installed cost; $2120.
4. Interest Rate: 9%.
5. Electricity Costs: $0.04/kwh for all except lost power cost, $0.024/kwh for that.
6. Maintenance Costs: 2%/yr. of initial cost of end use equipment; 5%/yr of initial cost for distribution system.
7. Capital Costs: use capital recovery factor to levelize costs; equipment lifetimes, 30 years.
8. Distribution System: water sent out at 220°F, returned at 160°F; dual steel pipe in concrete envelope.

COST DATA

	PER UNIT	
	ANNUAL	INITIAL
Capital:		
end use equipment:	$206	$2120
distribution system:	297	3050
Maintenance:		
end use equipment:	42	
distribution system:	152	
Electricity:		
pumping power	28	
Energy Cost at Plant:		
Lost Power	89	
TOTALS	$814 or $6.8/$10^6$ Btu	$5170

TABLE 2.10 - District Heating Option. Apartment Model.



ASSUMPTIONS

1. Urban Model: 100% low-rise apartment buildings, 18 units per building, 4500 dwelling units per square mile; total population 54,000.
2. Heat Demand: peak load, 300,000 Btu/hr; annual load, 1080 X 10^6 Btu (includes space and water heating).
3. End Use Equipment: Hydronic heaters, several units per building chosen to meet peak load; installed cost of heating system, $12,100.
4. Interest Rate: 9%.
5. Electricity Costs: $0.04/kwh for all except lost power cost, $0.024/kwh for that.
6. Maintenance Costs. 2%/yr of initial cost for end use equipment; 5%/yr of initial cost for distribution system.
7. Capital Costs: Use capital recovery factor to levelize costs; equipment lifetimes, 30 yrs.
8. Distribution System: water sent out at 220°F, returned at 160°F; dual steel pipe in concrete envelope.

COST DATA

	PER BUILDING	
	ANNUAL	INITIAL
Capital:		
end use equipment:	$1180	$12,100
distribution system:	1380	14,150
Maintenance:		
end use equipment:	242	
distribution system:	708	
Electricity:		
pumping power	173	
Energy Cost at Plant:		
Lost Power	799	
TOTALS	$4482 or $\$4.2/10^6$ Btu	$26,250

somewhat in Chapter III by a glimpse at some of the possible economic pitfalls, but the rewards for successful implementation are substantial, from both economic and energy conservation points of view.

2.6 Conclusions

Table 2.11 shows the results for the above analyses. The gas furnace costs less than all other options except district heating, but recent rapid rises in gas prices (e.g., to 14.2¢/100 cubic feet at the well-head in interstate commerce with more rises to come) make the gas option less attractive and even less realistic in future years. Of course, the district heating option costs relate to new cities, but the margin is sufficient to allow for large increases in energy costs (the most probable cause for a cost increase in old cities, higher pipeline costs, is discussed in Chapter III). If probable oil and gas prices are considered, district heating is even more attractive.

Present-day heat pumps produce energy that is considerably more expensive than that from either of the two cheaper options, even when an unrealistically long 20-year lifetime is assumed. If electricity prices increase less rapidly than gas prices, quite a likely prospect, the heat pump might compete with the gas furnace.

The condenser temperature water-heat pump option is far too expensive to compete with any other option except resistance heating. High capital costs are responsible for this; the electricity cost savings associated with improved heat pump performance is overcome by distribution system capital costs. The district heating option is clearly superior to the condenser temperature water-heat pump option.

The initial cost comparisons show one potential reason that other

	GAS FURNACE		ALL-ELECTRIC		CONDENSER TEMP. WATER-HEAT PUMP		DISTRICT HEAT VIA HOT WATER	
	House	Apt-12	Resistance Heating (Houses)	Heat Pump (Houses)	Apt-12	Houses	Apt-18	Houses
Initial Capital Per Unit ($)	1800	290	1140	3290	3450	8320	1460	5170
Annual Capital $\$/10^6$ Btu	1.79	0.42	0.97	2.82	4.79	7.38	2.37	4.19
Elect. or Fuel $\$/10^6$Btu	6.06	6.06	11.8	5.88	4.15	4.58	0.16	0.23
Mainten. $\$/10^6$Btu	0.33	0.08	0.08	0.43	1.00	2.29	0.88	1.62
Lost Power Cost $\$/10^6$Btu	-	-	-	-	0.25	0.25	0.74	0.74
Total ($\$/10^6$Btu)	8.18	6.56	12.8	9.13	10.2	14.5	4.15	6.78
Primary * Energy Use	100%	100%	200%	100%	75%	84%	23%	25%

*Relative to gas furnace with an efficiency of 65%

Table 2.11 Comparison of Options

options may compete with district heating (actually, there are several reasons). A comparison of the house cases illustrates the relatively large capital investment required for district heating. Two problems are associated with this high capital cost; if the consumer were required to pay the entire initial cost of the end use equipment and the distribution system, consumer acceptance would be quite difficult as the initial cost is much higher than that of the heat pump system. However, the consumer is likely to pay only the cost of the end use equipment initially (about $2200 for the house model), and this cost is comparable to the cost of the gas furnace system. The remaining initial investment is likely to be borne by the utility company (or other developer) and poses a different problem. There are large elements of risk associated with district heating system implementation which might make capital attraction difficult for the developer, thus retarding implementation.

The relative contributions to total energy cost by the various components reveal essential differences among the options. The options vary from being very fuel intensive (resistance heating and the gas furnace) to very capital intensive (district heating). The low temperature water-heat pump option suffers from having both high capital costs and high fuel costs, which is clearly the reason for its demise. One might be tempted to conclude that the energy costs at the plant are higher for the distributed water options than for the other options, but this is merely an artifact of the inclusion of electricity transmission costs and fossil fuel delivery costs with fuel costs.

There are major differences between the options in the total primary energy use and in the type of fuel used to supply the primary energy.

All options except the gas furnace option can rely on coal or uranium as the primary energy source. No scarce oil or gas resources are needed. The condenser temperature water-heat pump option and the district heating option require much less primary energy than the other options. The percentages shown for these options are extremely low compared to the others because only the primary energy needed to generate electricity for power, heat pumps, and sacrificed electricity are included. The thermal energy actually put into the pipeline can be considered free if it is assumed that electricity would be generated anyway, because most of the energy would be discharged by the plant cooling system.

The primary conclusion of these analyses was that district heating with hot water warranted closer examination. The remainder of this study is devoted to that task.

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CHAPTER III

STATIC URBAN MODEL ANALYSIS

3.1 Introduction

This chapter is devoted primarily to a discussion of the economics of district heating for a new city with the heating system installed at a fixed point in time. Systems and cities are not built instantaneously, of course, but a treatment of growth effects is postponed until next chapter. While the emphasis is on new cities, the costs for an old city are compared to those for a new one later in this chapter. Because new cities have not been very successful in the U.S., it is probable that most opportunities for district heating will be found in existing urban areas, and this is where district heating must succeed if it is to have a significant impact on national energy conservation; thus, this comparison is very important. Nevertheless, the effects of variations in important parameters may still be shown satisfactorily with new city data.

On the basis of a survey of housing types for recently proposed new cities, two dominant housing types, single family houses and low-rise apartment buildings, are identified and used to construct two idealized urban models, as in the previous simple calculations. Each model consists of only one of the two housing types; the costs obtained for these models should bracket the range of probable costs for a more realistic city containing a mixture of the two housing types without the confusion caused by additional structural details.

The residential thermal loads are based on the requirements and suggestions of the proposed building code, ASHRAE 90/75. Space heating loads for each building are assumed proportional to the outdoor air temperature for temperatures down to the design temperature and constant at the design load for lower air temperatures. Experience has shown that the peak load for a district heating system is less than the sum of all consumer peak loads, because not all users require these loads simultaneously (5). The same effect has been reported for single family houses heated by heat pumps (15). An empirically determined coincidence factor (ratio of the system peak load to the sum of all consumer peak loads) is used to account for this effect. The effect of using a coincidence factor rather than designing for nondiversified loads is examined in a sensitivity analysis. The water heating load is modeled more crudely by assuming a constant load which integrates to the correct annual load.

No commercial or industrial energy uses are included, but the probable effect of commercial loads will be discussed by comparing the heat load profiles of the residential and commercial sectors. Nor are air conditioning loads included in the analysis; in the climate considered for most of the calculations (New York City), the air conditioning load is characterized by a high peak load but by a low annual useage.

The design of a district heating system is determined largely by the choice of the heat carrying medium. Water and steam are presently the only proven candidates, although other media are being investigated. Water is chosen here, primarily because it is attractive for long distance heat transmission and allows more electricity to be generated if a combined heat-electric plant is used.

The cost estimates are based on dual pipe systems consisting of supply and return pipes (steel) surrounded by calcium silicate insulation and then by an insulating concrete envelope, all buried in a trench so that the top of the pipe (the insulation thickness is small, typically a few inches) is six feet under the surface. To simplify the design and generate data useful in the next chapter, the cities are divided into identical subsections, each of which is served by an independent subsystem (distribution system). The piping network structures are selected in accordance with principles shown by Yee (7) to result in a relatively low cost system, but no claim is made that the structure is the optimum one. Such a design is beyond the scope of this study and most likely meaningless anyway for such an idealized city structure.

The pipes making up the system are chosen to minimize the life-cycle cost of the system subject to required engineering constraints. The cost items entering into the cost analysis are capital cost, maintenance cost, pumping power cost, and the cost of energy at the plant. The latter is estimated by assuming that the plant could have generated electricity with the steam which is instead extracted to produce hot water. The busbar value of the electricity not generated is then equated to the cost of heat at the plant.

The effects of changes in the economic and urban parameters are examined in a series of sensitivity analyses. Parameters examined include the interest rate, maintenance cost, initial cost, electricity costs, population, population density, penetration fraction, plant-city separation distance, coincidence factor, and design temperature.

3.2 Urban Structure and Piping Network Structure

The market for district heating will necessarily be restricted to urban areas where the load density is great enough to justify the large capital expenditure required. Large cities (populations of one million or more) are preferable because their thermal energy requirements for space heating and water heating are well-matched to the waste heat available from large electricity generating plants. For example, a northeastern U. S. city of one million people requires about the same amount of thermal energy for space heating and domestic water heating as that discarded by a 1000 Mwe power plant. A new city is a more attractive target for implementation of district heating than is an existing city, because there are many difficult economic and political obstacles to pipe installation and building retrofit in an existing city.

Unfortunately, U. S. new city developments have been less than spectacular. Only small cities (generally less than 100,000 projected population) have been planned recently (see Figure 3.1 and Table 3.1), and even these have been plagued by problems. It now appears likely that most new urban growth in the foreseeable future will take the form of expansion and densification of existing cities. Thus, if district heating is to have a significant national impact, smaller new developments and, more importantly, existing cities must be served. Nevertheless, analyses for a new city serve well to illustrate the sensitivities of energy costs to major economic and urban characteristics; the following analyses serve that purpose. A reference

FIGURE 3.1

Characteristic Populations and Development Times
Proposed U.S. New Cities

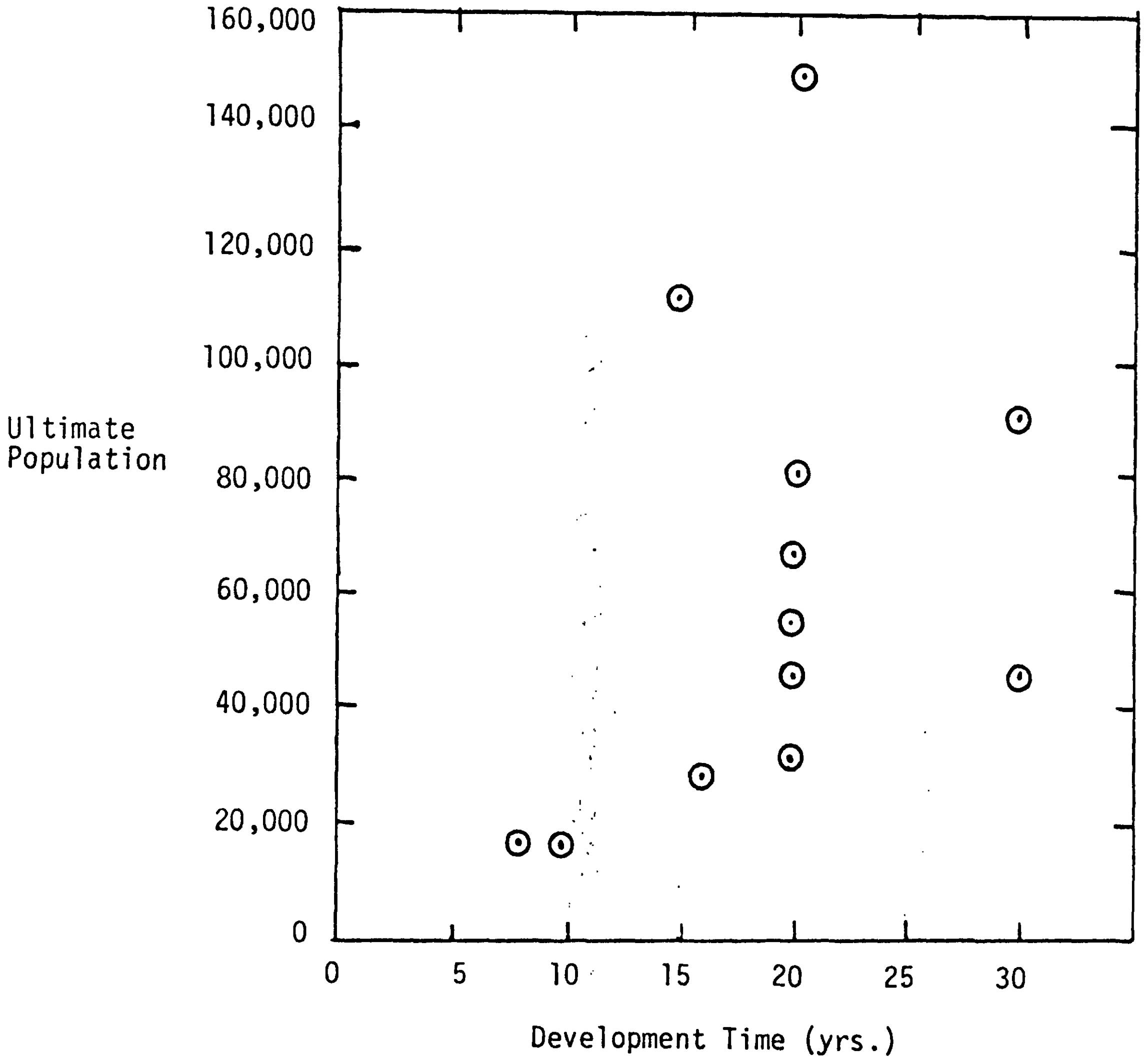


Table 3.1 - New Town Development Statistics

New Town	Dev. Time	Ult. Pop.	Pop. Density	single family dwellings / multiple family dwellings
The Woodlands, Texas	20 yrs.	150,000	15,600/mi^2	40/60
St. Charles Comm., Md.	20	79,000	10,000	?
Soul City New Comm., N.C.	30	44,000	?	?
San Antonio Ranch, Texas	30	88,000	13,400	?
Riverton, N.Y.	16	26,000	16,000	?
Park Forest South, Il.	15	110,000	15,000	31/69
Maurielle, Ark.	20	45,000	14,000	?
Lysander, N.Y.	8	18,000	13,000	60/40
Jonathan, Minn.	10	18,000	?4,000?	?
Ganada, N.Y.	20	56,000	14,000	?
Flower Mound, Texas	20	65,000	14,000	53/43
Cedar Riverside, Minn.	20	30,000	190,000	?
Columbia, Md.		110,000	9,000?	?

Source: Federally Assisted New Communities: New Dimensions in Urban Development, a ULI Landmark Report by Hugh Mields, Jr., 1973 (except for Columbia).

case population of 54,000 is used in this chapter, but the economic effect of greater populations is examined in a sensitivity analysis.

The two housing types used in the analyses appear in different ratios in different cities, as evidenced by the data in Table 3.1. For existing cities the single family house accounts for a larger fraction of total housing than for new cities as illustrated by Tables 3.1 and 3.2. Two urban models based on these housing types are constructed and used in the analyses; each model consists entirely of <u>one</u> building type. The total number of dwelling units (total population) and their densities (population density) are varied to determine the sensitivity of energy costs to these variations. Neither basic urban model is a good model for a real city (though the single family house model is nearly correct for many new suburbs), but the two models serve to expose economic effects attributed to each housing type and to identify cost bounds for a more realistic case in which both housing types are present.

Figures 3.3 and 3.4 show the assumed building pattern for a city of 54,000 people living in single family houses, while Figures 3.5 and 3.6 show the pattern for a city of 54,000 people living in low-rise apartment buildings. For larger populations or lower population densities than the reference cases, the same patterns are used but land area and dwelling unit density are changed. Convenient (for the engineer or planner) rectangular cities are used for all cases.

The piping networks are designed so that a city of 54,000 people is divided into 20 identical subsections. This simplifies the network design and proves useful in the following chapter for an analysis

Table 3.2 - Percent Of Households Living In Specified Unit Type

Dwelling Units/Bldg.	FEA Region Number									
	1	2	3	4	5	6	7	8	9	10
1d[1]	56.8	43.8	57.3	76.8	69.7	80.4	77.1	72.1	64.2	76.0
1a[1]	0.8	2.7	13.9	0.9	0.8	1.3	0.6	1.1	2.9	1.2
2	14.7	14.1	7.6	5.6	9.6	4.5	5.6	5.8	4.9	3.9
3-4	12.2	7.0	4.8	3.3	5.1	2.4	5.5	5.1	5.3	2.6
5-9	6.7	5.5	4.1	2.6	3.7	2.2	3.4	2.4	5.5	3.2
10-19	3.4	6.0	4.6	2.5	3.5	2.3	2.2	2.9	5.7	3.6
20-49	2.2	8.1	1.7	1.3	2.5	1.8	1.5	3.1	5.1	3.4
50+	1.9	11.9	3.3	1.7	2.5	2.5	1.0	1.4	3.1	2.5
mobile[2]	1.3	1.0	2.7	5.2	2.5	2.6	3.1	6.1	3.3	3.6

1. 1a and 1d refer to single family attached and single family detached, respectively.

2. Mobile homes.

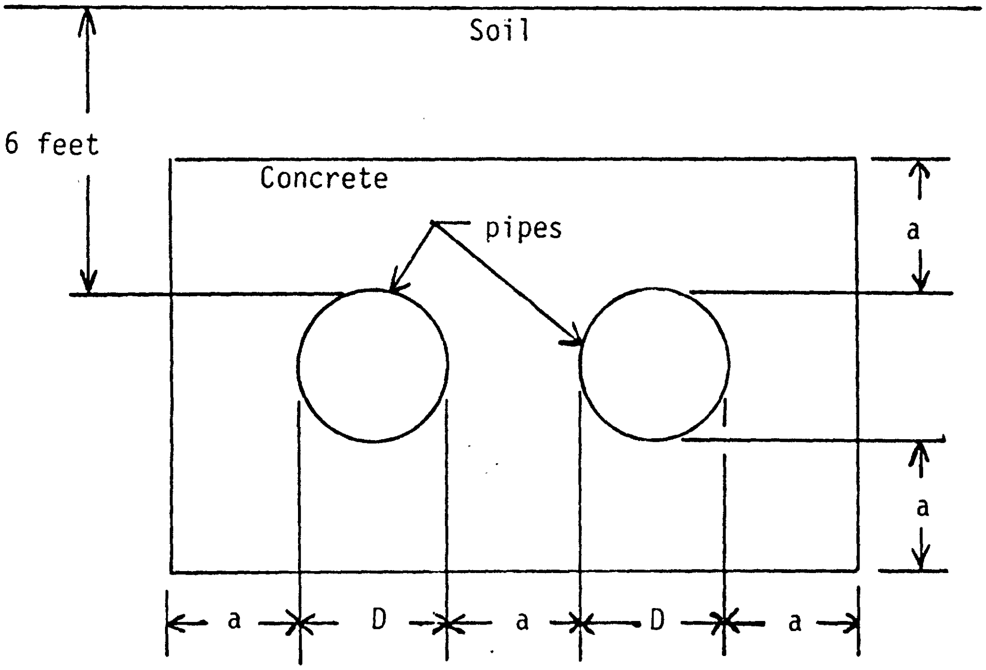


FIGURE 3.2

Pipeline Design

Figure 3.3

Subsection Design

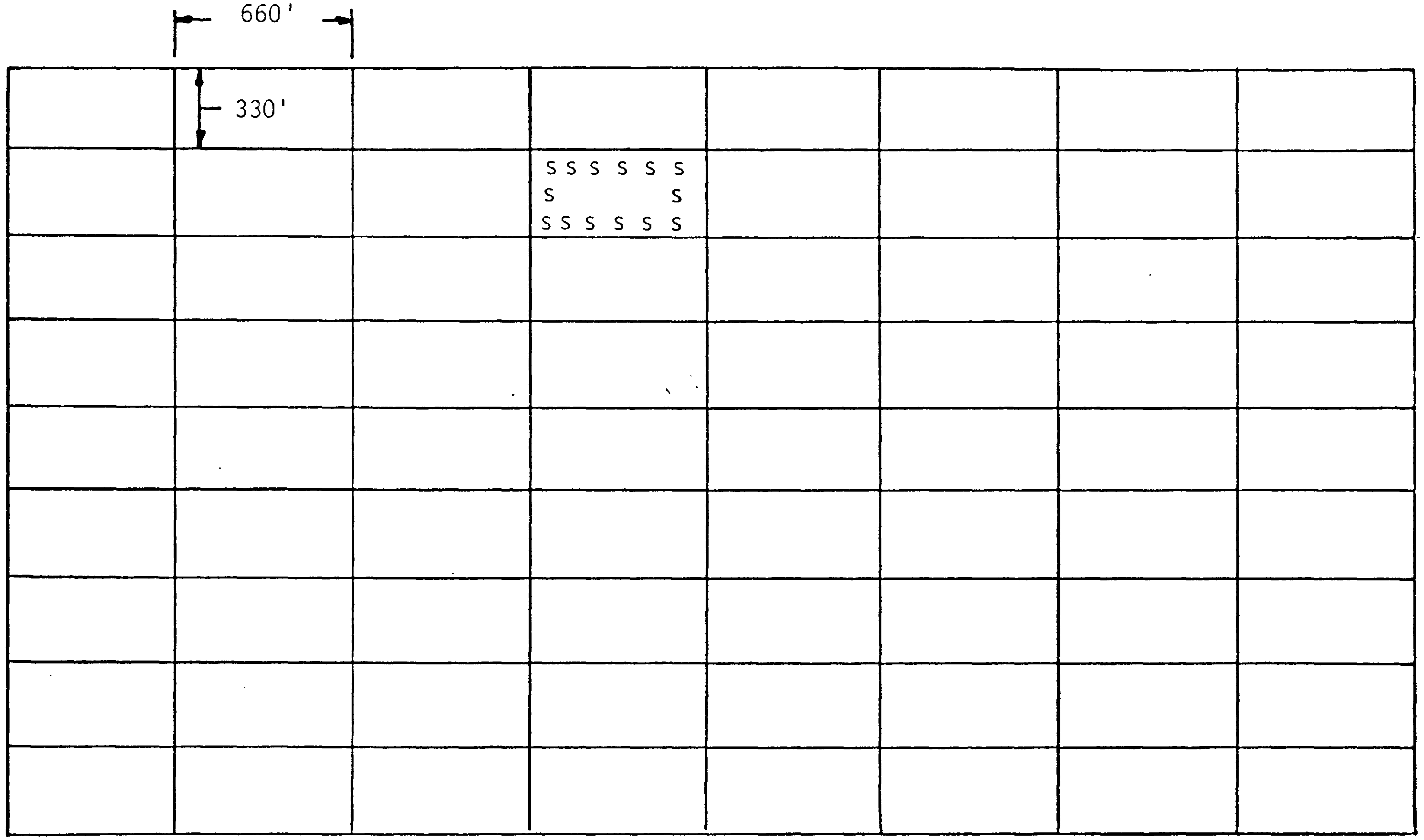


Figure 3.4

Entire City

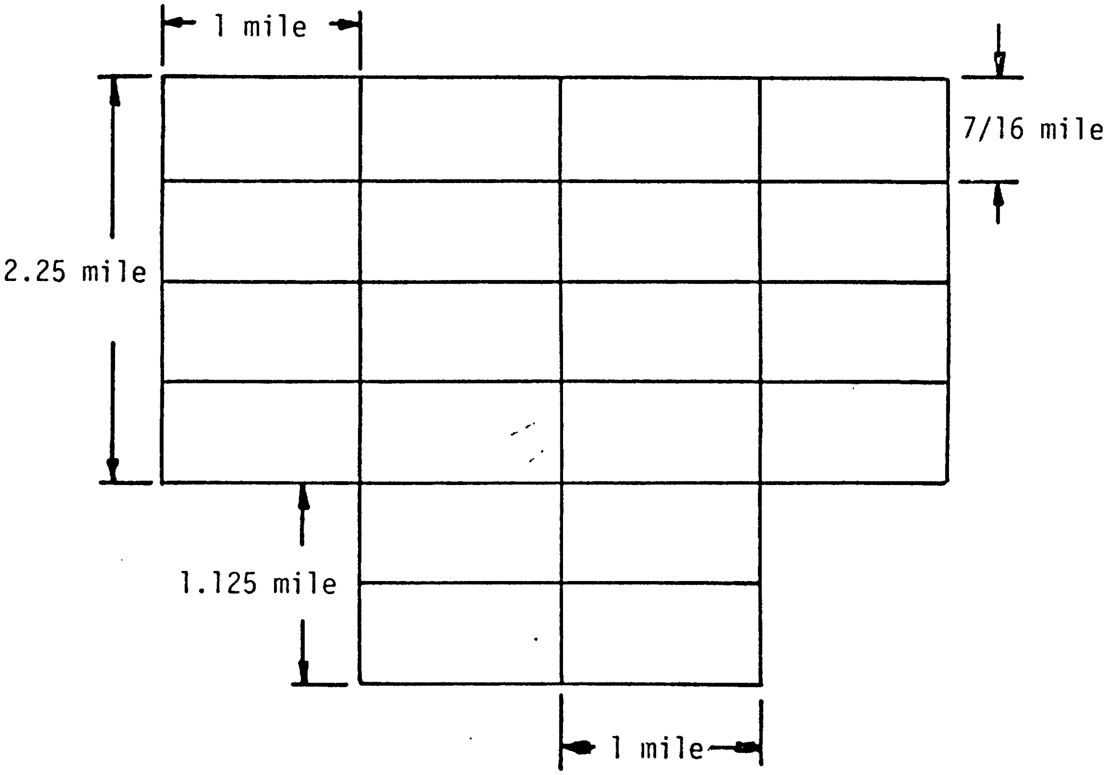


FIGURE 3.5

Subsection Design. Apartment Building Urban Model.

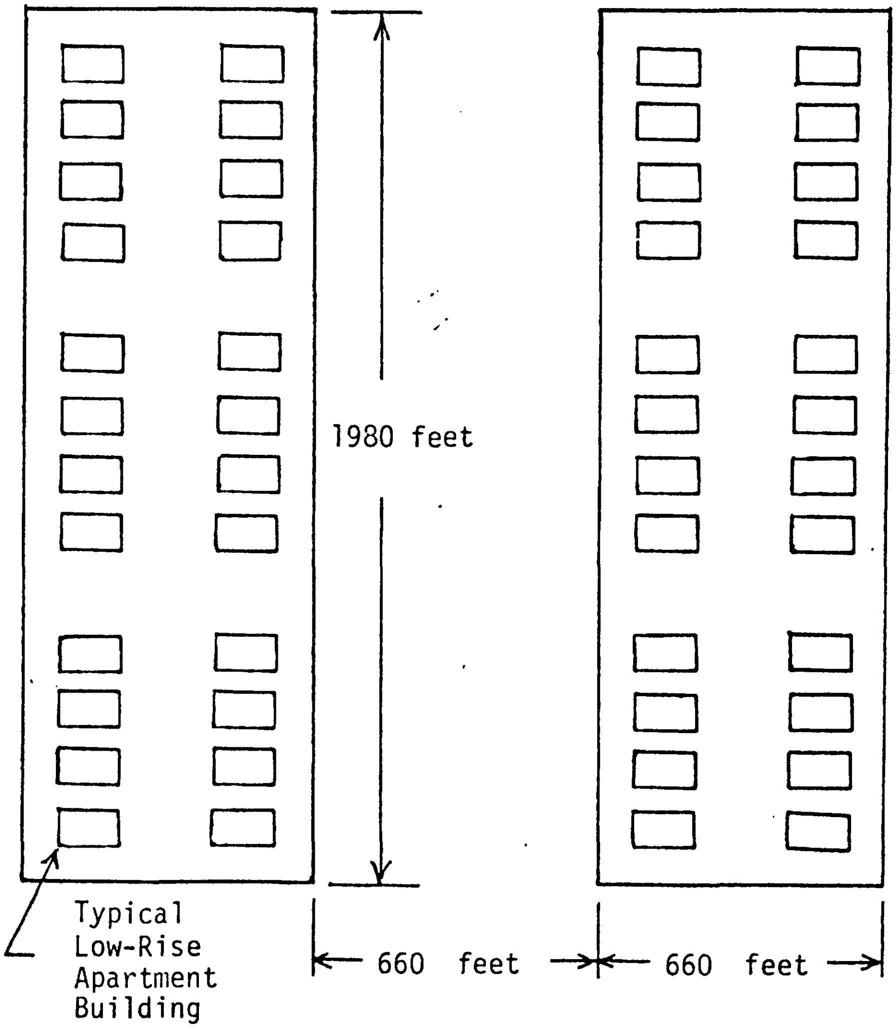
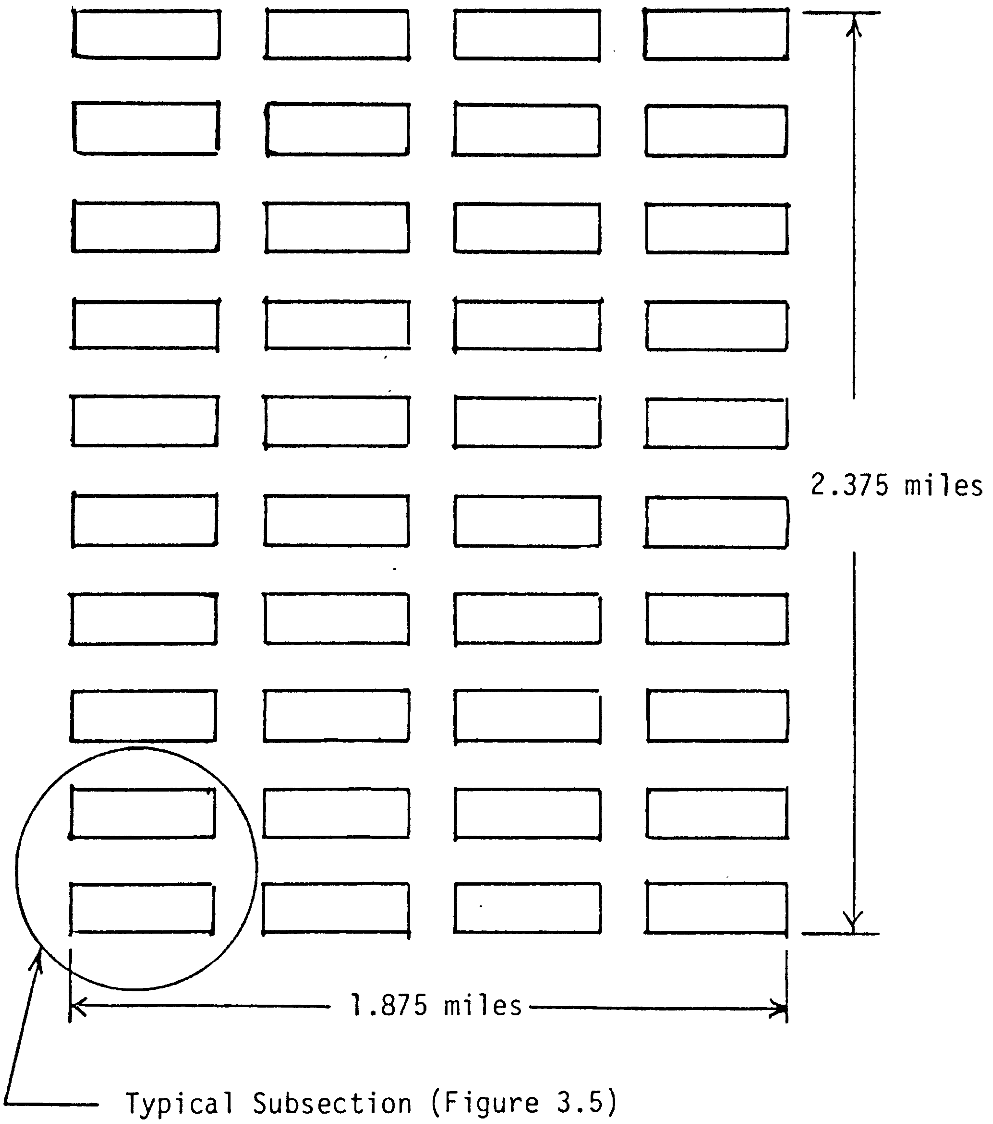


FIGURE 3.6

Entire City Structure

Apartment Building Urban Model



of the economic effects of urban growth patterns. No effort has been made to optimize the structure of the networks, but Yee (7) has shown that the cost of this type of design is probably within ten per cent of the cost of an optimally designed network.

Figures 3.7 and 3.8 show the assumed network structure for a single family house model subsection and mains connecting twenty subsections, respectively. Figures 3.9 and 3.10 show the same items for the low-rise apartment building city. Not shown in Figures 3.7 and 3.9 are the service lines connecting the buildings to the system. These items are included in the system cost, however. The piping network is a dual one with both supply and return pipes enclosed in the same concrete envelope (see Appendix A). The primary main lines (transmission system) may be coupled to the distribution system (subsections) by a heat exchanger or mixer to take advantage of economically desirable higher sendout temperatures for long plant-city separation distances.

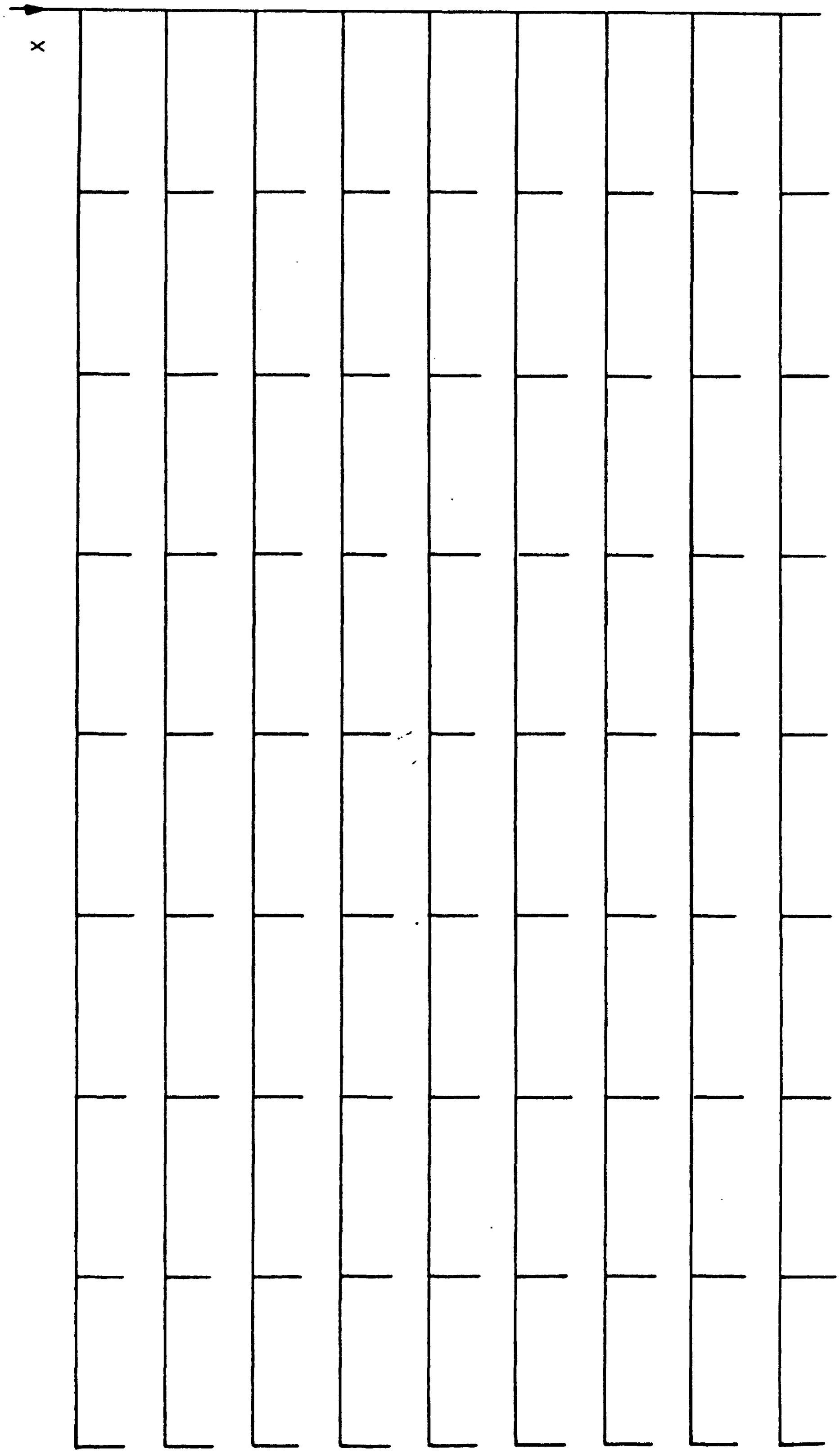


Figure 3.7

House Model Subsection Distribution System

Figure 3.8

House Model Mains Network

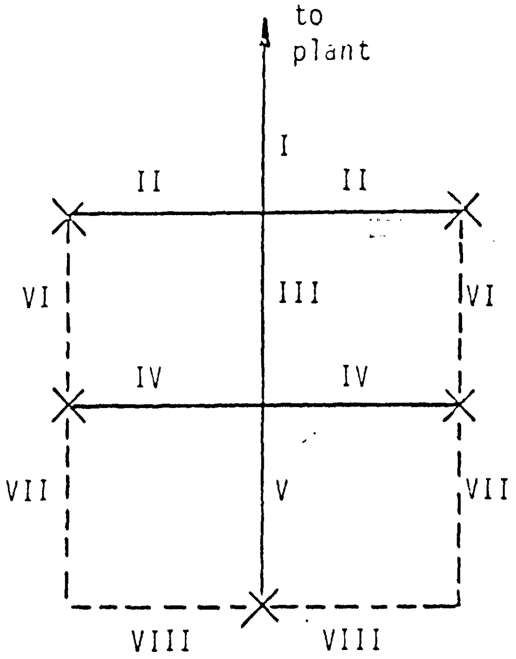


FIGURE 3.9

Apartment Model Subsection Distribution System

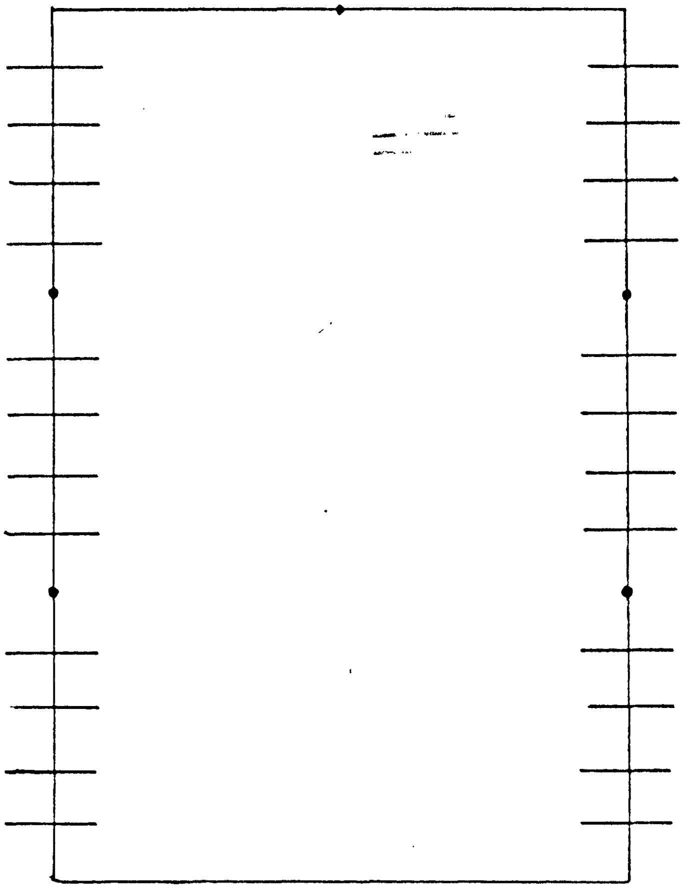
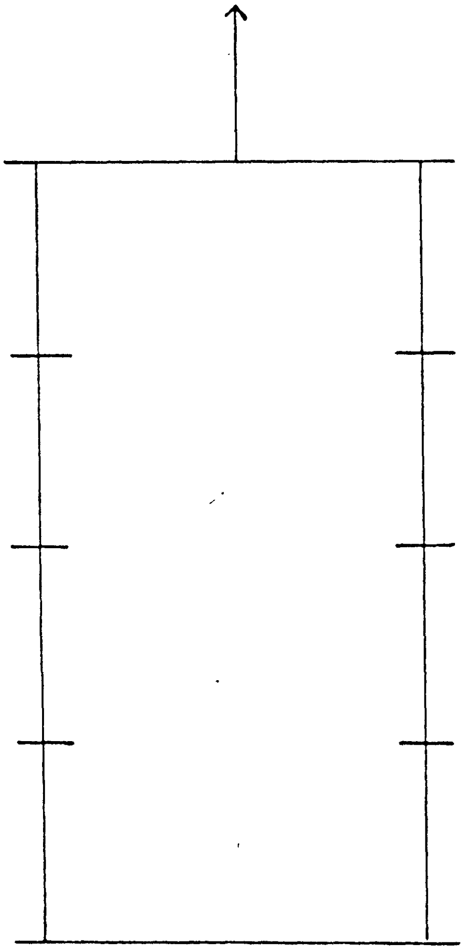


FIGURE 3.10

Apartment Model Mains Network



3.3 Thermal Distribution System

3.3.1 Heat Carrying Medium

The first step in the design of a thermal distribution system is the selection of the heat carrying medium. Historically, water has been favored in Europe and the USSR, where district heating has become popular and often national policy, while steam has been chosen in the U. S. Excellent discussions of the relative advantages and disadvantages of each are available in the literature (2,3,4,5). Some of the more frequently quoted differences between the two media are listed below.

1. The thermal energy storage capacity of hot water systems is much greater than that of steam systems for equal volumes.
2. Hot water systems require pumps in both supply and return lines, while steam systems require only condensate return pumps, producing some cost savings for steam systems, but this savings is usually offset by the higher capital and maintenance costs caused by the required condensate traps.
3. Because of the possibility of using an extraction turbine and a counterflow heat exchanger to generate hot water, much less electricity production must be sacrificed to generate hot water than to generate steam at the same temperature. This will depend on the temperature drop across the hot water system, but was found to be true for our case of a 60°F drop.

4. Because of the need to extract steam at pressures high enough to overcome the pressure drops in the supply line, hot water is favored for long distance heat transmission, as the reduced capital cost of the smaller required lines for the water system counteracts the cost of pumping power, resulting in a net advantage for hot water. This is very important because the trend is to site large plants far from cities.
5. Hot water lines can follow natural land contours, while steam lines must be sloped to provide for condensate drainage.

Particularly important to our analyses are the long distance transmission cost advantage and the reduced amount of sacrificed electricity generation for hot water. Other studies have shown that the long distance cost advantage for hot water applies to distances greater than about ten miles. In addition, an analysis for the base case apartment building urban model for both steam and hot water distributed showed an energy cost of $\$4.82/10^6$ Btu for the steam system and $\$3.58/10^6$ Btu for the hot water system. A sendout of 220F was used for both systems and $\Delta T = 60F$ for the water system. If longer plant-city separations (10 miles is base case) are considered, the water system is even better. These results indicate that hot water system costs are likely to be below those of comparable steam systems, especially if the condensate is to be returned. Based on these pieces of information, water was chosen as the carrier medium in this study.

Before leaving the discussion of thermal media, it is appropriate to mention one possible development which might eventually reduce the cost of long distance heat transmission. This is the chemical heat pipe, which relies on storing energy via endothermic chemical reactions at the heat source, transportation of the carrier at low temperature and pressure, and finally, release of energy at the point of use by a complementary exothermic reaction (11). Transportation costs are about the same as for gas pipelines, since high pressure, insulated pipe is not required. Aside from the fact that the commercial feasibility is not yet demonstrated, the most promising chemical reactions, involving methane, require a source temperature of at least 1000°K, and the only presently promising source of energy at this temperature is the HTGR (or VHTR in Germany). As these reactors have encountered serious difficulties in achieving commercialization, it is apparent that chemical heat pipes may be delayed indefinitely unless a substitute reaction is found and demonstrated to be feasible.

3.3.2 Building Thermal Requirements

Two sources of residential thermal energy demand are considered in this analysis, water heating loads and space heating loads. The water heating loads are modeled in a very simple way; each person is assumed to use 58 gallons of hot water per day , and a temperature rise of 80°F is assumed for the water. The hourly load is assumed to be constant at 1/24 of the daily load.

The space heating load is assumed to vary linearly with the outdoor temperature for temperatures between the design temperature and 62°F. Internal sources are assumed capable of supplying enough energy to raise the temperature from 62°F to 72°F (the indoor design temperature recommended by ASHRAE 90/75). For outdoor temperatures below the design temperature, the heat load is assumed to be equal to the design peak load. The rationale for this choice is that lower temperatures occur for a small number of hours each year, and a large economic penalty is associated with designing a heating system for these larger loads. The implication of this design procedure is that either the temperature indoors falls below 72°F on the colder days, peaking capacity is provided to supply these loads, or the system is pushed a little harder (e.g., additional pumps, higher supply temperatures, or lower return temperatures). A smaller safety factor is implied, of course, but the logical way to increase it is with auxiliary boilers, which are much cheaper than excess distribution capacity.

Ten year average temperature data are used to calculate the space heating profile. These data show the average number of hours per year the temperature falls in each five degree Farenheit interval. For the cases analyzed below, New York City weather data are used. This information is summarized in Table 3.3.

The analyses presented below ignore industrial and commercial space and water heating demands. The industrial space heating and water heating demands are somewhat difficult to estimate from available data and are not discussed below. However, these demands undoubtedly share many of the characteristics of the commercial sector demands which are discussed below.

Table 3.3

Hours Spent in 5°F Temperature Bands - 10 Year Average
(New York City Data)

TEMP (F°)	HOURS
105-109	
100-104	+
95- 99	5
90- 94	28
85- 89	96
80- 84	265
75- 79	604
70- 74	926
65- 69	877
60- 64	754
55- 59	745
50- 54	722
45- 49	796
40- 44	838
35- 39	858
30- 34	603
25- 29	330
20- 24	188
15- 19	96
10- 14	26
5- 9	10
0- 4	+
-1- -5	1
-6- -10	

The first useful characteristic for evaluating the importance of commercial sector space and water heating demands is magnitude. All non-residential buildings contribute about 25% to the overall space heating and water heating demands, with schools, shops, and offices contributing 18% out of this 25%. With the exception of hospitals, water heating loads are not generally important for commercial buildings.

Perhaps the more significant characteristics of these commercial sector demands are the load factor and peak load. As the data in Appendix D show, the peak loads per unit area are very similar for commercial buildings and low-rise apartment buildings*; however, the load factors are significantly lower for commercial buildings (0.2 as compared to 0.5), mostly because of the large heat input from high lighting levels in commercial buildings.

While the low space heating load factor of commercial buildings is disadvantageous to district heating economics, another building characteristic, large floor area, may offset this disadvantage somewhat. It will be shown below that the larger the quantity of heat carried by a pipe, the cheaper is the cost per unit of delivered energy. This effect may actually dominate over the load factor effect for commercial areas having high ratios of floor area to land area. While the exact effect of commercial buildings would depend on the urban structure and the building size distribution, it is possible that their inclusion could as easily have a negative effect on system economics as a positive one. Hospitals, which have high load factors for both space and water

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*This assumes that ASHRAE 90/75 standards are met for both building types.

heating, are an important exception, and would be very attractive customers to a district heating system.

3.3.3 Pipe Selection Methodology

In the above sections, the urban models, the pipe network structures, and the choice of heat carrier medium were discussed. The cost of energy was considered only briefly (in the comparison of water to steam). The problem considered below, the choice of pipes for the networks, is necessarily tied closely to economics, because the cost of thermal energy from district heating will depend strongly on the installed piping cost. Thus, what follows is primarily an engineering economic analysis of the piping network.

For the purposes of this analysis, the piping network has been divided into two independent types of subsystems. A distribution system consists of all necessary hardware to distribute hot water from a local supply point to each dwelling unit in a defined geographical area and return the cooler water from which thermal energy has been extracted to a single point on the return line. In this study, a separate distribution system has been used for every 2700 people, so that there are twenty identical subsystems for the reference city size of 54,000 people. The second type of system is the transmission system. This system consists of all hardware required to supply water to and return water from all the distribution systems.

Because of an essential difference in the pipe selection procedures, the discussion is split into two parts, the first part for the transmission system and the second part for the distribution systems.

The pipe selection procedures differ in that the cost of thermal energy at the heat source is considered in the design of the former system but not of the latter, and in that a pressure drop limitation is applied to the distribution system, but not to the transmission system.

An important assumption made concerning the pipe selection process is that pipe sizes can be selected independently for each pipe section. It is recognized that this design might differ from the optimum network design, but Yee (7) has shown that the cost difference is likely to be less than five per cent.

3.3.3.1 Distribution System Design

Two important design constraints are applied to the distribution systems. First, the water supply and return temperatures are fixed at 220°F and 160°F, respectively. These temperatures are chosen to match the characteristics of available hydronic space heating equipment. Second, the peak load pressure drop along the longest path from supply to return (within a distribution system) is limited to a maximum of 150 psi. This constraint is applied so that only one pumping station is needed per distribution system; available centrifugal pumps can handle heads no greater than about 150 psi.

Centrifugal pumps can be designed to handle larger heads, but such pumps are a special order item, and costs are not readily available. The possibility of using another type of pump was considered, but it was soon clear that only the centrifugal pump can compete in the large capacity, high head applications such as this one. Other types of pumps can compete neither on an initial cost basis nor on a reliability and maintenance cost basis. These constraints will be shown to dominate the pipe selection process for the distribution systems.

The heat losses from the buried pipes are not presented below. Estimates of the heat loss for a well-designed and maintained system are typically in the range of 3-5% of send-out energy. In addition, some of the thermal energy lost by heat conduction is actually replaced by the heating effect of the friction between the flowing fluid and the pipe walls. Since the energy input to the fluid from friction is ignored below, the error caused by neglecting conduction losses will be negligible.

The cost items included in the delivered energy costs associated with the distribution systems are capital amortization costs, system maintenance costs, and pumping power costs. The cost of the energy as supplied at the heat source (before distribution) is not included because it is included with the transmission system costs. The annual cost for a given pipe section is given by

Annual Cost= (Installed Pipe Cost) X (Capital
Recovery Factor + Maintenance Percentage)
+ Pumping Power Cost

The annual cost for each pipe section is calculated in this way for each standard pipe diameter, and the pipe size chosen for that section is the one which gives the lowest annual cost while satisfying the pressure drop constraint mentioned above.

3.3.3.2 Transmission System Design

The pipe selection process for the transmission system (i.e., the piping network connecting the heat source to the distribution systems) is very similar to that for the distribution systems, but there is an important additional cost component. The cost of heat at the heat source prior to distribution is equated to the busbar cost of any electricity which could otherwise be generated if no heat were to be supplied by the plant. Such a cost is encountered because, to extract thermal energy at useful temperatures, the expansion of steam in the turbine must be stopped before condenser conditions (typically 2.5 inches of mercury at 90°F) are reached. Thus, some usable mechanical energy, hence, electricity generation, is sacrificed; if there is demand for this electricity, and the plant is capable of supplying it in the absence of a heat demand, then this cost for the heat is certainly reasonable. If there were no market for the electricity because of excess system capacity, for example, then a lower cost such as the marginal cost of generating the thermal energy in addition to the demanded electricity is more appropriate (that cost will be lower than the lost power cost).

The details of the thermal energy cost calculation are included in Appendix B. It is shown there that the cost of energy at the plant (lost electricity busbar cost) increases linearly with sendout temperature for a constant return temperature. Increasing the supply temperature also affects the economics of the piping network in two other ways. Increasing the temperature drop reduces the volume of water to be transported, thus allowing reduced pumping power costs and/or a reduced pipe diameter, hence reduced costs. Increasing the supply temperature also increases the system pressure required to avoid flashing of water into steam. This mandates the use of a thicker pipe wall, which increases the pipe cost. In general, the reduction of cost because of reduced pipe diameter is the dominant effect of the two until the sendout temperature rises above about 350°F. Thus, a new cost tradeoff appears for the transmission system--the increase in thermal energy costs at the plant with increasing supply temperature must be balanced with reduced distribution costs.

All other annual cost components for the transmission system are the same as for the distribution system. The annual cost for a given pipe section is given by

Annual Cost = (Installed Pipe Cost) X (Capital Recovery Factor +
Maintenance Percentage) + Pumping Power Cost +
Cost of Thermal Energy at the Plant Site

Whereas the distribution systems were designed subject to a pressure drop restriction of 150 psi per mile of pipe, no such restriction was applied to the transmission system. The pressure drop was left as a free variable, and pumping stations were used wherever needed to compensate for friction losses. The cost of the pumping stations was included in the annual cost equation for the transmission system pipes, however, so that the pressure droo does enter implicitly into the pipe selection process. The distance between pumping stations was adjusted so that the pressure drop between them at peak system load was 150 psi.

3.3.4 Major Cost Items

In the preceding section, four major cost components were identified as significant contributors to total annual network cost. These items and some of the major assumptions used to estimate them are displayed in Figure 3.4, and a discussion of these items follows below. For additional details on the capital charges and lost power costs, consult the appendices.

3.3.4.1 Capital Costs

The capital amortization costs include all interest and depreciation charges associated with the entire installed pipe system (including hardware material costs, labor costs, land acquisition costs, etc.). The pipe and conduit system used for costing purposes is a dual steel pipe system with supply and return pipes surrounded by a field-constructed poured-in-place vermiculite-cement mixture conduit. The design is illustrated in Figure 3.11. Expansion loops are installed in concrete vaults at intervals of 300 feet. These loops increase the installed network costs by about 25% because of material and labor costs. Expansion joints may be more desirable than loops in congested areas because of their smaller space requirements, but they require much more frequent maintenance. Because of the inconvenience and cost associated with frequent maintenance, loops are used rather than joints wherever practical. In addition to expansion loops, provision should be made for the pipe to move freely within

Table 3.4

Network Cost Variables

1) Pipe and Pump Capital Charges

   Initial Cost x Capital Recovery Factor (CR)

2) Maintenance Charges

   5% of initial cost per year

3) Lost Electrical Power Charges

   Assumptions:

   - Rankine power cycle
   - Eight equally spaced (in temperature) steam extraction points between sendout and return temperatures
   - Turbine outlet conditions, 2.5 inches mercury outlet pressure at 90°F
   - Busbar power cost, $0.024/kwh

4) Pumping Power Costs

   $0.030/kwh and an assumed pump and driver efficiency of 85%

The pipe diameter is chosen from standard values for steel pipe to minimize annual cost. The sendout temperature is assumed constant, and the mass flow rate is varied with the heat demand.

the concrete conduit during expansion and contraction. The cost of pipe supports or guides to provide for pipe movement was not included here, but as discussed in Appendix , the error resulting from ignoring these costs is likely to be no more than 5%.

The initial cost of the piping network will be very sensitive to the installation environment. The soil conditions and the degree of underground congestion (e.g., sewer pipes, telephone lines, water pipes, electric lines, etc.) can increase costs severalfold over the ideal conditions cost. The reference cases for this analysis have assumed ideal conditions, that is, average soil without other interfering underground structures, mire or rock. The costs for this case are often referred to as "cross country costs". The degree to which costs may be changed by less favorable conditions is illustrated by Table 3.5, where the relative costs for ideal conditions, suburban conditions, and inner city conditions are estimated for one pipe size. It is shown that substantial cost increases because of higher excavation costs, street work, and service costs may quadruple the ideal conditions cost. The procedure used to derive the pipe costs is described in Appendix A. Figure 3.11 shows the costs used in this study in comparison to costs used elsewhere. Note especially that for the purposes of this analysis, costs are a function of pipe size and fluid temperature. The required pressure rating of the pipe is assumed to be saturation pressure of the water (at the given temperature) plus 150 psi for pumping head.

Figure 3.11

Installed Pipe Cost Comparison

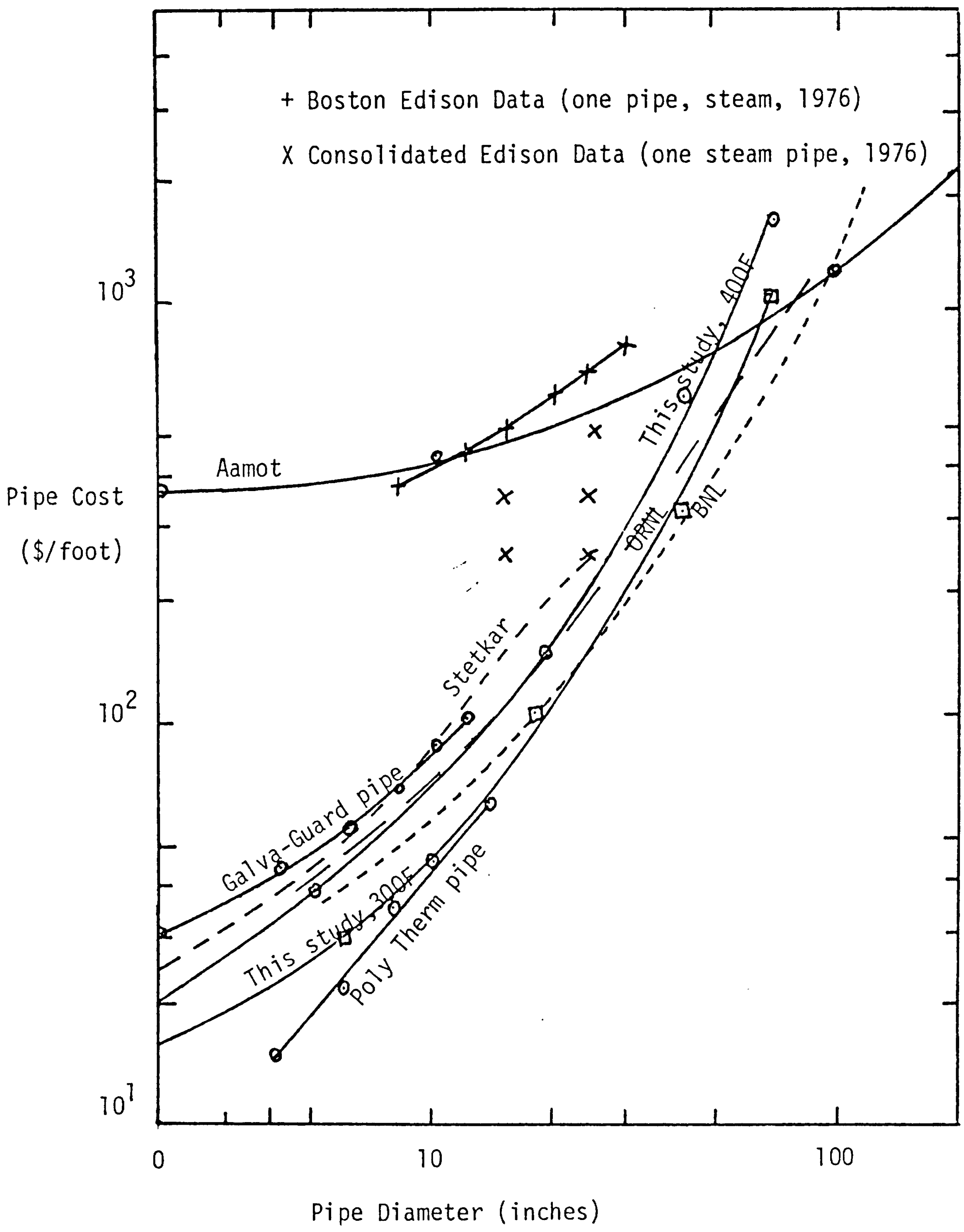

Table 3.5 - Effect of Urban Congestion on Installed Pipe Costs (24-inch pipe diameter)

	Ideal Cond. ("cross-country")	Medium Diff. Cond. (suburbs)	Difficult Cond. (Inner City)
Pipe Material Costs ($/meter)	89	89	89
Pipe Labor Costs	63	63	63
Concrete Culvert costs	74	74	74
Excavation, refilling	41	78	200
Street work	0	85	289
Service, winter work, etc.	0	0	196
TOTALS	267	389	911

Source: "District Heating - A Step by Step Approach," by Erik Wahlman, from "Technical Papers Presented At the Swedish Trade Commissions, Toronto, Canada, October 28, 1976, on District Heating and Power from a Single Plant."

The extent of likely market penetration of district heating will depend strongly on existing city installation costs. It will be observed in results to be presented later that the cost of heat generally decreases with increasing population density, installation costs remaining constant. But installation costs do not remain constant; rather, they increase substantially with increasing population density. Thus, cost of energy is quite likely to have a minimum in the cost versus population density curve. The cost increases at densities lower than that at the minimum point because of the economics of scale effect for piping, while the cost increases for higher densities because of increased installation costs associated with congestion.

The amortization costs are determined by assuming a thirty year lifetime for system components and a nine per cent interest rate. This interest rate is chosen to reflect the cost of money to a utility (in 1976) as well as the cost of money for home mortgage loans.

3.3.4.2 Maintenance Costs

The annual maintenance cost is assumed to be five per cent of initial system costs. While this figure is approximately correct for steam distribution systems, it is probably somewhat high for hot water systems.* A large fraction of the maintenance cost for steam systems is attributed to condensate trap maintenance, and these are not used for hot water distribution. However, lacking sufficient data to demonstrate that hot water systems really do have lower maintenance costs, it was decided that the five per cent figure should be used.

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*For example, Lieberg (4) uses 2-3% and ORNL-HUD-14 (9) uses 3%.

3.3.4.3 Lost Electrical Power Charges

The cost of heat at the source is equated to the busbar value of electricity sacrificed to generate hot water. The heat source is assumed to be a large utility heat source designed to generate electricity. Hot water is generated by extracting steam at eight equally spaced temperatures between the sendout and return temperatures, passing the steam through counterflow steam-to-water heat exchangers, and returning the condensed water to the feedwater stream (where it goes is immaterial to my analysis as long as it does not affect the power generation).

Calculation of the electricity sacrificed requires a knowledge of steam conditions during expansion, the condenser inlet conditions, and the turbine efficiency in addition to the information above. For this calculation it was assumed that steam expansion starts from the 550°F saturated state (superheated steam conditions at the turbine inlet change the result insignificantly). The expansion occurs with an isentropic efficiency of 82%, and the condenser inlet conditions (in the absence of steam extraction) are 2.5 inches of mercury pressure and 90°F.

In order to assign a value to the lost electricity, a busbar cost of 2.4 cents/kwh is assumed. A higher cost may be appropriate if the lost electricity must be replaced by a less economic peaking plant. Conversely, a lower cost may be appropriate if there is excess generating capacity and the power need not be replaced. In the latter case, only the marginal costs of generating the heat should be charged to the district heating system. The additional costs of an extraction turbine and heat exchangers are ignored as they are small compared to other costs.

The steam expansion conditions used above are appropriate for a nuclear plant, but the amount of sacrificed electricity is insensitive to all plant thermodynamic parameters except exhaust conditions which are independent of plant type. Lost power costs differ in coal and nuclear plants only insofar as the busbar costs vary; variation of busbar costs will be considered below in a sensitivity analysis.

More details of the lost power calculation are presented in Appendix B, where results for varying numbers of extraction points and varying sendout temperatures are displayed. In particular, the case of one extraction point is displayed. This case yields the lost power costs appropriate for a steam district heating system; the savings resulting from using hot water rather than steam are clearly visible (about 40%). The largest question about this calculation is whether turbines with eight extraction points can be obtained. Turbines with three or four extraction points are readily available. If a relatively small portion of the steam (<10%) is to be extracted at each point, there should be no problem with using eight extraction points, but if a large portion of the steam is to be extracted at each point, mechanical design of the turbine may be difficult (12).

3.3.4.4 Pumping Power Costs

The last major item entering into the pipe selection process is the pumping power cost. Expressions for the pumping energy are derived below.

If the thermal demand profile, the desired temperature drop, and the average temperature are known, the mass flow rate can be calculated from equation (1).

$$(1) \qquad \dot{Q} = \dot{m}c_p\Delta T$$

where $\dot{Q}$ = energy flow (Btu/hour)

$\dot{m}$ = fluid mass flow (lb/hour)

c_p = fluid specific heat (Btu/lb-°F)

ΔT = system temperature drop (°F)

$= T_{supply} - T_{return}$

The fluid mass flow is related to the pipe cross sectional area (A) and the flow velocity (V) by equation (2).

$$(2) \qquad \dot{m} = \rho AV = \rho \; D^2V/4$$

where ρ = fluid density (lb/ft^3)

D = pipe diameter (ft)

V = fluid velocity (ft/sec)

Selection of the actual pipe size requires that V be specified, which requires further information. This information is contained in the Darcy equation, (3) $\Delta p = f \frac{L}{D} \frac{V^2}{2g}$

where Δp = fluid pressure drop (lb/ft^2)

f = friction factor (dimensionless)

L = length of pipe (ft)

D = diameter of pipe (ft)

g = gravitational acceleration (ft/sec^2)

The Darcy equation is used in two ways for selecting pipe sizes. First, the maximum pressure drop per unit length is specified for the distribution systems. Second, the annual cost of pumping energy is one component of the total annual cost, which is minimized subject to engineering constraints. The instantaneous pumping power is given by

$$(4) \qquad P = \Delta p\dot{m}/\rho\eta_p \qquad \text{(ft-lb/sec)}$$

where η_p = pump and driver combined efficiency

The annual pumping energy is calculated from the expression

$$(5) \qquad E_p = \sum_i \Delta pQ_i t_i/\eta_p$$

where the sum is over the intervals displayed in the average weather data, and the subscripts indicate that the quantities are calculated assuming the appropriate outdoor temperatures. t_i is the number of hours spent in that temperature interval, using the values modified by application of the coincidence factor where appropriate.

Finally, in order to convert the calculated pumping energy into a cost, a value must be assigned to η_p, and a value must be given to the pumping electricity. For η_p, a value of 0.85 has been used. The pumping electricity has been assumed to cost three cents per kilowatt-hour, which approximates an industrial electricity rate. Since the pumping power cost was found to be a minor contributor to total cost, little effort was made to specify these numbers more accurately.

3.3.5 Computer Program Description

3.3.5.1 Methodology

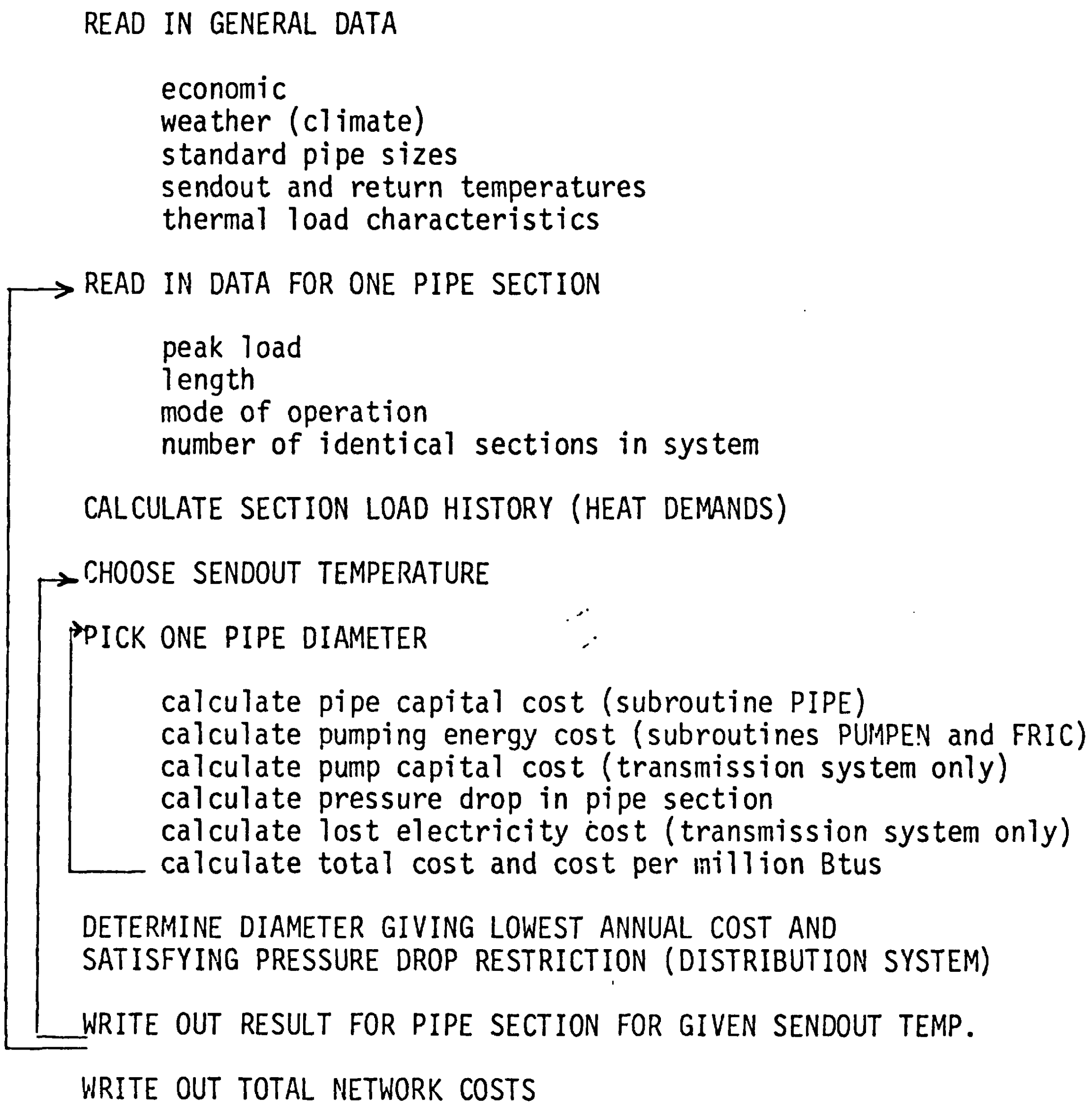
Although choosing pipe sizes for the previously displayed networks is straightforward, calculation of the cost items requires that many economic and engineering parameters be specified, and the calculations are laborious. In addition, since economic parameters cannot be predicted with certainty, sensitivity analyses are useful in interpreting results. Because of the amount of work involved, a computer program was written to do the calculations. A brief discussion of the program methodology follows below, and a complete program listing is included in Appendix F.

The program flow scheme is displayed in Figure 3.12, and the required input data in Figure 3.13. It will be noticed that the program consists of a main program and three subprograms. The functions of the main program are data input and output, performing less often repeated calculations, and coordination of subprogram calculations. Examples of main program tasks are calculation of needed economic parameters and thermal demand profiles, calculation of cost components, and selection of pipe diameters. Total cost for all network components is also calculated in the main program.

The function PUMPEN calculates the peak pressure drop, flow history, annual pumping energy requirements, and capital costs of required pumping stations (transmission system only). The pumping energy and pressure drop are calculated by the methods described in Section 3.3.4.4. Internal to PUMPEN are functional forms for water density and viscosity as functions of temperature. The range of validity of these functions limits the generality of the subprogram.

Another subprogram, FRIC, is called by PUMPEN to calculate the friction factor for use in the Darcy equation. FRIC requires as input the pipe

Figure 3.12. Flow scheme for computer program



```
READ IN GENERAL DATA

     economic
     weather (climate)
     standard pipe sizes
     sendout and return temperatures
     thermal load characteristics

READ IN DATA FOR ONE PIPE SECTION

     peak load
     length
     mode of operation
     number of identical sections in system

CALCULATE SECTION LOAD HISTORY (HEAT DEMANDS)

CHOOSE SENDOUT TEMPERATURE

PICK ONE PIPE DIAMETER

     calculate pipe capital cost (subroutine PIPE)
     calculate pumping energy cost (subroutines PUMPEN and FRIC)
     calculate pump capital cost (transmission system only)
     calculate pressure drop in pipe section
     calculate lost electricity cost (transmission system only)
     calculate total cost and cost per million Btus

DETERMINE DIAMETER GIVING LOWEST ANNUAL COST AND
SATISFYING PRESSURE DROP RESTRICTION (DISTRIBUTION SYSTEM)

WRITE OUT RESULT FOR PIPE SECTION FOR GIVEN SENDOUT TEMP.

WRITE OUT TOTAL NETWORK COSTS
```

Figure 3.13. Input data for computer program

The computer program requires the following information to select the pipe size for each section:

--List of standard pipe diameters
These diameters are chosen from standard diameters available from a nominal size of one inch to 120 inches.

--Busbar electricity cost (dollars/kwh)

--Pumping power electricity cost (dollars/kwh)

--Interest rate

--Economic lifetime of pipe and equipment

--Annual maintenance cost; expressed as a fraction of initial system cost

--Coincidence factor

--Single building peak water heating and space heating loads (Btu/hour)

--Bin weather data; midpoint of temperature interval and number of hours per year the outdoor temperature falls in that interval (five degree Farenheit intervals)

--Temperature of water returning to heat source (°F)

--Number of water sendout temperatures considered

--List of water sendout temperatures (°F)

--One card for each section of pipe network showing:
    -peak heat load (Btu/hour at design outdoor temperature)
    -length of pipe section (feet)
    -integer code for mode of operation of section
        0 - transmission system
        1 = distribution system (except for service line or standby line)
        2 = service line
        3 - standby use only
    -total number of pipe sections in network which are identical to this one
    -optional description of pipe

roughness, internal diameter, and the Reynold's number. The friction factor calculation is equivalent to the use of a Moody diagram (13).

The third subprogram is the function PIPE, which calculates the installed cost of a section of pipe (per foot) given its diameter and the water temperature. Only the dual pipe system described in the next section and in greater detail in Appendix A is included in the program as presented, and several important assumptions have been made. See below for a discussion.

3.3.5.2 Assumptions

Several key assumptions which significantly affect district heating system design and the related energy costs are discussed below. Many other assumptions have been presented previously, and the interested reader is advised to review especially Sections 3.3.2, 3.3.3, and 3.3.4 for a more complete understanding of the significance of the results presented in Sections 3.4 and 3.5

The peak loads for each pipe section are not the sum of all individual building peak loads supplied by the pipe. It is assumed that not all buildings will demand the peak load at the same time. This assumption is reflected by the use of a coincidence factor to calculate the pipe design peak load. The coincidence factor is defined as the ratio of the peak system load to the sum of individual building peak loads. The value used for the coincidence factor throughout this analysis is 0.72. A sensitivity analysis is performed to illustrate the affect of this assumption later. The obvious effect will be to reduce the size of the pipe required for a particular section and hence reduce the capital cost of the network.

Once the heat load history of a given pipe section is determined from application of the given peak load, the design temperature, the weather data and the coincidence factor, the flow history, hence, the pumping power history, can be determined. This pumping power history is used along with an assumed cost of pumping electricity (3.0 cents/kwh) and an assumed pump and motor efficiency (85%) to obtain the annual cost of pumping energy for the given pipe section.

For all the analyses presented below the water return temperature is fixed at 160^{0}F to match presently available hydronic space heating equipment. The program can accommodate several sendout temperatures, and the calculations built into the program are accurate for sendout temperatures between 200°F and 400°F. For temperatures outside this range, new functional dependences for the water density and viscosity must be put into the subroutine PUMPEN, and new pipe cost functions must be built into the subroutine PIPE.

The pipe costs built into the program assume dual steel pipeline construction with the pipe surrounded by calcium silicate insulation, then by insulating (concrete-vermiculite mixture) concrete, with the line buried so that the top of the pipe is six feet below the ground surface. The costs include an allowance for the materials, the labor required to install the concrete and insulation, and the excavation costs for "cross country" conditions, that is, no difficult soil conditions interfering underground obstacles. Allowance is also made for the cost of expansion loops, but no allowance is made for anchors or guides for the pipe. Including the guide and anchor cost would increase the installed pipe costs by about five per cent for the base case where the sendout temperature is 220°F. The energy cost increase would be somewhat less, because the pipe cost increase would, in some cases, result in selection of a smaller pipe size at the expense of higher pumping power cost. For deriving pipe wall thickness, the design internal pressure was assumed to be equal to the saturation pressure of water at the sendout temperature plus a 150 psi pumping head. Pipe wall thicknesses were then chosen to satisfy the code requirements of ANSI Section 31.1. Although no explicit allowance was made for maintenance of the pressure at a value slightly above saturation pressure to avoid flashing, the wall thicknesses chosen (standard values only) are always sufficient to handle this extra pressure.

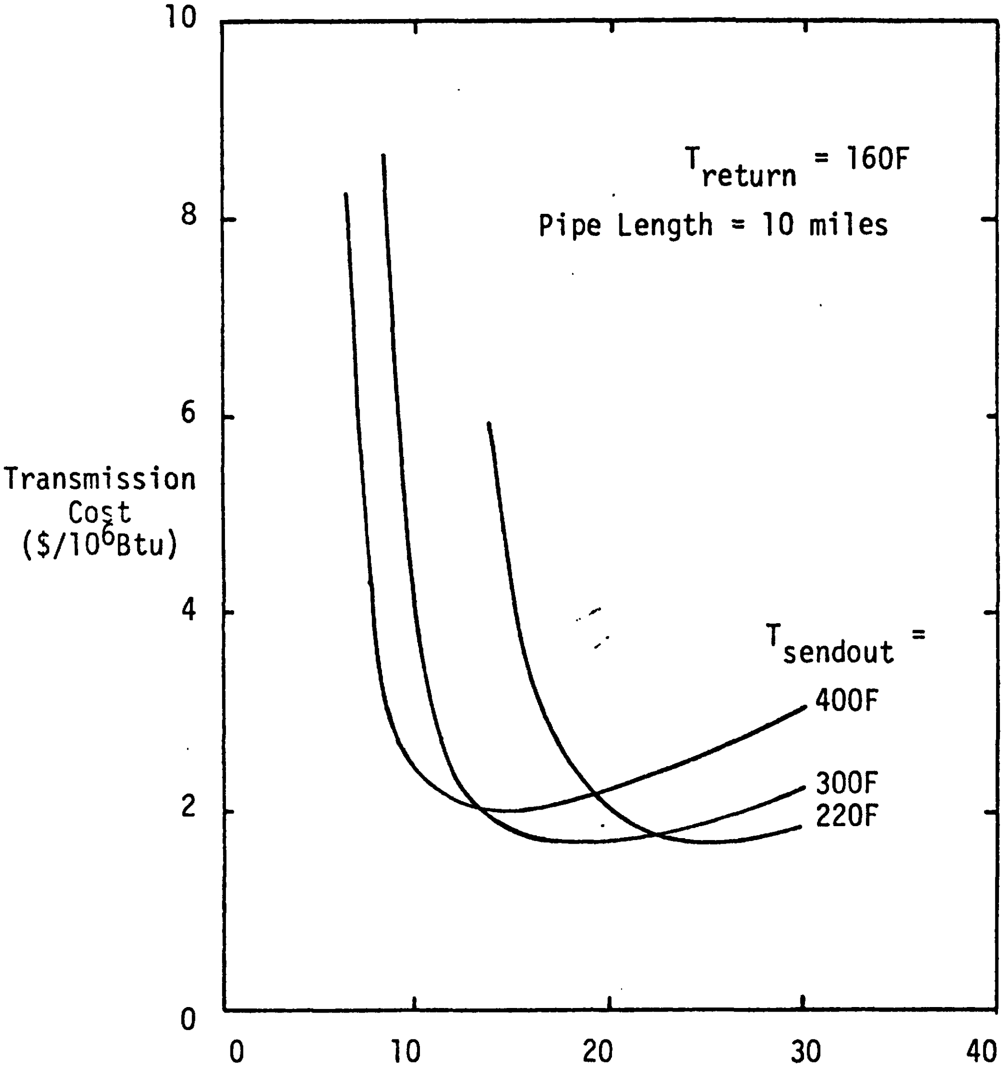
3.3.5.3 Selected Intermediate Results

Some intermediate results shown in Figure 3.14 may help give the reader a better intuitive feeling for the results to be presented later; the variation of total annual cost of a ten-mile length of transmission line with pipe diameter for three sendout temperatures is displayed. This transmission line is sized to supply energy to the single family house city of 54,000 people. It can be seen that the annual cost is not very sensitive to pipe diameter--choosing one size larger or smaller than the optimum size will have little effect on the annual cost. Also, there is an apparent optimum sendout temperature for this case. Again, the cost is not very sensitive to the sendout temperature, but it is better to err on the low side than on the high side.

As the above results may at first seem somewhat surprising, some explanation is in order. First, one expects the annual cost to decrease with increasing sendout temperature for fixed return temperature, because the quantity of fluid to be transported is decreasing. This behaviour is observed as the sendout temperature is increased from 220°F to 300°F, but

Figure 3.14

Annual Cost Variation With Pipe Diameter



the cost increases as the temperature is increased further to 400°F. This occurs because the saturation pressure of water increases very rapidly as the temperature increases above 300°F, and the pipe wall thickness must be increased accordingly to contain this pressure. In addition, the lost electricity cost increases linearly with sendout temperature. For high temperatures, these effects become more important than the cost reduction because of the decreased quantity of water to be transported. Second, the very rapidly rising annual cost as the pipe diameter is reduced from the optimum diameter is striking. The strong dependence of pumping power on velocity (approximately as $V^{5/2}$) is responsible for this effect. The contribution of pumping energy cost to annual cost is rather small for the optimum diameter, and consequently, reductions in this cost component with increasing diameter are negligible. However, as the pipe diameter is reduced below the optimum, the contribution of pumping power cost to total cost rises rapidly, because the velocity must be increased with reduced diameter to retain the same volumetric flow rate.

The relatively slow increase of total cost with increases in pipe diameter beyond the optimum also tells us that the restriction on the maximum pressure drop for the distribution systems will not greatly increase the cost above the optimum cost. Similar restrictions on the flow velocity for noise abatement purposes would therefore not be expected to cause large cost penalties to be incurred.

3.4 Base Case Results

Using the calculational methods and assumptions (included in Table 3.5 as an aid to the reader) discussed in previous sections of this chapter,

Table 3.6

Relevant Parameters

Economic:

Interest Rate = 9%

Equipment (pipe, pumps, etc) lifetime = 30 years

Maintenance Cost = 5% per year of initial cost

Busbar Electricity Cost =$0.024/kwh

Pumping Power Cost = $0.030/kwh

Urban Models:

City Population = 54,000

Housing Models:

Single Family House Model

-Housing Density = 14 houses per 5 acres, or 1792 houses per square mile

-Population Density = 9.8 persons/acre, or 6200 persons/square mile

-Housing Type: 1600 square feet, ranch style with 3.5 persons per house

Low-Rise Apartment Building Model

-Housing Density = 4 buildings (72 units) per 10 acres, or 256 buildings (4608 units) per square mile

-Population Density = 24 persons/acre, or 15,000 persons per square mile

-Housing Type: 18,000 square feet, two stories: 18 apartments with 3.3 persons per apartment

Continued on next page.

Table 3.6 (continued)

Energy Demands:

-Climate: New York City, 21°F design temperature.

-Design Standards: ASHRAE 90/75 requirements and recommendations.

-Peak Loads:

Heat: Apartment Building, 259,000 Btu/hour.
House, 42,000 Btu/hour.

Water: Apartment Building, 58,000 Btu/hour.
House, 5400 Btu/hour.

-Annual Loads:

Apartment Building, 1080×10^6 Btu

House, 120×10^6 Btu

-Load Variation:

Heat: linearly with outdoor temperature down to design temperature, then flat at peak load.

-Coincidence Factor = 0.72

Distribution System:

-Length of main connecting plant to rest of system is 10 miles.

* -$T_{sendout} = 220°F$

-$T_{return} = 160°F$

-Service line lengths:

Apartment Building, 60 feet.

House, 65 feet.

*Main lengths longer than 10 miles are allowed to have higher sendout temperatures if it is economically desirable.

Table 3.7

Costs by Components

(Base Case Parameters)

Item	House Model	Apt. Model
Sub-section pumps	\$0.17/10^6Btu	\$0.22/10^6Btu
Valves	0.004	0.01
Pumping power (Included below)	(0.23)	(0.16)
Lost Electricity	0.74	0.74
Sub-Section Dist.	2.68	0.66
Transmission Lines (less lost power)	1.12	1.20
TOTALS	\$ 4.71/10^6Btu	\$ 2.83/10^6Btu

energy costs for district heating were calculated for both reference urban models and displayed in Table 3.7. It should be emphasized that the costs obtained are on very simple urban models and for new city (i.e. the lowest likely) pipe installation costs, and therefore, should <u>not</u> be considered as accurate numbers for existing real cities. Sensitivity analyses presented in Section 3.5 show many variables that can change the cost results presented here.

The costs include all items except the end use equipment in the buildings. The pumping power is hidden in the final two items, but amounts to only about $0.23/$10^6$Btu for the single family house model and about $0.16/$10^6$Btu for the low-rise apartment model.

The subsection capital and maintenance cost contributions are much more important for the single family house model than for the low-rise apartment model. This difference arises from both housing types and population density. First, the contribution of service lines to the total cost is more significiant for houses (more than 20%) than for apartments (less than 6%). Second, the population (or more significantly dwelling unit) density is much lower for the single family house model than for the low-rise apartment model (6000/sq.mi. as compared to 15,000/sq.mi.). Thus, the heat must be spread over a larger area at a higher cost per energy unit.

Since the total costs are the costs of delivered energy, they are directly comparable to the cost of delivered fossil fuel to the extent the end use equipment costs are the same (a good approximation). In the winter of 1976-77, the cost of heating oil in New England is typically $0.44 per gallon. Assuming a furnace efficiency of 65%, the cost of heat energy is about $5.00/$10^6$ Btu. Thus, district heating is now economically competitive with fossil fuels for the assumed urban structures in New England.

3.5 Sensitivity Analyses

3.5.1 Interest and Maintenance Costs, Capital Costs

Since the capital and maintenance costs dominate total costs, energy costs, will be very sensitive to changes in them. Only the sum of these costs need be considered, because both are proportional to initial cost. For the base case, capital and maintenance costs are 0.09737 and 0.05 times the initial cost, respectively. These factors vary over a wide range, depending on financial arrangements and construction quality. For example, municipal ownership with financing done with municipal funds may yield an interest rate as low as six percent, and maintenance costs as low as two percent are claimed by some district heating proponents. The base case interest rate is applicable to public utility ownership. Ownership by a private developer (or developers) will result in interest rates of 15-20% or more. This range is covered in Figure 3.15 which shows the variation in energy costs with changes in the sum of the capital recovery factor (CR*) and the fraction of initial costs required for annual maintenance (M). If the interest and maintenance factors are assumed constant, the abscissa may also be interpreted as representing variations in initial system cost. For example, 0.15 represents the base case, and 0.30 represents a doubling of initial costs. A doubling of CR+M (or of the initial cost) would make district heating economically uncompetitive with fossil furnaces for the single-family house model, but not necessarily for the low-rise apartment model. Conversely, reducing CR+M (or the initial cost) would make the system more attractive. A quadrupling of costs might result from installation in an old city, and district heating would be prohibitively expensive for either urban model.

---

*$CR = \frac{(1+i)^n i}{(1+i)^n - 1}$ where i is the interest rate and n the economic lifetime in years.

FIGURE 3.15

Effect of Interest Rate plus Maintenance Cost Variations

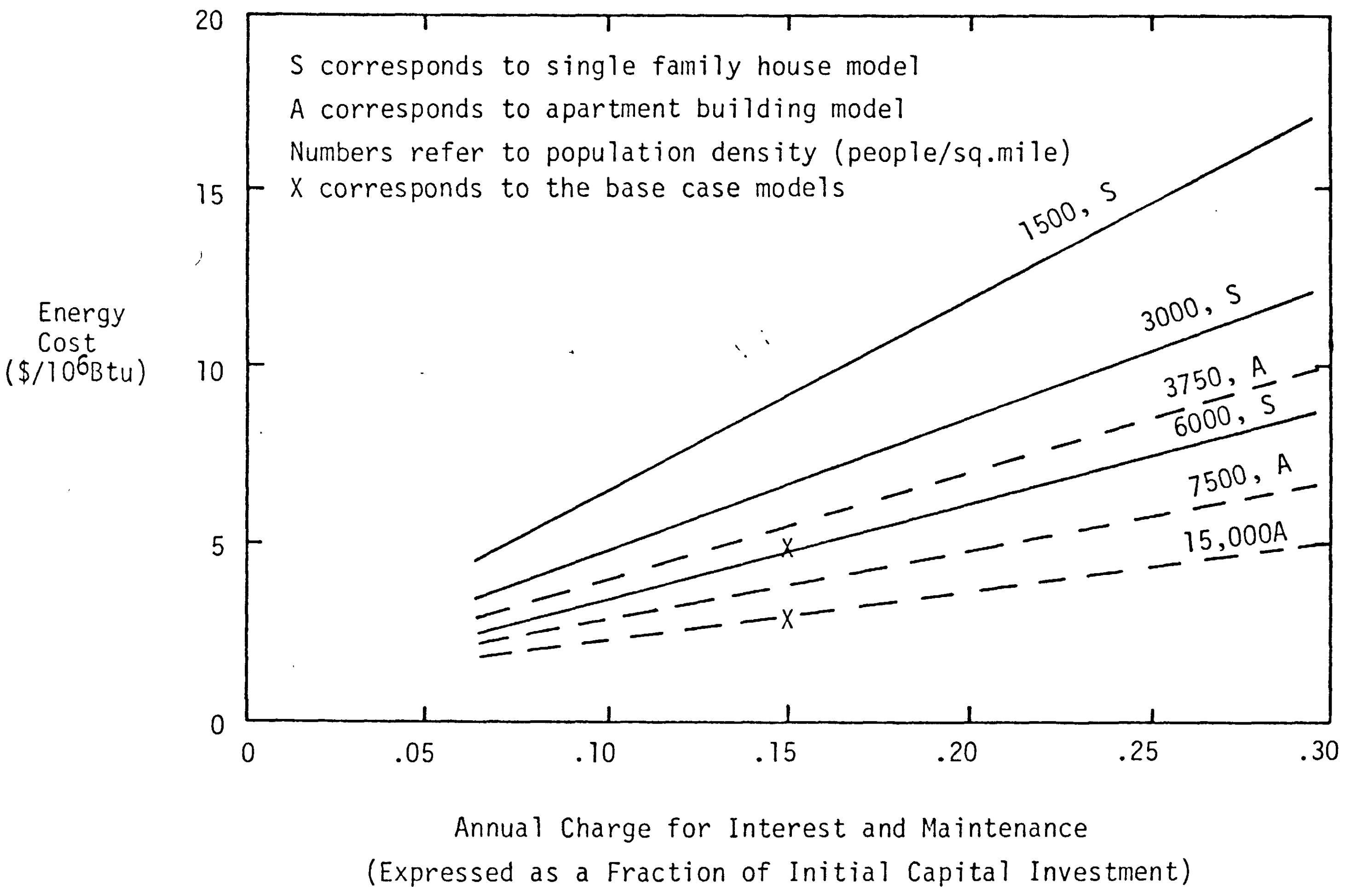


Figure 3.5 shows a quadrupling of installation costs in suburban area. In order to estimate the effect of such a change on the costs of thermal energy, a run was done using the base case parameters for the single-family house model, but quadrupling the installation costs given in Appendix A. The energy cost for this case is \$6.94 per 10^6 Btu as compared to \$4.71 per 10^6 Btu for the base case. This large increase in cost (47%) points out the necessity of knowing local conditions prior to system implementation. Lack of this knowledge can lead to economic disaster for developers.

3.5.2 Electricity Costs

The remaining important economic variable is the electricity cost. As pointed out above, there are two electricity costs, the busbar cost and the pumping power electricity cost. The busbar cost is used for the "lost power" charge as this power is not distributed, but the electricity used for pumping power is taken from the distribution system at the pumping station locations. The appropriate cost for this electricity is taken to be $0.03/kwh in this study. This rate is approximately equal to the average industrial electricity rate in New England in 1974 (14). As Figure 3.16 shows, there is little sensitivity to variations in the pumping power electricity rate because pumping power contributes little to total cost. Note that the network cost is reoptimized when the electricity cost is changed in this figure.

The energy cost depends more strongly on busbar cost (Figure 3.16) because lost power costs contribute significantly to total costs. Note that when the busbar cost is varied, the pumping power cost is varied to keep the ratio of these rates constant.

Though the sensitivity of energy costs to variations in electricity costs is not negligible, it will pose few planning difficulties. Many other factors will be shown to be more important, and to cause more difficulty in making economic predictions.

3.5.2 Population

Figure 3.17 shows the effect of total urban population on energy cost. Curves are drawn for both housing models (A for apartment and S for single family house) for various plant-city separations (50, 30, and 10 miles). These curves show the cost of the main lines (connecting the subsections

Figure 3.16

Energy Cost Variation with Electricity Cost

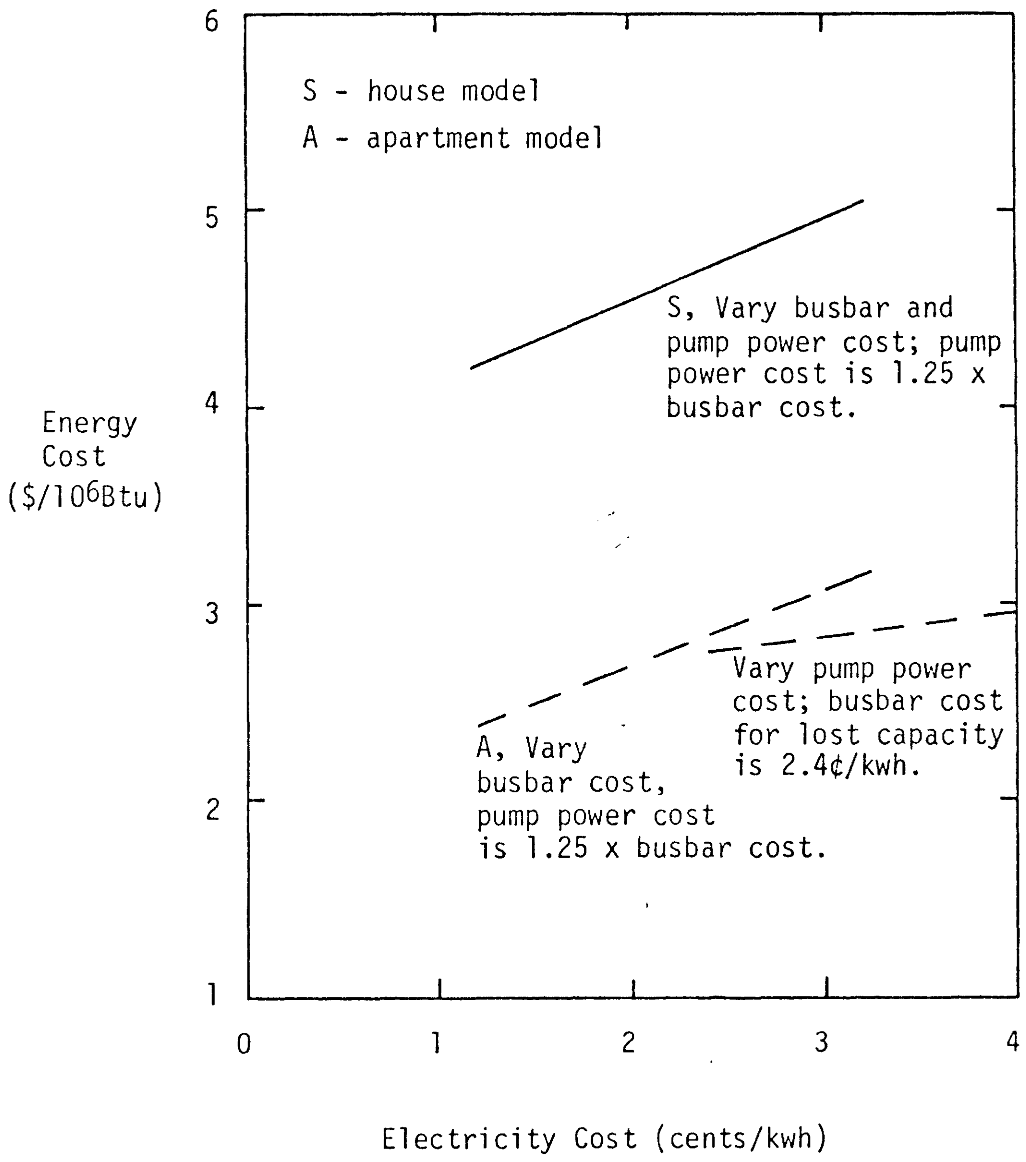
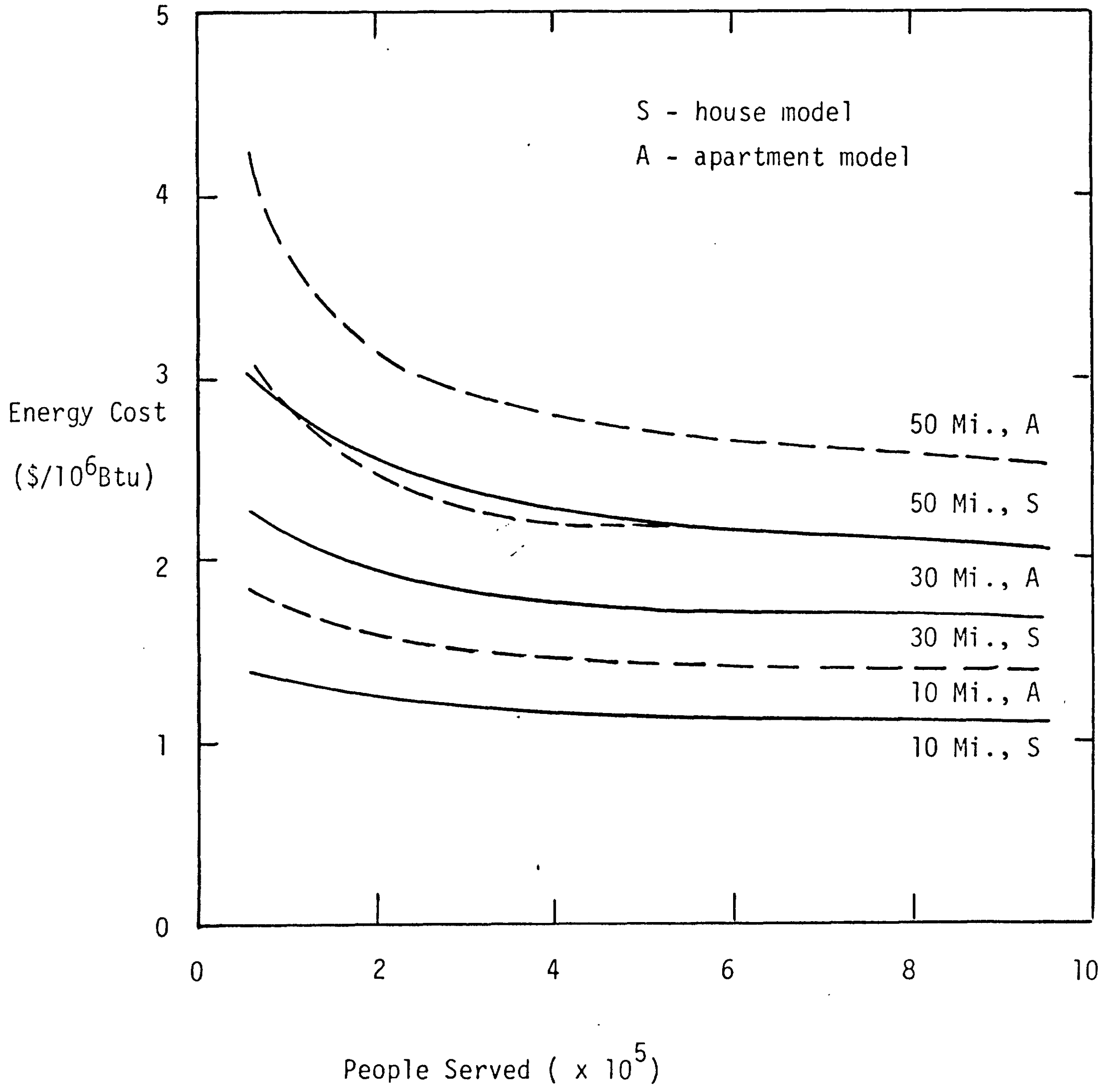


Figure 3.17

Transmission Cost Versus Population Served
("Cross-country" costs)



to the plant) only, but adding in the subsection costs would only shift the curves up a constant amount (different amount for each housing type). Thus, the cost variations with population apply also to total delivered energy cost. Surprisingly, energy costs are relatively insensitive to total population except for long mains, and then only for populations smaller than two or three hundred thousand. This is important because it tells us that there is no apparent need to restrict district heating to very large cities, particularly if the heat source can be within 30 miles of the city.

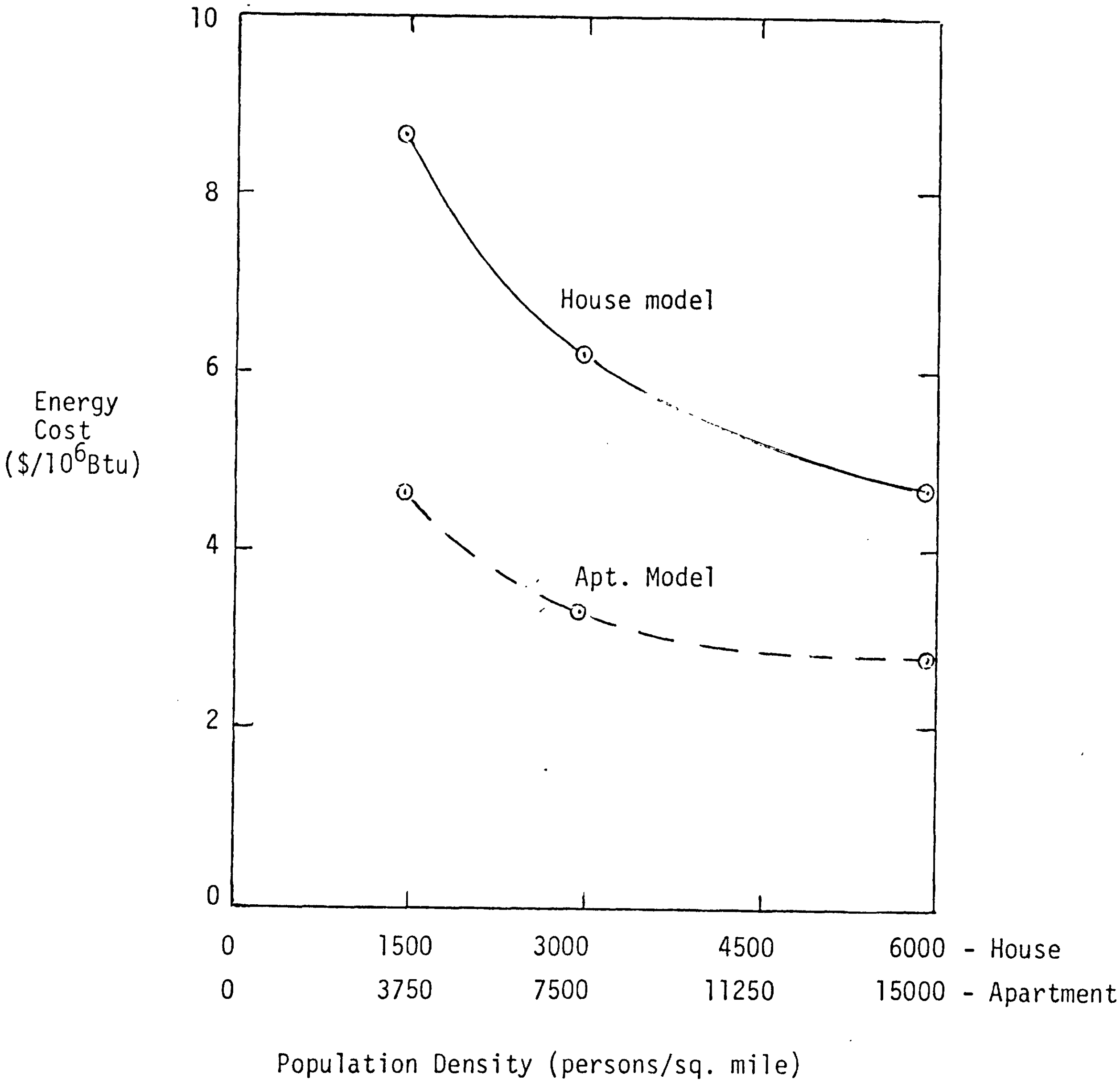
The location of the single family house curves are at first somewhat surprising, but there is a quite simple explanation. A much greater quantity of energy is distributed in the single family house case than for the low-rise apartment case, and there are economies of scale associated with heat distribution. However, because the difference in annual heat demands per dwelling unit more than compensates for the lower rate, the house dweller still pays more.

3.5.4 Population Density

Energy cost will depend strongly on population (or more accurately, dwelling unit) density. Figure 3.18 shows the variation of energy cost with population density for both urban models. The subsection designs are as previously shown, but the dwelling unit densities are varied to obtain the desired population density, and more subsections are added as required to maintain the total population at 54,000. In all cases, the distribution systems are economically optimized for the population density of interest (as opposed to the following sections, where the system is designed for a fixed size and density). The upper limit

FIGURE 3.18

Effect of Population Density on Energy Cost



densities correspond to the reference cases for each urban model. Higher population densities than used here would reduce costs further, but such higher densities are unlikely for a new urban area, and for an older urban area, considerably higher pipeline costs and more political difficulty in achieving a high penetration fraction make lower energy costs unlikely.

It is interesting to note that only very low density predominantly single family house suburban areas are ruled out entirely by our results, but minimum lot-size restrictions put many newer suburbs in this class (e.g. two acre lot size for single family house implies about 1000 persons per square mile). When end use equipment costs are included (about \$2.00/10^6Btu for single family houses), heat pumps appear to be more economically attractive in such areas. For lot sizes smaller than one acre, district heating might still be economically viable _if_ all homes are connected to the system (see below). For the apartment building urban model, district heating is apparently competitive with other heating methods for all densities considered. For real cities, which would consist of a mixture of the two housing types, the costs would fall somewhere between the costs for these models depending on the exact mixture.

3.5.5 Penetration Fraction

Political acceptability of a district heating system will probably require that it be designed to serve all buildings within its range. What will be the economic effect if a significant fraction of these buildings choose not to use the system? Since the energy costs are dominated by capital charges and only operating costs are saved by reducing the use of the system, one intuitively expects the energy costs to rise substantially if a large fraction of the design load is not served. Figure 3.19 confirms this intuition by showing a plot of energy costs as a function of penetration fraction, defined as the fraction of the design load actually connected to the system. A penetration fraction of one corresponds to the reference case models.

The economic penalty associated with substantially less than complete penetration of the system is large. For the single family house model, less than about 50% penetration might not destroy the economic viability of the system, but it would greatly increase the cost to the users and would certainly leave open the possibility of unfavorable changes in other parameters tipping the economic balance to the red. It should be noted that, for older cities (of equal density), the cost curves will be shifted upward, and the breakeven cost (compared to the heat pump, for example) will occur for higher penetration fractions.

3.5.6 Plant-City Separation

Figure 3.20 illustrates the importance of the location of the heat source with respect to the city. That energy costs increase with increasing heat source-city separation is expected. What is somewhat surprising is that even a 50-mile separation does not make the system prohibitively expensive. For city populations of more than 54,000, the costs are even lower, as shown in Figure 3.17. Siting policy need not be changed greatly from present practice for nuclear plants to make them useful for combined heat-electric plants.

3.5.7 Coincidence Factor and Design Temperature

For the purposes of the above analyses, an outdoor temperature of 21°F was assumed for a NYC climate. This corresponds to the recommendations of ASHRAE 90/75, but is considerably higher than pre-ASHRAE 90/75

Figure 3.19

Effect of Penetration Fraction on Energy Cost

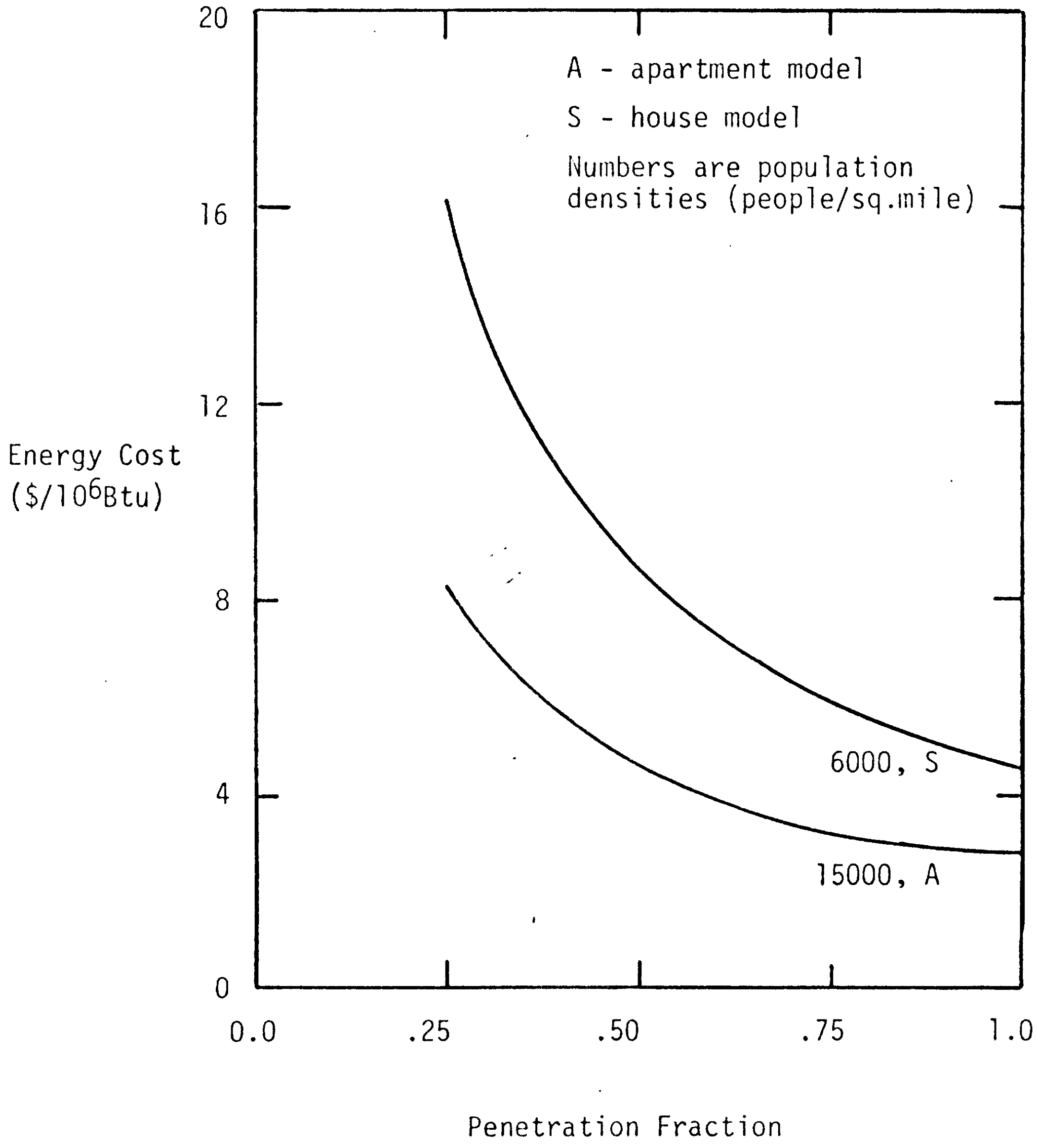
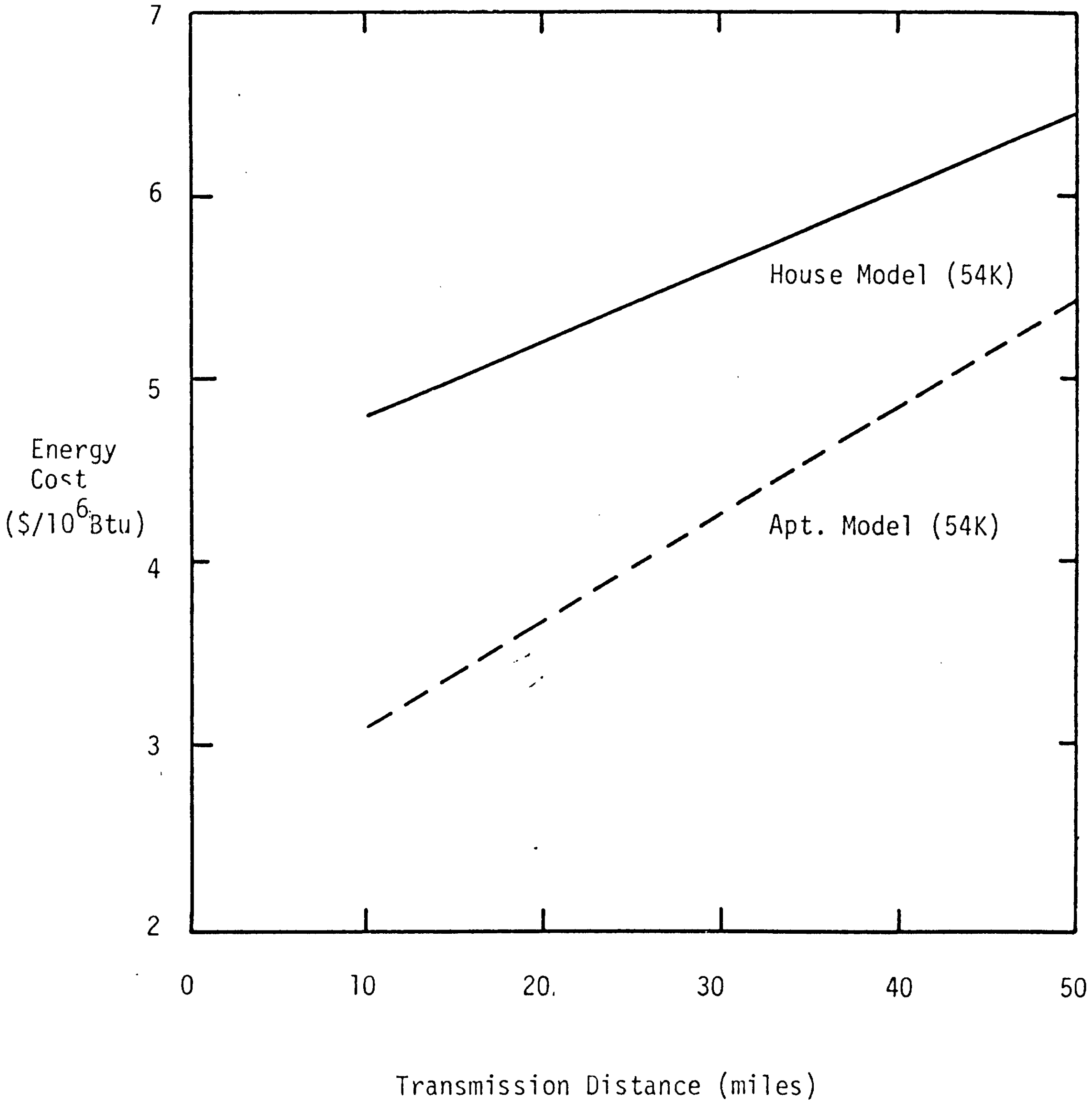


Figure 3.20

Effect of Plant-City Separation on Energy Cost



~ 40¢/mi

convention of designing for 10°F.

The higher design temperature is motivated by a desire to improve the load factor of heating equipment (hence, the efficiency of small fossil furnaces, whose efficiency decreases as the load decreases) and to reduce the capital investment required. No variation of system efficiencies with load has been included in this analysis, but the effect of system size on cost does show up.

Use of a system coincidence factor also has an effect on initial investment. Examination of Table 3.8 shows that each of the above factors has about the same effect on energy costs for the single family house model. If the coincidence factor is changed to 1.0 rather than the 0.72 used in the above analyses, and the design temperature is reduced from 21°F to 0°F, the system design is adequate to supply the sum of all individual peak loads on the worst case day for the ten-year average weater data. The cost increases about ten per cent if both changes are made; approximately half of the total increase comes from each change.

3.6 Conclusions

The results of the economic analysis for the base case urban models show that capital, maintenance, and lost power costs are dominant. Pumping power costs are a minor cost item. As expected, the cost of delivered energy is higher for the single family house urban model than for the apartment model because of the larger capital investment per dwelling unit for the former case. For both urban models, however, the delivered cost of heat is now competitive with the cost of heating oil or natural gas in New England during the winter of 1976. The heat cost

Table 3.8. Effect of Coincidence Factor and Design Temperature on Energy Cost

Coincidence Factor	Design Temp.	Cost (dollars/10^6Btu)*
.72	21	5.47
.80	21	5.53
.90	21	5.63
1.00	21	5.74
.72	10	5.63
1.00	10	5.95
.72	0	5.68
1.00	0	6.00

*Costs estimated assuming 40 gallons/day per person hot water load; other assumptions identical to base case conditions for single family house urban model.

does not include end use equipment cost, but the initial cost of the equipment appears to be about the same as for conventional heating equipment, while the economic lifetime is likely to be longer and the annual maintenance costs lower.

Increases in the interest rate, maintenance cost, or initial cost (all are closely related in this study framework) can destroy the economic viability of district heating for the single family house urban model, but probably not for the low-rise apartment model. Factors causing such increases could include required profit margins, property taxes, low quality workmanship, and underground obstacles interfering with pipeline installation. The latter factor will be very important for installation of district heating in existing cities, and as shown earlier in this chapter, may increase capital costs by as much as 300%.

Electricity costs are not found to be a very significant variable, and more importantly, are more readily predictable than are other variables.

Of the urban parameters, total population was found to be the least significant variable in determining energy costs. The base case assumes a population of 54,000, and larger populations make a large economic difference only if the plant-city separation is large (more than 30 miles). Even then, there is little economic incentive for total populations larger than two or three hundred thousand.

Population density is a somewhat more significant parameter, but it is found that low-rise apartment cities are apparently attractive for district heating for the entire range of densities considered in the study (down to about 4000 people per square mile). The single family house model becomes unattractive for district heating at population densities below about 1500 per square mile (about 1 acre lots). The base case densities used are 6000 and 15,000 people per square mile for the house and apartment models, respectively. For population densities below the lower limits given above, the heat pump appears to be a cheaper option.

The most crucial variable is probably the penetration fraction, that is, the fraction of customers for which the district heating system is designed who actually use it. Because of the large fixed capital charges associated with a district heating system, the energy costs rise rapidly with decreasing penetration fraction. If less than about half of the target customers use the system, the economic viability of it is probably destroyed for the house model. Although such a low penetration fraction might not kill the system profitability for the apartment model, it would be reduced to the extent that an undesirable change in any one of the other variables could tip the balance.

The effect of plant-city separation is significant, but normal plant siting practice for large electrical power plants does not preclude their use as combined heat-electric plants. Plant-city separations of 30 miles will not pose insurmountable economic problems, even for a city of 54,000 people. For somewhat larger cities (two or three hundred thousand people), distances of up to 50 miles can be accommodated with a relatively small economic penalty and substantially ease the problem of power plant siting.

Finally, it was shown that using a conservative design approach to size the pipes in the network, that is using a coincidence factor of 1.0 and a design temperature low enough to cover the worst case day, results in an increase of about ten per cent in the delivered energy cost.

In conclusion, district heating is apparently an economically viable option for most new urban areas and for existing urban areas where low enough pipe costs can be achieved. In either case nearly full penetration of the system must be obtained for economic success. While economic success is probable for a new city even if the system is privately financed, the very high installation costs likely to be encountered in an existing city may require some form of public subsidization (low interest loans or direct payments) to ensure success. Even if economic success is assured after implementation, a large remaining question is "Can we get there from here?" The next chapter will examine the effects of finite rates of urban growth and of district heating system implementation.

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CHAPTER IV

DYNAMIC IMPLEMENTATION EFFECTS

4.1 Introduction

Chapter III dealt with the static, or non-growing, urban model. The city and the district heating system were assumed to be built simultaneously. The energy costs so obtained are lower than those realizable in practice because of the finite length of time required for full implementation of the system.

In an existing city sections of the system must be built all at once, but there will be a time lag between installation of the system and the achievement of full market penetration. This time lag is likely to be several years because of the need to modify or replace existing heating systems. The economic effect of varying the implementation time is discussed in Section 4.2 using the data for cost versus penetration fraction developed in Chapter III.

For a new or growing city the situation will be quite different. Annual additions are likely to be in the form of geographically concentrated developments of 1000 housing units or less. The developments are likely to be confined to the minimum land area acceptable to prospective buyers of housing. Thus, there is no need to install the distribution system for the entire city initially, but in order to avoid foreclosing the district heating option, it will probably be necessary to install the portion of the system required to serve the new development in such a way to be compatible with eventual conversion to a centralized system. Small temporary heat sources can supply the heat in the interim. This scheme is considered in Section 4.3.

4.2 Retrofit of Existing Cities

For district heating systems to contribute substantially to U.S. space and water heating needs, existing cities as well as new cities must be served. The potential market for district heating is larger in existing cities, but so are the obstacles to implementation. In particular, conversion of existing building heating systems to use the district heating system is likely to be a slow process because of natural consumer reluctance to replace existing systems. Although conversion of existing buildings to the district system may require a period of several years, the high cost of pipe installation requires that the entire piping network (except service lines) be installed at once. The economic penalties associated with a large amount of underused distribution capacity will be substantial.

It is probable that a substantial fraction of the ultimate load would have to be committed to immediate connection to a district heating system before private developers would begin construction. Presented below are the results of calculations of the heat cost as a function of implementation time. The implementation (load growth) is assumed to be linear in time. Two costs are directly relevant to policy decisions--the "instantaneous" energy cost during implementation, which reflects the effect of underused capacity and the resultant early losses to be absorbed, and the average cost over the economic lifetime of the system. How the costs are apportioned among users will certainly influence the implementation pattern, making the relationship between cost and implementation pattern a complicated nonlinear one.

The following presentation assumes that the system is built at time zero with a specified fraction of the ultimate load connected to the system. After a specified number of years of linear growth, all the ultimate loads have been connected. Figures 4.1 (apartment model, 0.25 initial penetration fraction), 4.2 (house model, 0.25 initial penetration fraction), and 4.3 (house model, 0.50 initial penetration fraction) show the annual cost of energy derived from the energy cost versus penetration fraction curve from Chapter III (Figure 3.19). These curves assume capital and maintenance costs are levelized but charged against the actual energy consumed in a given year. This method of billing could never be used, or the system would fail to attract customers because costs are extremely high initially, but the curves illustrate well the effects of growth on energy costs.

One alternative to the above "instantaneous" costs is to levelize energy costs over the economic lifetime of the system. Figure 4.4 shows the levelized energy cost as a function of implementation time for the two urban models and for an initial penetration fraction of 0.25 (the models in Chapter III). Zero growth time corresponds to the already built city cases of Chapter III. Large economic penalties are associated with finite implementation times; e.g., increasing the implementation time from zero to twenty years increases the levelized energy cost by about 50%.

If the implementation pattern can be anticipated and financial arrangements are flexible, the developer can plan to absorb early losses until later, more profitable years. The problem arises when the implementation pattern is different than anticipated. Implementation may be achieved at a slower pace than planned, in which case Figure 4.4

FIGURE 4.1

"Instantaneous" Energy Cost during Development;
Development Times (t_D): 5, 11, 20 yrs. Apt. bldg. urban model.

25% initial penetration fraction.

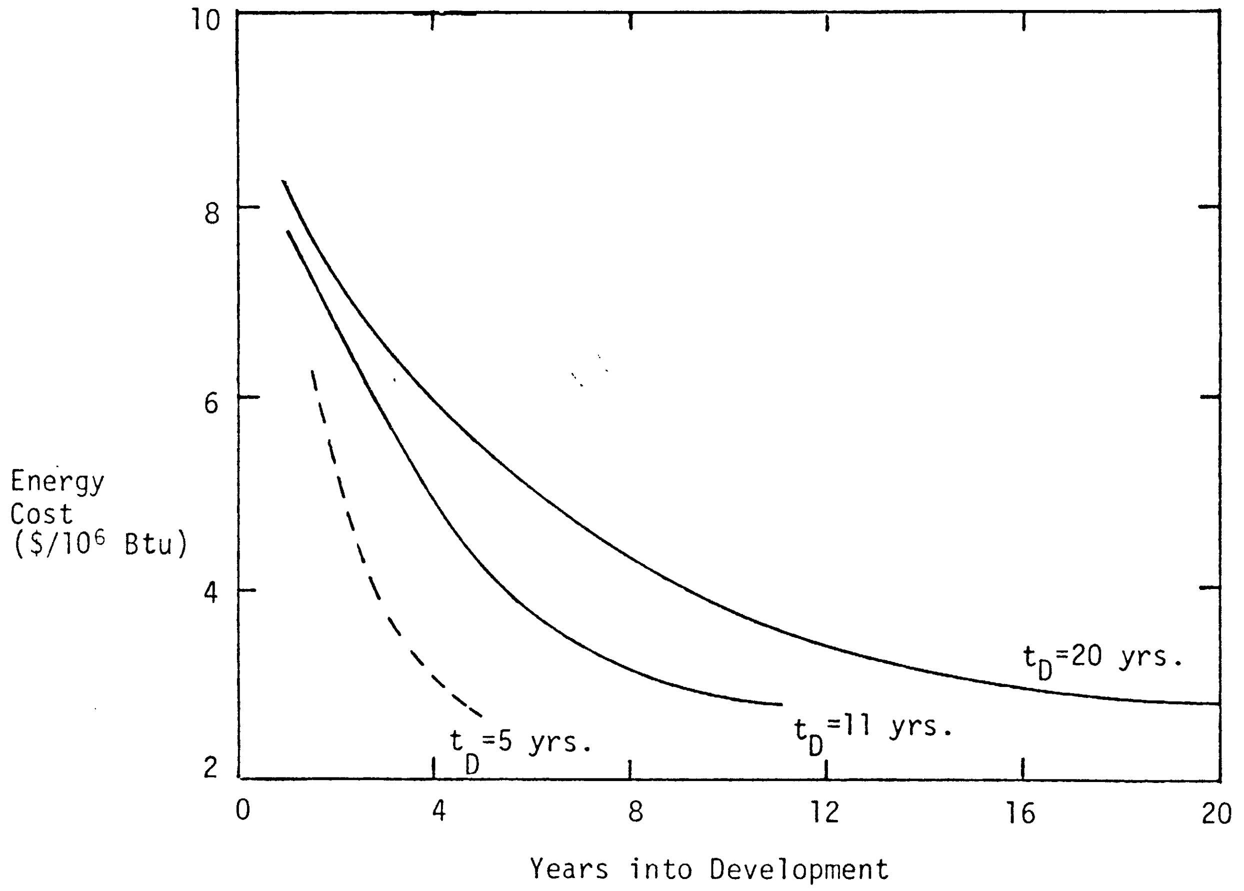


FIGURE 4.2

"Instantaneous" Energy Cost during Development; Development Times (t_D) of 5, 11, and 20 years.

Single family house model; 25% initial penetration fraction.

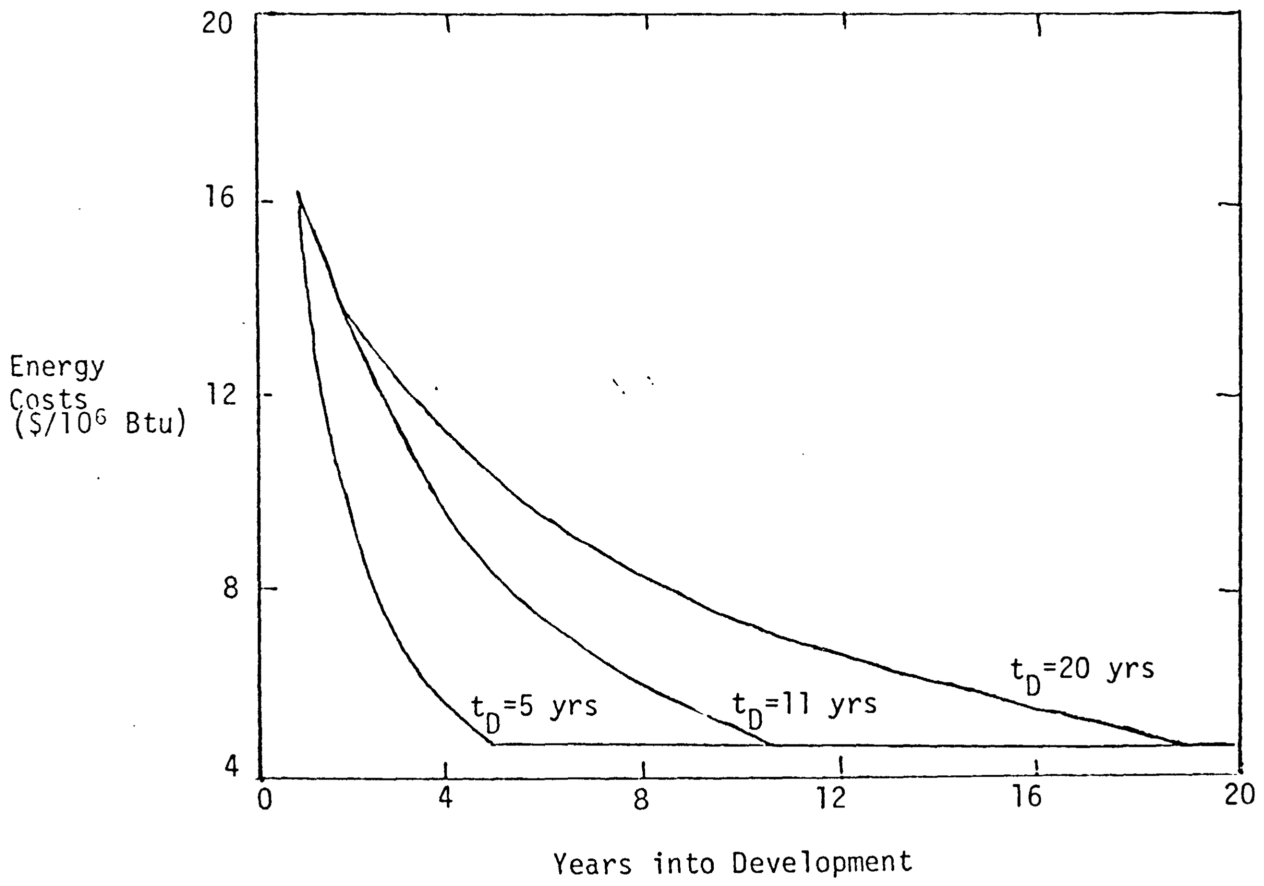


FIGURE 4.3

"Instantaneous" Energy Cost during Development; Development Times (t_D) of 5 and 11 years. Single family house model. 50% initial penetration fraction.

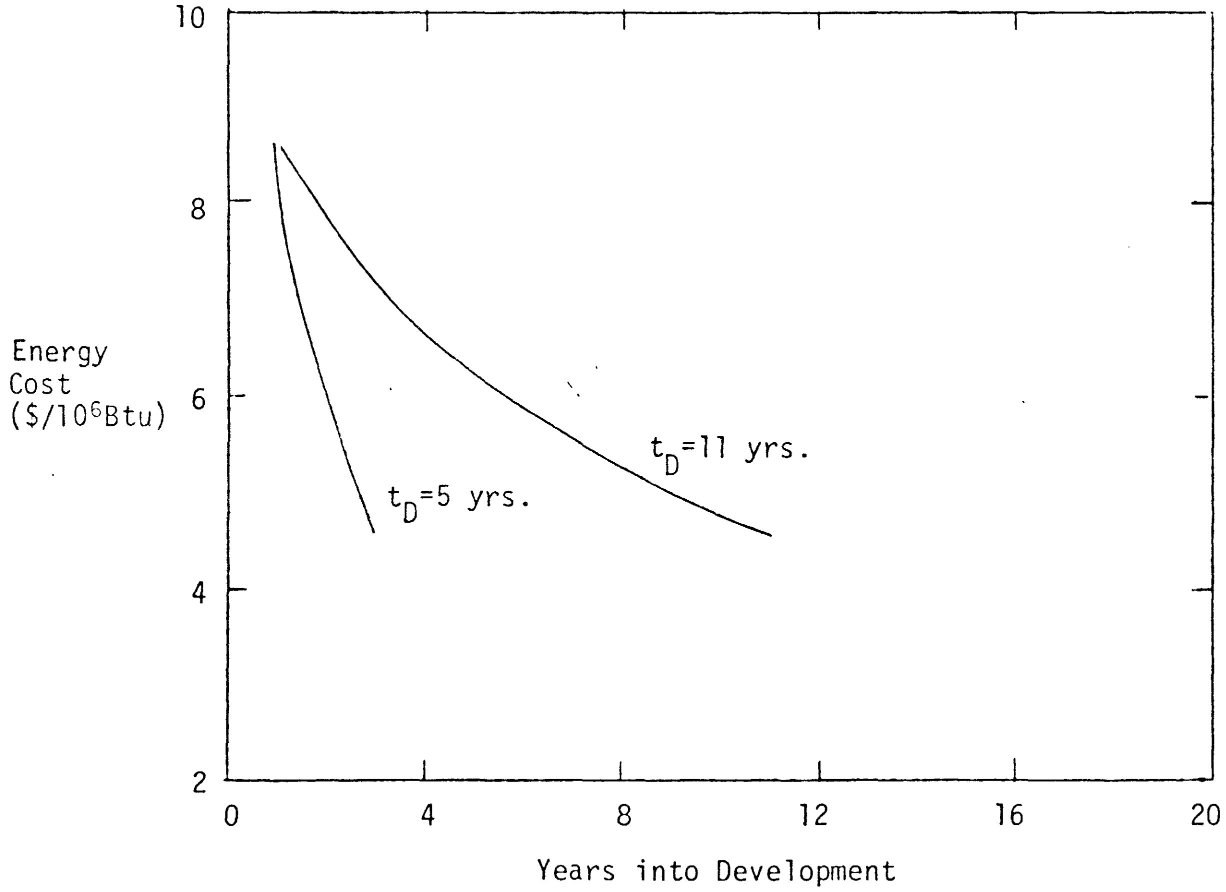
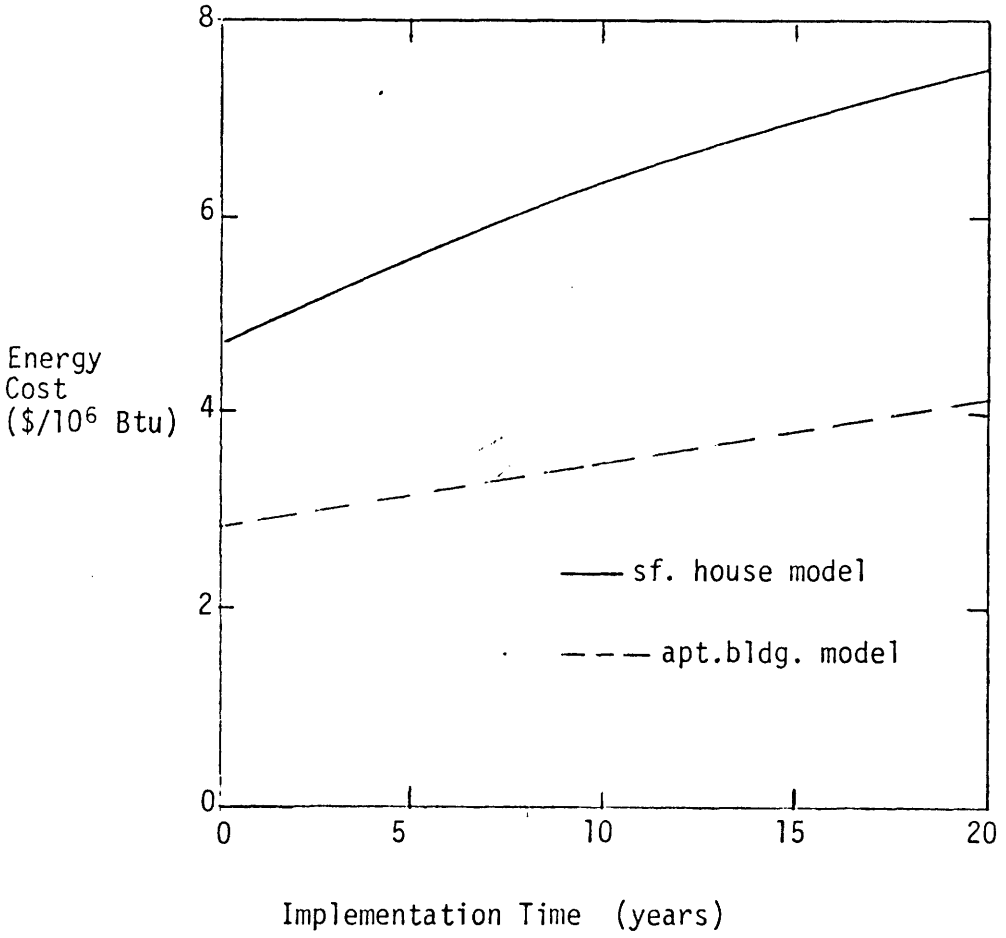


FIGURE 4.4

Levelized Energy Cost as a Function of Time to Achieve 100% Penetration.



shows the magnitude of the penalty, or the implementation may stop short of the ultimately planned load. The latter is most important because of its long term implications; the discussion of the effects of penetration fraction in Section 3.5.5 is relevant in that case.

The retrofitting of existing cities with district heating systems will be facilitated if the existing furnaces can simply be replaced with heat exchangers which extract heat from the district heating system. Replacement of entire systems is possible, but implementation will certainly be slower and, consequently, as seen above, the energy cost will be higher.

The desired sendout temperature for new cities was 220°F or lower because of the characteristics of available hot water space heating equipment. This sendout temperature should prove acceptable for conversion of warm-air and hot water space heating systems in existing buildings, but steam systems are more difficult. The usual steam temperature in existing systems is 220°F; in order to raise steam at 220°F economically with a district heating system, the supply temperature must be 250-300°F.

Census data (summary in Table 4.1) was examined in an attempt to estimate the mixture of different types of existing heating systems. Unfortunately, the data are not broken down to show steam and hot water systems separately; rather, these are grouped together. Warm-air furnace systems are listed separately, however, and it is noteworthy that these systems dominate in all regions of the U.S. except the northeast. In that region, steam and hot water systems

TABLE 4.1

Summary of Types of Existing Heating Systems

(Source: U.S. Bureau of the Census, Census of Housing: 1970. Metropolitan Housing Characteristics, Final Report HC(2)-1. US and Regions, USGPO, Washington, D.C., 1972.)

	Northeast Region		North Central Region	
	Percent of System		Percentage	
System Type	Owner Occupied	Renter Occupied	Owner Occupied	Renter Occupied
Hot Water or Steam	48.6	65.2	9.6	28.3
Warm-air*	42.8	19.7	76.7	45.9
Electricity	2.8	3.0	1.5	3.5
Floor, wall, etc.	4.4	1.5	3.8	4.6
Other	1.3	10.6	8.4	17.7
None	0	0	0	0
	99.9	100.0	100.0	100.0

	South Region		West Region	
	Percentage		Percentage	
System Type	Owner Occupied	Renter Occupied	Owner Occupied	Renter Occupied
Hot Water or Steam	5.0	9.0	2.5	8.3
Warm-air*	42.4	25.4	53.8	24.1
Electricity	7.1	7.5	6.1	11.8
Floor, wall, etc.	13.1	9.0	21.5	24.1
Other	32.3	49.2	14.4	28.4
None	0	0	1.6	3.3
	99.9	100.1	99.9	100.0

*Includes Heat Pumps.

together outnumber warm-air systems. Thus, in that region, the send-out temperature must be considered carefully, and retrofit is likely to prove more difficult.

Availability of equipment for retrofit applications is not considered in this work, but it is known that low cost heat exchangers made of plastic are being developed in Sweden. The availability of low cost equipment to convert existing buildings to district heating could greatly improve the prospect for swift implementation of district heating.

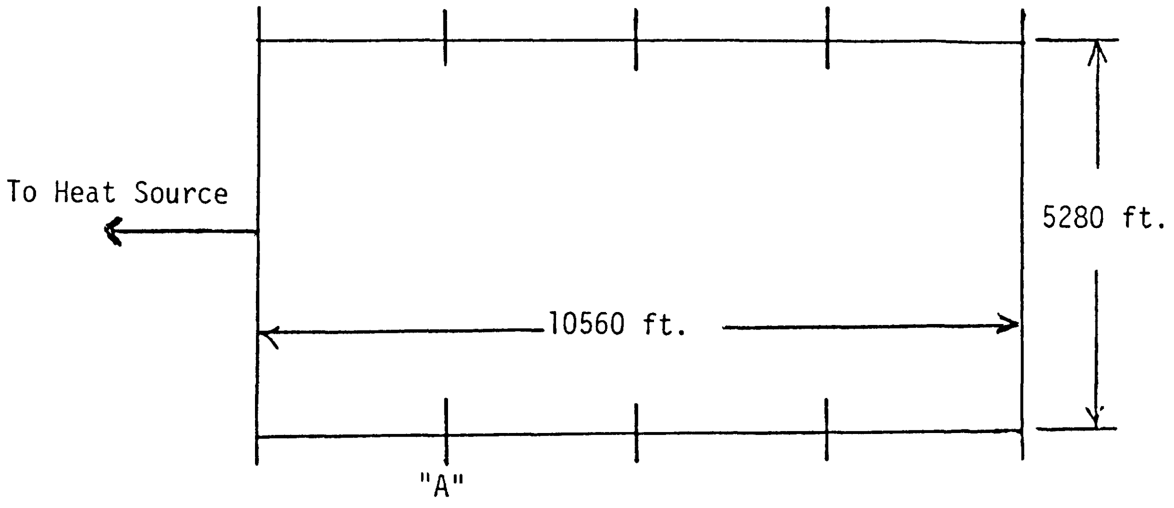
4.3 New City Case

As mentioned in Section 4.1, a new city implementation pattern is likely to be a series of subdevelopments of 1000 housing units or less with a unit density equal to the ultimate density. That is, the urban area increases with time, but the housing unit density is constant.

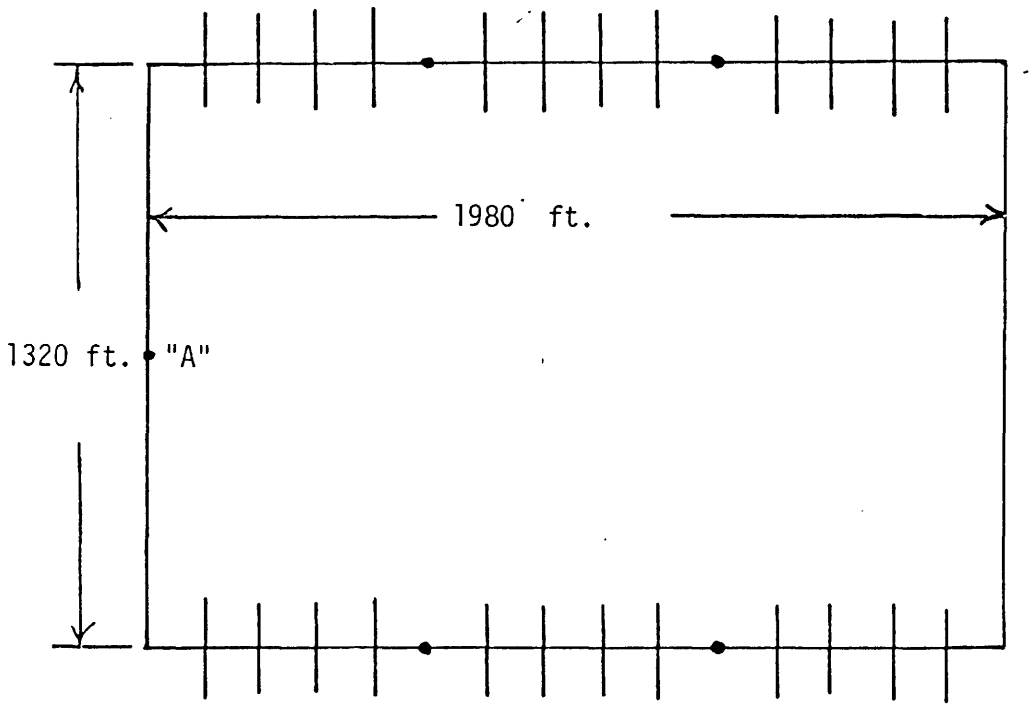
While it is desirable to provide district heating from the outset to avoid the later difficulties of retrofitting buildings, connection to a large remotely-sited heat source (even as close as ten miles) will be very expensive at early periods in the city's development. For convenience, the piping network is divided into a transmission system and a distribution system as illustrated in Figure 4.5; the latter includes all piping within the subdevelopments, while the former includes all the piping required to connect the subdevelopments together and to a central heat source. Full use of the distribution systems may be achieved immediately upon completion as the construction is done in phase with building construction, but the transmission system could

FIGURE 4.5

Apartment Building Urban Model Piping Network (54,000 total population).



a) Transmission System



b) Distribution System

not be used to full capacity until completion of all planned urban growth. Rather than installing the transmission system connecting the load to a large plant at the beginning of urban growth, it may prove economically attractive to use temporary small local heat sources to supply hot water to the distribution systems and defer the transmission system installation until a more favorable time during urban growth. The appropriate time for transmission system implementation and conversion to a central heat source will depend on the rate of urban growth and on the cost of heat from the temporary heat sources.

The economics of the timing of system consolidation was investigated by calculating the levelized cost of energy over a 30-year period as a function of the time of consolidation. Urban development time (five to thirty years) and the total levelized cost of heat from the temporary heat sources (two to six dollars per 10^6 Btu) were used as parameters to generate the series of curves shown in Figures 4.6 through 4.11. The urban growth was assumed to occur linearly in time, and a 9% interest rate was used for the economic calculations. Note that the only urban model shown is the reference case apartment building model of Chapter III and that the energy cost refers to the cost of energy delivered to the entrance of the subsection distribution systems (as defined in Figure 4.5b). Similar calculations for the single family house urban model reveal no significant differences, qualitative or quantitative, from the apartment building model.

The development times are consistent with proposed new city development times discussed in Chapter III. The temporary heat source energy costs are difficult to predict because of the uncertainty in

FIGURE 4.6

Apartment Building Urban Model

Effect of Implementation Time for 5-Year Development Time.

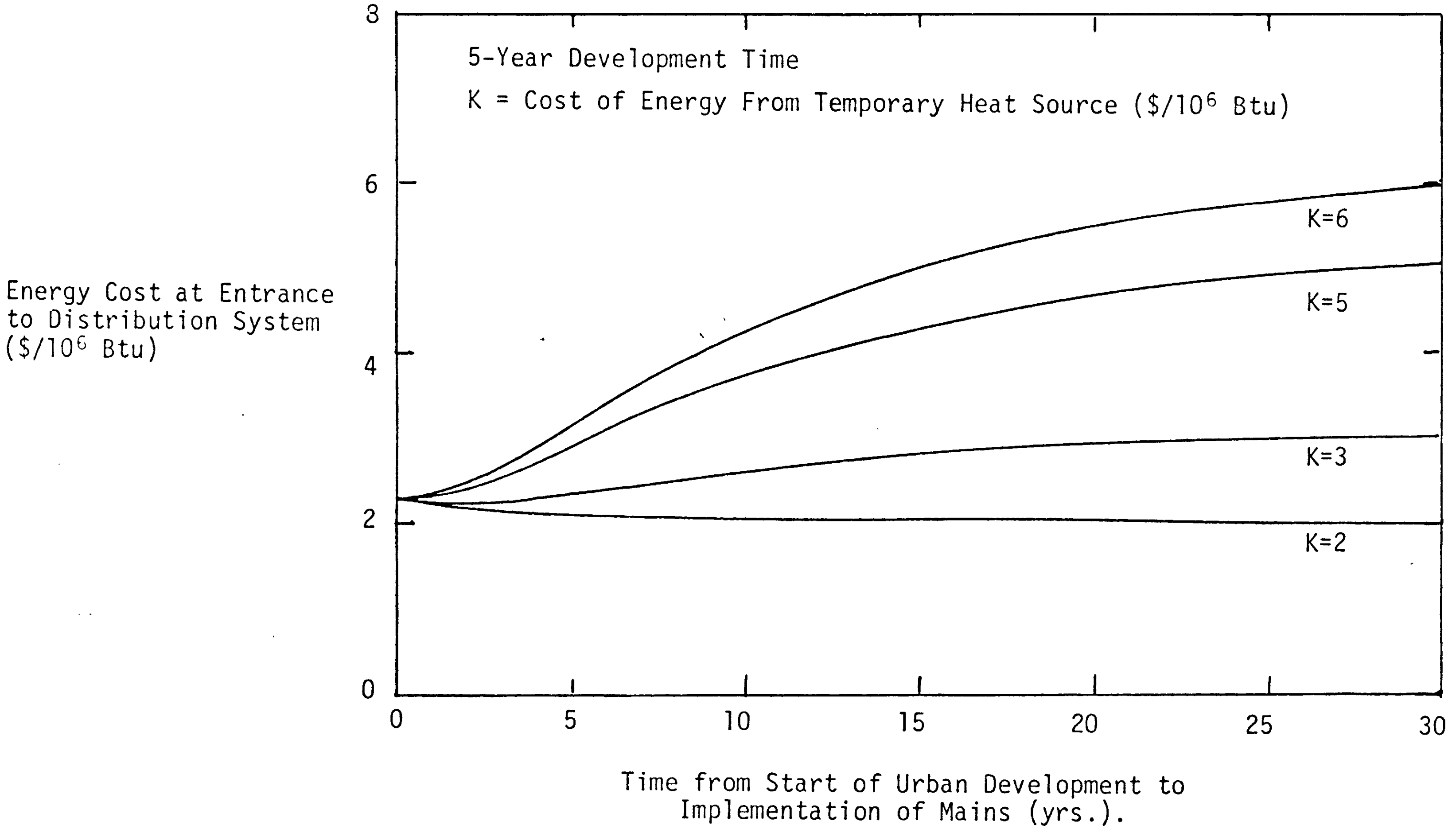


FIGURE 4.7

Apartment Building Urban Model

Effect of Implementation Time for <u>10-Year</u> Development Time.

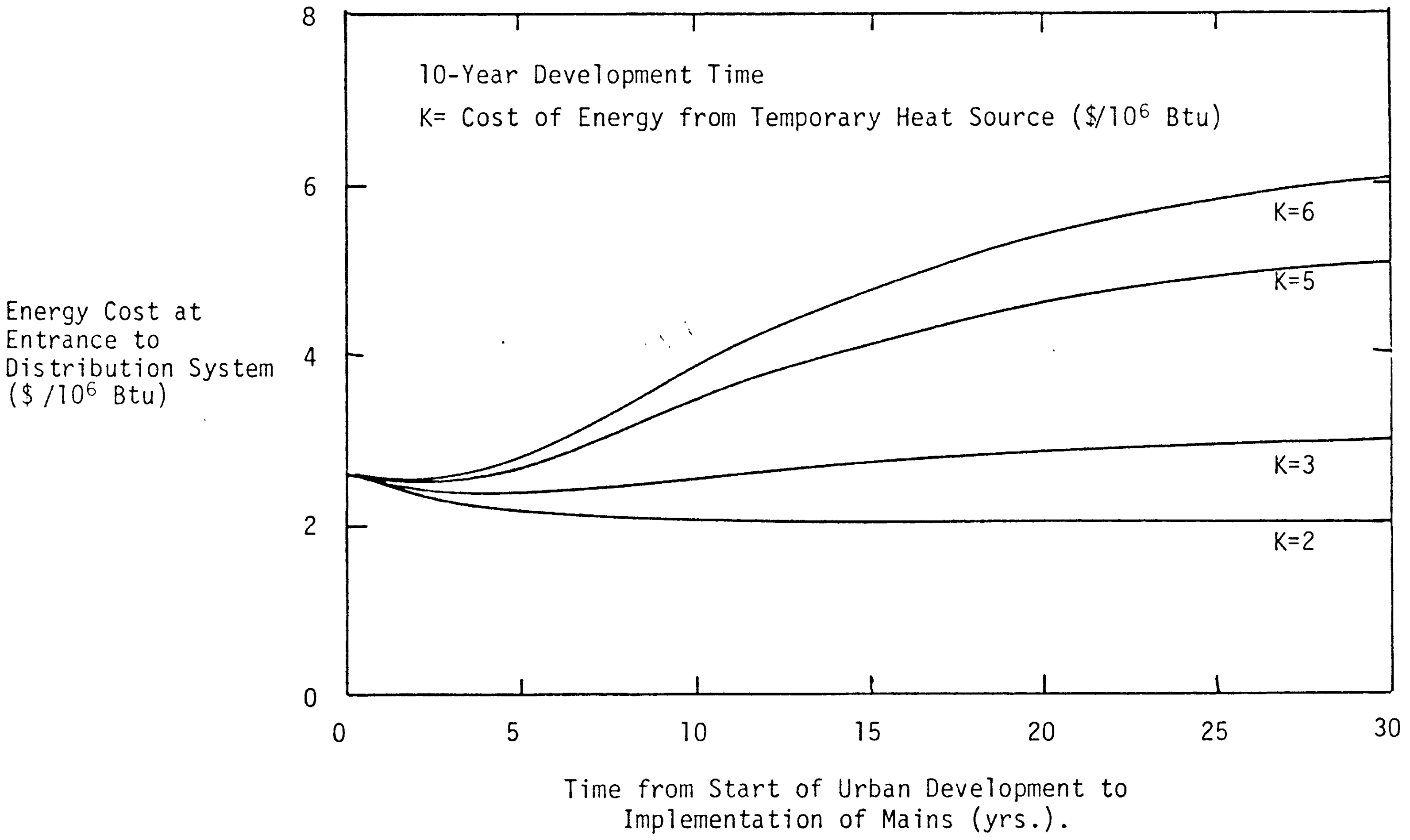


FIGURE 4.8

Apartment Building Urban Model

Effect of Implementation Time for 15-Year Development Time.

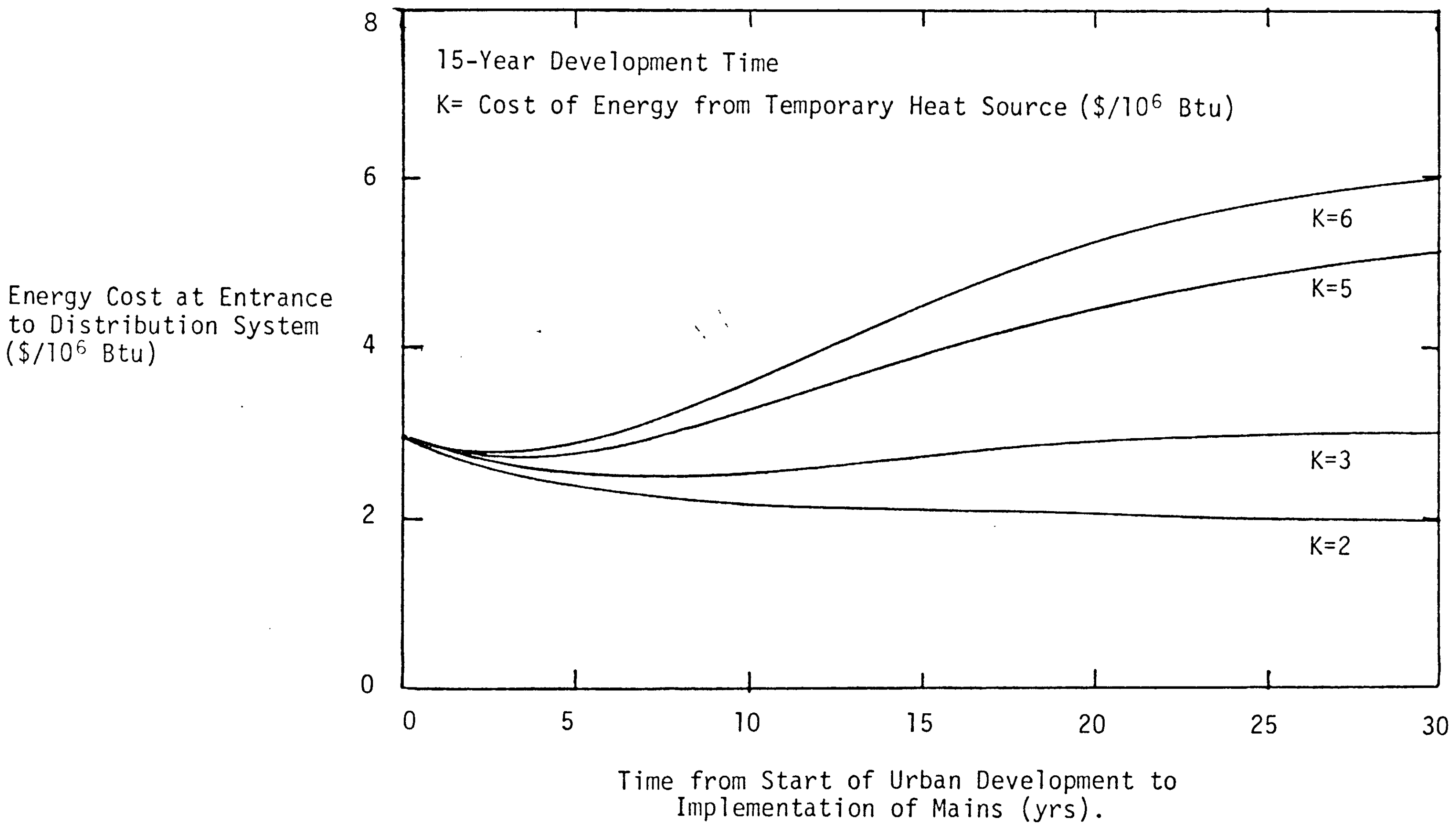


FIGURE 4.9

Apartment Building Urban Model

Effect of Implementation Time for 20-Year Development Time.

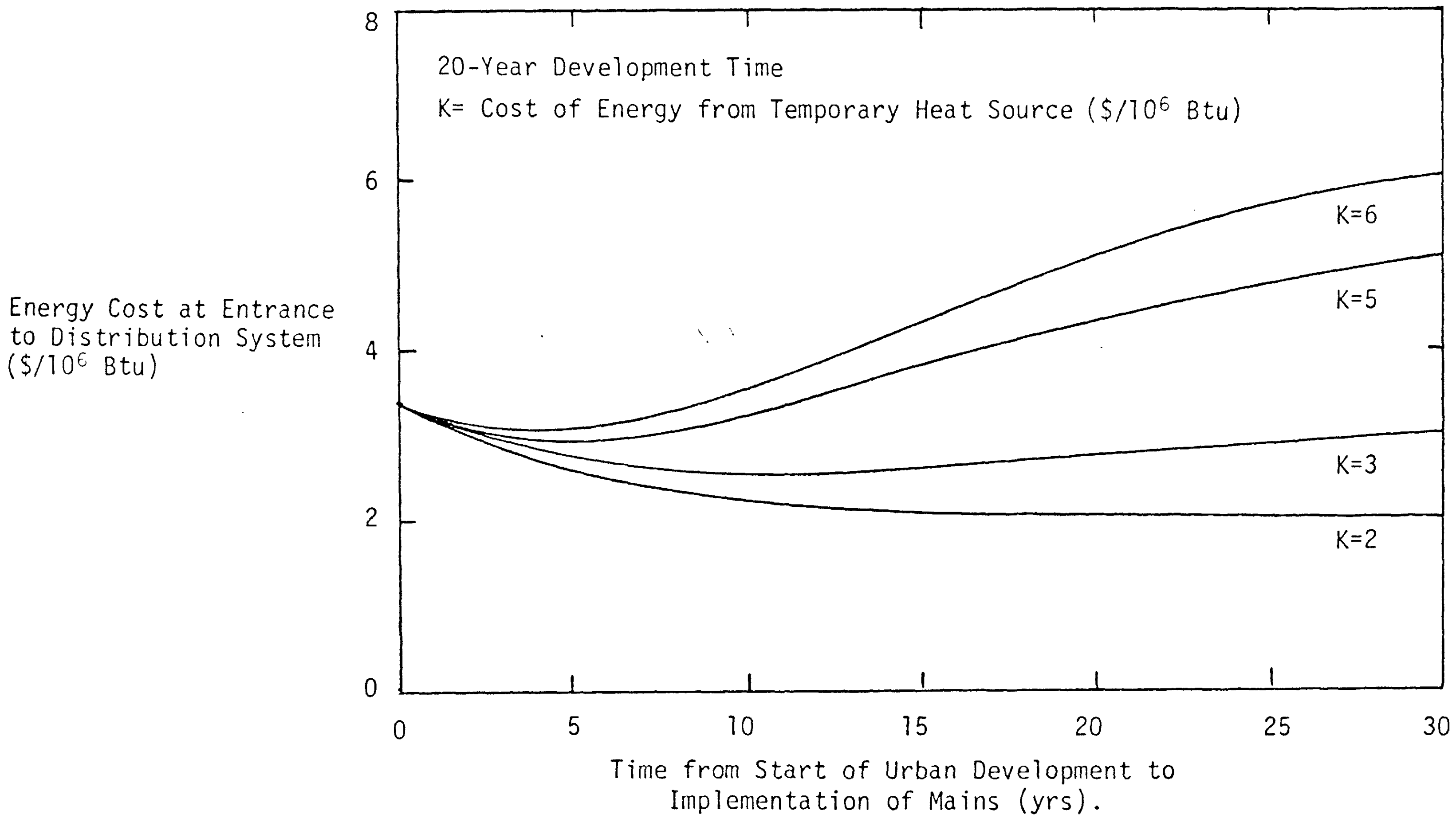


FIGURE 4.10
Apartment Building Urban Model
Effect of Implementation Time for 25-Year Development Time.

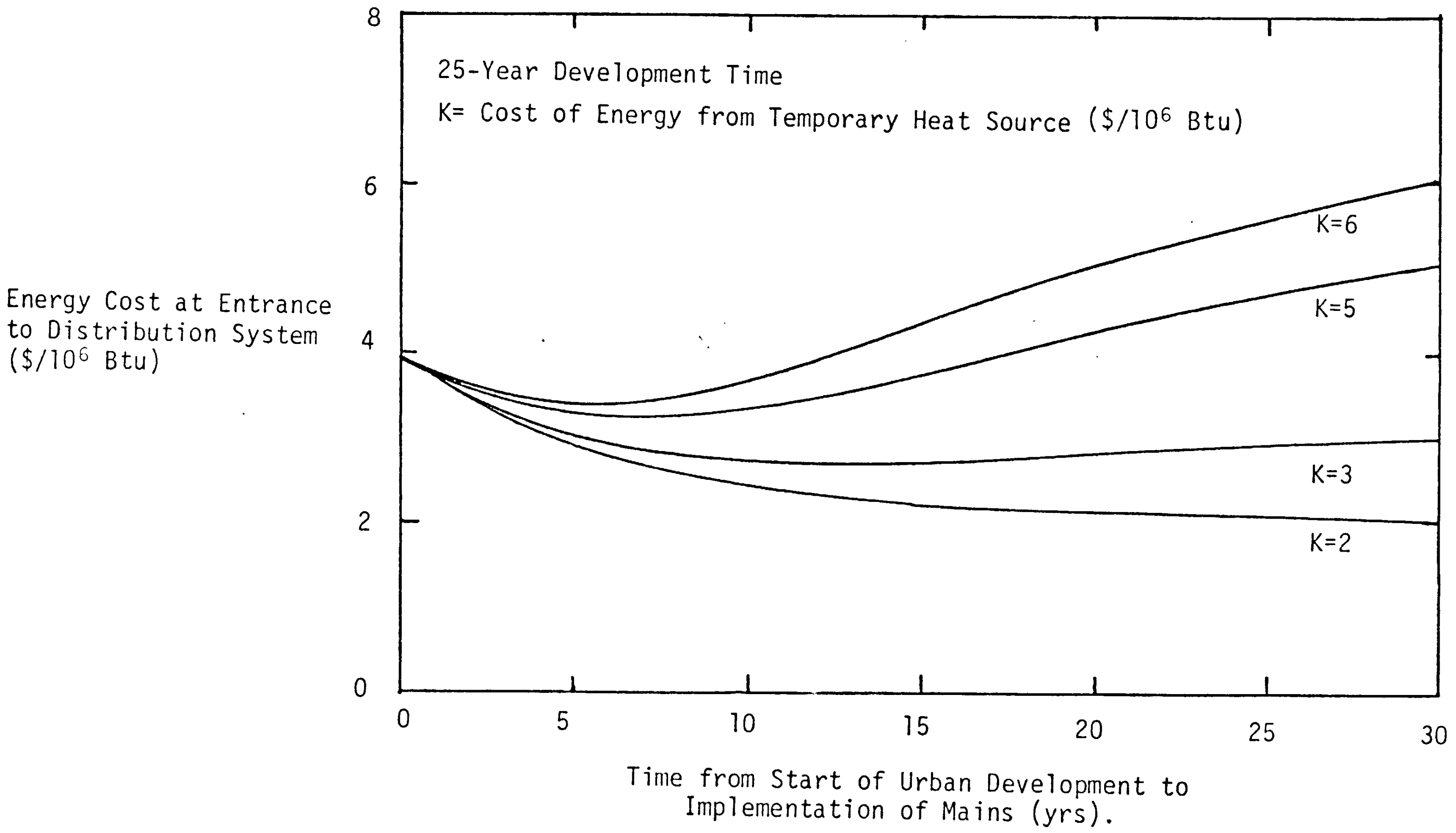
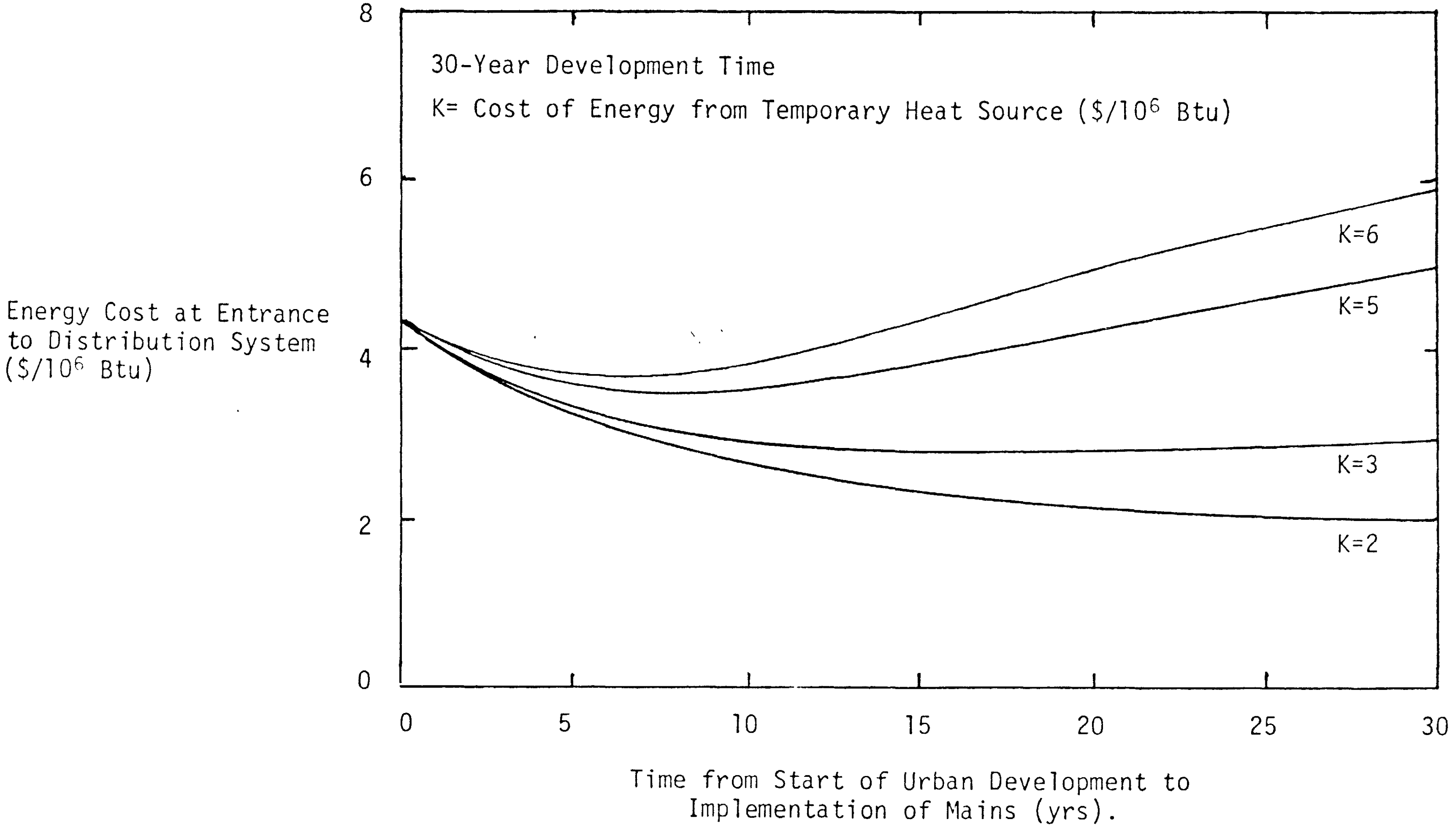


FIGURE 4.11
Apartment Building Urban Model
Effect of Implementation Time for 30-Year Development Time.



future fuel prices. For reference, industrial and commercial natural gas or oil prices in New England in 1976 were about \$2.50-3.00/10^6 Btu (100% efficiency). Assuming a boiler efficiency of 75% and accounting for boiler capital and maintenance costs results in a levelized cost of \$3.50-4.50/10^6 Btu. The boiler cost is less than 15% of the total unless it is used less than three years.

The curves in Figures 4.6 through 4.11 show expected trends. The results were devised for a ten-mile plant city separation distance and costs levelized over 30 years, but will be qualitatively similar for other assumptions. If the temporary heat source energy costs are greater than three dollars per 10^6 Btu and the preceding paragraph shows that this is probably the case, it will be economically advantageous to convert to a single large heat source at some point during the growth, as evidenced by the minima in the relevant curves in the figures. The higher the temporary heat source costs, the sooner the optimum conversion date. In order to estimate the levelized fuel cost, it is necessary to consider the effect of rising fuel costs (probably oil or natural gas because of undesirable features of small coal plants now available); this subject is the topic of the following paragraphs.

To illustrate the effect of fuel price increases on energy costs, the levelized cost of heat from a temporary heat source relative to the initial cost of heat has been calculated as a function of development time in years and a given annual rate of increase of these energy costs. The levelized cost is calculated by assuming linear growth during the development period and a constant load for the remainder of the assumed economic lifetime of a district heating system. An interest rate of 9% is used in a present worth calculation. The results are displayed in Figures 4.12 and 4.13.

For a 6% rate of increase of fuel cost and a 19-year development time, the equivalent levelized fuel cost would be double the initial cost. Thus, fuel costs alone would be about four dollars per 10^6 Btu. Figure 4.9 shows that the appropriate implementation time would be between five and ten years (neglecting additional fixed and operating costs) for a four dollar per 10^6 Btu fuel cost.

While Figure 4.12 shows the levelized fuel cost for the case of fossil fuel use throughout the 30-year system lifetime, fossil fuel actually would be used only until conversion to district heating was judged appropriate. Figure 4.13 shows the levelized fuel costs for this case.

For a 20-year development time, with fossil fuel used for the first fifteen years of growth and a 6% rate of fuel cost increase, for example, the levelized cost would be 1.74 times the initial cost. Including other fixed and operating costs, and assuming a two dollar per 10^6 Btu initial fuel cost, the levelized cost would be \$4-5 per 10^6 Btu for the temporary heat sources. Figure 4.9 shows that district heating implementation is favorable at some time between five and eleven years into the urban development. (To get a more accurate implementation time, one must perform iterations between calculating levelized cost and proper implementation time.) Clearly, the consideration of fossil fuel price increases makes district heating more attractive than it would appear if district heating costs were compared only to present (1977)

FIGURE 4.12

Levelized Temporary Heat Source Costs for Growing City
(Fossil Fuels used Indefinitely)

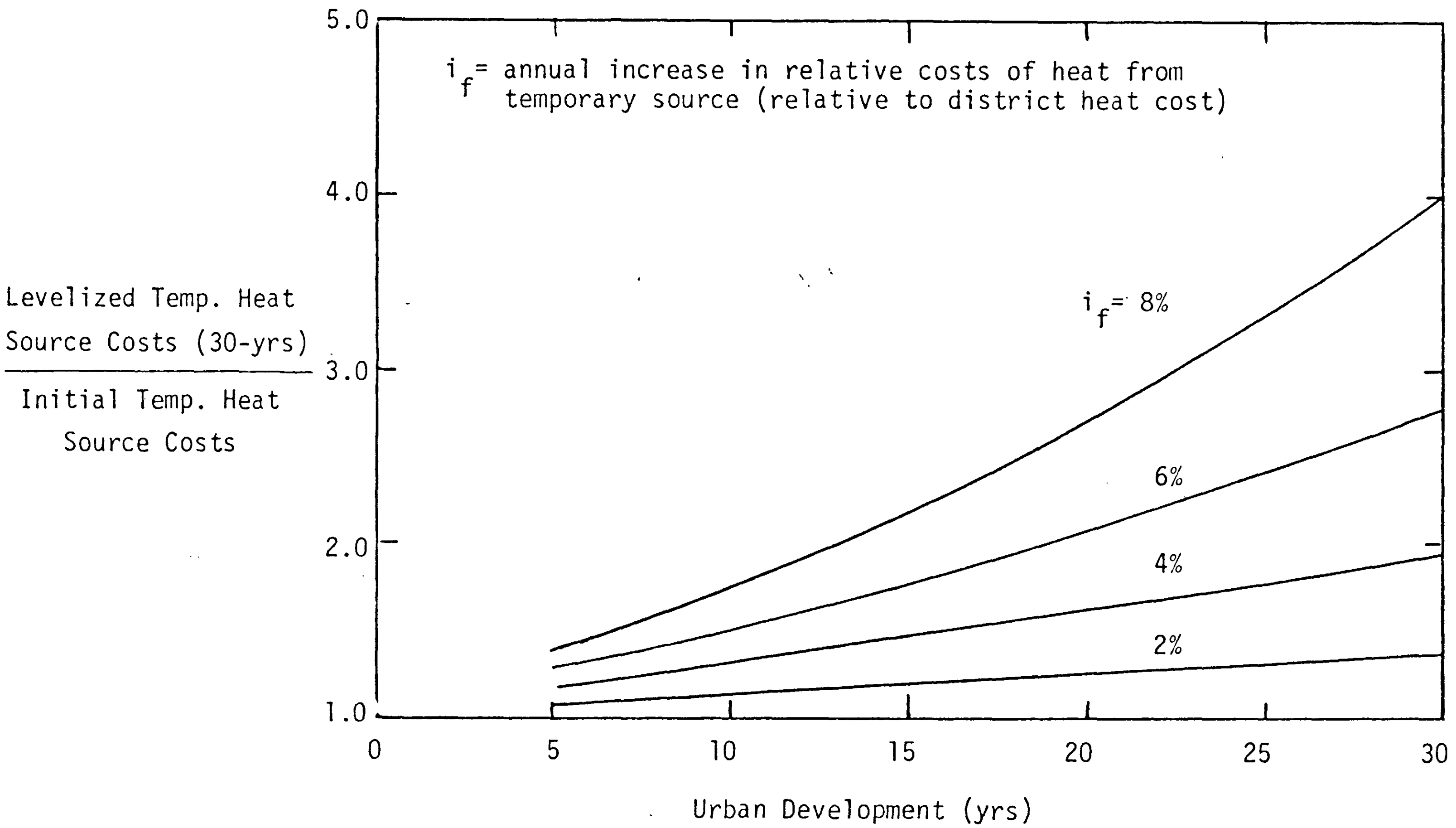
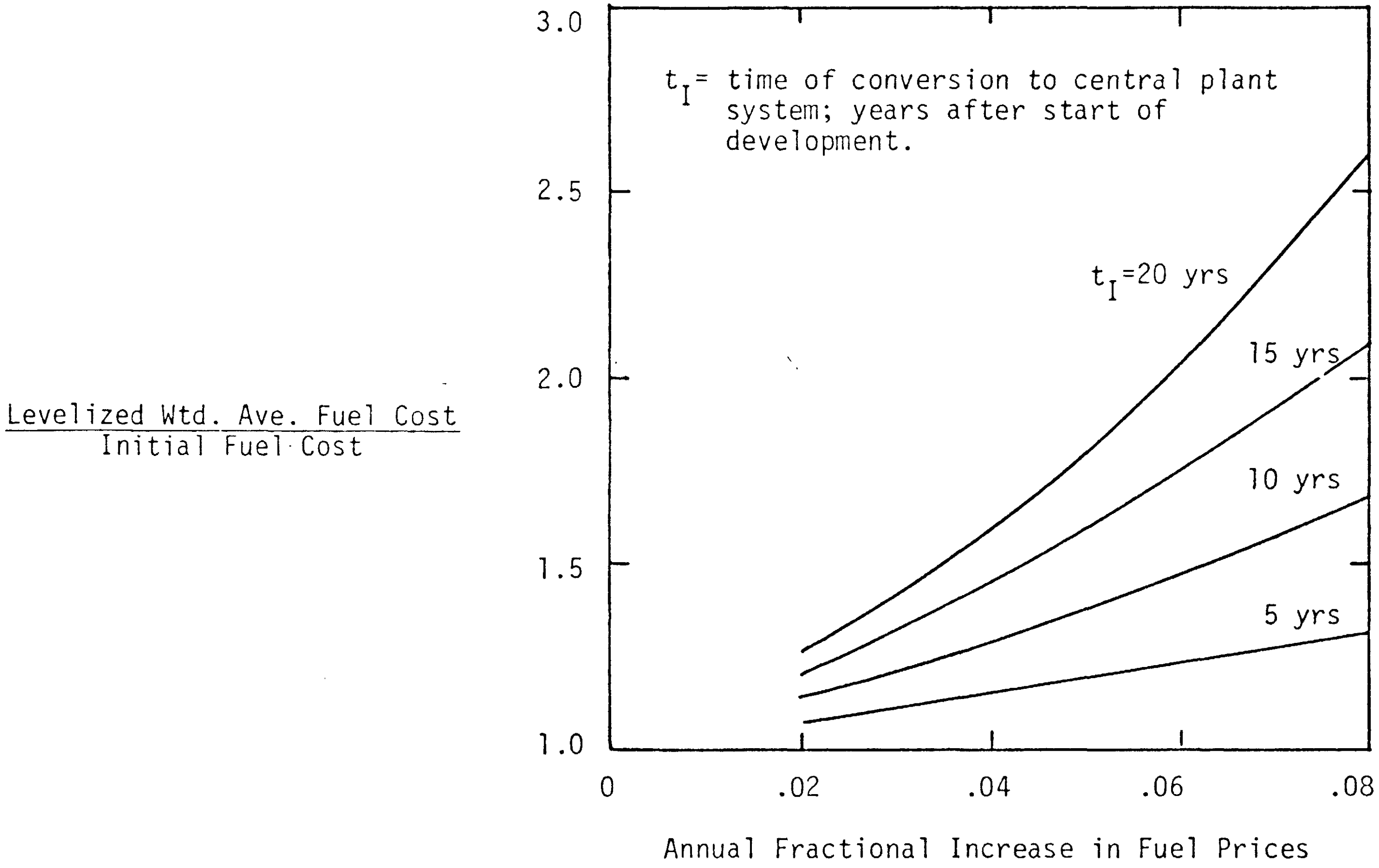


FIGURE 4.13

Levelized Temporary Heat Source Costs for Growing City
(Fossil Fuels used Temporarily)



fossil fuel prices.

All the above arguments can only be made crudely as the future of fossil fuel prices is uncertain (except that one can be rather confident in predicting increasing prices). Price increases are likely to be in the form of step increases rather than continuous increases, but when they will occur and their magnitude is unknown. The above arguments do show, however, that even modest rates of price increase greatly enhance the desirability of district heating.

For increasing lengths of urban development time and constant temporary heat source energy costs, the optimum time for connection to a large centralized heat source occurs later. For levelized costs of three to four dollars per 10^6 Btu, the appropriate time for centralization. is approximately halfway through the development time, but the cost is not very sensitive to implementation time. The developer is relatively free to wait until the development is proceding as desired before converting to a central plant heat source. At the same time, careful attention must be given to the trend of temporary heat source fuel prices. The important conclusion is that there is a great deal of flexibility in the timing of the central system implementation.

Nor is the levelized cost very sensitive to the urban development time if the conversion to a central plant occurs at about the optimum time. This fact, coupled to the fact that the exact time for conversion to a central plant is not critical, implies that a slowing of the urban development need not cause great difficulty in planning; the implementation pattern can merely be modified in a way consistent with new estimates of growth time and temporary heat source energy costs. In summary, it would be difficult to make a planning error which would have serious long term economic consequences, provided that flexible financial arrangements can be made.

One of the primary motivations for district heating is fuel conservation, particularly of increasingly scarce oil and natural gas. Thus, it is of interest to estimate the fossil fuel used in the temporary heat sources during the implementation process and the fuel saved after implementation. Figure 4.14 displays the cumulative oil use during implementation as a function of implementation time (time after beginning of urban growth) of the transmission system and central plant for three urban growth times. For simplicity it is assumed that oil is consumed at 75% efficiency in the temporary sources. The apartment building urban model, a total population of 54,000, and a New York City climate are assumed. It is also assumed that the temporary heat sources are not used after conversion to a central plant.

For the purpose of estimating the fuel savings over the conventional fossil furnace case, it is appropriate to use a lower conversion efficiency. Assuming a conversion efficiency of 65% and the same urban model as above, the annual oil savings for a city of 54,000 would be 300,000 barrels per year, or 5.6 million barrels per year for a city of one million people. For a single family house urban model, the annual fuel savings would be about twice as much. In both cases, a New York City climate is assumed.

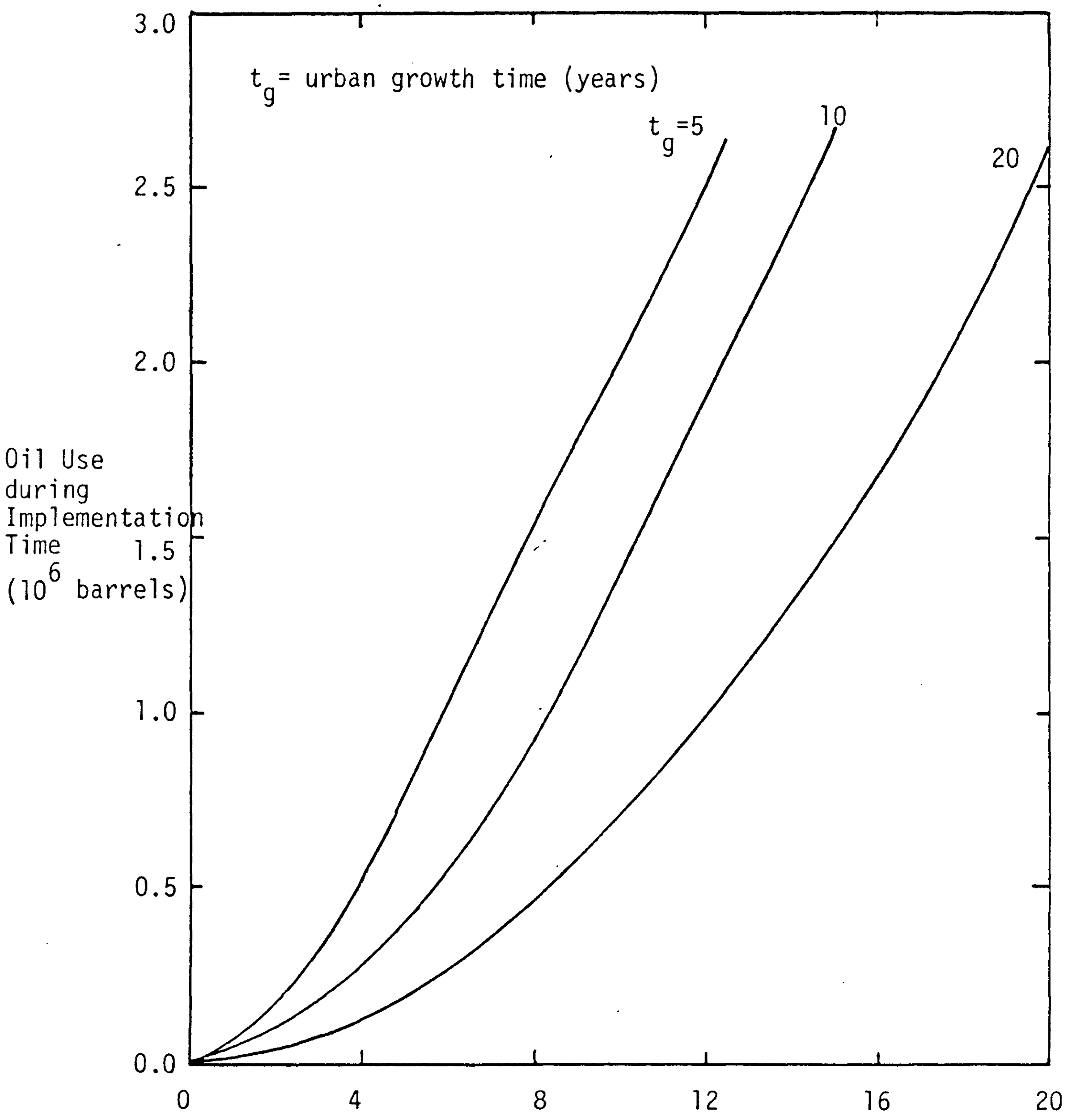
4.4 Institutional Factors Affecting Implementation

District heating systems require a substantial front-end

FIGURE 4.14

Fossil Fuel (Oil) Use during System Implementation

Apartment Building Urban Model, 54,000 people.



investment, and the financial arrangements made to cover this investment will largely determine the success or failure of the system. A great deal of flexibility in repaying the investment is desirable and, perhaps, necessary if the system is to successfully cross the economic threshold to become a profitable venture.

This flexibility will be especially important in an existing city. Until the penetration fraction is well over 0.5, heavy losses will be incurred. The magnitude of the losses will be determined by the legal, political, and economic climate during implementation. For example, if market forces alone must be used to encourage conversion to district heating, the cost of district heat is restricted to a value low enough to attract customers and encourage modification or replacement of most existing systems within a reasonably short time (5-10 years). Financing must be adequate to cover losses during the early stages of implementation; such financing may be difficult to obtain because of the relatively high risk due to potential competing technologies.

A policy by government requiring or encouraging the conversion to district heating or relatively higher costs associated with competing energy sources could both speed up implementation and reduce the risk to investors. If it were legally mandatory that buildings be retrofitted to use the district heating system within a certain number of years, and some sort of aid, e.g., tax credits or low interest loans, were made available to building owners, the risk to investors could be made negligible. Implementation could be speeded up further by using gradually increasing connection changes for later hook-ups. One might well envisage such an occurrence in the U.S. because of oil and gas shortages combined with continued difficulty in adding new electricity generation capacity.

Perhaps of most interest to persons contemplating the development of district heating systems is the course of development of substitutes for oil and gas, e.g., synthetic liquids and gases from coal. Except in those areas already largely electrically heated (primarily the southern and northwestern U.S.) the conversion of buildings to electric heating is of the same order of difficulty and expense to the building owner as is conversion to district heating. However, if synthetic fuels become available to replace oil and gas, the required modifications of existing heating systems are relatively minor. It would be difficult for district heating to achieve rapid market penetration if synthetic fuel prices are low enough to compete with district heating. It might be necessary for the developer to finance the end use equipment in order to get building owners to retrofit for district heating.

Another important consideration is the regulatory policy related to the rate structure and range of service. These two parameters are closely related because of the generally increasing cost of district heat with decreasing load density. Depending on the installed pipe cost, an alternative energy source, such as electricity, will be more economical for load densities below a certain value. However, the choice of a cutoff distance for service range (or a minimum load density) might be difficult for the utility to impose in practice. It is conceivable that a utility may be obligated to serve anyone desiring service within its franchise boundaries, as for electric utilities. Moreover, rates may not be allowed to reflect the higher cost of serving lower density areas, but, rather, an average rate for all consumers in the same class may be required. The effect of such regulations will depend on whether other energy sources compete, the effect being stronger in the latter case. In order to avoid the problem of service area boundary definition, it may prove necessary to consider that to utility is in the business of providing space and water heating with their option as to method (e.g. heat pump or district heating). Though this institutional concept is new to the U. S., combined heat and electric utilities may require just such new arrangements.

Equally important is the change of rate structure over time. Will preferential rates be given to earlier customers to encourage swift implementation? Will it be politically acceptable for later customers to, in effect, subsidize older customers? Or will the rate structure simply be a flat one, all customers paying the same rate? Will rates change to reflect increasing costs for competing energy sources?

There are also questions pertaining to the public policy required or acceptable to encourage district heating. Although policy could be unfavorable toward district heating because of a desire to encourage alternative energy sources, a neutral attitude (allowing district heating to compete freely in the market place) or positive attitude is more likely, especially if the economics proves favorable to district heating. Some of the problems likely to be encountered for the case of a neutral government policy have been discussed above.

The extent to which a local government (or state and federal governments) can adopt a positive policy toward district heating is not altogether clear. It is important, of course, that government policy be at least positive enough to allow district heating system construction. Two methods could be used to ensure the success of district heating. First, the government could require that all new buildings connect to a district heating system as they are built. Because of the favorable economics of district heating, this path would probably lead to little building-owner resistance. For an old city, the government could require that, wherever feasible, buildings be retrofitted to use district heating within a specified time period. Even if aid were provided to owners to finance the retrofitting, this path is likely to lead to considerable dissatisfaction among consumers unless all competing alternatives also require retrofit. Alternatively, the pressure could be levied indirectly on consumers by a decision to pay for the distribution network with public funds. Even if the consumers were required to pay all operating costs (maintenance costs, heat costs at plant, etc.), the cost paid directly by consumers would be far less than the cost of competing energy sources (about a 25% cost reduction would be achieved this way), thus encouraging a more rapid market penetration than if all costs were borne directly by consumers. Of course, the resistance of taxpayers to additional taxes is well-known and will certainly be in the minds of government officials considering this approach. Government backed financing of the system could be used to lower the interest rate; such an approach would be likely to meet with less taxpayer opposition. This alternative will be discussed further in Chapter V.

4.5 Conclusion

In this chapter we have considered the economic effects of the dynamic nature of the district heating system implementation and urban growth. It was shown that, for an existing city, implementation should be as rapid as possible; there is no advantage in delaying full implementation, and, in fact, a substantial penalty. There are many institutional barriers which could impede the implementation and, consequently, increase the energy cost. Most barriers could be eliminated or rendered insignificant by a positive policy toward district heating by government bodies, but political acceptability may limit the extent to which such policies can be adopted.

For new cities the picture is very different. Even at oil or gas prices much higher than today's (1977) prices, it will usually prove economically advantageous to delay conversion to a central plant for a period of years (the number being a function of fuel price and development time), meanwhile supplying the heat energy from temporary fossil heat sources. Only the piping network necessary to distribute water within the residential areas need be installed until the appropriate conversion time. The time delay for conversion arises because of the high cost of underused capacity of mains connecting the subsections. It is for a time cheaper to pay for locally available higher cost energy than to pay for its distribution from a central plant. The exact time of conversion is not crucial; the cost does not rise sharply as the time is varied. This makes policy-making much easier, as a wait-and-see attitude is acceptable as long as one does not wait more than two or three years beyond the apparently optimum implementation time.

In addition, it was shown that if one considers realistic rates of increase of fossil fuel prices for the temporary heat sources, the attractiveness of district heating is greatly enhanced over its attractiveness in comparison to present-day (1977) fuel costs.

The most important problems are the institutional problems identified in Section 4.4. No solutions are proposed here, but it is pointed out that many of these problems must be addressed before realistic planning for district heating can begin.

REFERENCES - CHAPTER IV

There were really no necessary references for this chapter because little work has been done on the problems of urban growth and its effect on district heating. The following may be useful to the reader who wishes to pursue this topic, however.

1. "Low-Temperature Heat Systems, Part I, Waste Heat Utilization Potential with Conventional and Newer Technology", Peter Margen and Kjell Larsson, report AE-VS-180, AB Atomenergi, Sweden, December 1975.
2. "Low Temperature Heat Systems, Part II, Computer Model for the Optimization of a District Heating System", Kjell Larsson, report AE-VS-181, AB Atomenergi, Sweden, December 1975.
3. The Economics of Sewage Disposal, Paul B. Downing, Frederick A. Praeger, Publishers, New York, 1969.
4. Public Utility Economics, Paul J. Garfield and Wallace F. Lovejoy, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1964.

CHAPTER V

INSTITUTIONAL PROBLEMS ASSOCIATED WITH DISTRICT HEATING

5.1 Introduction

The previous chapters presented the relatively straightforward, though multifaceted, technical and economic aspects of district heating. The technical problems of district heating implementation were seen to be relatively easy to solve, and although there is room for significant improvements in piping and end use equipment technology, none are necessary for the success of district heating. On a life-cycle cost basis, the economics of district heating is favorable now in many cases.

Institutional obstacles now prevent the widespread immediate implementation of district heating and are likely to continue to do so unless steps are taken to eliminate them. It would be a mammoth job to attempt to propose solutions to these problems, but it is possible to present some of the options available to society in dealing with them. That is the purpose of this chapter.

Although many of the institutional problems are interrelated, it is convenient for discussion purposes to separate the problems into three classes. These classes are financing the initial investment, ownership related problems, and service cost structure determination.

System financing is the topic of Section 5.2. It was shown in

Chapter III that the cost of capital will have a strong effect on the economics of district heating. Both the interest rate and the availability of capital will be influenced by the source of funds (public or private), the amount of capital needed, and by the perceived risk to investors. The risk to investors is primarily due to unanticipated deviations from the planned urban growth or from the planned market penetration of the system, as discussed in Chapter IV. Private investors may be deterred by the combination of the magnitude of the initial investment (over half a billion dollars for 100,000 houses) and the risk of loss. For reference, the investment in electricity generating capacity sufficient to handle the peak electrical load of 100,000 houses with heat pumps is $1.3 billion. Thus, the size of the investment is not a unique problem. The use of public funding can be a powerful tool for taking into account factors usually ignored by the private capital market, and several precedents for such action are discussed. Finally, is the problem of what capital investments are supplied by the customers and what portion by the utility (and ultimately by the consumers in their bills). The effect of this tradeoff on the penetration of district heating will depend on consumer attitudes toward large single investments versus higher bills over a long period of time.

Closely related to the financing problem is the problem of ownership. Several methods of financing may be available to a publicly-owned system which are not available to a privately-owned one. Also, several important policy questions will be influenced by the ownership arrangements. Examples are the service range, the pricing policy, and the policy toward encouraging new customers to connect. In addition to the public versus private ownership question, there is the problem of the division of ownership between the customers and the utility. The larger the initial cost to the customer, the more difficult it will be to convince new customers to connect. On the other hand, the larger the amount of capital that a utility must raise, the more difficult the utility financing will be. Section 5.3 contains a discussion of these topics.

Section 5.4 contains a discussion of the determination of service charges for the energy supplied. While the determination of energy pricing for a utility supplying either thermal energy or electricity is straightforward, the pricing of services from a combined heat-electric utility is arbitrary and will probably be subject to approval by a utility commission. In the previous analyses the busbar cost of the sacrificed electricity was charged to the thermal distribution system, but this is only one possibility. Second, there is a problem of how to allocate the costs of initial losses during early years of operation of the system. Similarly, how does one allocate costs due to variations of service cost because of varying load densities or unfavorable geography? Finally, there is the question of incentive pricing to encourage early and complete use of the system. Should a sliding scale (over time) of connection charges be established? Is public subsidization of some type appropriate to serve as an inducement (or a coercion) to prospective customers? All these questions are discussed in Section 5.4.

The importance of the problems discussed in this chapter cannot be overemphasized. Although these matters have not received the dominant attention in this thesis, it is strongly felt that the success of district heating in the U.S. will depend on the solution of these problems. It is in these areas and in the areas of urban growth and system market penetration that work is most needed in future studies.

5.2 Financing the System

It was previously shown that district heating requires a large initial investment and that, for a nine per cent interest rate, the amortization of the investment dominates the life-cycle energy cost. Further, a system is likely to incur substantial early losses until an adequate number of customers connect to the system. The risk of the investment depends on the ability of the system to expand according to the original plan. If significant deviations from planned development occur, it may be difficult for the system to ever become profitable. This element of risk may make it more difficult to attract capital, and even if capital can be obtained through private channels, the interest rate might be so high as to reduce or eliminate the competitive advantage of district heating. If district heating is held to be a socially desirable goal, government intervention may be used to reduce the risk and/or the interest rate. These topics are discussed below.

In order to assess possible financing arrangements for district heating, it is helpful to know how financial arrangements are made for similar services such as water, sewage disposal, telephone systems, and electricity. At first glance, many similar problems are expected, but these services differ from district heating in an essential way. First, there is no question about the desirability of providing these services, and there are no good alternative methods of providing them. Although small towns may be able to function with individual water supply systems and septic tanks, at some point in the urban growth, resource availability and public health considerations force a conversion to municipal water and sewer service. Similarly, most people consider electricity and telephone service to be indispensible to modern life. The public acceptance of, indeed, demand for, all these services is illustrated by the fact that all services except sewer service are usually supplied by private companies, though often the companies are granted monopolies. District heating, on the other hand, is likely to have several competitors in supplying the service of heating, fossil fuels (while they last), electricity, and possibly synthetic fuels from coal.

The effect of interest rate on energy cost is displayed in Figure 3.15. Generally, the use of low interest bonds or other forms of public financing will fix the abscissa of that figure on the lower portions of the curve (less than 0.15), while private financing will fix the abscissa at greater values. For all except the lowest population densities, the resultant energy costs for publicly financed systems will be competitive with all alternative forms of space heating. For higher interest rates, corresponding to private financing, district heating becomes less competitive for all except relatively high population density areas. As this figure applies directly to new cities, and existing cities will be more expensive to serve, district heating will be restricted to high load density urban areas unless a social decision is made to subsidize the system with low interest loans or direct capital investments.

The expected shortages of fossil fuels, the difficulty of supplying sufficient electrical generation capacity to meet growing demand, and the favorable environmental effects expected if district heating is implemented all can be used to justify public subsidization of district heating. For example, consider the apartment building urban model. If heat pumps are used to supply space heating loads, the poor performance at low outdoor air temperatures implies that the peaks must be supplied with resistance heating. A 1000 Mwe plant is adequate to supply the undiversified peak loads of about 37,500 people. 2000 Mwt is simultaneously discharged to the environment. With district heating, the full 3000 Mwt can conceivably be used to supply the space heating loads of about 100,000 people for the same urban model. The comparison is somewhat rough, but the clear result is that the utility heat source capacity requirements are reduced with district heating as compared to the all-electric scenarios. Environmental benefits accrue because of the reduced emissions from plant sites and from reduced thermal discharges.

Precedents exist to justify public financing of district heating. Sewer systems are generally financed by taxation, and consumers pay only operating costs in their bills (1). The Tennessee Valley Authority and the Rural Electrification Administration are results of public decisions to use low cost loans to achieve socially desired goals. For example, in 1943 Congress authorized REA loans having a two per cent interest rate and a 35-year repayment period. The purpose was to make electricity available to rural areas that private companies found economically unattractive (2). The TVA was established to provide flood control and hydroelectricity in the Tennessee Valley region (3), but it has become primarily a public power authority whose purpose is to supply low cost electricity to the region through federal funding.

Project success may be more likely when public, rather than private, financing is used. The discount rate on government bonds is about half the private rate because there is no tax on government bonds, but about a 50% tax on private bonds. Discount rates for school bonds are generally 5-7%. If district heating can be financed at 5%, all other Chapter III base case parameters being used, the delivered energy costs are reduced by 16% and 20% for the apartment and single family house models, respectively.

If private discount rates are low enough to finance a system, potential investors may still be deterred by the risk of loss caused by deviations from planned implementation patterns. A government guarantee of the private loans may be sufficient encouragement if this happens.

An important related issue is the division of initial investment between customers and the utility. More directly, how much of the cost is borne in one lump sum by consumers and how much appears in the heat bills? Higher priced equipment with lower life-cycle costs has always been difficult to sell to consumers. If the service lines and the end use equipment must be financed by consumers, some of the same institutional barriers which plague heat pumps, solar heating systems, and energy efficient appliances may plague district heating. Repayment of these capital costs as part of the monthly bill would force consumers to think in terms of life-cycle costs. However, much higher capital investments for this equipment will aggravate the problems already mentioned for the body implementing the system. At the same time, utility financing of the connection and end use equipment costs might ensure rapid system penetration. This would reduce the risk to investors and possibly the interest rate they require.

5.3 Ownership of the District Heating System

Ownership arrangements will influence the system structure and service range, potential capital sources, and energy pricing methodology. Also, the division of ownership between utility and customers will affect the market penetration pattern of the system. Realization of potential economic benefits and energy savings from combined heat-electric utilities may require modification of existing institutional arrangements as discussed below.

The nature of the service provided and the naturally monopolistic character of the system guarantee that district heating will be regarded legally as a public utility. This classification affords special benefits, including monopoly privileges and the right of eminent domain, but also obligations; for example, a public utility must "supply all reasonable demands for service by those who can pay for it, ···provide service adequate to the needs of its customers, and···secure approval from public authority before terminating a service or abandoning a market." (4)

The thermal energy and electricity provision services of a combined heat-electric utility may be treated as independent entities by regulatory agencies. This is done for most utilities which sell both electricity and natural gas. If so, the obligation to supply all reasonable demands for service is very important because the cost of service varies strongly with population density. Electricity rate structures often vary among consumer classes, but not with geographical service cost variations within a consumer class. If a similar pricing methodology is used for district heating, the service range must be carefully defined to avoid any obligation to serve unprofitable areas.

The special district is often used when existing political boundaries are incompatible with provision of a desired service (5). Essentially, a special district is a political body created for a single purpose and having physical boundaries independent of anteceding political bodies. Creation of a special district (and the implied public ownership of the system) facilitates system installation by permitting definition of an economically desirable service area and financing with tax revenues or low interest bonds. The advantages of these arrangements have been explained in Sections 3.5.4 and 5.2 and need not be repeated here.

The financial advantages associated with the special district result from public ownership. Public ownership also allows incorporation of longer time perspectives and noneconomic factors into the decisionmaking process. In addition, mandatory connection to a publicly owned system is likely to be more palatable to consumers than to a privately owned system.

Modification of existing regulatory structures will not be difficult if significant economic benefits and energy savings are demonstrated for combined heat-electric utilities. Discussions with various state public utility commissions and regulatory agencies have shown that this is the prevalent opinion about the probable legal status of utility owned fuel cells for total energy systems (6). For example, a utility may be given a charter to provide building thermal energy demands with no distinction between supplying electricity and thermal energy so that it can provide district heating where profitable and all-electric heating elsewhere.

Allowance must also be made for rate structure adjustment and/or partial subsidization of consumer end use equipment to reflect the fact that the service provided is space conditioning and water heating. This modification is but one possibility, of course, and others suited to local conditions will undoubtedly be considered if warranted.

5.4 Determination of Energy Prices

Determination of an appropriate price structure for district heating will be complex and controversial. First, there is no unique way to apportion costs between electricity and thermal energy at the plant. The sum of revenues from both must cover utility expenses, but beyond that, prices will be determined by the local political, regulatory, and economic environment. The time and geographical variations in the cost of providing service can only be accounted for in a crude way at best in a practical rate structure, but even this may prove less desirable politically than charging all similar customers in the service area the same average rate. Even if the above problems are resolved, one important difficulty remains; metering of energy use (Btu meters) is presently (1977) too expensive to be justified in residential applications (7). These factors are discussed in more detail below.

The data in Chapter III show that load density significantly affects the cost of service because proportionately larger capital investments are required as load density decreases. Water, electricity, natural gas, telephone, and sewage disposal utilities commonly charge a uniform rate for provision of services to all similar customers in the service area. Unless institutional modifications similar to those discussed in Section

5.2 are made, the service range may have to be restricted to protect the utility. Of course, uniform rates rather than rates proportional to the cost of service can be advantageous--if the rate is lower than competing space heating costs, a uniform rate permits extension of the service range with consequently increased energy savings.

The problem of appropriate determination of geographical price variations may contain a blessing to district heating. Two meaningful price levels can be used to determine appropriate service ranges. The first is the average cost of service discussed above. If marginal cost of service at the boundary increases with expanding service range, the boundary of the largest economically acceptable service range is defined by equating the average cost of service to the cost of the cheapest competing heating method. The marginal cost itself may be used to determine the service range. One natural limit is provided by choosing the service range boundary so that the marginal cost of service equals the cost of the cheapest competing method. This latter definition of the service range would be the more profitable to the utility, but the former would produce more energy savings. The existence of two defined service ranges might enable a utility to choose a natural political or geographical boundary intermediate between the above two boundaries in many cases, bypassing the politically difficult problem of defining the range.

The variation of energy costs over time must also be considered carefully. If the capital costs must be repayed from revenues received, the consumers must pay for initial losses during system or urban growth. It will be somewhat unpopular to expect that consumers connecting to a system many years after the system is fully developed should pay these costs, but if consumers are required to pay the full costs of service during early years, no one will choose to connect (see Chapter IV). To encourage early connection and rapid penetration, it will be desirable to give early customers preferential treatment. One relevant but incomplete criterion in setting proper cost is that it should be less than the cost of competing heating methods.

The price of energy to a customer ideally should reflect the cost to the utility of providing the service. Besides the time and geographical variations, the cost of providing service depends on the thermal load profile and total energy use. Affordable time-of-day metering systems for small residential customers are not now available; even meters to measure total energy use over a long period of time are economically justifiable only for large customers. Charges probably will be based on connected capacity and total fluid flow through each system until low cost meters are developed.

Connection charges were considered in Section 5.2 in relation to the division of initial cost between consumers and the utility. If it is granted that the consumer should pay all or part of the initial connection cost, the distribution of the payment over time must still be determined. Natural gas utilities often gave customers the option of paying a nominal connection charge at the time the mains were installed or a higher charge at a later date. The importance of such a policy will depend on the amount of competition to district heating at the time of implementation.

For a publicly owned or subsidized system, prices may be reduced by subsidizing the costs with public funds. Public funds could be used to pay all fixed costs of operation (including initial investment and interest charges), leaving only operating costs for consumers to pay. This effectively mandates conversion to district heating by all customers in the service area because the costs will be below those of competing heating methods. Some have proposed that water supply utilities charge customers only the marginal cost of providing service and that the average cost of service be paid with public funds. Through different in principle, either pricing method will help to speed system penetration. Both methods require substantial tax support, however, and may be politically unacceptable.

Clearly, there are many difficulties involved in determining the appropriate consumer energy cost. These problems are not unique to district heating, but are shared by all utilities. The appropriate price structure must be determined by local circumstances, just as for other utilities. Most importantly, these problems are necessarily tied to the problems of ownership and financing discussed earlier, and they must be solved simultaneously with these problems.

5.5 Conclusion

While most of this study was devoted to studying the economics of district heating, it is not economics per se that is the greatest barrier to district heating implementation. Economic failure of district heating is quite likely to be a result of institutional failure. For example, it was shown in Chapters III and IV that the fraction of the market captured and the time needed to penetrate the market are crucial variables for an existing city, while the rate of urban growth is also important for a new city or development. Failures of systems due to unanticipated changes in these factors will be manifested as economic failures, but will in fact result from institutional failure.

System financing is an area where institutional and political questions abound. District heating is highly capital intensive, causing energy costs to be quite sensitive to changes in piping installation cost and interest rates. Financing large investments which are deemed socially desirable is an area in which governments at all levels have extensive experience. It is apparent from the results of Chapter III that government intervention by low interest loans or direct subsidization can have a profound effect on system economics. Whether such intervention is realized depends on the perceived benefits of district heating and on the extent of private sector interest. Benefits most likely to cause government action are the possibility of minimizing dependence on oil and natural gas for residential use and of drastically reducing the number of large power plants needed, especially if all-electric systems appear to be the primary alternative to district heating.

System ownership arrangements are likely to directly affect system economics as well as the market penetration of district heating. First, public ownership rather than private ownership increases the probability of low cost system financing with the desirable effects as discussed above. The legal and political status of the system owner might also affect the service boundary and, consequently, the capital cost. For example, municipal ownership probably implies that municipal political boundaries are also service boundaries. This will cause problems if the service provided is district heating, but not if a combined heat-electric utility is chartered to provide space heating (the method decided by the utility). Finally, the division of system capital investments between utility and customers will influence the penetration of district heating. The smaller the consumer capital investment the more attractive to the customer, but the more difficult for the utility to raise capital. This problem is essentially just the problem of selling life cycle costing to consumers.

The final major institutional problem is pricing of the energy sold to customers. For a combined heat-electric utility, there is no unique way to divide costs between heat and electricity. The total revenue must be adequate to cover utility expenses, but its distribution is undefined. Similar ambiguities exist in pricing energy to consumers in different locations and in recovering initial investments over a period of time. Pricing can also be used as a tool to promote connection to the system if allowed by regulatory agencies.

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CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that district heating combined with electricity generation can compete economically with conventional alternatives including fossil furnaces and electrically-driven heat pumps in new cities in the northern U.S. Significant energy savings (and more because most of the thermal energy demand is supplied by power plant "waste heat".

Many assumptions were made to obtain the above economic result. The most important ones are listed in Table 6.1 and a complete list in Table 3.6. To test the importance of the assumptions, a series of sensitiveity analyses was done. From the results of these analyses many conclusions can be drawn.

For the base case urban models, capital, maintenance, and lost power costs are dominant. Pumping power costs are a minor cost item. As expected, the cost of delivered energy is higher for the single-family house urban model than for the apartment model because of the larger capital investment per dwelling unit for the former case. For both urban models, however, the delivered cost of heat is now (winter of 1976) competitive with the cost of heating oil or natural gas in New England. The cost does not include end use equipment cost, but the initial cost of the equipment, while the economic lifetime is likely to be longer and the annual maintenance costs lower. Probable increases in natural gas or oil prices will make district heating even more attractive.

Table 6.1

Important Assumptions

- Residential space heating and water heating loads only; Coincidence factor, 0.72
- One location - New York City
- Two urban models
  - All single family houses 6000 people/sq mi
  - All low-rise apartment buildings (18 units/building) 15,000 people/sq mi
- Base Case Population 54,000
- Thermal Distribution System
  - Hot water heat carrier
    T sendout = 220F; T return = 160F
  - Plant-City Separation; 10 miles
  - Dual Pipeline, supply and return line enclosed in insulating concrete
- Base Case Economic Assumptions
  - Installed pipe costs based on new city installation costs
  - 9% interest rate
  - 30 year lifetime
  - 5% of initial costs for annual maintenance
  - Electricity costs - busbar $0.024/kwh
    - pumping power 0.030/kwh

This study has shown that there are no insurmountable technical or economic barriers to district heating implementation in the U.S.; institutional factors are far more likely to impede implementation. District heating has achieved significantly greater success in other countries because of more favorable institutional arrangements. The following paragraphs summarize recommended actions to be taken by government officials wishing to encourage district heating and suggest directions for future research. The topics are presented approximately in order of importance.

Since district heating is dominated by capital and maintenance costs, these must be kept low for any chance of success. Skilled contractors should be selected, and the work should be inspected frequently during and after construction to ensure low maintenance costs. The usual practice of awarding the construction contract to the lowest bidder may be inappropriate. The service area should be chosen to avoid areas of extremely high excavation costs, hence reducing initial costs.

Public financing should be used when possible in order to speed the market penetration of district heating. It is unlikely that a private developer other than a public utility company can obtain financing at a low enough interest rate for economic success of the system. For a new city public utility financing will probably succeed, but for an existing city public financing (e.g., municipal) is the only attractive prospect.

The penetration fraction (i.e., the fraction of the potential load actually connected to the system) must be high for system success. Therefore, applicable laws and regulatory policies must strongly encourage or mandate swift connection to the system. This can be done directly with laws restricting the use or availability of alternative fuels, or economically by direct payments or tax incentives supporting district heating.

Policy makers should realize that, while the trend is toward suburbanization or decentralization of cities, *a commitment to district heating is also a commitment to increasing centralization of cities*. The cost of district heating varies significantly with population density. Low cost district heating requires that the population density be kept high, effectively encouraging centralization of cities.

New regulatory approaches should be developed to deal with the supply of thermal and electrical energy by the same utility and from the same plant. The utility must have sufficient flexibility to balance thermal and electrical loads for maximum energy use efficiency and to optimize the district heating service range for minimum cost. For example, it may prove desirable to charter the utility to provide space heating and water heating, the method being left to the utility. Heat pumps could be used in low density areas and district heating in high density areas. Proper pricing of thermal and electrical energy from a combined plant is ambigious, and also requires regulatory attention. The thermal energy price must be low enough to compete with the cheapest alternative, but electricity customers should be given some benefit arising from combining the two services.

The plant-city separation distance appropriate for electrical utilities may be acceptable for district heating, but a large penalty is imposed on the thermal energy cost. *Siting policies should be reviewed in light of the increased benefits offered by combined heat-electric utilities*, and the plant-city separation distance reduced accordingly.

The urban growth analyses showed that only the local distribution systems should be implemented in phase with city growth, temporary fossil-fueled heat sources being used locally to supply hot water. Easements must be reserved for the ultimate paths of the transmission lines, as is now done for sewer and water lines, but installation of these lines should be delayed until the best time determined by the urban growth rate and fossil-fuel prices. Government officials must be willing to make long term plans and commitments to a much greater extent than is now done.

Air conditioning was excluded from this study. If it must be supplied by a district heating system, it will increase the system cost considerably. Every effort should be made to discourage the use of air conditioning where it is not necessary, and to improve building design for new buildings and the thermal integrity for existing buildings to minimize the cooling demand. Not only should the shell of the building and operation of the HVAC systems be considered, but also the orientation and external environment of the building (e.g., shading). Further study of both the related technical and institutional problems is needed.

The costs of pipe installation as a function of urban environment and the costs and feasibiltiy of retrofitting existing buildings to a district heating system should be explored. Preliminary estimates indicate that the installed pipe costs will be about four times higher than "cross country" costs for relatively new suburbs and as much as ten times higher for inner city areas. Few problems are likely to be encountered in retrofitting buildings with warm air or hydronic systems to a district heating system, but buildings with steam systems may be difficult.

Backup and peaking energy sources and thermal energy storage should be included in future district heating system analyses. Fossil plants are the prime candidates for backup and peaking applications because of their low capital cost as compared to excess system capacity. They do require growingly scarce resources, however, and siting may be a problem. Thermal storage might reduce the required peaking capacity somewhat, but a computer code capable of simulating the actual system time behavior is required to analyze its effect.

The thermal energy production mechanism will have a significant effect on energy costs. The extraction turbine with eight extraction points was found to produce significantly less expensive energy than a back-pressure turbine. The cost and availability of extraction turbines and the engineering limitations which apply to them should be examined. The number of extraction points which are feasible, the quantities of steam which can be extracted at each point, and the load following characteristics are of particular importance. A comparison to the back-pressure turbine should be made to determine whether the overall advantage is retained by the extraction turbine.

Thermal energy meters are not readily available at a cost low enough to be justified for residential applications. While such meters can only increase the cost of energy as compared to a system without meters, they will help to achieve consumer acceptance of the system by enabling the utility to charge each customer according to his actual demand. They will also encourage energy conservation by penalizing those who open windows in the winter and by rewarding those who make improvements in building thermal integrity. Recent advances in electronics technology should make the development of low cost thermal energy meters possible, but research is needed to demonstrate that this is the case.

An important topic eliminated from this study is the air quality improvement which will result from district heating system implementation. Fewer emissions result from combined thermal and electric supply than from either individual fossil furnaces or from all-electric systems. The advantage over fossil furnaces arises because more effective control devices are economical for a single large source than for small scattered sources. The advantage over all-electric systems arises because fuel consumption is reduced with the combined system.

APPENDIX A

PIPE COST DATA

PIPE COST DATA

By far the major cost item in a district heating system is the capital charge for the piping network. The second largest cost item is the annual maintenance cost, which is assumed to also be directly proportional to the initial piping network capital cost. Therefore, it is very important that these costs be determined carefully and that the assumptions used in determining these costs be well defined for persons attempting to use the study results.

The costs of the pipeline installation are based on the design of Yee (1), and the same methods of cost estimation are used. The only differences between Yee's estimates and mine result from the addition of expansion loop costs and insulation costs to the estimates. The pipe is black steel pipe chosen to satisfy ASA B31.1 Code for Pressure Vessels for the given design pressure and temperature. It is surrounded by a layer of calcium silicate insulation and then by insulating concrete. The insulating concrete encloses both pipes (supply and return) of the dual pipe system as shown in Figure A.1. The pipeline is buried such that the top of the pipe is six feet below the ground surface. Table A.1 shows the concrete dimensions for selected diameters (1).

The excavation (labor) costs, that is the costs of digging the trench, laying the pipe, and backfilling the trench, were obtained by Yee from Boston contractors. Yee obtained both a high and a low estimate of which only the latter is used here. This trenching cost is applicable for average soil conditions with no unusual conditions

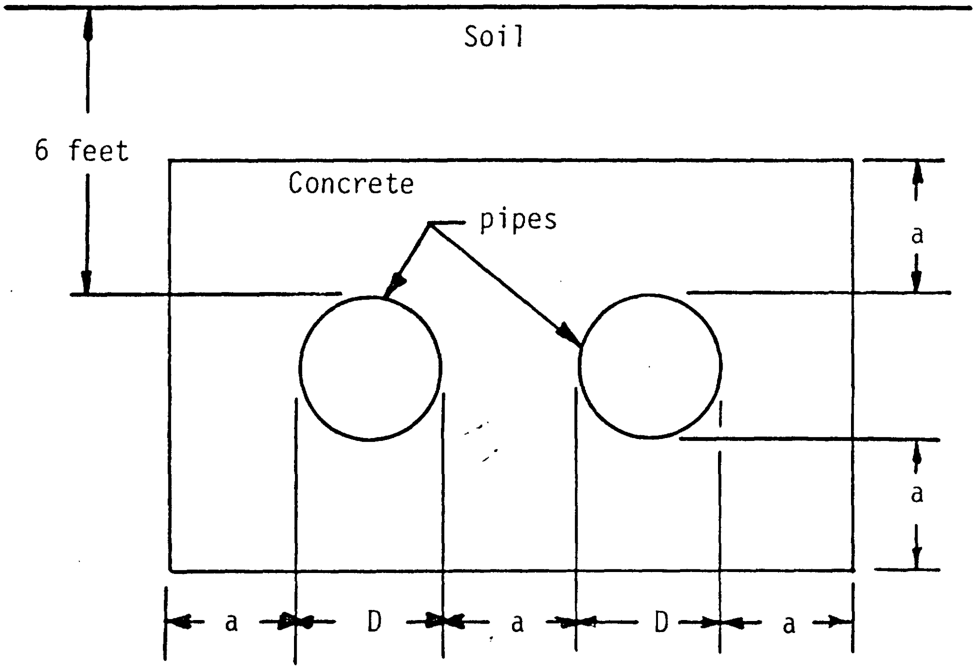


Figure A.1

Pipeline Design

Table A.1

Pipeline Dimensions and Concrete Volumes

Pipe Diameter (inches)	a (Figure 1) (inches)	Volume Concrete (yd^3/ft)
1	5	.038
6	5	.101
12	6	.245
24	6	.596
36	7	1.18
48	8	1.95
72	9	3.92
96	11	6.78
120	12	10.16

or interfering underground structures (e.g. telephone cables, sewers, and power lines). The high cost obtained by Yee assumed difficult soil conditions. Estimates of the increase in excavation costs for other conditions will be discussed later in this appendix.

Concrete costs are estimated by using a cost of 50 dollars per cubic yard for concrete in place. This cost was determined to be appropriate for the Boston area by Yee (1).

Following Yee, it is assumed that bedding material is used under the concrete; the bedding dimensions are two feet depth by concrete width plus three feet. The bedding material cost is three dollars per cubic yard.

The pipe cost is 0.40 dollars per pound. The material is carbon steel, and the dimensions are determined by the procedure given above subject to the additional requirement that the pipe thickness be a standard value.

The major contributor to pipe cost neglected by Yee is the cost of devices to accomodate the thermal expansion of the pipeline. Unless such devices are used, thermal expansion will produce untolerable stress levels or pipe movement. The two accepted expansion devices are expansion joints and expansion loops. The first relies on a bellows or on a pipe within a pipe sliding seal to accommodate expansion. The expansion loop consists of a U-shaped section of pipe whose dimensions are determined by the anticipated expansion and the pipe diameter. Such loops are usually a few hundred feet apart and the pipe is anchored at points between the loops. The expansion joints require less space than does an expansion loop, but require much more maintenance than does the loop. Where space permits most designers have chosen the loop; it has been chosen in this study. The expansion loop cost has been included by increasing the pipe cost for the appropriate diameter by the percentage increase in length of pipe required to form the loops at the given temperature. The length data is computed from the data presented by Lieberg (4) for pipe diameters up to 14 inches, where his data ends. For larger diameters his curves appear to be asymptotically approaching 20 per cent of additional pipe for a maximum temperature difference of 400 F between the design temperature and the ambient temperature. I use this result and assume for smaller design temperature differences that the percentage varies linearly with the temperature difference. The percentages are displayed in Table A.2.

Yee did consider insulation costs for his high temperature water case, but only by adding 15 per cent to his pipe cost estimates. I have tried to refine this estimate somewhat. The preferred insulation material is calcium silicate because of its desirable high temperature properties (3). Its cost has been estimated as follows. Data from ORNL-HUD-MIUS-22 and from the <u>1977 Building Cost File-Eastern Edition</u> agree well for installed insulation costs for pipe sizes from two to twelve inches in diameter. An analysis of these costs for thicknesses recommended at 300°F (4) shows that the insulation cost is rather constant at 28-30 per cent of total cost for all diameters up to twelve inches. A rough approximation is to assume that the insulation

Table A.2

Expansion Loop Additions to Pipe Lengths (%)

D(in)	450°F	400°F	340°F	300°F	250°F	200°F
1	4.0	3.5	3.0	2.5	2.0	1.5
2	6.7	5.9	5.0	4.2	3.4	2.5
3	8.7	7.6	6.5	5.4	4.4	3.2
4	10.3	9.0	7.7	6.4	5.2	3.8
5	11.7	10.2	8.8	7.3	5.9	4.4
6	12.7	11.1	9.5	7.9	6.4	4.8
8	14.7	12,9	11.0	9.2	7.4	5.5
10	16.0	14.0	12.0	10.0	8.0	6.0
12	17.0	14.9	12.8	10.6	8.5	6.4
14	17.3	15.1	13.0	10.8	8.7	6.5
>14	20.0	17.5	15.0	12.5	10.0	7.5

contributes 30 per cent of total costs for all diameters. Since the change in the installed insulation cost will vary by at most ten per cent as the temperature is changed by 100°F either way, I have assumed that the insulation cost is constant for all temperatures.

The cost breakdown for pipe costs at four sendout temperatures is displayed in Tables A.3, A.4, A.5 and A.6. These costs are used in the computer program used to design the distribution system. For use in the program analytical approximations to the curves in the above figures are used; these approximations are shown in Table A.7. The cost data used in this study is plotted in Figure 3.11 along with cost data from other related studies.

The costs for excavation in the pipe cost tables reflect costs for trenching and pipelaying in common soil in a new area with no underground interferences. The trenching can then be done entirely by machine. If the soil is more difficult to excavate, e.g., rock excavation or water seeping into trenches, or if there are interfering structures, the excavation costs and pipelaying costs may rise dramatically. For example, the backfilling of a trench by machine is estimated to cost forty-seven cents per cubic yard (5). Excavation through rock six to ten feet deep is estimated to cost $15.45 per cubic yard, while excavation through common soil is estimated to cost $3.05 per cubic yard. Clearly, the installation costs will be a sensitive function of the local conditions, but increasing the excavation and pipelaying costs by about an order of magnitude would give a rough upper bound to the expected worst costs in a difficult urban setting. That the effect on installed pipe costs would be substantial

Table A.3

Pipe Cost Data (\$/foot); T_{max} = 200°F.

D(in.)	Labor	Concrete	Bedding	Pipe	Exp. Loops	Insul.	TOTAL
1	4.5	2.4	1.0	1.1	0.2	4.4	13.6
6	4.5	4.9	1.2	7.4	1.3	8.9	28.2
18	9.0	14.3	1.7	37.9	6.9	29.1	98.9
42	20.0	42.0	2.7	135.0	21.6	88.8	310.0
72	45.0	93.2	3.8	481.0	69.2	300.0	992.0
120	90.0	220.0	5.8	1280.0	180.0	810.0	2590.0

Table A.4

Pipe Cost Data (\$/foot); T_{max} = 300°F.

D(in.)	Labor	Concrete	Bedding	Pipe	Exp. Loops	Insul.	TOTAL
1	4.5	2.4	1.0	1.1	0.3	4.4	13.7
6	4.5	4.9	1.2	7.4	2.1	8.9	29.0
18	9.0	14.3	1.7	37.9	11.5	29.1	104.0
42	20.0	42.0	2.7	135.0	36.0	88.8	324.0
72	45.0	93.2	3.8	540.0	123.0	300.0	1100.0
120	90.0	220.0	5.8	1570.0	337.0	810.0	3030.0

Table A.5

Pipe Cost Data ($/foot); T_{max} = 350°F.

D(in.)	Labor	Concrete	Bedding	Pipe	Exp. Loops	Insul.	TOTAL
1	4.5	2.4	1.0	1.1	0.4	4.4	13.8
6	4.5	4.9	1.2	15.2	3.3	8.9	38.0
18	9.0	14.3	1.7	47.2	15.2	29.1	116.0
42	20.0	42.0	2.7	270.0	63.5	88.8	487.0
72	45.0	93.2	3.8	692.0	170.0	300.0	1300.0
120	90.0	220.0	5.8	1790.0	437.0	810.0	3350.0

Table A.6

Pipe Cost Data ($/foot); T_{max} = 400°F.

D(in.)	Labor	Concrete	Bedding	Pipe	Exp. Loops	Insul.	TOTAL
1	4.5	2.4	1.0	1.1	0.5	4.4	13.9
6	4.5	4.9	1.2	15.2	3.8	8.9	38.5
18	9.0	14.3	1.7	65.6	23.9	29.1	144.0
42	20.0	42.0	2.7	359.0	102.0	88.8	615.0
72	45.0	93.2	3.8	923.0	273.0	300.0	1640.0
120	90.0	220.0	5.8	2560.0	737.0	810.0	4420.0

Table A.7

Pipe Cost Functions ($/foot).

D(in.)			
T_{max}(°F)	1 - 6	6 - 18	18 - 120
200	$13.6\ D^{0.407}$	$3.64\ D^{1.142}$	$.684\ D^{1.721}$
300	$13.7\ D^{.4185}$	$3.62\ D^{1.162}$	$.612\ D^{1.77}$
350	$13.8\ D^{.5683}$	$6.15\ D^{1.1016}$	$.690\ D^{1.773}$
400	$13.9\ D^{.5686}$	$4.48\ D^{1.201}$	$.781\ D^{1.805}$

A.2 Cost of Guides and Anchors

One omission from the installed pipe cost data used in this study is the cost of supports for the pipe between expansion loops to allow for movement relative to the concrete. To allow movement, the pipe must be surrounded by an air gap or by material offering relatively little friction to the pipe. This is relatively easy to accomplish by special design of the insulation or by the use of a material similar to corrugated cardboard (but moisture resistant). The problem is that supports must be provided to hold the pipe above the concrete.

No good cost information has been obtained for guide costs, but costs were obtained for anchors to define the direction of movement during expansion; these costs were obtained for prefabricated pipe-in-pipe conduit construction. An anchor consists of a steel plate welded or bolted to the pipe and embedded in a massive concrete block. The heavy construction is required because very large forces must be balanced during expansion and contraction. In contrast, the forces which must be sustained by a guide are due mainly to the weight of the pipe, although some lateral forces may be exerted during expansion or contraction. For this reason, guides will certainly cost less than anchors. If it is assumed that a guide costs the same as an anchor, and that two guides and two anchors are need per 300 feet of pipe, a conservative cost estimate results.

Data obtained for anchor costs are shown in Table A.8. The costs are for installed anchors for cross-country conditions. The anchors are designed for use with 400°F water systems; one expects that the costs for lower temperature systems would be less. Table A.9 neglects this correction; it is taken into account in Table A.10. For the dual pipe system, it is assumed that the guide and anchor costs (combined) per 300 feet of pipe is eight times the appropriate anchor cost. For Table A.10 the cost of guides and anchors for lower temperature systems has been adjusted in the same way as expansion loop costs were adjusted.

Most of the pipe in the systems considered in this study was designed for a water temperature of 220°F. Only the transmission system was allowed to have higher water temperatures. For the transmission system, pipes are generally larger than 12 inches in diameter. A conservative approach would be to add seven per cent to the cost of pipes carrying 220°F water, and nine per cent for the higher temperatures. The error resulting from neglecting this cost in the study is clearly no more than nine per cent, and probably closer to five per cent.

Table A.8 Anchor Costs Versus Pipe Size

Diameter (inches)	Installed Anchor Costs
2	111
3	137
4	137
6	154
8	193
10	245
12	285

Table A.9 Installed Guide and Anchor Costs Versus Pipe Diameter

Diameter (in.)	Guide and Anchor Cost (Dual Pipe)	Per Cent of Dual Pipe Cost
2	3.0	16.4
3	3.6	16.6
4	3.6	14.7
6	4.1	14.1
8	5.1	12.6
10	6.5	12.4
12	7.6	11.7

Table A.10 Cost of Guides and Anchors (% of Installed Pipe Cost)

Diameter (in.)	200F	300F	350F	400F
2	7.1	11.7	12.6	14.6
3	7.3	11.9	12.0	13.9
4	6.5	10.5	10.2	11.8
6	6.2	10.1	9.2	10.6
8	5.6	9.0	7.2	9.4
10	5.5	8.8	7.2	9.1
12	5.2	8.4	6.9	8.6

is clear from examining Tables A.3-A.6, but the costs would not generally be more than double the costs I have used - a case considered in the sensitivity analyses.

REFERENCES - APPENDIX A

1. Yee, Wee T., Urban Space Heating with a Heat Pump-Condenser Temperature Water System, MIT Thesis, Department of Mechanical Engineering, 1976.
2. Lieberg, O.S., High Temperature Water Systems, The Industrial Press, New York, 1963.
3. Thermal Insulation Thickness Charts and Material Characteristics for Piping, Federal Construction Council Technical Report Number 45, 1963.
4. Proceedings of a Symposium/Workshop on Underground Heat Distribution Systems, prepared for the National Academy of Science by the Building Research Advisory Board, Division of Engineering, National Research Council, 1966.
5. 1976 Heavy Construction Cost File, Unit Prices, Coert Englesman, Construction Publishing Company, Inc.

APPENDIX B

LOST POWER COST CALCULATIONS

B.1 Lost Electrical Power Costs

It is assumed in this work that heat for high temperature hot water is extracted from a base-loaded electricity generating plant operating on a Rankine cycle. The system envisioned extracts steam from the turbine at several points along the expansion process. This steam supplies heat to a hot water loop via a heat exchanger, and the hot water is distributed from the plant site to the users and returned to the plant to be reheated.

To produce high temperature water, the steam must be extracted from the turbine at pressures well above the usual exhaust pressure. Electricity generation will be decreased because of the extraction process; consequently the plant loses revenue equal to the number of kilowatt-hours sacrificed times the busbar electricity cost. This lost revenue is charged to the district heating system.

The temperature limits for the hot water distribution system are determined by economics and by available residential space heating equipment. Typical equipment is designed to operate with inlet temperatures between 140 and 220°F and outlet temperatures between 125 and 200°F. The exact temperatures chosen will depend on the tradeoff between equipment cost and delivered hot water cost. The capacity of a hydronic heater decreases as the average temperature of the water flowing through it decreases, because the heat transfer to the air is decreasing (fan power is limited). In order to retain approximately 80% of the design capacity of the equipment considered by Yee, a practical return temperature is about 160°F. If hot water heating is also included, the return temperature might be lowered to 140°F.

These temperature limits determine the fluid temperatures in the distribution system nearest the consumers. The high temperature limit (but not the low temperature limit) may be eliminated in the mains connecting to the plant, however, by using heat exchangers or mixers to divide the system into a primary loop and secondary loops. Ultimately, the maximum temperature in the primary loop is determined by economics. The optimum cost will be determined by minimizing the sum of pipe and pumping station capital and maintenance costs, pumping power costs, and lost electrical power costs. The purpose of this section is to estimate the variation of lost electrical power costs with sendout temperature for given return temperature, busbar power cost, condenser conditions, turbine inlet conditions, and turbine efficiency.

An estimate of this cost has been obtained by analyzing a Rankine cycle operating with turbine inlet steam conditions of 550°F and 975 psig and a condenser inlet pressure of 2.5 inches of mercury. The turbine was assumed to have a constant isentropic efficiency of 0.82 during the entire expansion process. A busbar electricity cost of $0.024 per kilowatt-hour was assumed. The turbine inlet steam is slightly superheated, but the results are little different if saturated steam at 550°F is assumed at the turbine inlet.

To minimize the lost electrical power, it is desirable to extract steam at several temperatures between the return temperature and the sendout temperature. This allows additional expansion of the steam beyond that possible if all the steam is extracted at the sendout temperature. The effect of the number of extraction points is shown in Figure B.1. Little benefit is derived by using more than eight (equally spaced in temperature and equal mass flow rates) extraction points between the sendout and return temperatures. Figure B.2 shows the cost of extracted heat as a function of maximum extraction temperature for one extraction point and for eight extraction points. In carrying out the economic analysis, eight extraction points are assumed.

Two points should be noted. First, no allowance has been made for increased capital costs at the plant, because heat exchanger costs and turbine modification costs will be negligible compared to lost power costs. Second, the steam conditions are typical of a nuclear plant. In order to investigate the difference in lost power costs between nuclear and fossil plants, the single extraction point costs for both are plotted in Figure B.2. The assumed steam conditions for the fossil plant (1) are 540 psig at 1000°F (after the steam has been reheated). The lost power costs are slightly, but not significantly, lower for the fossil plant. They are, in fact, similar enough that no distinction is made between fossil and nuclear plants in the analyses. In reality, there will be a larger difference between the two plant types than indicated because of differences in busbar costs for the plants. The figure of $0.024 per kwh is an average of the costs reported for large coal and nuclear plants (2).

An analytical function for lost power cost is useful for the computer program. For the conditions outlined above (160°F return

FIGURE B.1

Variation of Lost Power Cost with Number of Extraction Points

($T_{sendout}$ = 220F, T_{return} = 160F)

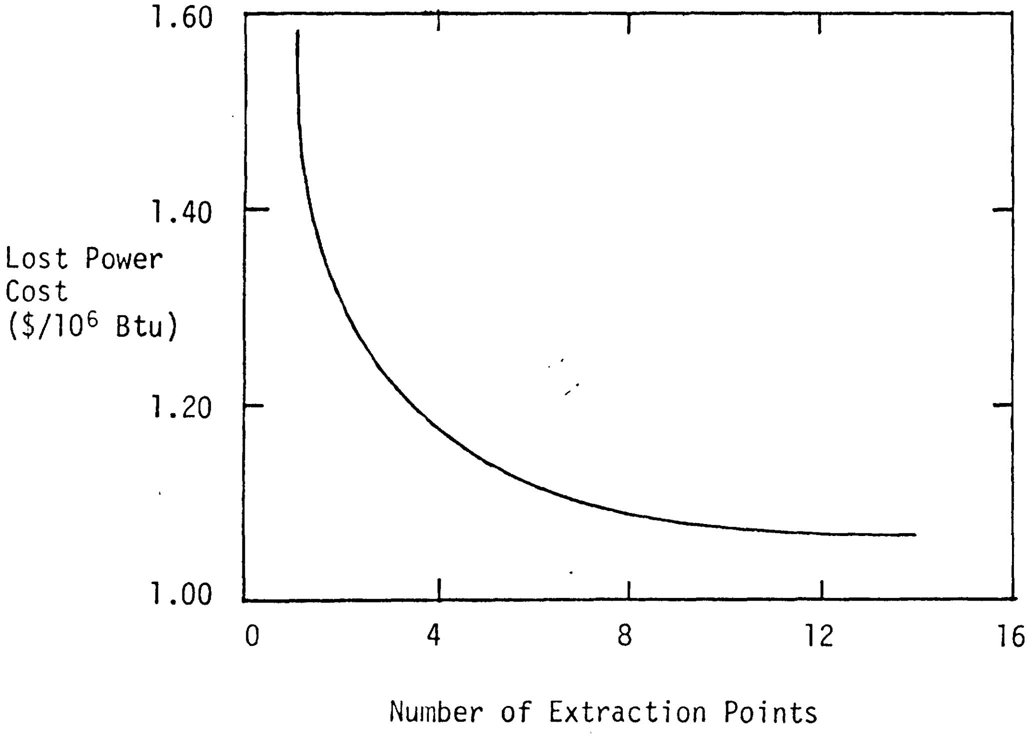
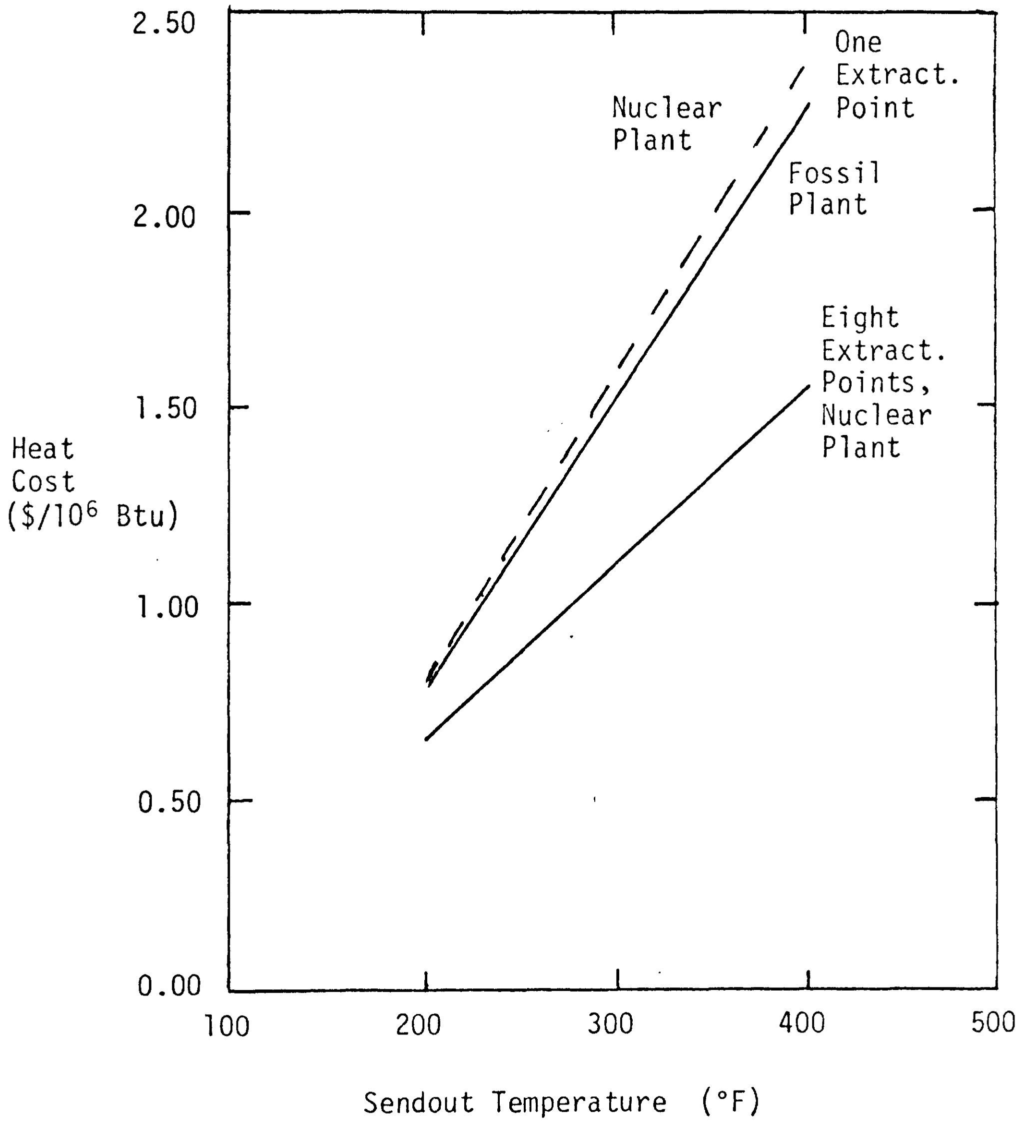


FIGURE B.2

Variation of Lost Power Cost with Sendout Temperature

(T_{return} = 160F)



temperature and eight extraction points), lost power cost depends linearly on temperature, as shown in Figure B.2. The functional dependence is:

$$\frac{\$}{10^6 \text{ Btu}} = 0.00438 \text{ T } (^{\circ}\text{F}) - 0.2227$$

B.2 Methodology for Calculating Amount of Lost Electrical Power

Figures B.3 and B.4 show sketches of the techniques for producing hot water for the back-pressure (single extraction point) and extraction turbine (three extraction points) cases, respectively. In this study no steam is assumed to be extracted from the prime steam line as shown in Figure B.4, but this technique might be used for peaking purposes.

Refer to Figure B.5, a TS diagram for water, for a full explanation of the variables used, but basically, h refers to enthalpy, s to entropy, the subscript f refers to the saturated liquid state, g to the saturated vapor state, and fg to the change in the appropriate quantity (h or s) in changing from the liquid state to the vapor state.

Procedure for a single extraction point

1) Pick parameters for starting point of expansion, h_2, s_2.
2) Pick extraction temperature, T_{ext}.
3) Find h_f (at T_{ext}).
4) Pick turbine isentropic efficiency, e_t.
5) Assume condenser inlet pressure, p_c.

Fig B.3 Schematic of thermal grid heat supply using back-pressure turbine. (From Reference 3).

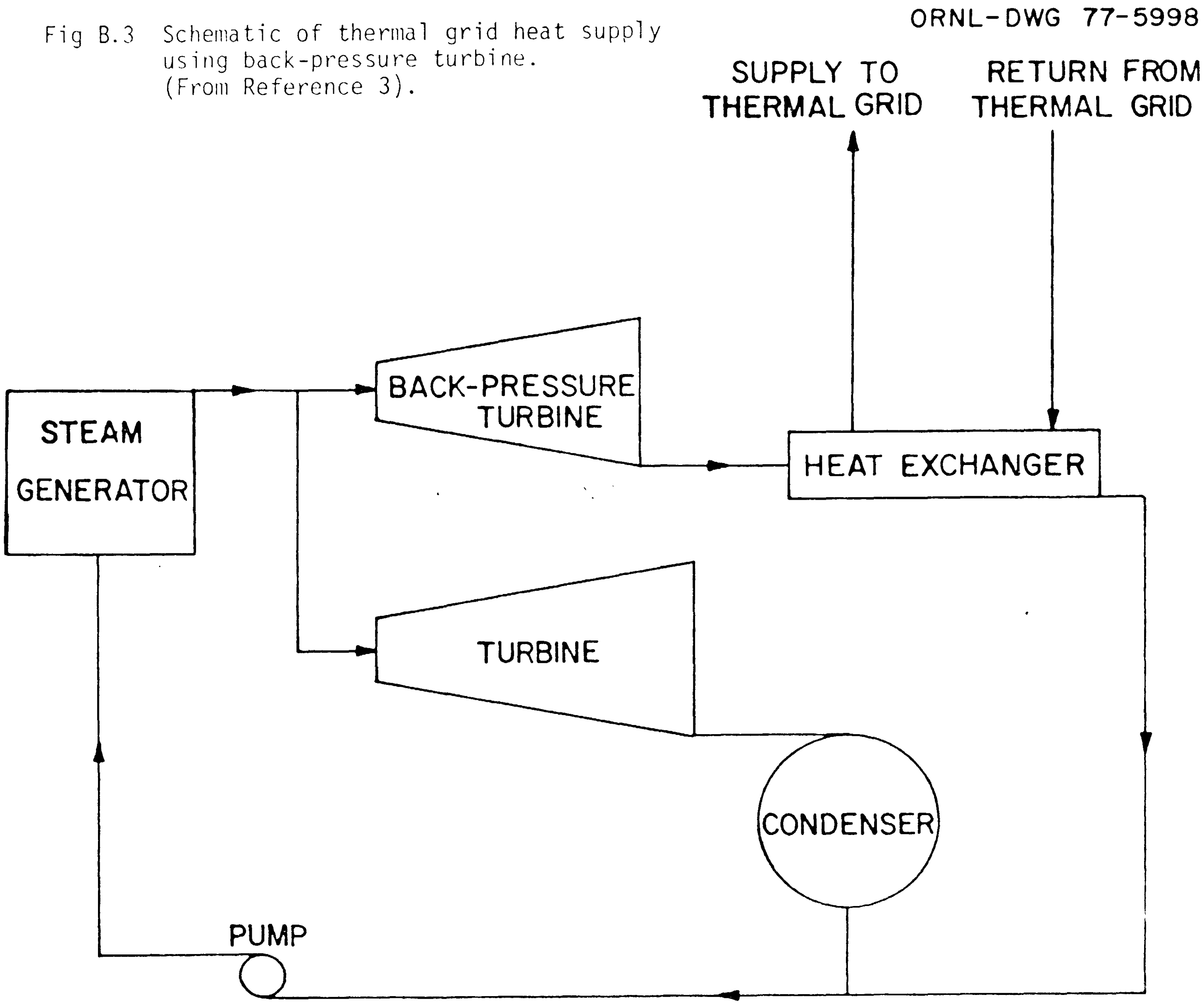


Fig B.4 Schematic of Thermal Grid Heat Supply Using Turbine Extraction Steam (adapted from Reference 3).

ORNL-DWG 77-5999A

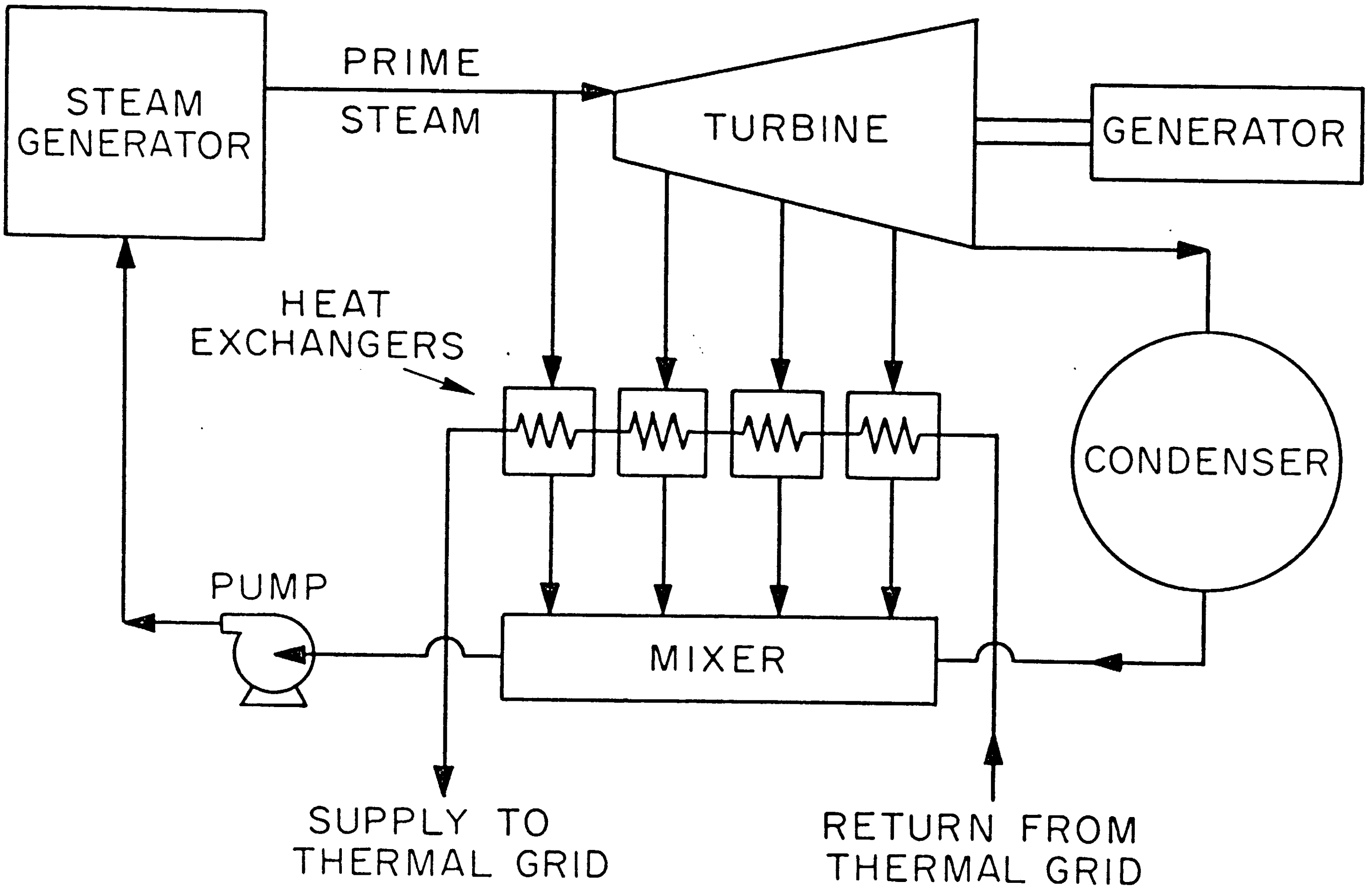
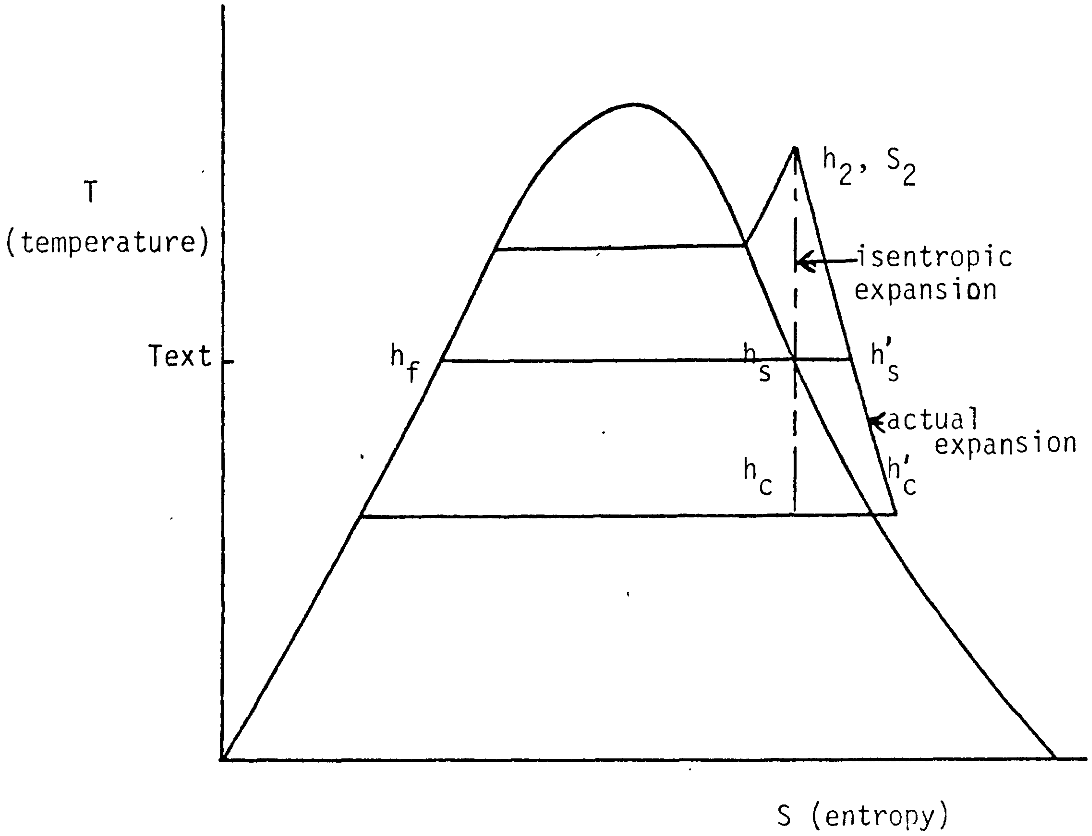


Figure B.5 Sketch of Assumed Electrical Power Cycle Showing Steam Extraction Variables



6) Calculate isentropic cycle enthalpy values at extraction point and condenser inlet, h_s and h_c, and at the corresponding actual cycle conditions, h'_s and h'_c.

Then

$$h_s = h_f + (s_2 - s_f)\, h_{fg}/s_{fg} \qquad \text{(values at } T_{ext}\text{)}$$
$$h'_s = h_2 - e_t\,(h_2 - h_s)$$
$$h_c = h_f + (s_2 - s_f)\, h_{fg} / s_{fg} \qquad \text{(values at } p_c\text{)}$$
$$h'_c = h_2 - e_t\,(h_2 - h_c)$$

7) Assume busbar power cost, C_p.

Finally,

$$\text{Lost Power Cost } (\$ / 10^6\text{Btu}) = 293\, C_p\, (h'_s - h'_c) / (h'_s - h_f)$$

where h_f is evaluated at T_{ext}.

Procedure for Multiple Extraction Points

1) Assume equal extraction mass flow rates at each extraction temperature. Check to see that the desired mass is actually available to extract.
2) Assume values for h_2, h_s, s_2, e_t, p_c, and C_p.
3) Calculate h_f, h_s, and h'_s for each extraction temperature.
4) Calculate h_c and h'_c.

$$\text{Lost Power Cost } (\$ /10^6\text{Btu}) = 293\, C_p \frac{(h'_{s1} + h'_{s2} + \cdots + h'_{sN} - Nh'_c)}{(h'_{s1} - h_{f1} + \cdots + h'_{sN} - h_{fN})}$$

where N is the number of extraction temperatures.

REFERENCES - APPENDIX B

1. Miller, A. J., et. al., "Use of Steam-Electric Power Plants to Provide Thermal Energy to Urban Areas," Oak Ridge National Laboratory report ORNL-HUD-14, 1969.
2. Murray, R. Michael, Jr., "The Economics of Electric Power Generation - 1975-2000," in *The Nuclear Power Controversey*, edited by Arthur W. Murphy, Prentice-Hall, Inc., 1976.
3. Olszewski, M., "Preliminary Investigations of the Thermal Energy Grid Concept," Oak Ridge National Laboratory report ORNL-TM-5786, October, 1977.

APPENDIX C

MISCELLANEOUS COST ITEMS

Miscellaneous Cost Items

C.1 Pumping Station Costs

The costs of the pumping stations for the subsections is not included in the computer optimization program. The subsection networks are designed so that one pumping station is required for each.

The station costs are estimated in the following simple way. Stetkar (4) derived a cost function for centrifugal pumps as a function of displacement. The pump cost was shown to vary as the volumetric flow rate raised to the 0.6625 power. This data applies strictly to the pump only, not to the building and accessory equipment. The 1976 Building Cost File-Eastern Edition contains data for the entire pumping station cost, including all accessories and installation costs, but only for a part of the size range of interest. To scale to larger and smaller sizes, Stetkar's scaling law is assumed to apply to the whole pumping station. For the two sizes given in the cost file (that is the two relevant sizes), the scaling law is accurate. Table D.1 gives the results of the cost calculations.

C.2 Valve Costs

The valve costs are caluclated by assuming valves are installed in pipe sections labeled -8 for the single family house subsections and A, B, C and D for the low-rise apartment subsections. One valve is used in the supply line and one in the return line for each pipe section. The cost data are those collected by Yee (5) for his thesis, and are summarized in Table D.2.

TABLE C.1

Pump Cost Data

URBAN MODEL	PUMP CAP. (gpm)	COST (EACH)	NUMBER SUBSEC.	TOTAL COST	HEAT LOAD (10^6 Btu)	$/$10^6$ Btu
SF, 6000 per sq.mi.	900	$ 130,000	20	$2.6x$10^6$	2.2x10^6	0.17
SF, 3000 " " "	450	84,000	40	3.4x10^6	2.2x10^6	0.23
SF, 1500 " " "	225	53,000	80	4.2x10^6	2.2x10^6	0.28
APT, 15K " " "	325	69,000	20	1.4x10^6	.98x10^6	0.22
APT, 7.5K " " "	160	43,000	40	1.7x10^6	.98x10^6	0.26
APT,3.75K " " "	80	27,000	80	2.2x10^6	.98x10^6	0.33

TABLE C.2

Valve Cost Data

URBAN MODEL	VALVE SIZE(S)	NUMBER(S)	COST EACH	TOTAL COST	HEAT LOAD (10^6 Btu)	\$/10^6 Btu
SF, 6000/sq.mi.	3 in.	360	\$ 190	\$ 68,400	$2.2\text{x}10^6$	.004
SF, 3000 " "	3	720	190	137,000	$2.2\text{x}10^6$	.009
SF, 1500 " "	2	1440	150	216,000	$2.2\text{x}10^6$	.014
APT, 15,000 " "	4,3	240, 80	210, 190	65,000	$.98\text{x}10^6$	.010
APT, 7,500 " "	3,2	480, 160	190, 150	115,000	$.98\text{x}10^6$	.017
APT, 3,750 " "	3,2	640, 640	190, 150	218,000	$.98\text{x}10^6$	.033

REFERENCES - APPENDIX C

1. "A Total Energy System for Boston", report for Subject 22.33, Spring 1976, Massachusetts Institute of Technology.
2. Kreith, Frank, Principles of Heat Transfer, 2nd Edition, International Textbook Company, Scranton, Pennsylvania, 1965.
3. Geiringer, P. L., High Temperature Water Heating, John Wiley and Sons, Inc., New York, N.Y., 1963.
4. Stetkar, John W., "On the Design, Simulation and Policy Implications of Total Energy Systems", MIT Thesis, Department of Nuclear Engineering, 1976.
5. Yee, Wee T., "Urban Space Heating with a Heat Pump-Condenser Temperature Water System", MIT Thesis, Department of Mechanical Engineering, 1976.

APPENDIX D

BUILDING HEAT LOAD DATA

Table D.1

Peak Heat Loads (Space plus Water) [Btu/hr]

Building Type	NE (New York City)	NC (Omaha)	S (Atlanta)	W (Albuquerque)
1600 ft^2 - SF House	47,000	67,000	50,000	58,000
18,000 - Low rise apt.	320,000	350,000	330,000	320,000
40,500 - Office *	830,000	880,000	930,000	940,000
40,000 - School *	1,200,000	1,700,000	1,200,000	1,300,000
32,400 - Shop *	950,000	1,300,000	940,000	1,050,000

Table D.2

Annual Heat Loads (Space plus Water) [Btu]

Building Type	NE	NC	S	W
S.F. House	1.5×10^8	1.7×10^8	9.1×10^7	1.1×10^8
Low-rise apt.	2.1×10^8	8.1×10^8	6.1×10^8	6.2×10^8
Office *	1.0×10^9	1.5×10^9	1.1×10^9	1.4×10^9
School *	1.0×10^9	1.4×10^9	9.9×10^8	1.2×10^9
Shop *	2.3×10^8	4.5×10^8	2.1×10^8	3.0×10^8

* Space heating loads only

Table D.3

Peak Air Conditioning Loads (Btu/hr)

Building Type	NE	NC	S	W
1600 ft^2 - House*	(13,000) 37,000	(19,000) 46,000	(22,000) 40,000	(55,000) 50,000
18,000 - Low-rise	252,000	240,000	264,000	276,000
40,500 - Office	$1.1x10^6$	$1.2x10^6$	$1.3x10^6$	$1.2x10^6$
40,000 - School	$1.5x10^6$	$1.6x10^6$	$1.6x10^6$	$1.6x10^6$
32,400 - Shop	$1.4x10^6$	$1.5x10^6$	$1.5x10^6$	$1.5x10^6$

*Loads calculated assuming ratio of peak loads is same for cooling as for heating. Ratios from Tables 4 and 5 used.

Table D.4

Annual Air Conditioning Loads (Btu)

Building Type	NE	NC	S	W
SF House	$3.5x10^6$	$5.8x10^6$	$8.3x10^6$	$1.8x10^7$
Low-rise	$7.0x10^7$	$7.2x10^7$	$1.0x10^8$	$9.0x10^7$
Office	$3.9x10^8$	$4.3x10^8$	$5.1x10^8$	$4.4x10^8$
School	$1.5x10^8$	$1.6x10^8$	$2.0x10^8$	$1.5x10^8$
Shop	$9.8x10^8$	$9.9x10^8$	$1.3x10^9$	$1.1x10^9$

APPENDIX E

PIPE SIZE RESULTS

FIGURE E.1
House Model Subsection Distribution System

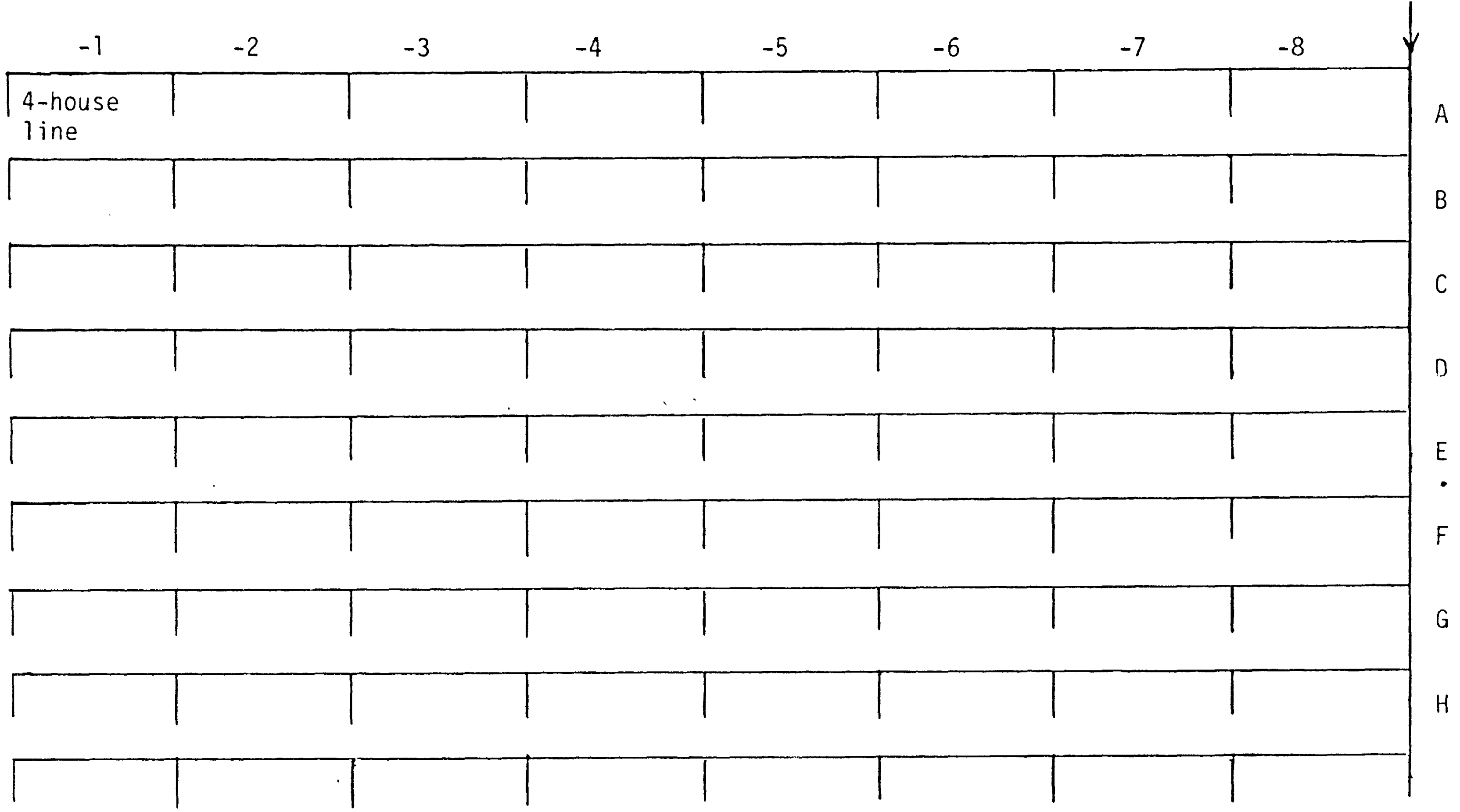
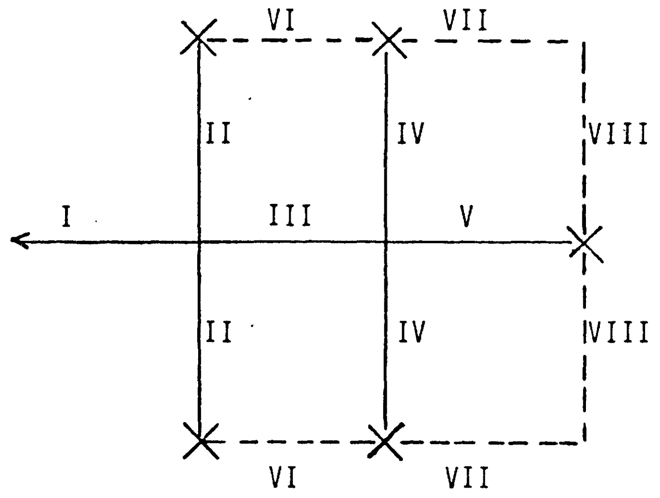


FIGURE E.2

House Model Mains Network



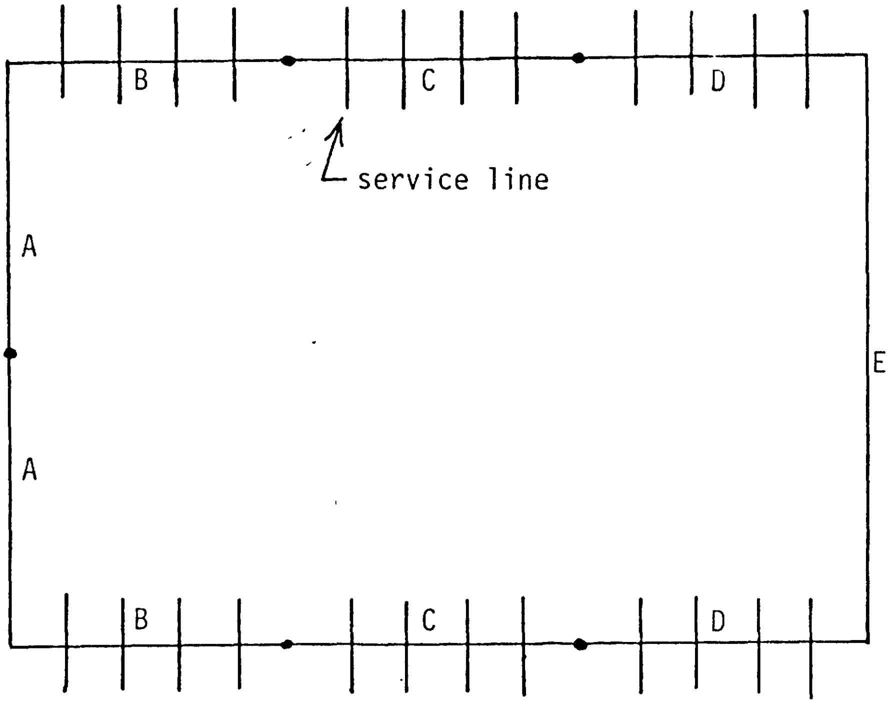


FIGURE E.3

Apartment Model Subsection Distribution System

FIGURE E.4

Apartment Model Mains System

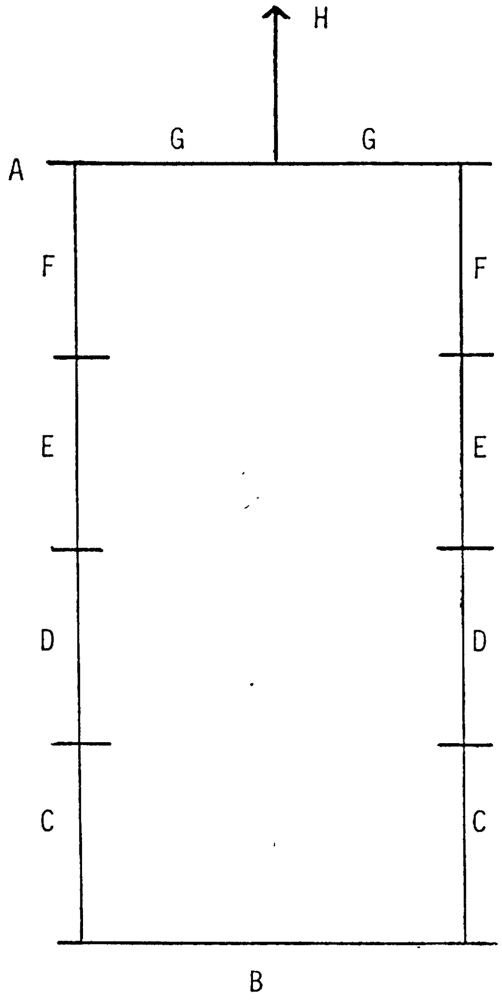


Table E.1

Pipesize Data (dia. in inches)

Single Family House Model

54,000 people; 6000 people/mi^2.

Section	2% interest 2% maint.	6% interest 2% maint.	9% interest 5% maint.	19% interest 10% maint.
I	24	24	22	20
II	12	12	12	12
III	20	18	18	18
IV	18	16	16	16
V	12	12	12	12
VI, VII	14	14	14	14
VIII	14	14	14	14
Service line	1	1	1	1
4 house line	1	1	1	1
-1	2	2	2	2
-2	2	2	2	2
-3	3	3	3	3
-4	3	3	3	3
-5	3	3	3	3
-6	3	3	3	3
-7	3	3	3	3
-8	3	3	3	3
A	8	8	8	8
B	8	8	8	8
C	6	6	6	6
D	6	6	6	6
E	6	5	5	5
F	5	5	5	5
G	4	4	4	4
H	3	3	3	3

Table E.2

Pipe Size Data

Single Family House Model

54,000 people; 3000 people/mi^2.

Section	2,2	6,2	9,5	x 2*	x 10*
I	14	14	14	14	14
II	10	10	10	10	10
III	14	14	14	14	14
IV	12	12	12	12	12
V	10	10	10	10	10
VI, VII	10	10	10	10	10
VIII	10	10	10	10	10
Service line	1	1	1	1	1
4 house line	1	1	1	1	1
-1	2	2	2	2	2
-2	2	2	2	2	2
-3	2	2	2	2	2
-4	2	2	2	2	2
-5	2	2	2	2	2
-6	3	3	3	3	3
-7	3	3	3	3	3
-8	3	3	3	3	3
A	6	5	5	5	5
B	5	5	5	5	5
C	5	5	5	5	5
D	5	5	5	5	5
E	4	4	4	4	4
F	4	4	4	4	4
G	3	3	3	3	3
H	3	3	3	3	3

---

*Sum of Interest and Maintenance Charges Adjusted to be Displayed in Multiples of 9,5 Column.

Table E.3

Pipe Size Data

Single Family House Model

54,000 people; 1500 people/mi^2.

Section	2,2	6,2	9,5	x 2 *	x 10 *
I	14	14	12	12	12
II	8	8	8	8	8
III	10	10	10	10	10
IV	10	10	10	10	10
V	8	8	8	8	8
VI, VII	8	8	8	8	8
VIII	8	8	8	8	8
Service line	1	1	1	1	1
4 house line	1	1	1	1	1
-1	1	1	1	1	1
-2	2	2	2	2	2
-3	2	2	2	2	2
-4	2	2	2	2	2
-5	2	2	2	2	2
-6	2	2	2	2	2
-7	2	2	2	2	2
-8	2	2	2	2	2
A	4	4	4	4	4
B	4	4	4	4	4
C	4	4	4	4	4
D	4	4	4	4	4
E	3	3	3	3	3
F	3	3	3	3	3
G	3	3	3	3	3
H	2	2	2	2	2

---

*Sum of Interest and Maintenance Charges Adjusted to be Displayed in Multiples of 9,5 Column.

Table E.4

Pipe Size Data

Apartment Building Model

54,000 people; 15,000 people/mi^2.

Section	2,2	6,2	9,5	x 2*	x 10*
Secondary Mains					
A,B	4	4	4	4	4
C	4	4	4	4	4
D	3	3	3	3	3
E	4	4	4	4	4
service line	2	2	2	2	2
Mains					
A	5	5	5	5	5
B	14	12	12	12	12
C	8	8	8	8	8
D	10	10	10	10	10
E	10	10	10	10	10
F	12	12	12	12	12
G	14	12	12	12	12
H	18	18	16	16	14

---

*Sum of Interest and Maintenance Charges Adjusted to be Displayed in Multiples of 9,5 Column.

Table E.5

Pipe Size Data

Apartment Building Model

54,000 people; 7500 people/mi^2.

Section	2,2	6,2	9,5	x 2*	x 10*
Secondary Mains					
A,B	3	3	3	3	3
C	3	3	3	3	3
D	2	2	2	2	2
E	3	3	3	3	3
service line	2	2	2	2	2
Mains					
A	4	4	4	4	4
B	10	10	10	10	10
C	5	5	5	5	5
D	8	8	8	8	8
E	8	8	8	8	8
F	10	10	10	10	10
G	10	10	10	10	10
H	14	12	12	12	10

---

*Sum of Interest and Maintenance Charges Adjusted to be Displayed in Multiples of 9,5 Column.

Table E.6

Pipe Size Data

Apartment Building Model.

54,000 people; 3750 people/mi^2.

Section	2,2	6,2	9,5	x 2*	x 10*
Secondary Mains					
A,B	3	3	3	3	3
C	2	2	2	2	2
D	2	2	2	2	2
E	3	3	3	3	3
service line	2	2	2	2	2
Mains					
A	3	3	3	3	3
B	8	8	8	8	8
C	4	4	4	4	4
D	5	5	5	5	5
E	6	6	6	6	6
F	8	8	8	8	8
G	8	8	8	8	8
H	10	10	8	8	8

---

*Sum of Interest and Maintenance Charges Adjusted to be Displayed in Multiples of 9,5 Column.

APPENDIX F

COMPUTER PROGRAM LISTING

```
LEVEL  21.8 ( JUN 74 )                                 OS/360    FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=50,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002               DIMENSION DIA(30),T(20),HRS(20),HEAT(20),C1(30),C2(30),C3(30),
                        1CT(30),PDROP(30),C4(30),CPMB(30)
  ISN 0003               DIMENSION TMAX(20)
  ISN 0004               DIMENSION DSCRP(36)
  ISN 0005               DIMENSION TC(20),ELEC(20),PUMPP(20),PUMPC(20),PIPEC(20)
  ISN 0006                REAL HRS,INT,MAINT
  ISN 0007               COMMON HEAT,NW,HRS,DPDX,PUMCOS,A
  ISN 0008               K=5
  ISN 0009               M=6
  ISN 0010               II=30
  ISN 0011               DO 707 I=1,20
  ISN 0012               PIPEC(I)=0.
  ISN 0013               PUMPC(I)=0.
  ISN 0014               PUMPP(I)=0.
  ISN 0015               ELEC(I)=0.
  ISN 0016           707 TC(I)=0.
                   C     READ IN PIPE SIZES
  ISN 0017               READ (K,70) DIA
  ISN 0018            70  FORMAT (10F8.4)
  ISN 0019               DO 1 I=1,30
  ISN 0020               IF (DIA(I).LE.0.0) GO TO 2
  ISN 0022             1 CONTINUE
  ISN 0023               GO TO 2222
  ISN 0024             2 II=I-1
                   C     II=NUMBER OF PIPE SIZES USED
  ISN 0025          2222 READ (K,69) BUSBAR,ECOST,INT,YRS,MAINT
  ISN 0026            69 FORMAT (3F4.3,F4.0,F4.3)
  ISN 0027               CR=INT*(1.0+INT)**YRS
  ISN 0028               CR=CR/(((1.0+INT)**YRS)-1.0)
                   C     CR=CAPITAL RECOVERY FACTOR
                   C     READ IN WEATHER AND DEMAND DATA
  ISN 0029               READ(K,71) DIVF,TDES
  ISN 0030            71 FORMAT (F5.3,F5.1)
  ISN 0031               READ (K,171) WATHT,SPCHT
  ISN 0032               SPCHT=SPCHT*(62.-TDES)/41.
  ISN 0033           171 FORMAT (F10.0,F10.0)
  ISN 0034               READ (K,72)(T(I),HRS(I),I=1,20)
  ISN 0035            72 FORMAT (16F5.1)
  ISN 0036               DO 3 I=1,20
  ISN 0037               IF (T(I).GE.70.0) GO TO 4
  ISN 0039             3 CONTINUE
  ISN 0040             4 NW=I-1
                   C      NW=NUMBER OF TEMPERATURE INTERVALS GIVEN. READ IN MAX HEAT LOAD AND PIPE
                   C     READ IN RETURN TEMP. AND TNTHALPY.
  ISN 0041               READ (K,75) TMIN
  ISN 0042            75 FORMAT (F10.0)
  ISN 0043               READ (K,76) KK
  ISN 0044            76 FORMAT (I2)
  ISN 0045               READ (K,74) (TMAX(I),I=1,KK)
  ISN 0046            74 FORMAT (8F10.0)
                   C    LENGTH AND TYPE.ITYPE=0,MAIN LINE.  ITYPE=1, SECON DARY MAIN.  ITYPE=2,
                   C     SERVICE LINE.  ITYPE=3, STANDBY LINE.
  ISN 0047            37 READ (K,73) QMAX,FEET,ITYPE,NP,DSCRP
  ISN 0048            73 FORMAT (E8.2,F6.0,I1,I7,36A1)
  ISN 0049               IF (QMAX.EQ.0.) GO TO 9999
                   C     CALCULATE HEAT LOAD DATA.
```

```
ISN 0051          QMAX=QMAX*(62.-TDES)/41.
ISN 0052          IF(ITYPE.NE.2) GO TO 11
ISN 0054          A=1.0
ISN 0055          GO TO 737
ISN 0056       11 A=DIVF
ISN 0057      737 DELTES=62.0-TDES
ISN 0058          ANHEAT=0.0
ISN 0059          DO 5 I=1,NW
ISN 0060          DELT=62.0-T(I)
ISN 0061          IF(DELT.GE.DELTES) GO TO 6
ISN 0063          HEAT(I)=QMAX*(DELT/DELTES)*A+WATHT*QMAX/SPCHT
ISN 0064          ANHEAT=ANHEAT+(HEAT(I)+(A-1.)    *WATHT*QMAX/SPCHT)*HRS(I)/A
ISN 0065          GO TO 5
ISN 0066        6 HEAT(I)=QMAX*A+WATHT*QMAX/SPCHT
ISN 0067          ANHEAT=ANHEAT+(HEAT(I)+(A-1.)    *WATHT*QMAX/SPCHT)*HRS(I)/A
ISN 0068        5 CONTINUE
            C      ANHEAT=ANNUAL HEAT LOAD CARRIED BY PIPE IN BTU
            C     CALCULATE COST ITEMS.  C1=PIPE CAPITAL PLUS MAINTENANCE.  C2=PUMPING POWER
            C     COST.  C3=LOST POWER COST.
ISN 0069          DO 999 JJ=1,KK
ISN 0070          DO 8 I=1,II
ISN 0071          C1(I)=PIPE(DIA(I),TMAX(JJ))*(CR+MAINT)*FEET
ISN 0072          IF (ITYPE.NE.3) GO TO 177
ISN 0074          C2(I)=0.
ISN 0075      177 C2(I)=PUMPEN(TMAX(JJ),TMIN,DIA(I))*ECOST*FEET
ISN 0076          IF (ITYPE.EQ.0) GO TO 277
ISN 0078          C4(I)=0.
ISN 0079          GO TO 377
ISN 0080      277 C4(I)=PUMCOS*(CR+MAINT)*FEET
            C     PUMCOS IS THE TOTAL CAPITAL COST PER FOOT OF PIPE (FOR PUMPING
            C     BOTH WAYS) OF INSTALLED PUMPS.
ISN 0081      377 PDROP(I)=DPDX*FEET/5280.
ISN 0082          IF(ITYPE.NE.0) GO TO 777
ISN 0084          C3(I)=(BUSBAR*ANHEAT/1000000.)*(.1825*TMAX(JJ)-9.279)
ISN 0085          GO TO 888
ISN 0086      777 C3(I)=0.
ISN 0087      888 CT(I)=C1(I)+C2(I)+C3(I)+C4(I)
ISN 0088        8 CPMB(I)=CT(I)/(ANHEAT/1000000.)
            C      CHOOSE MINIMUM COST DIAMETER
ISN 0089          B=CT(1)
ISN 0090          DO 9 I=1,II
ISN 0091          IF (CT(I).GT.B) GO TO 9
ISN 0093          B=CT(I)
ISN 0094          L=I
ISN 0095        9 CONTINUE
ISN 0096      466 DPDX=PDROP(L)*5280./FEET
ISN 0097          IF (DPDX.LE.75..OR.ITYPE.EQ.0) GO TO 553
ISN 0099          L=L+1
ISN 0100          GO TO 466
ISN 0101      663 CONTINUE
ISN 0102          IF (DPDX.LE.150.) GO TO 656
ISN 0104          L=L+1
ISN 0105          GO TO 466
            C     WRITE OUT DESIRED RESULTS.
ISN 0106      666 WRITE (M,62) DSCRP,NP,FEET
ISN 0107       62 FORMAT(1H0,36A1,5XI7,14H OF THEM EACH ,F10.0,11HFEET LONG. )
ISN 0108          WRITE (M,81) ITYPE,ANHEAT,TMAX(JJ),TMIN
ISN [illegible]       81 FORMAT (1H ,5HTYPE ,I1,10X,25HANNUAL HEAT LOAD (BTU) = ,E10.2,10X,
```

```
                 114HSUPPLY TEMP = ,F10.0,10X,14HRETURN TEMP = ,F10.0)
ISN 0110          WRITE (M,89) DIA(L),CT(L),CPMB(L),C1(L),C2(L),C3(L),C4(L),PDROP(L)
ISN 0111       89 FORMAT (1H ,5XF8.3,5XE11.3,5XF5.2,5XE11.3,5XE11.3,5XE11.3,5XE11.3,
                 15XF8.0)
ISN 0112          ANP=NP
ISN 0113          TC(JJ)=TC(JJ)+ANP*CT(L)
ISN 0114          ELEC(JJ)=ELEC(JJ)+C3(L)
ISN 0115          PUMPP(JJ)=PUMPP(JJ)+ANP*C2(L)
ISN 0116          PUMPC(JJ)=PUMPC(JJ)+ANP*C4(L)
ISN 0117          PIPEC(JJ)=PIPEC(JJ)+ANP*C1(L)
ISN 0118      999 CONTINUE
ISN 0119          GO TO 37
ISN 0120     9999 CONTINUE
ISN 0121          WRITE (M,61) (TC(JJ),ELEC(JJ),PUMPP(JJ),PUMPC(JJ),PIPEC(JJ),TMAX(J
                 1J),TMIN, JJ=1,KK)
ISN 0122       61 FORMAT (1H0,11H TOTAL COST ,10X,5(5XE11.3),5XF4.0,5XF4.0)
ISN 0123          WRITE (M,463) INT,MAINT,CR,YRS,TDES ,DIVF
ISN 0124      463 FORMAT (1H0,3HI= ,F8.4 ,5X,7HMAINT= ,F8.4,5X,4HCR= ,F9.5,5X,10HLIFE
                 1TIME= ,F4.0,1X,5HYEARS,5X,13HDESIGN TEMP =,F4.0,5X,6HDIVF= ,F4.2)
ISN 0125          WRITE (M,464) BUSBAR,ECOST
ISN 0126      464 FORMAT (1H0,19HBUSBAR POWER COST =,F8.4,5X,17HPUMP POWER COST =,F8
                 1.4)
ISN 0127          STOP
ISN 0128          END
```

```
LEVEL 21.8 ( JUN 74 )                                    OS/360   FORTRAN H

           COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                              SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002               FUNCTION PIPE(D,T)
  ISN 0003               IF (T.GT.210.) GO TO 10
  ISN 0005               IF (D.LE.6.) GO TO 1
  ISN 0007               IF (D.LE.18.) GO TO 2
  ISN 0009               PIPE=.684*D**1.721
  ISN 0010               RETURN
  ISN 0011             1 PIPE=13.6*D**.407
  ISN 0012               RETURN
  ISN 0013             2 PIPE=3.64*D**1.142
  ISN 0014               RETURN
  ISN 0015            10 IF (T.GT.300.) GO TO 20
  ISN 0017               IF (D.LE.6.) GO TO 11
  ISN 0019               IF (D.LE.18.) GO TO 12
  ISN 0021               PIPE=1.24*D**1.587
  ISN 0022               RETURN
  ISN 0023            11 PIPE=26.8*D**.252
  ISN 0024               RETURN
  ISN 0025            12 PIPE=6.42*D**1.041
  ISN 0026               RETURN
  ISN 0027            20 IF (T.GT.350.) GO TO 30
  ISN 0029               IF (D.LE.6.) GO TO 21
  ISN 0031               IF (D.LE.18.) GO TO  22
  ISN 0033               PIPE=.690*D**1.773
  ISN 0034               RETURN
  ISN 0035            21 PIPE=13.8*D**.5653
  ISN 0036               RETURN
  ISN 0037            22 PIPE=6.15*D**1.016
  ISN 0038               RETURN
  ISN 0039            30 IF (D.LE.6.) GO TO 31
  ISN 0041               IF (D.LE.18.) GO TO 32
  ISN 0043               PIPE=.781*D**1.805
  ISN 0044               RETURN
  ISN 0045            31 PIPE=13.9*D**.5689
  ISN 0046               RETURN
  ISN 0047            32 PIPE=4.48*D**1.201
  ISN 0048               RETURN
  ISN 0049               END
```

```
LEVEL 21.8 ( JUN 74 )                                   OS/360   FORTRAN H

        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=50,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002            FUNCTION PUMPEN(TMAX,TMIN,D)
  ISN 0003            DIMENSION HEAT(20),HRS(20)
  ISN 0004            COMMON HEAT,N ,HRS,DPDX,PUMCOS,A
                C     PROGRAM CALCULATES THE PUMPING ENERGY REQUIRED TO PUMP FLUID THROUGH ONE
                C      FOOT OF SUPPLY PIPE AND ONE FOOT OF RETURN PIPE.  PUMP EFFICIENCY, POWER
                C     COST, AND PIPE LENGTH ARE CONSIDERED IN MAIN PROGRAM.
  ISN 0005            RHO(T)=121.4*T**(-.133)
  ISN 0006            VNU(T)=9.9E-04*T**(-1.069)
  ISN 0007            EPSIL=.00015
  ISN 0008            PTES=2.
  ISN 0009            ENERGY=0.
  ISN 0010             T=TMIN
  ISN 0011            DO 10 J=1,2
  ISN 0012            DO 9 I=1,N
  ISN 0013            FLOW=HEAT(I)/(TMAX-TMIN)
  ISN 0014            FLOW = FLOW/3600.
  ISN 0015            FLOW=FLOW/RHO(T)
  ISN 0016            V=FLOW*(4./3.1416)/(D/12.)**2
  ISN 0017            REYN=V*(D/12.)/VNU(T)
  ISN 0018            Z=D/12.
  ISN 0019            DELP=RHO(T)*FRIC(EPSIL,Z,REYN)*(12./D)
  ISN 0020            DELP=DELP*(V**2)/64.4
  ISN 0021            DENG=DELP*FLOW*HRS(I)*.00135532/A
  ISN 0022          9 ENERGY=ENERGY+DENG
  ISN 0023            DPDX=DELP*5280./144.
  ISN 0024         10 T=TMAX
  ISN 0025            PUMPEN=ENERGY
  ISN 0026            PUMCOS=DPDX*(.00578*FLOW+.00555)
  ISN 0027            RETURN
  ISN 0028            END
```

```
LEVEL 21.8 ( JUN 74 )                                          OS/360   FORTRAN H

         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                                   SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002                FUNCTION FRIC (ROUGH,DIA,REYN)
  ISN 0003                Z(A,B,C)=1./SQRT(C)-0.8686*ALOG(A/(1.+18.7*A/(SQRT(C)*B)))-1.74
  ISN 0004                IF(REYN.EQ.0.) GO TO 15
  ISN 0006                RE=DIA/2./ROUGH
  ISN 0007       30       IF(REYN.LE.2000.) GO TO 10
  ISN 0009                XX=REYN**0.871/455.3
  ISN 0010                IF(RE.GT.XX) GO TO 20
  ISN 0012                FRIC=(1.74+0.8686*ALOG(RE))**(-2)
  ISN 0013                RETURN
  ISN 0014       10       FRIC=64./REYN
  ISN 0015                RETURN
  ISN 0016       20       DELF=0.0375
  ISN 0017                F1=0.005
  ISN 0018                Z1=Z(RE,REYN,F1)
  ISN 0019                IF(Z1.GT.1E-4.OR.Z1.LT.-1E-4) GO TO 60
  ISN 0021                FRIC=F1
  ISN 0022                RETURN
  ISN 0023       60       F2=0.08
  ISN 0024                Z2=Z(RE,REYN,F2)
  ISN 0025                IF(Z2.GT.1E-4.OR.Z2.LT.-1E-4) GO TO 70
  ISN 0027                FRIC=F2
  ISN 0028                RETURN
  ISN 0029       70       IF(Z1.GT.0..AND.Z2.LT.0..OR.Z1.LT.0..AND.Z2.GT.0.) GO TO 80
  ISN 0031                WRITE(3,75)
  ISN 0032       75       FORMAT(54H ERROR...NO ZERO SOLUTION TO FRICTION FACTOR.KILL RUN.) .
  ISN 0033                 GO TO 9999
  ISN 0034       80       F3=F1+DELF
  ISN 0035                Z3=Z(RE,REYN,F3)
  ISN 0036                IF(Z3.GT.1E-5.OR.Z3.LT.-1E-5) GO TO 90
  ISN 0038                FRIC=F3
  ISN 0039                RETURN
  ISN 0040       90       DELF=DELF/2.
  ISN 0041                IF(Z1.GT.0..AND.Z3.GT.0..OR.Z1.LT.0..AND.Z3.LT.0.) GO TO 110
  ISN 0043                F2=F3
  ISN 0044                Z2=Z3
  ISN 0045                GO TO 120
  ISN 0046      110       F1=F3
  ISN 0047                Z1=Z3
  ISN 0048      120       F3=F1+DELF
  ISN 0049                Z3=Z(RE,REYN,F3)
  ISN 0050                IF(Z3.GT.1E-4.OR.Z3.LT.-1E-4) GO TO 90
  ISN 0052                FRIC=F3
  ISN 0053                RETURN
  ISN 0054       15       FRIC=0.
  ISN 0055                RETURN
  ISN 0056      9999      CONTINUE
  ISN 0057                RETURN
  ISN 0058                END
```

APPENDIX G

EFFECTS OF FUEL PRICE ESCALATION ON INITIAL COMPARISONS OF OPTIONS

In Chapter II 1976 natural gas prices and electricity prices were used to compare conventional options (gas furnace, resistance heating, and the electric heat pump) to district heating. The nine per cent interest rate used for capital cost includes the effect of inflation implicitly. For consistency, the fuel prices should also be escalated according to expected inflation rates as well as for real price increases.

An estimate of the long-term inflation rate anticipated by lenders has been obtained by comparing interest rates on long-term loans and bonds during a period of low inflation (1960-63) to 1977 interest rates for the same sectors. This technique yields a long-term inflation rate of about 3.5% (1).

The real prices of natural gas and electricity to the residential sector have been projected by DOE to rise by about 2.8% and 0.2%, respectively, during the time period between 1976 and 1990. To a first approximation, the combined effect of real price increases and inflationary increases can be estimated by adding the two rates of increase. This results in an annual average price increase of 6.3% for natural gas and 3.7% for electricity.

Using the nine per cent interest rate to derive a ratio of levelized annual cost to initial cost and assuming the above trends continue over a 30-year period, the appropriate levelized gas cost is 1.9 times the initial cost, while the levelized electricity cost is 1.4 times the initial cost.

When these costs are used in place of 1976 costs in Table 2.11, the following results are obtained. The gas furnace option energy costs are increased from \$8.18/10^6 Btu to \$13.6/10^6 Btu for the single family house model, and from \$6.56/10^6 Btu to \$12.0/10^6 Btu for the apartment model. The resistance heating and electric heat pump option costs are increased from \$12.8/10^6 Btu and \$9.13/10^6 Btu to \$17.5/10^6 Btu and \$11.5/10^6 Btu, respectively, for the same two models. The net effect is that district heating is now even more attractive than it was before. Further, the heat pump is now favored over the gas furnace because gas prices increase faster than electricity prices.

REFERENCES

1. Luttwak, A. R., staff member, Resource Planning Associates, Inc., private communication, January, 1978.
2. "Federal Energy Administration Energy Audit Procedures," Federal Register, Vol. 42, Number 125, Wednesday, June 29, 1977.

BIOGRAPHICAL NOTE

The author was born in Terre Haute, Indiana on May 21, 1947. Except for a few years in the Phoenix, Arizona area, his childhood was spent in Marshall, Illinois. He developed an early interest in amateur radio and electronics – hobbies he still pursues.

Upon graduating from Marshall High School in 1965, he attended the University of Illinois. In 1969, he received his B. S. degree with highest honors in General Engineering. He was inducted into Tau Beta Pi and Sigma Tau, engineering honor societies, and he also received the G. E. Department's E. S. Fraser Outstanding Student Award. In 1970 he was awarded a three-year AEC Special Fellowship in Nuclear Science and Engineering, and he completed his M. S. in Nuclear Engineering at the University of Illinois.

After admission to the Nuclear Engineering Department of M.I.T. in September 1970, he was involved in an experimental plasma physics project until 1975 when he began this study. In 1976, he was elected as an associate member of Sigma XI, scientific research society. He has accepted employment as a staff member of the Energy Division of Oak Ridge National Laboratory.