URBAN SPACE HEATING
WITH A HEAT PUMP-CONDENSER
TEMPERATURE WATER SYSTEM

by

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Submitted to the Department of Mechanical Engineering on August 9, 1976 in partial fullfillment of the requirements for the Degree of Master of Science.

Abstract

A study is undertaken to determine the economic feasibility of an urban space heating system using electric power plant coolant water as a heat source for residences equipped with water to air heat pumps.

Water networks were developed from which annual costs were obtained, based on a housing distribution analogous to Boston's. It was found that the lowest warm water-heat pump system cost is obtained by using a high power plant coolant water temperature rise, a combination of steel and concrete piping, and a heat pump system augmented by auxiliary heat. Using a gas furnace system as a reference, the gas rate would have to increase by about 1.5 times for the heat pump system to be competitive. However, the heat pump system offers primary energy savings of up to 30%. The cost difference between the two systems becomes smaller when summer cooling is considered in addition to winter heating. For this case, an air to air heat pump system is shown to be less expensive than a water to air system, and is currently competitive with a gas heating-electric cooling system. Finally, a rough study of a high temperature water system shows that this system can be cost competitive with a gas heating system if gas rates were to increase only 1.3 times.

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CHAPTER 1

Introduction

1.1 Background

Since the Arab oil embargo of 1973, there has been increased awareness of the need to practice energy conservation and to develop alternate sources of energy. Alternate sources range from fast breeder reactors to windmill electric generators. On the conservation side, examples are better home insulation and more efficient automobiles. Additionally, there is a need to further develop energy end use methods and equipments.

Examination of energy statistics show that by 1980, the projected total energy needs of residential and commercial consumers is 702,000 MW(e), of which 363,000 MW or 52% is for space heating. (1)* By considering another statistic, the U.S. expects to generate 3×10^5 MW(e) by 1980, but will use 8×10^5 MW of energy to do so. (1) The remaining 5×10^5 MW is dumped into the biosphere as waste energy. The rejection of such a large percentage of energy as waste is a characteristic of electric generating power cycles. Under ideal theoretical conditions, which one can not hope to achieve, the maximum efficiency permitted by

---

* Numbers in parentheses indicate references.

thermodynamics is around 60% for the temperature range of power plant operation (1000° F - 100° F). Hence a large quantity of energy is wasted even under ideal circumstances. By noting that while a large amount of energy is being wasted, a somewhat smaller amount is being generated for space heating, one could conclude that a great deal of conservation is possible by merging the apparent waste with the heating needs.

The waste heat from electric power plants are rejected from condensing steam at about 1 psia and 100° F. A frequently used heat sink for waste heat is river water, which enters at about 55°F and exits at 75°F. Because the water temperature is only 75°F, it is difficult to extract heat from the water, and therefore space heating uses are somewhat limited. Alternate suggested uses include using the warm water for aquaculture, green houses, and sewage treatment. (2) However, the problem of providing for space heating is not alleviated.

1.2 Total Energy Systems

In contrast to individual residential space heating, systems are available in which home heating originates from central sources. Two common forms of central energy systems are district steam and high temperature hot water systems. Both systems involve the piping of high temperature heat to the consumer from central furnaces. District steam heating is relatively common and exists in several large American cities as well as numerous sites in Europe. (3) High temperature hot water systems are less common but may become important in the future. (4,5) Both systems, however, are usually pure thermal systems using valuable fuel which might otherwise generate electricity. Some systems generate small quantities of electricity.

An important concept that has become prominent is the "total energy system." The object of such a system is to plan a power system from a perspective such that total energy usage is maximized. Frequently the embodiment of this idea is in the form of a "dual purpose" or "heat-electric" plant. In essence, higher quality heat, in the form of hot water at about 300° F or steam at about 500 psi, is rejected for heating purposes. Thus for a given amount of fuel, both electricity and heat are generated. Because a higher quality heat is rejected, the electric generating efficiency is necessarily reduced but the overall energy usage of the primary fuel is improved. Miller, et al (1) have examined the potential of such a system by modeling a reference city of 400,000 people supplied with electric and thermal energy in the form of high temperature water from a nuclear reactor. Their conclusion is that such a system is indeed feasible and economical. In Ayorinde's Underground Transmission of Heat (6), heat-electric plants save up to 31% more fuel than single-purpose electric plants.

Another approach to the "total energy system" is to use heat pumps in conjunction with piped warm water from the power plant as a heat source. This is a potential solution to the problem of using warm water for space heating. The heat pump can transfer heat from a low temperature region to a high temperature region, thus alleviating any necessity to degrade electrical generation efficiency to make the rejected heat useful. Such a system promises better energy usage, but it is not known whether it is economically advantageous. A schematic of such a hypothethical system is shown in Figure 1-1. The power plant burns primary fuel, which by use of a turbine generates electricity. The waste heat is rejected into a closed water network. Pumps will circulate the warm water to a city where the residents are equipped with heat pumps. During the heating season, heat is extracted from the water network at each consumer. The network is designed such that the water temperature drop as seen by the power plant is equivalent to conventional cooling methods (river water or cooling towers), so that during warm weather when space heating is not needed, the plant can switch over to those modes of heat rejection (Figure 1-1). This design allows minimal changes for the plant coolant system. On a less ambitious scale, the working of a small system using pond water as both a sink and a source for an apartment building is discussed in (10) and a heat pump solar system is investigated in (11).

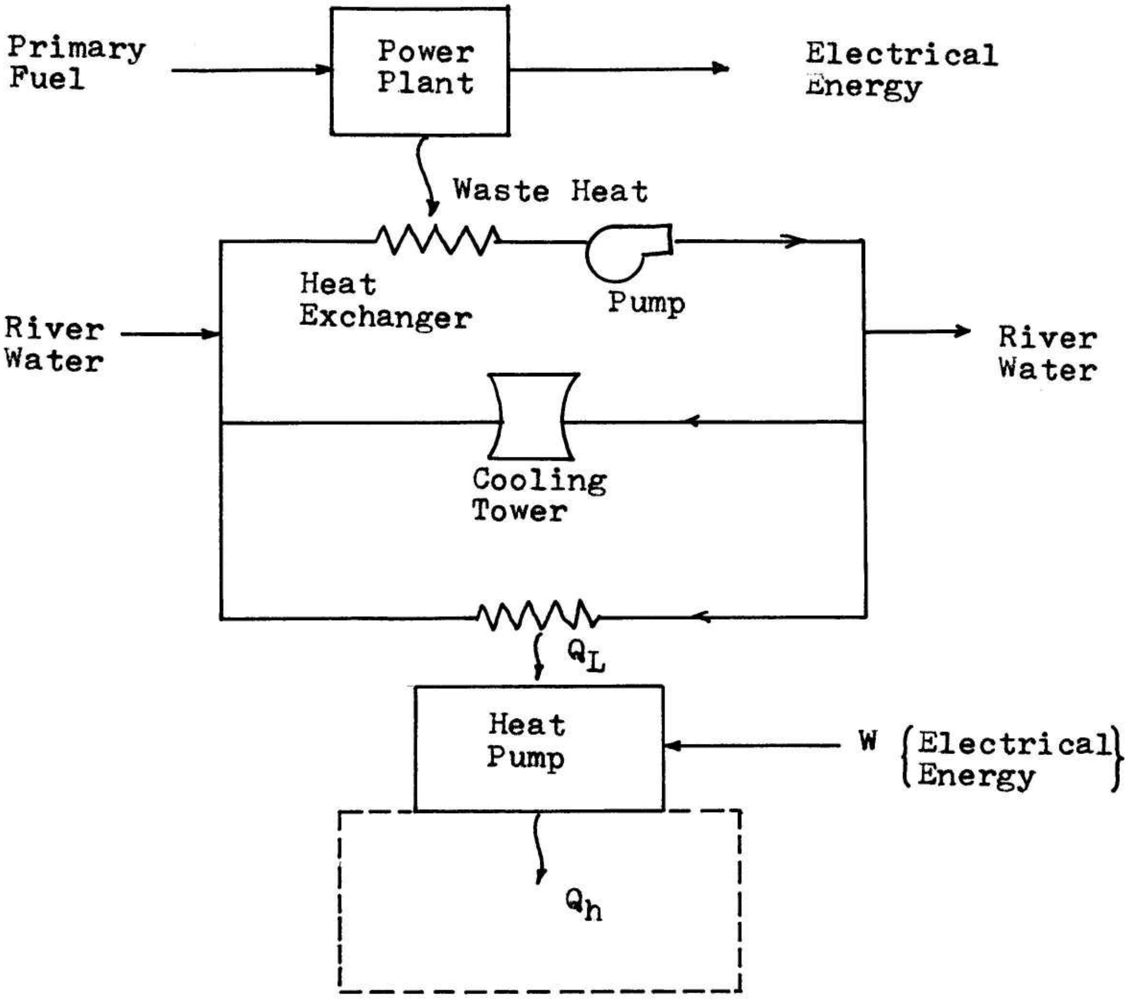


Figure 1-1

Schematic of Total Energy System with Power Plant and Heat Pumps

1.3 Heat Pumps

A heat pump is a reversed power cycle. Whereas a conventional power cycle uses a flow of heat (high to low) to produce work, a heat pump uses work to cause heat flow (low to high). A schematic of a heat pump system using a vapor-compression cycle is shown in Figure 1-2. By the law of energy conservation:

$$Q_h = W + Q_L \qquad (1.1)$$

where Q_h = heat flow to high temperature region
Q_L = heat flow from low temperature region
W = external work to the heat pump

The low temperature heat (Q_L) is augmented by work leading to the situation where the useful heat (Q_h) is larger than the work put in. A heat pump's performance is characterized by its coefficient of performance (COP) defined as:

$$COP = Q_h / W \qquad (1.2)$$

The COP or "efficiency" of a heat pump is greater than 1.0 and typically between 2.0 and 3.0. One can see the advantage of the heat pump's ability to transform energy from a low temperature heat source to a usable high temperature heat source with a small work input.

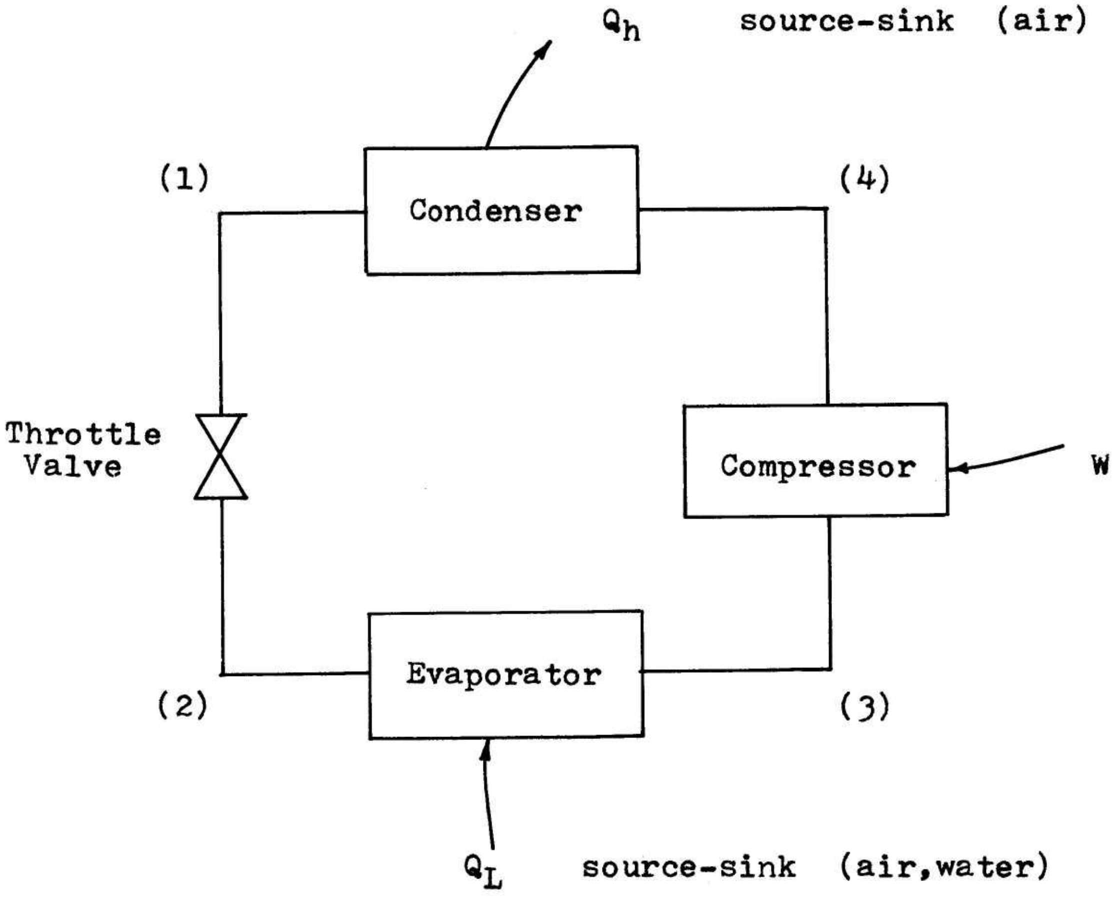


Figure 1-2a

Heat Pump Schematic

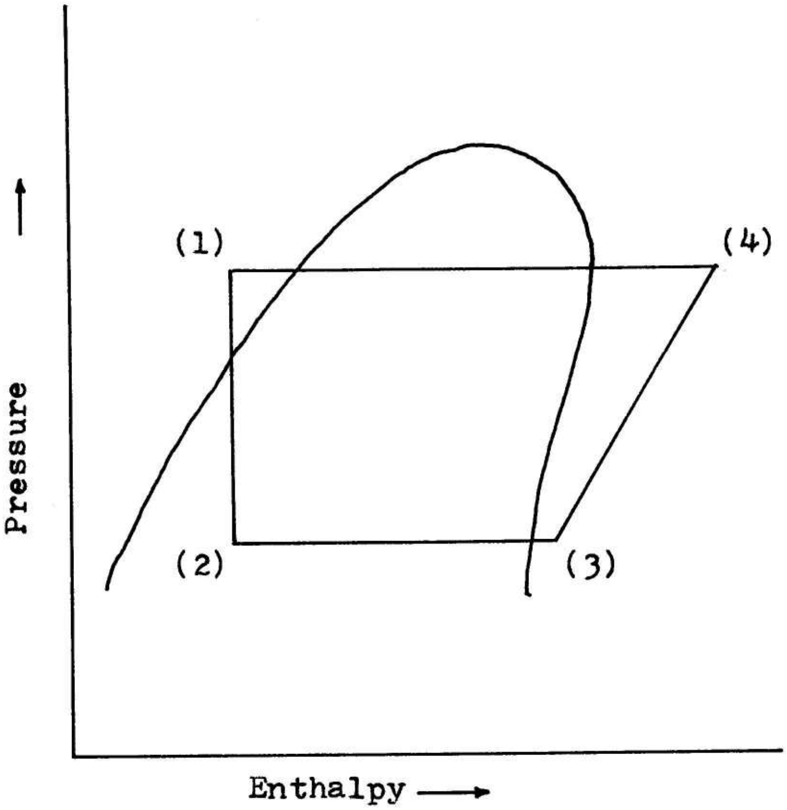


Figure 1-2b

Heat Pump Vapor Compression Cycle

Heat pumps are not new but commercialization has been somewhat limited due to high initial cost, although this high cost may be becoming acceptable due to rising fuel costs. The predominate type of heat pump is air to air, which uses ambient air as a low temperature source and transfers heat to the interior of a building. Heat pumps also serve as air conditioners during hot weather. The heating capacity and COP of a heat pump go down with source temperature (Figure 1-3) so that using winter air as a source, the air/air heat pump is least effective when needed the most. Hence in the colder regions, the annual average COP of a heat pump is lower than an identical pump in a warmer region. The effect of ambient air temperature can be alleviated by using a water/air heat pump which uses water as a heat source and a sink. The temperature of waste water from a power plant is relatively high compared to ambient air, and in conjunction with the stability of the source, the water/air heat pump enjoys effective operation the year round. Since the capacity is also greater at the higher temperature, a smaller water/air heat pump may be used relative to an air/air unit for the same load.

1.4 Objectives and Methods

The basic objective of this study is to undertake a preliminary study of the economic feasibility of a resi-

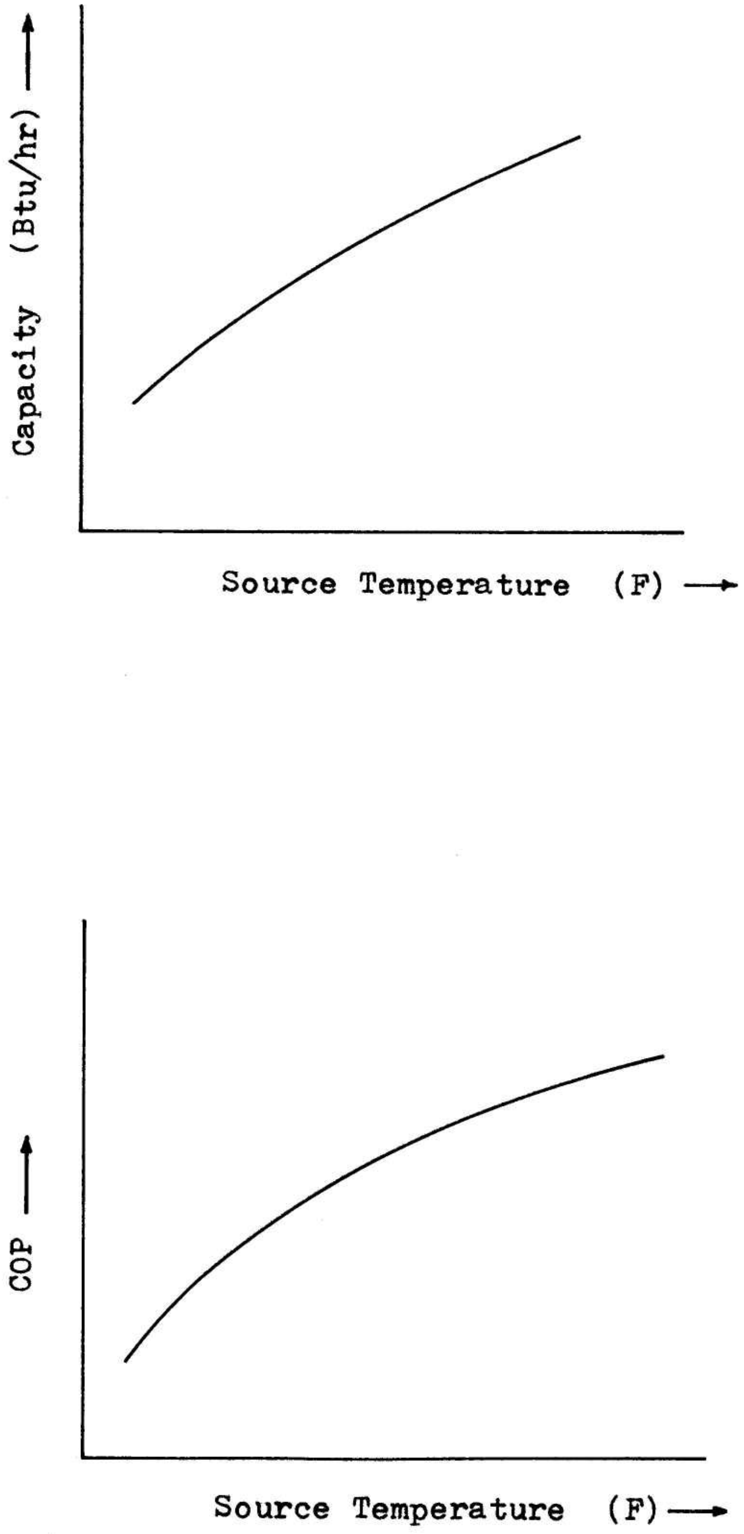


Figure 1-3

Typical Heat Pump Heating Characteristics dential space heating system for a city which uses power plant waste heat in conjunction with present day water/air heat pumps. The major costs of such a system consist of the piping network and the heat pumps. Power plant modification is minimal as noted in Section 1.2, and therefore this cost is neglected. For the network cost component, piping layouts will be modeled for various housing types and unit densities. An existing city will then be used as a weather and a residential layout reference from which a rough cost estimate for installing a piping network for that configuration may be made from the models. Current heat pump costs will be used and performance will be based on present technology. Total annual heating costs of this system will then be compared to other space heating modes. Finally, an energy usage comparison will be made to determine relative merits from that perspective.

This work is a preliminary study undertaken to determine the feasibility of the proposed heat pump-condenser temperature water system concept. Only design details having first order effects on the system cost and performance will be dealt with. This preliminary study will point out the major factors effecting feasibility.

CHAPTER 2

System Model

This chapter is a description of the model for the warm water-heat pump space heating system. A reference city is initially introduced. Next, model residences are discussed and thermal loads determined. Residential loads are then expressed in terms of water flow rates. Flow rate distribution is then translated into a load map. Finally, piping network layouts are discussed, followed by the method used for determining costs.

2.1 Reference City

Rather than assuming an arbitrary housing density and distribution for piping network modeling, a reference city is used so that the residential layout is realistic. Boston is used as the reference city because much of the cost information obtained would be from the Boston metropolitan area. It is emphasized that this study's objective is to determine roughly whether a low temperature water system coupled to a water/air heat pump system is economically feasible. Hence, the important questions to be answered are:

1. Is the system economically feasible?
2. What are the major controlling cost parameters?

3. What are the energy savings?

The selection of Boston is arbitrary.

The 1970 U.S. census survey (29) was used as a basis for modeling Boston's population and housing distribution. The tract as divided by the Census Bureau is shown in Figure 2-1. Each rectangular subdivision is 7.08 mi x 5.05 mi, which for the purpose of this study is estimated to be 36 square miles each. The smaller subdivisions are estimated at 9 square miles each. Residential areas for tracts 67 and 68 are reduced to account for the areas covered by water. Compiling the data in the tract record, the distribution of residential housing and population is summarized in Table 2-1. A "unit" is defined as rooming space for a group of people living together, whether it is a family or otherwise. The tract record provides housing data in the form of total units, one-unit structures and structures of 10 or more units. For this study, the residences are arbitrarily divided into single, four and twelve unit structures. The distribution breakdown is thus not an exact representation of actual buildings. The "three building types only" approximation is necessary to keep the study at a manageable level, and yet still have some relevance. Commercial buildings are not included and are not within the scope of this study. It is noted that each unit averages 3 occupants.

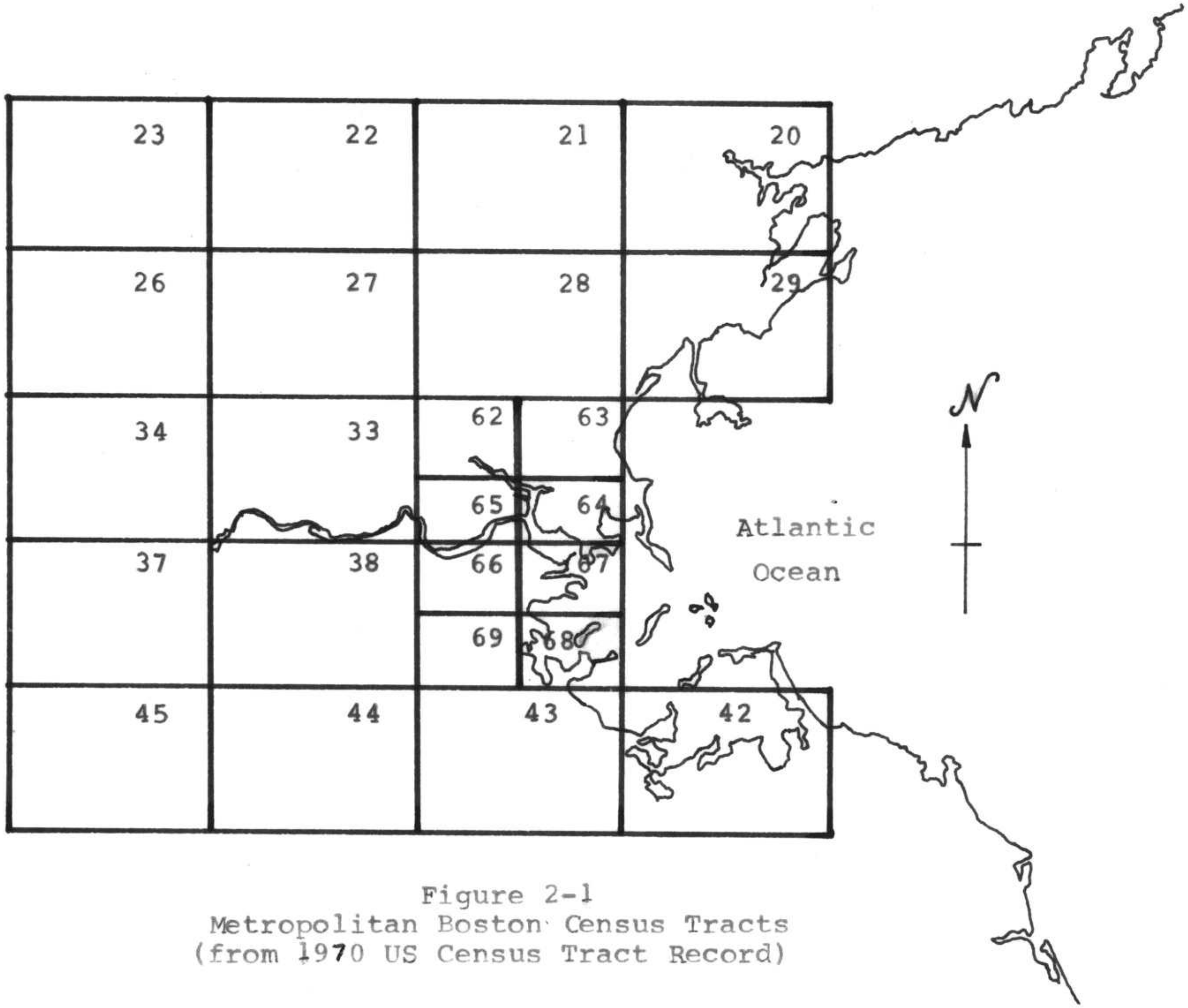


Figure 2-1
Metropolitan Boston Census Tracts
(from 1970 US Census Tract Record)

Table 2-1

BOSTON METROPOLITAN DENSITY AND HOUSING DISTRIBUTION

Tract #	Area (mi^2)	Population Density	Housing Unit Density	% Single Units	% 4 Unit Apartments	% 12 Unit Apartments
20	36	3238	1068	49.8	43.5	6.7
21	36	1714	482	82.5	17.1	0.4
22	36	1289	334	86.0	12.6	1.4
26	36	743	197	67.7	32.0	0.3
27	36	2510	795	71.0	24.4	4.6
28	36	3789	1154	61.1	30.9	8.0
29	36	3415	1217	43.1	46.5	10.5
33	36	7079	2331	33.8	55.8	10.5
34	36	414	125	84.5	0.0	15.5
37	36	2070	576	86.4	13.5	0.1
38	36	6080	2088	39.5	40.9	19.6
42	36	1865	541	74.1	22.9	3.0
43	36	4765	1554	43.8	47.6	8.6
44	36	3079	925	62.7	32.8	4.5
45	36	538	154	83.4	16.6	0.0
48	36	413	99	86.8	12.2	1.0
49	36	1514	436	68.6	24.1	7.3
50	36	1453	393	82.5	12.5	5.0

Table 2-1 (continue)

Tract #	Area (mi^2)	Population Density	Housing Unit Density	% Single Units	% 4 Unit Apartments	% 12 Unit Apartments
51	36	1216	350	74.0	15.5	10.5
62	9	11157	3870	21.8	71.5	6.7
63	9	9325	3175	29.3	66.0	4.7
64	9	6752	2368	11.3	82.8	5.9
65	9	16459	6357	9.4	70.2	20.5
66	9	17941	7584	6.3	51.3	42.5
67	4.5	7994	2944	13.5	70.9	15.7
68	2.25	10096	3080	26.8	50.7	22.5
69	9	19122	6251	10.0	80.1	9.9

2.2 Housing Approximation and Thermal Load

The study will deal with 3 basic types of residential buildings:

1. Single unit homes
2. Four unit apartments
3. Twelve unit apartments

A unit is previously defined in Section 2.1.

Based on census data, it is assumed that an average of 3 persons occupy each unit and that each person averages 5000, 4200, 3600 ft^3 of heated rooming space for the single, four, and twelve unit structures respectively. A thermal load of 1200 Btu/dd kft^3 was used for the house and a load of 1185 Btu/dd kft^3 was used for each of the apartment types. A degree-day (dd) is defined as the difference between 65°F and the average ambient temperature for a given day. Negative degree days are meaningless. Both loads are within the range of values listed in (3).

The design dry bulb temperature for a Boston winter is 0°F or equivalently 65 dd per day. (3) The peak load for each building type is summarized in Table 2-2.

From the <u>District Heating Handbook</u> (3), Boston's heating season averaged over 48 seasons is shown in Table 2-3. With the 65 dd design, the annual load factor (actual/design) is 0.25.

Unit Buildings	Volume ($K\ ft^3$)	Specific Load $\frac{Btu}{dd\ K\ ft^3}$	Degree Day Load (Btu/dd)	Peak Load (Btu/hr)
1	15	1200	1.8×10^4	4.88×10^4
4	50.4	1185	5.97×10^4	1.62×10^5
12	129.6	1185	1.54×10^5	4.16×10^5

Table 2-2

Residential Heat Loads

	July	Aug	Sept	Oct	Nov	Dec
Degree Days	7	15	98	338	647	1008

	Jan	Feb	Mar	April	May	June	Total
Degree Days	1108	1025	841	538	245	66	5936

Table 2-3

Boston Heating Season

2.3 Thermal Loss Analysis

Before a network supplying heat to each residence can be determined, it is necessary to determine the expected temperature of the heat source at the consumer. The basic heat loss per foot is:

$$q = \frac{T_w - T_a}{R_i + R_s} \tag{2.1}$$

where T_w = water temperature (°F)

T_a = ambient temperature (°F)

R_i = thermal resistance of the insulation $\left(\frac{\text{hr ft °F}}{\text{btu}}\right)$

R_s = thermal resistance of the soil $\left(\frac{\text{hr ft °F}}{\text{btu}}\right)$

Details of the buried pipe line configuration is discussed in Section 3.1. For the purpose of this thermal analysis, a simple geometry of concentric cylinders is used to approximate the system. See Figure 2-2.

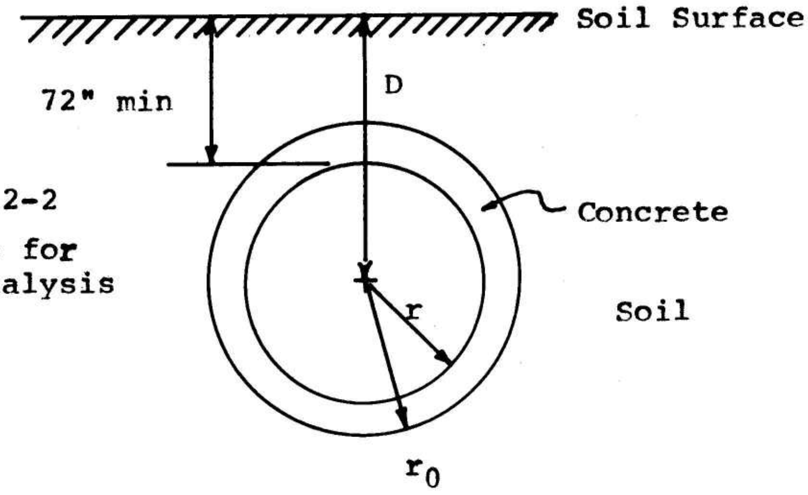


Figure 2-2
Buried Pipe for Thermal Analysis

As in utility water piping, a minimum of 72" cover from pipe to soil surface is required to keep the pipe below the frost line and also to avoid interference with other utility cables and lines. (4,31)

The send out temperature for the water will not exceed 100°F since that is generally the temperature limit of present day heat pumps. As such, this water system is classified as a low temperature water system, although "warm water" is used synonymously throughout this text. (7) Because the temperature is low, heat loss is expected to be minimal, and only a sheath of insulating concrete is used for analysis as opposed to separate insulation followed by total encasement in concrete. This arrangement is in fact common in even in high temperature water systems where temperatures reach 300°F. (4) The insulation consists of 1 part portland cement and 4 parts vermiculite, and the thermal conductivity is 0.066 Btu/hr ft°F. (3) Because of the cylindrical geometry:

$$R_i = R_{concrete} = \frac{\ln(r_o/r)}{2\pi k_c} \qquad (2.2)$$

The conductivity of soil varies from a low of 0.33 Btu/hr ft°F for healy clay (4% moisture) to a high of 1.83 Btu/hr ft°F for crushed quartz (4% moisture) according to <u>District Heating Handbook</u> tables. (3) The Louden equation (30) for soil resistance is:

$$R_s = \frac{\ln (D/r_o)(1+\sqrt{1-(r_o/D)^2})}{2\,k_s} \tag{2.3}$$

where k_s = soil conductivity

Some values of soil thermal resistance are tabulated in Table 2-4. Total thermal resistance of the underground piping is shown in Figure 2-3.

The heat loss from a section of pipe, length dx, due to heat transfer to the soil is:

$$dq = \frac{T_1 - T_0}{R}\,dx \tag{2.4}$$

where q = Btu/hr

T_1 = water temperature (°F)

T_0 = soil surface temperature (°F)

R = total thermal resistance (hr ft°F/Btu)

An energy balance of the entering and exiting water across length dx is

$$dq = \dot{m}\;C_p\;dT \tag{2.5}$$

where $\dot{m}$ = mass flow (lb_m/hr)

C_p = specific heat (Btu/lb_m °F)

By energy conservation:

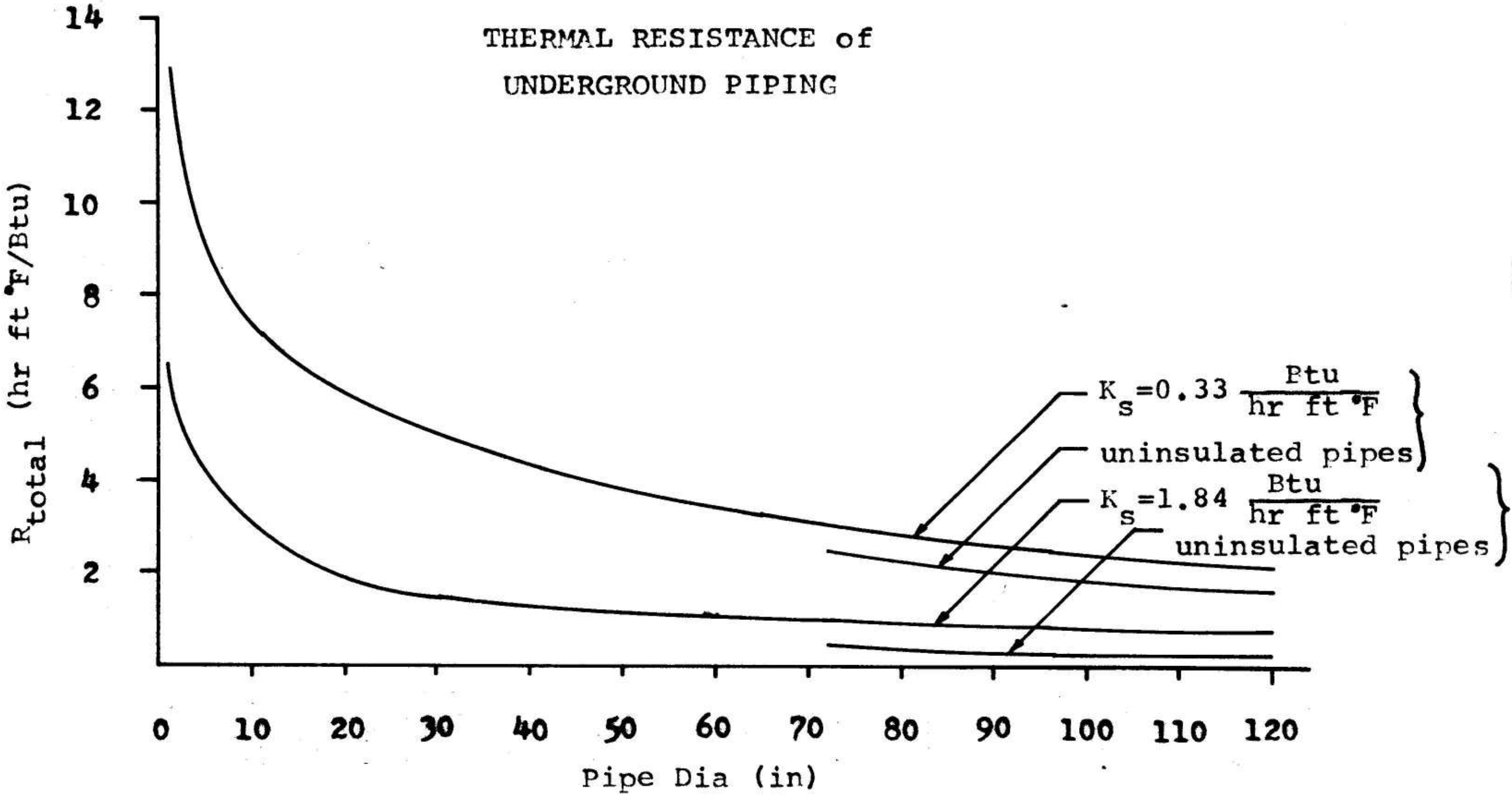
Pipe Dia (in)	r (in)	r_0-r (in)	D (in)	R_{total} $\frac{hr\ ft\,°F}{Btu}$	
				high	low
1	0.66	5	72	12.87	6.56
6	3.31	5	75	8.87	3.41
12	6.38	6	78	7.14	2.59
24	12	6	84	5.59	1.81
36	18	7	90	4.60	1.47
48	24	8	96	3.92	1.27
72	36	9	108	3.07	0.99
96	48	11	120	2.51	0.86
120	60	12	132	2.13	0.74

Table 2-4

Soil Resistances

Figure 2-3

THERMAL RESISTANCE of UNDERGROUND PIPING



$$-\dot{m}\, c_p\, dT_1 = \frac{T_1 - T_o}{R}\, dx \qquad (2.6)$$

Integrating with $x = 0$ at $T = T_{in}$ (source temperature):

$$T_x = (T_{in} - T_o)\exp\left(\frac{-x}{\dot{m} C_p R}\right) + T_o \qquad (2.7)$$

or

$$T_x = (T_{in} - T_o)\exp\left(\frac{-x}{497\, G\, C_p R}\right) + T_o \qquad (2.8)$$

where G = pgm

In a preliminary analysis (see Appendix A), it was determined that the water temperature from the source (power plant) to the furthest hypothetical user is at worse 1.2°F and only 0.4°F for the low value of soil conductivity. The analysis assumes a soil surface temperature of 10°F and a source temperature of 100°F. Solutions of a similar flow path, but with bare pipes, show a high temperature drop of approximately 10°F and a low of 2°F. In conclusion, it will be assumed that the source temperature at the consumer is less than at the plant outlet by 1°F.

2.4 Water Temperature Drop at Consumers

Generally, coolant water enters a power plant condenser at 55°F and exits at 75°F with the steam side condensing temperature at about 100°F. As discussed in Section 2.3, the expected temperature at the furthest user is about 1°F less than the plant exit temperature. In order to represent residential thermal load in terms of flow rates, heat pump performances must be considered. See Section 3.4 on heat pumps. Using 74°F as the initial temperature at the consumer for a plant coolant water ΔT = 20°F system, a single unit home (49,000 Btu/hr peak load) is sized with a series 52 heat pump at 7 gpm; two single unit homes can be placed in series with the exit water temperature at the second consumer at 55.9°F. The peak load for a four unit home (162,000 Btu/hr), on the other hand, can be met by a single series 200 heat pump rated at 12 gpm. For a twelve unit structure, it is necessary to use two series 240 heat pumps to supply the peak load of 416,000 Btu/hr. See Table 2-5.

Exit temperature of the power plant coolant water can be increased to 95°F by either steam extraction from a high pressure turbine stage or by back pressuring (condensing the steam at a higher pressure and temperature). A ΔT of 40°F is desirable, since a lower flow rate would be required, and hence less costly pipe networks and water pumping power would be needed. In addition, the maximum capability of the water/air heat pumps would be utilized. For a ΔT = 40°F system, four single unit homes or two four unit apartments can be placed in series. The twelve unit apartment still requires two heat pumps, although the flow rate is reduced. See Table 2-6.

Table 2-5a

2 Single Unit Homes in Series

Series 52
7 gpm

T_{in} (°F)	COP	T_w (°F)
74	2.84	9.1
64.9	2.79	9.0
55.9		

Table 2-5b

Four Unit Home

Series 200
12 gpm

T_{in} (°F)	COP	T_w (°F)
74	3.17	18.6
55.4		

Table 2-5c

Twelve Unit Home

2 Series 240
30 gpm

T_{in} (°F)	COP	T_w (°F)
74	3.22	9.6
64.4	3.08	9.4
55		

Table 2-5

WATER TEMPERATURE DROP at CONSUMER
$\Delta T = 20°$ F SYSTEM

Table 2-6

WATER TEMPERATURE DROP at CONSUMER
$\Delta T=40°F$ SYSTEM

Table 2-6a

4 Single Homes in Series

7 gpm

T_{in} (°F)	HP Series	COP	T_w (°F)
94	42	3.32	9.8
84.2	42	3.14	9.6
74.6	52	2.84	9.1
65.4	52	2.79	9.0
56.4			

Table 2-6b

Four Unit Home

Series 200
12 gpm

T_{in} (°F)	COP	T_w (°F)
94	3.33	19
75	3.18	18.6
56.4		

Table 2-6c

Twelve Unit Home

Series 240
15 gpm

T_{in} (°F)	COP	T_w (°F)
94	3.47	19.9
74.1	3.22	19.2
54.9		

2.5 Generalized Pipe Network Cost as a Function of Housing Density

To approximate a piping network cost as a function of housing density and housing type distribution, the following method is adopted:

1. Draw pipe networks for a square mile area, assuming various housing densities with the same housing structure spread uniformly throughout the entire area. Three structural types, single unit, four unit apartments, and twelve unit apartments, are used.

2. Given the peak thermal load of each of the three types of structures, and the design conditions (ambient temperature, water temperature, and heat pump performance), a load map, consisting of water flow requirements, can be drawn for each structural type. The flow requirements are proportional to the thermal load, when the overall water temperature drop is specified.

3. For a given building type, the cost for various networks corresponding to different housing densities can be calculated so as to obtain a functional relationship between cost and housing density for each of the three types of building structures.

4. From the census tract record, a city is broken down into subdivisions, each defined by the area, housing density, and distribution of housing types. Hence,

for any housing density, three network costs can be interpolated from the respective cost-density curves for each of the housing types. The total cost for a network with a given distribution is then approximated by multiplying the respective costs by the percentage ratios of the total housing units for each of the three housing types and then summing the components.

2.6 Load Maps

Section 2.4 described the water temperature drop at the consumer and also specified the water flow rates required. These flow requirements represent the housing unit's thermal load. The load map, in essence, consists of nodes defined as sinks for water flow. The connection of these nodes to sources would result in a network from which cost and pumping power can be calculated. The topic of determining a network configuration is treated in Section 2.7.

2.7 Water Distribution Network Layout

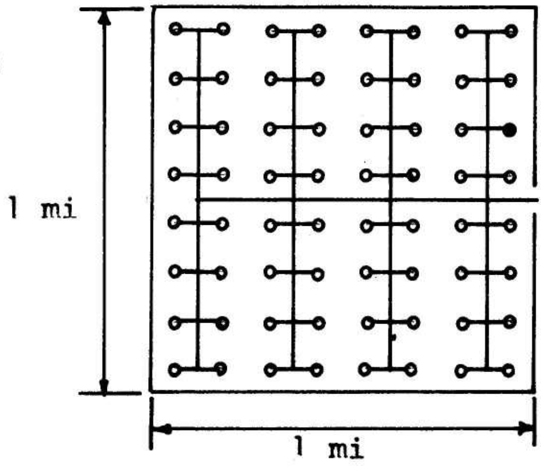
Public water utility networks were initially studied as a guide for determining the warm water network for this system. Utility water networks are of three general types; circle/belt, gridiron, and tree. Networks usually are combinations of these types, but the gridiron network is preferred. The advantages are the elimination of deadends, flow to a node from different direction, and easy maintenance. (23, 24, 25) Its drawback is its expense. Branch networks, on the other hand, are cheaper but require periodic flushing, and the water may develop taste and odor. Comparison of the requirements for utility networks to warm water circulation networks shows that the major objection to a branch network is that interruption in the large mains would disrupt service to a large number of customers. A gridiron network, on the other hand, is too expensive. One of the gridiron's design functions is to have the standby capability to supply 600 gpm at fire hydrants, whereas maximum required flow per customer for the heating network is about 30 gpm. A compromise is thus desirable to establish some degree of multiple flow paths for reliability, and yet keep the cost down.

A study was undertaken to determine a reasonable design for the warm water circulation system. The goal of the study was to obtain some general guidelines for a network layout. Five designs were considered and are shown schematically in Figure 2-4. Each line in the network represents a feed and a return line. The study used a reference square mile of 8000 housing units of twelve unit apartments. Cost estimates were based on a preliminary optimal pipe sizing study, which includes the cost of feed and return lines. While the cost figures are necessarily crude, a general comparison can be made. It was found that Design I is the least expensive. The following cost ratios, based on

Figure 2-4a

Square Mile Network Layout Designs

Design 1

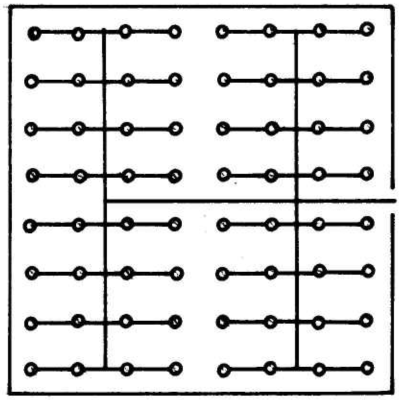


o—o Each circle is a load node to a residential block.

--- Loop Closure

Note: Each line represents feed and return piping

Design 2



Design 3

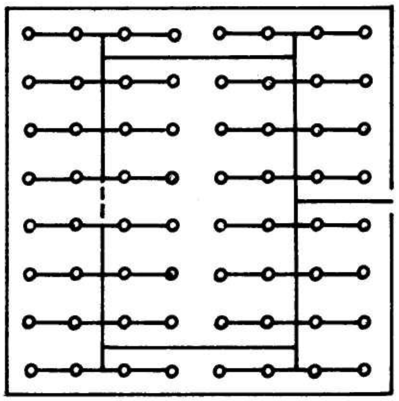
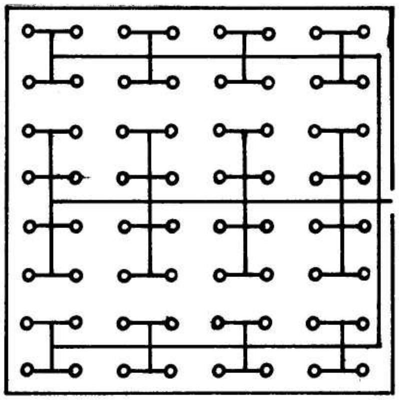
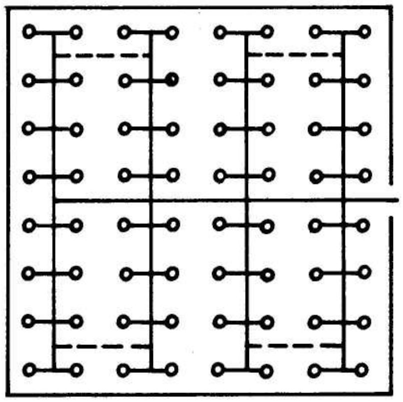


Figure 2-4b
Square Mile Network Layout Designs

Design 4



Design 5



Design I, are obtained (Table 2-7).

Designs I and II are both tree designs, with Design I having finer branching (each block getting a separate line). Design III can be visualized as a two-branch tree network with the end branches connected to form a loop. The two long horizontal lines contributed significantly to the high cost of this design. Design IV is basically a tree with 3 branches. This design also suffers from long pipelines carrying large flows. Design V is the same as Design I but with 4 loops obtained by connecting the 8 branch ends.

Overall conclusions of this study can be summarized in some general rules for network design.

1. The design should involve as fine a tree network as possible.

2. If looping is desired, branches should be formed so as to be as fine as possible and still allow closing of loops with relatively short pipe sections.

3. Avoid routing long lines without flow takeoffs.

Design I is not suitable as a network design for the warm water distribution network, because maintenance can be a problem. Large city sections can be deprived of services if certain portions of the tree are damaged. Design V is selected as a reasonable design. It is believed that Design V provides the flow redundancy likely to be considered

Table 2-7

Square Mile
Network Design:
Cost Comparisons

Design	Cost %
I	100
II	108
III	114
IV	117
V	105

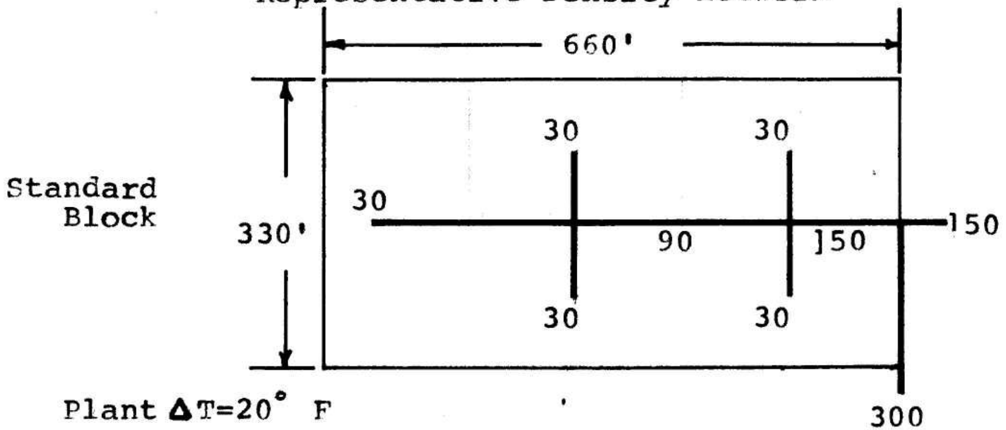
acceptable. With only minor modifications at the pump station, it is possible to circulate water within the network by channeling exit water back to the inlet. A 36 square mile network with the above design for 8000 units per square mile and for twelve unit apartments has the capacity to supply peak heating needs for about half an hour without heat input.

2.8 Density Networks

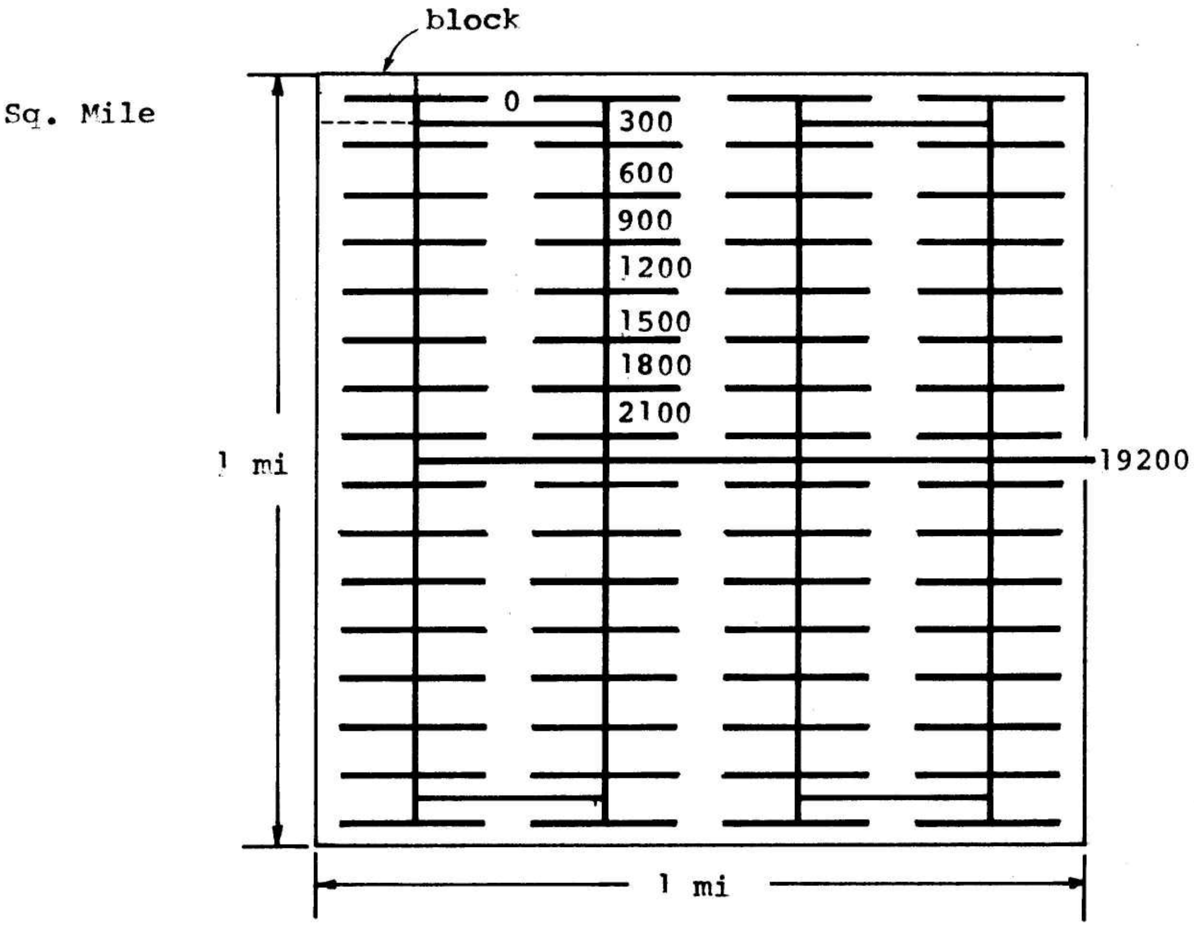
Branch networks with looping as described in Section 2.7 are used to model each of the density networks. Densities (in units per square mile) used are 8000, 6000, 4000, 2000, and 1000. This range was chosen by inspecting the density distribution of the Boston metropolitan area. With two reference plant coolant water ΔT's (20 and 40) and three housing types (single unit homes, four unit apartments, and twelve unit apartments), the total number of networks to be modeled is thirty.

The model consists of standard blocks, 660 ft by 330 ft, which make up a square mile network. The square mile network in turn makes up a 36 square mile network. The latter network was included for convenience. With the exception of the downtown areas, each census tract for the Boston metropolitan area is about 36 square miles. Illustrated in Figure 2-5 is the network for the case of plant $\Delta T = 20^\circ F$, twelve unit apartments, and 8000 units per square mile. Analogous to district heating network design procedures,

Figure 2-5a
Representative Density Network

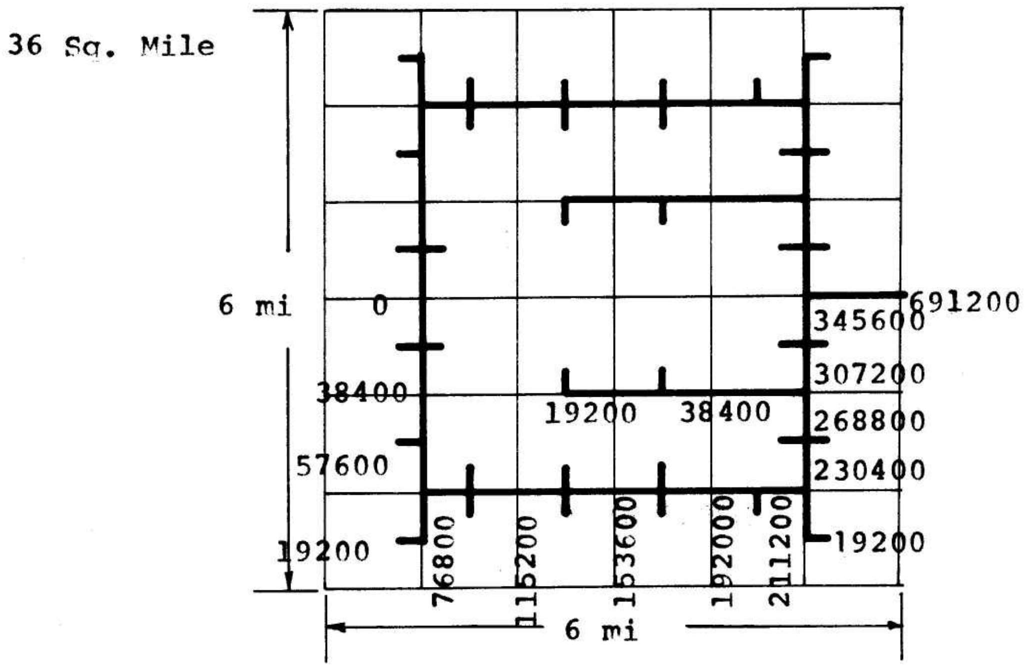


Plant $\Delta T=20^\circ$ F
Twelve Unit Apartments
8000 Units/mi^2
128 Blocks/mi^2



*Note: numbers in network refers to water flowrates(gpm)

Figure 2-5b
Representative Density Network



branch networks (either 1 or 36 square miles) are connected with looping added subsequently. (3) The network is pressure balanced such that under normal circumstances, flow through the loop pipe segments is negligible. Pressure balancing is further discussed in Section 2-10. Diagrams of each network are included in Appendix B.

2.9 Pipe Sizing

Because of the large flow rates involved, it is important to obtain an optimal balance between the cost of the pipe network and the cost of pumping the water. Annual costs are used for comparison. For a given water flow rate, a characteristic annual cost curve as seen in Figure 2-6 can be obtained. The optimum pipe diameter is the diameter corresponding to the minimum cost point. Hence for a given set of cost conditions and flow rate, there exists a best pipe size resulting in lowest cost. (For details on the cost of piping, refer to Section 3.1.)

The pressure drop per length of pipe section is:

$$\frac{\Delta P}{L} = \frac{8 f Q^2}{\pi^2 g D^5} \qquad (2.9)$$

where f = friction factor

L = length

Q = flow rate

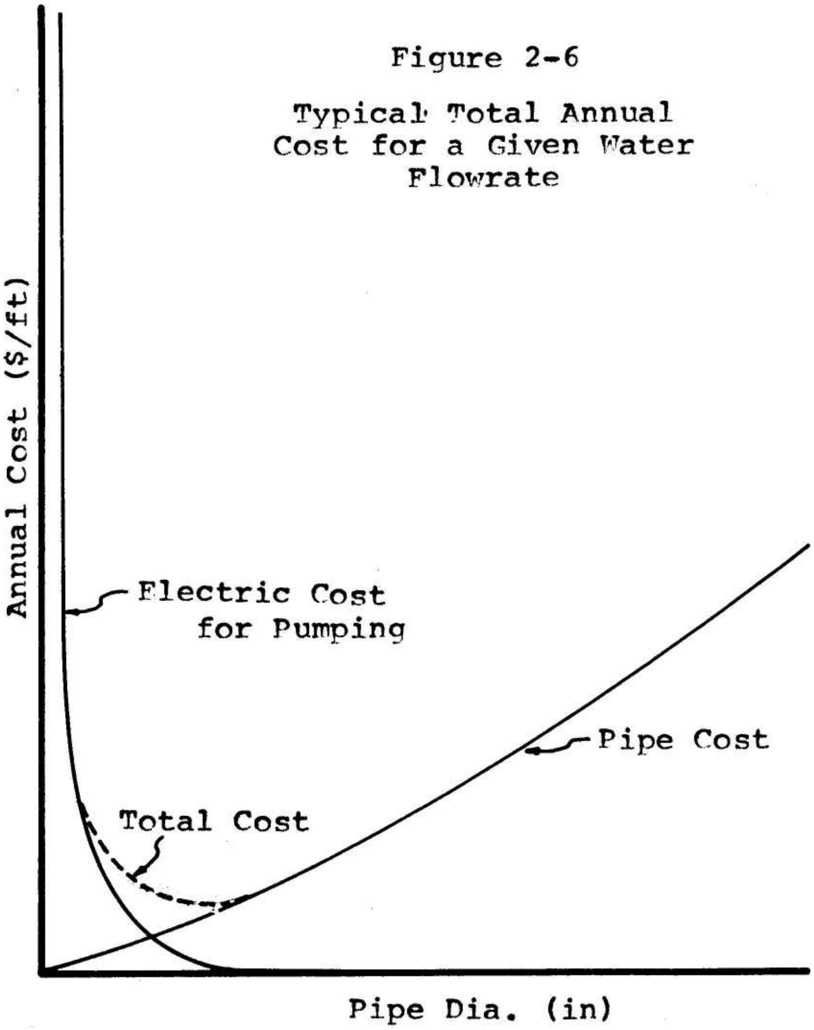


Figure 2-6

Typical Total Annual Cost for a Given Water Flowrate

D = pipe diameter

P = pressure drop

Therefore, pumping cost reaches very high values for small pipes, unless the flow is correspondingly small. The friction factor defined as :

$$f = \frac{h_L}{\left(\frac{L}{D}\right)\frac{V^2}{2g}} \tag{2.10}$$

where h_L = head loss (ft)

V = velocity (ft/sec)

$g = 32.2$ (ft/sec^2)

L = length (ft)

D = diameter (ft)

The friction factor is determined from the Moody diagram for friction in commercial piping. Pao (27) compiled the following analytic expressions applicable to the Moody diagram.

laminar $R_e \leq 2000$ $f = 64/R_e$ (2.11)

transition $2000 < R_e < ?$

$$\frac{1}{\sqrt{f}} - 2\log_{10}\left(\frac{r_0}{e}\right) = 1.74 - 2\log_{10}\left(1 + 18.7\frac{(r_0/e)}{R_e\sqrt{f}}\right) \tag{2.12}$$

turbulent $? < R_e$ (2.13)

$$\frac{1}{\sqrt{f}} = 1.74 + 2\log_{10}\left(\frac{r_0}{e}\right)$$

where $R_e = VD/\nu$

r_0 = pipe radius (ft)

e = pipe roughness (ft)

The line separating transition and turbulent flow was determined by curve fitting and can be expressed in the form:

$$\log_{10}\left(\frac{r_o}{e}\right) = 0.871 \log_{10}(R_e) - 2.6583 \qquad (2.14)$$

For example, when $0.871 \log_{10}(R_e) - 2.6583 < \log_{10}(r_o/e)$, the flow is in the transition region and the appropriate transitional friction factor equation is used.

Computer solution of the optimal pipe diameter for a given flow is achieved by a search technique. Additionally, it is desired for practical reasons to limit pumping stations to only one per square mile network. With pumps rated at about 150 psi, a limit of 75 psi drop maximum per mile of pipe is used. It was found that use of this criteria results in total pressure drops (feed and return lines) on the order of 90-120 psi for a square mile network which is within the capacity of the pumps. Without this pressure drop limit, square mile networks have total pressure drops ranging from 90-175 psi. Network cost difference was found to be about 1-2% for the apartments and about 15% more expensive for the single unit networks with the reduced pressure drop.

Figures 2-7 to 2-10 show results of an optimized 1 ft section of dual piping. Piping cost and electric pumping cost are discussed in Sections 3.1 and 3.8 respectively. With an upper limit of 120 inch diameter pipe, the optimum

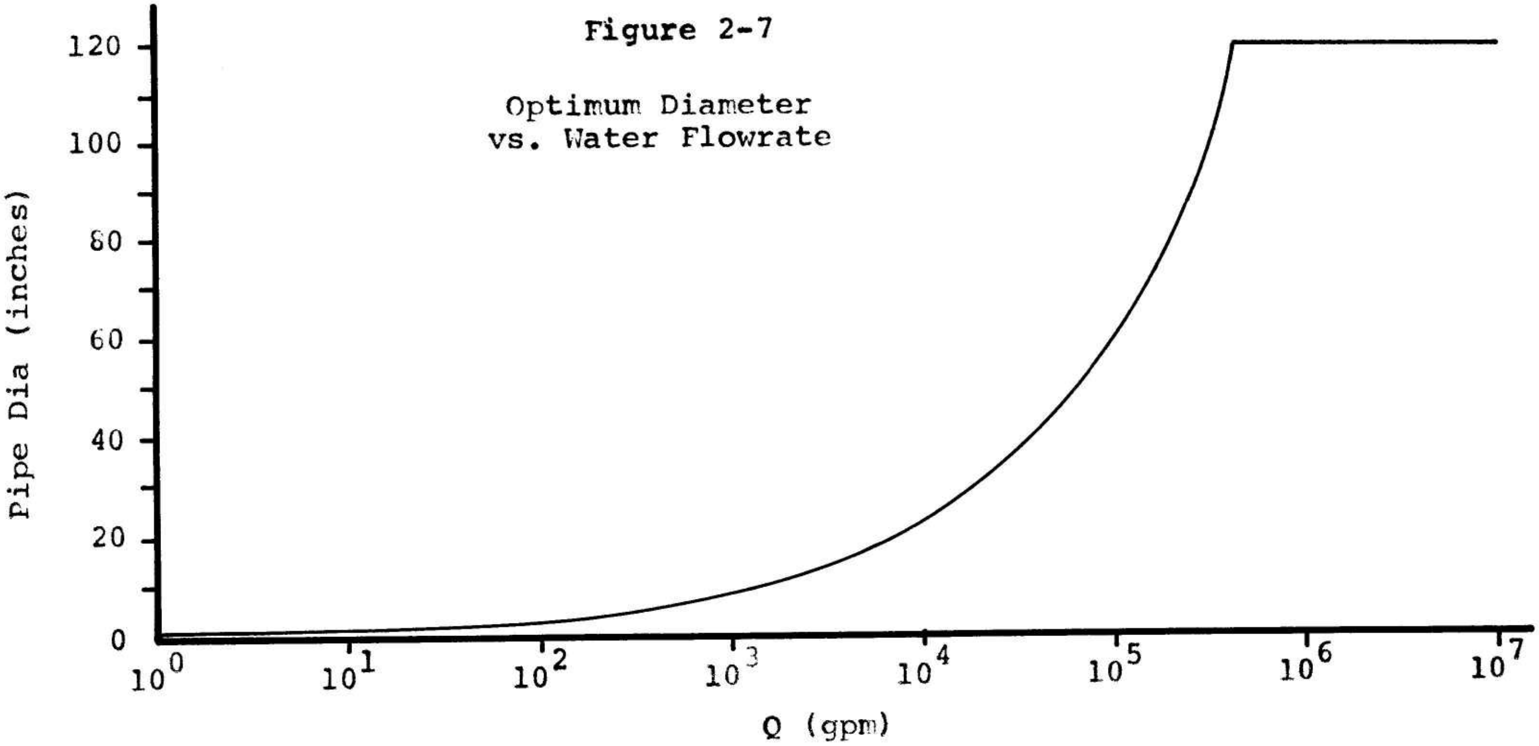


Figure 2-7

Optimum Diameter
vs. Water Flowrate

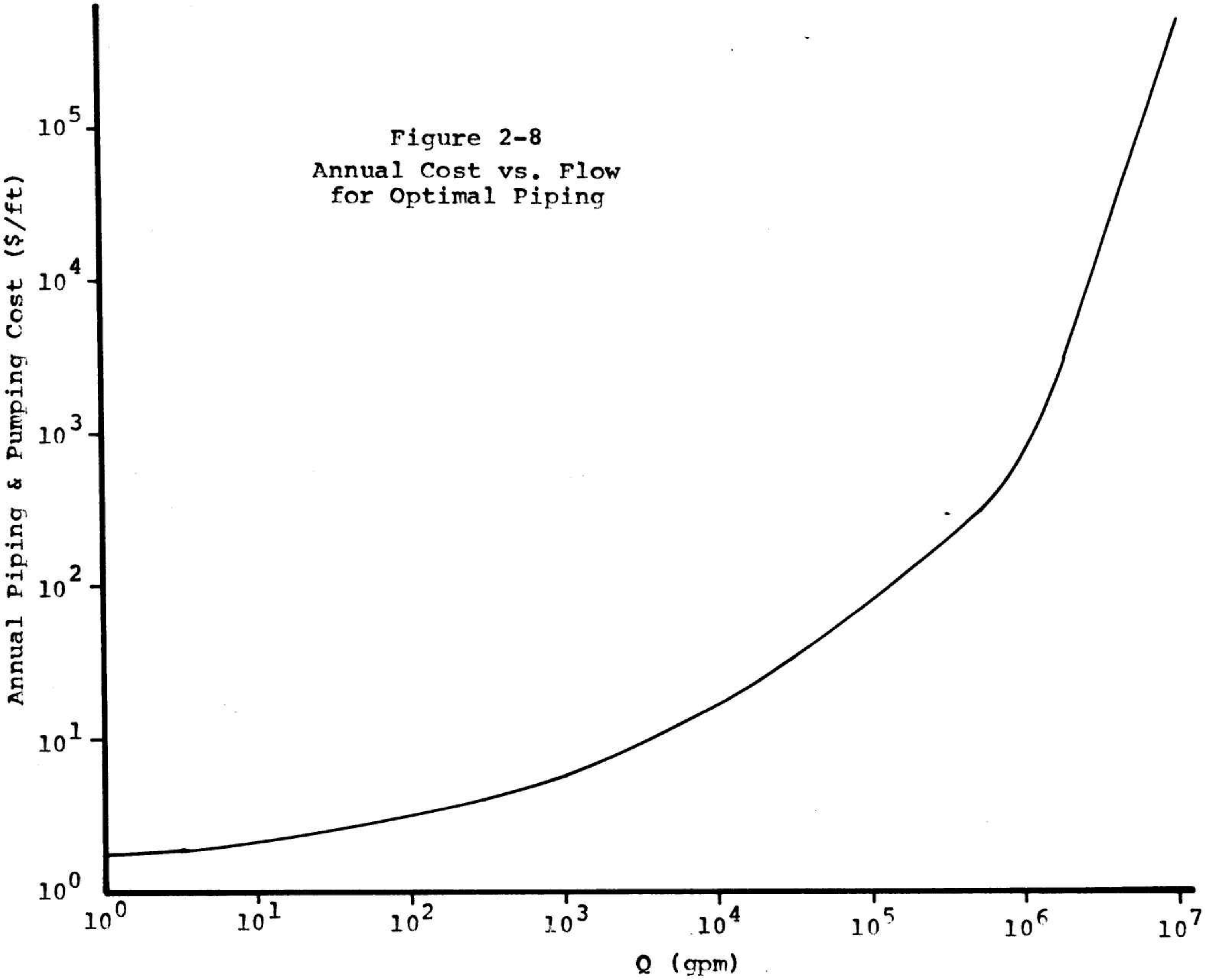
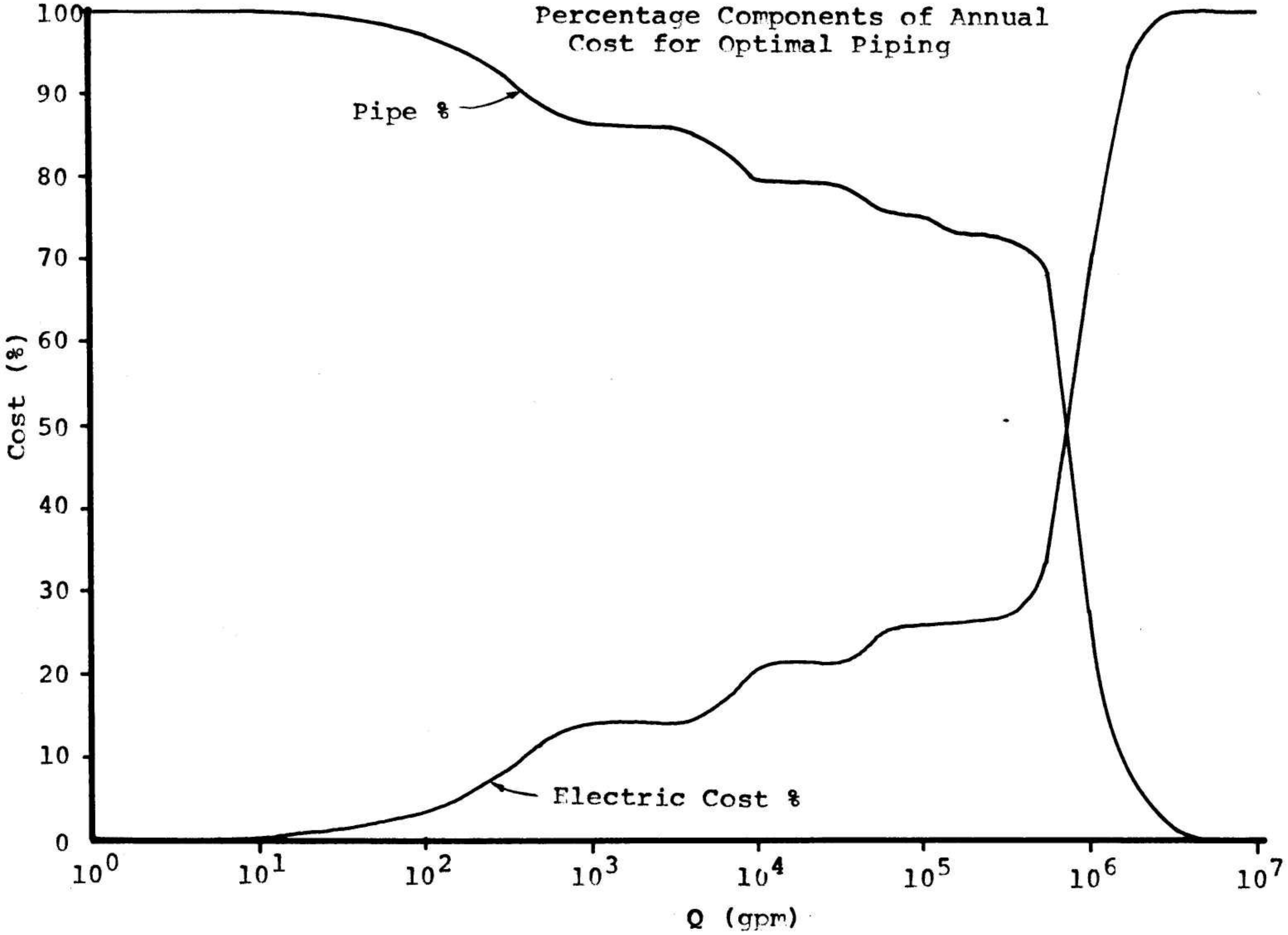


Figure 2-8
Annual Cost vs. Flow
for Optimal Piping

Figure 2-9

Percentage Components of Annual Cost for Optimal Piping



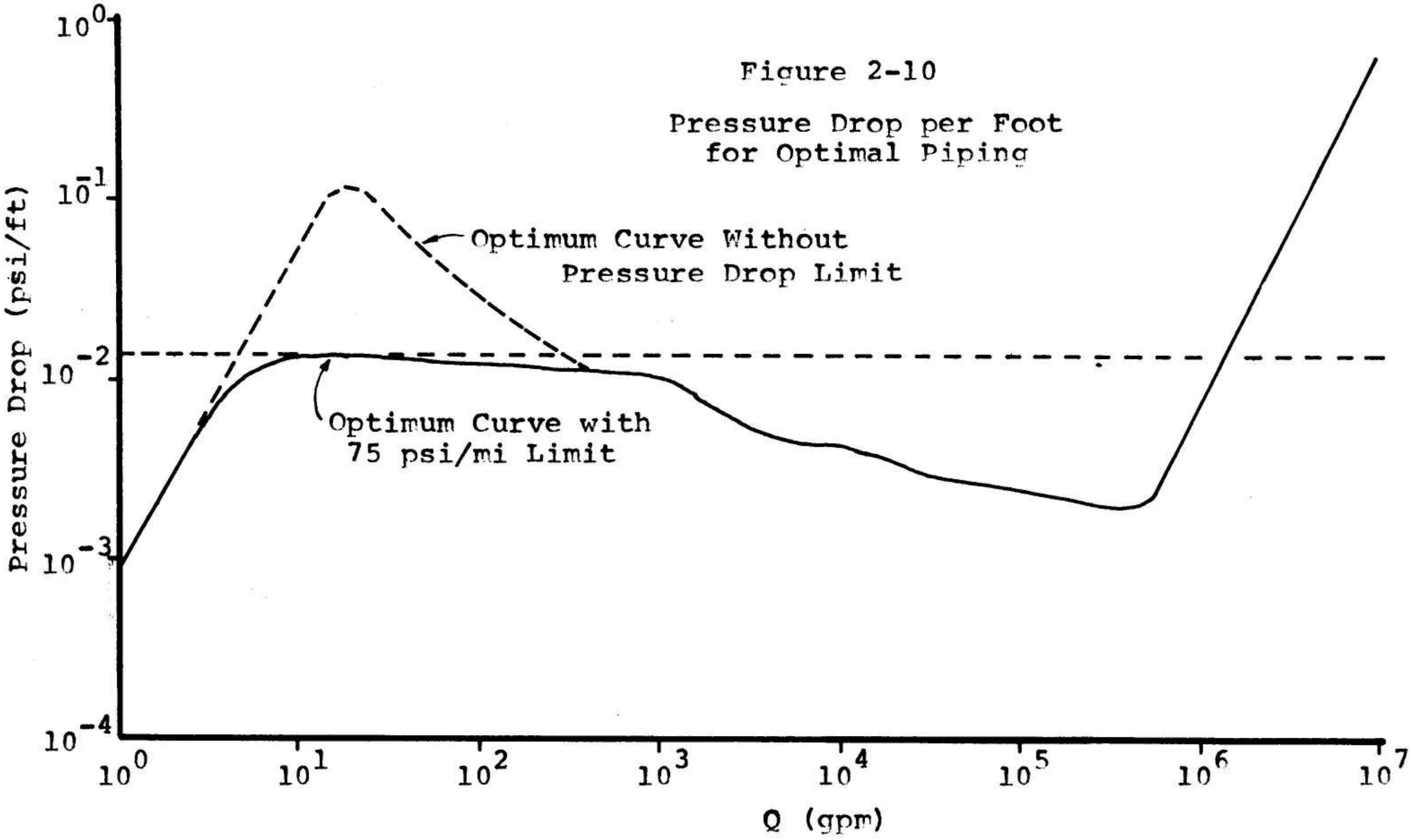


Figure 2-10

Pressure Drop per Foot for Optimal Piping diameter curve plateaus at about 400,000 gpm. Referring to the cost curve, it is noted that past 500,000 gpm, the annual cost becomes larger than the annual cost for two pipes each carrying half the flow of the original. Hence a limit of 500,000 gpm is used as a transition from a single pipe to a double pipe configuration. A single pipe configuration refers to both a feed and a return line. In the pressure drop curve, the 75 psi/mile limit does not apply at the very high flow range because it is not possible to reduce pressure loss by going to a larger size, due to the pipe size limit of 120 inches diameter. Finally, because the computer program uses a discontinuous piping cost function, steps appear in the cost percentage curves for piping and electricity.

Since actual pipes are not manufactured in fine graduations, calculated ranges of optimum flow rates are used for each commercial pipe size. The sizes (inches diameter) used are as follows; 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 42, 48, 54, 60, 72, 84, 96, 108, and 120.

For the above calculations and in the subsequent network cost calculations, the following conditions are specified. The roughness for steel is 0.000 15 ft. An average water temperature of 70° F is used. Pump life is estimated at 25 years with pipes and valves rated for 50 years. (23) A pumping efficiency of 85% is used in conjunction with an electricity rate of 3.36¢/Kw Hr (see Section 3.8). As shown previously, the load factor for Boston 0.25. It is noted (32) that from the fourth quarter of 1974 to the first quarter of 1976, public utilities are borrowing at a 9% rate of interest.

2.10 Network Cost

For each type of housing structure, networks are defined according to density, area, and a list of water flow rates and the associated lengths and number of branches. The commercial pipe size for each branch is determined from the optimal pipe study of the previous section. The pipe cost is amortized to obtain yearly costs using life and interest rates used previously. From the discussion on piping cost, Section 3.1, the pipe network is about 1.5 times the cost for single pipe installation.

Other components of the annual capital cost are valves and pumps. Each piping branch larger than 4 inches is assumed to have a valve. A branch in this case refers to a combined feed and return pipe segment. Initial results based on optimum piping show that each housing block is usually isolatable. In conventional utility distribution practice, a valve is placed every 800-1200 ft. (23) Pump cost is estimated as a function of flow rate and pressure drop at the network entrance for each square mile.

The cost for engineering this water network system should also be included. Engineering cost is recommended to be 15% of initial capital. (1) An annual maintenance and network operating cost of 5% of initial capital is used. (30)

Another operating cost component is the electrical pumping energy needed to overcome pipe friction. According to Geiringer (4), effects due to piping elements such as valves and pipe fittings, and bends, increase a network's losses from 1.3 to 1.45 equivalent pipe lengths. Therefore, a square mile network pressure drop is about 1.4 times the frictional losses from network inlet to furthest user and back. The 1.4 multiplier is used in all piping pressure drop calculations.

It is recognized that sizing all pipes using optimal piping as calculated in the cost versus pumping power tradeoff does not result in an optimal network cost. The reason is that for a square mile network, each branch must be pressure balanced with respect to each of the other branches. If this is not done, then flow maldistribution and/or undesirable secondary flow may result. Referring to Figure 2-11, each branch A through D carries identical flows. (Mirror images of branches A through D on the other side of the main is omitted for this discussion.) Each corresponding piping section for the branches is sized identically, since they carry the same flows. However, flow from the pump to

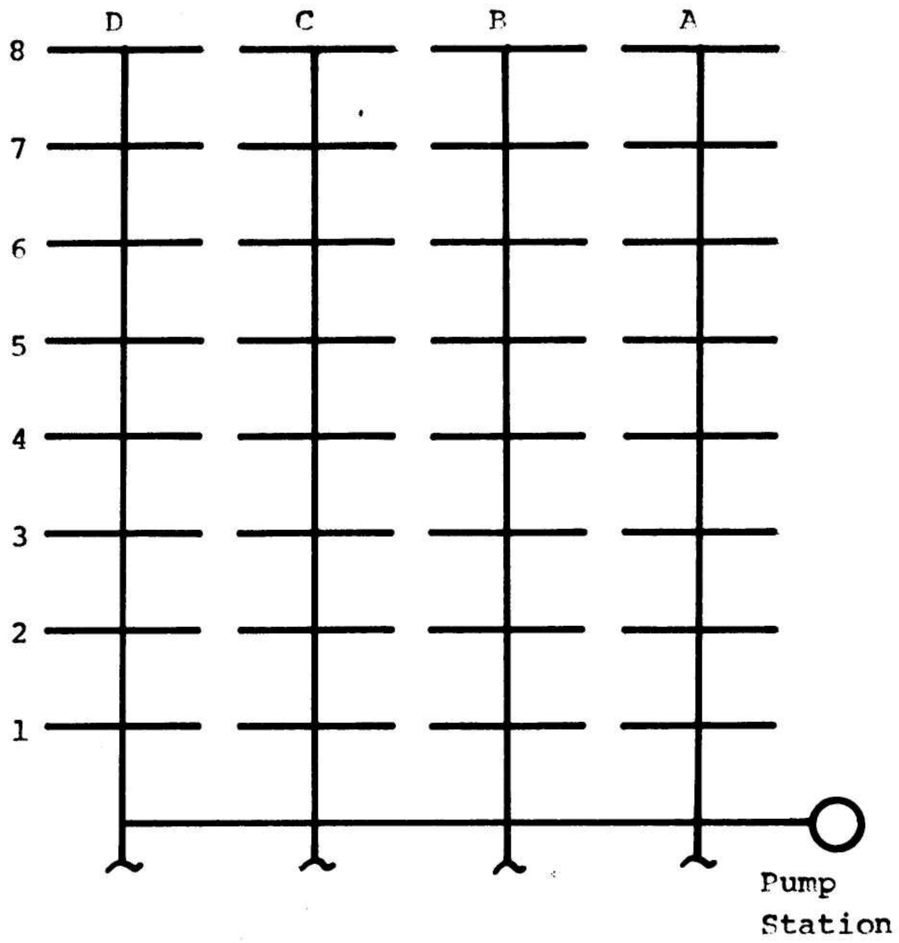


Figure 2-11

Network Pressure Balancing

feedline 8D is longer than flow to line 8A, so that frictional drop for A is less than for D, C or B. Because the branches must be balanced, control devices such as valves are needed to cause pressure drops equivalent to the frictional drops incurred in the paths to the more distant branches. By sizing the branch piping in A smaller, a cost saving is achieved as well as pressure balancing, since frictional losses for that branch would increase. The same applies to branches B and C. It should be noted that no additional pumping power is required; the overall network pressure drop remains the same. In an analysis using a $\Delta T = 40^{\circ}F$ network of twelve unit apartments and 8000 units/mi^2, it was found that equalizing branch pressures by using smaller pipes result in an annual saving of only 0.8%.

Feedlines 1 through 8 are also balanced with respect to one another. Once again, application of optimal piping from the previous section results in slightly oversized pipes for lines 1 through 7 in each of the branches, requiring pressure balancing with valves. Calculations of cost savings using smaller pipes to balance the pressure show an annual cost saving of only 5% for the same network as above. In conclusion, while application of optimal piping from the tradeoff study of Section 2.9 does not result in an overall optimal network cost, the estimate is sufficiently close to optimal for the purpose of this preliminary feasibility study. This is especially true in light of the large variances in piping cost from situation to situation and locale to locale.

2.11 Metropolitan Tract Calculations

Each census tract for the Boston metropolitan area is characterized by area, density, and housing type ratios. Cost, pumping power, and flow requirements are interpolated from the generalized cost-density curves (see Section 4.1) as well as corresponding pumping power and flow curves. Each tract is then linked into another network from which annual parameters (cost and pumping power) are calculated. The sum of the tracts and the connecting network is the total estimated piping system cost.

2.12 Penalty for Lost Power Generation

Conventional fossile power plants generally operate at 2400 psia and 1000° F with reheat to 1000° F at 530 psia. In (6), the gross cycle efficiency is calculated to be 45% for 100° F steam withdrawal. For a system temperature drop of 40° F, where coolant water exits the plant at 95° F, steam needs to be withdrawn at a higher temperature with a resultant decrease in overall plant efficiency. Assuming that the withdrawn steam is 125° F, the gross cycle efficiency is decreased by 2 %. For this reason, the overall plant efficiency for a delta T=40° F system is decreased from about 33% to 31.5%. The plant losses 1.05×10^{-5} Kw in electrical generating capacity for each btu/hr sent into the coolant water. This constitutes a lost power which is included as a charge in addition to the normal charge for electricity. Alternatively, larger plant steam condensers may be used. The temperature of the exiting coolant water will increase while the steam condensing temperature remains close to 100° F. Thus the decrease in overall plant efficiency and the resulting loss generating capacities are small. It can be shown that the increased annual cost of the larger condensers per consumer is negligible. However, it can also be shown that the cost of loss generating capacity makes up approximately 3.5% of the annual heat pump cost per consumer for the delta T=40° F system. Consequently, the overall effect of either condensing arrangements on the annual cost is small.

CHAPTER 3

Equipment and Cost Items

This chapter presents data on current cost for items pertinent to the system model and for items of interest for comparison purposes. Also discussed are performances of water/air and air/air heat pumps.

3.1 Piping

Piping for the warm water/heat pump system can be of three general configurations; above ground, underground in tunnels, and underground buried. The first configuration is not suitable for a city-wide distribution system because of possible potentially dangerous obstructions to movement of people or traffic and vulnerability to damage. The second configuration is cost justifiable only in special circumstances where accessibility is at a premium. Buried pipelines can be installed in molded conduits or in larger conduits with elaborate insulation and air spaces. The underground configuration with molded conduits is selected for this system. The use of insulating concrete has been generally successful, except in cases where the pipeline is below water tables, in which case waterproofing methods such as pipe sheathing or trench sheeting are used.(4)

Before pipeline installation cost is discussed, the term "simple pipe installation" should be defined. A simple installation is the digging of a trench, compacting a bed, laying and installing the pipe, pouring concrete around the pipe, and finally refilling the trench. The cost formulation which follows is for a simple installation. Three Boston metropolitan construction contractors cooperated in providing piping cost estimates. J. F. White Contracting Co. (Newton, Mass.) in particular provided a detailed method for estimating costs which compares favorably with information provided by Perini Corp. (Framingham, Mass.) and D. L. Maher Co. (Reading, Mass.). The method is as follows:

1. Dig/lay/backfill

   (includes pipe installation and bedding compaction)

Pipe Diameter (in)	Cost ($/ft) High	Low
1	6	3
6	6	3
18	10	6
42	20	10
72		30
120		60

2. Pipe purchase

   $0.40/lb for "black" steel pipes

3. Bedding (purchase)

   $3.00/cubic yard

   General bedding dimensions are 2 ft depth and pipe diameter plus 3 ft width.

4. Concrete (purchase and installation)

   $50.00/cubic yard

Some assumptions implicit in this cost formulation are

1. Standard 6 ft minimum depth from top of pipe to soil surface.
2. Cost is for single pipe laying. For double pipe system (feed and return lines), multiply dig, lay, and backfill costs by 1.5.
3. Steel pipes are welded.
4. Pipes are above water line.
5. Trenches are open cut.
6. No rock excavation.

The general specifications for a double pipe pipeline are shown in Figure 3-1. The "a's" were used as concrete thicknesses in the heat loss analysis of section 2.2, where it was shown that by using insulating concrete, the temperature drop under the worst conditions is about 1°F.

Since the system will see a maximum temperature of 100°F (i.e., subcooled water) there is no need to pressurize the system beyond what is needed to pump the water. High capacity pumps are generally not rated at greater than 150 psi, so that an operating pressure of 150 psi is appropriate. Water pipes must satisfy ASA B31.1, Code for Pressure Vessels, which prescribes pipe minimum thickness by the formula

$$t_m = \frac{PD}{(2S + 2yP)} + C \qquad (3.1)$$

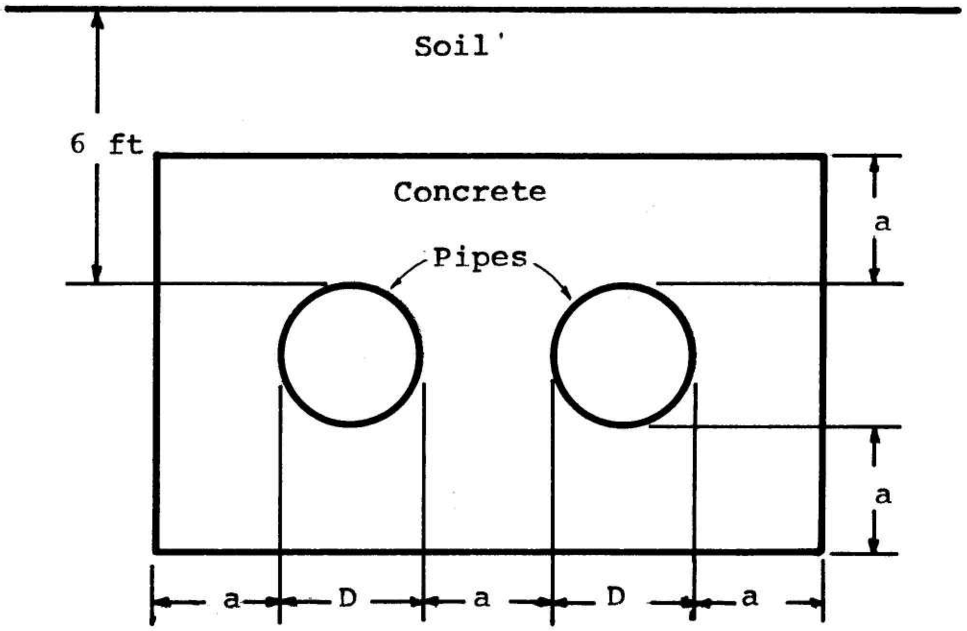


Figure 3-1

General Piping Layout

where t_m = minimum wall thickness (in), P = working pressure (psi), D = pipe outer diameter (in), S = allowable stress (psi), y = 0.4 for ferritic steel, and C = allowance for miscellaneous effects.

The above equation is not applicable to cast iron pipes. For the temperature range -20 to 100^oF, ASTM A120 states that the allowable stress is 10800 psi. C = 0.065 for plain end pipes with diameters of one inch and greater. Pipe cost is estimated by calculating minimum wall thickness and selecting a standard thickness just above minimum, using a steel density of 506 lb/ft^3 and pipe cost of $0.40 per lb. A summary of piping cost for a simple installation at 150 psi is shown in Table 3-1.

In order to obtain a credible total cost estimate for a piping netwerk, a survey was undertaken to determine some actual cost breakdowns of pipeline constructions. From various issues of the Engineering News Record (a construction contractor-oriented periodical), examples of actual bids were available from which one could analyze the cost structure of a project.

A summary of the 12 cases analyzed is presented in Table 3-2. The locales are in the eastern portion of the United States. Job sizes ranged from $734,500 to $2,596,900. Nearly all of the jobs are sewage pipelines. The cases were analyzed to determine the major cost items which were not covered by the simplified pipe laying formula. This is necessary because one must include effects deviating from the ideal simple installation. Resulting data show that costs not covered by the

Table 3-1

DUAL PIPE SIMPLE INSTALLATION COST SUMMARY

Dia (in)	Dig/Lay/Backfill ($/ft)		Pipe ($/ft)	Bedding ($/ft)	Concrete ($/ft)	Total ($/ft)	
	high	low				high	low
1	9.0	4.5	1.20	0.81	2.4	13.4	8.9
6	9.0	4.5	14.0	0.99	4.9	28.9	24.3
18	15.0	9.0	39.2	1.44	14.3	69.9	63.9
42	30.0	15.0	138.0	2.01	42.0	212.0	197.0
72		45.0	394.0	3.51	93.2		535.7
120		90.0	1051.0	5.34	220.2		1366.5

Table 3-2 SUMMARY of CONTRACTOR BIDS

Locale	Discription	Sucessful Bid	Nonsimple Piping Cost %	Notes
Columbus, Ohio	3.7 miles of sanitary sewers	$1,670,381	59.7%	45.9% tunneling & carrier piping 9.2% manholes
Portland, Maine	1.3 miles of RC pipe sewer	$1,078,957	45.5%	12.6% manholes 8.3% regulators 5.6% RxR crossing 7.2% special construction
DeSoto County, Miss.	8 miles of sewer work	$2,952,831	34.3%	17.8% tunneling for RxR 6.3% manholes
York, Maine	3 miles of RC gravity sewer	$1,149,810	23.0%	11.1% manholes 7.0% ledge & rock excavation
Chesterfield, Va.	2.4 miles of trunk sewer	$807,078	26.8%	7.4% manholes 10.3% tunneling 5.5% ventilation system
Wash., D.C.	1 mile of RC gravity sewer	$2,596,941	41.4%	30.4% tunneling under RxR & Hwy 5.3% gravel below subgrade
Northeast, Texas	13 miles of DI water main	$1,128,278	10.8%	6.1% control station
Plymouth, Conn.	5.2 miles of sewer with pump station	$1,353,840	55%	13.3% pump stations (2) 11.4% pavement replacement 10.0% waterline sheeting 7.8% rock excavation 5.8% manholes

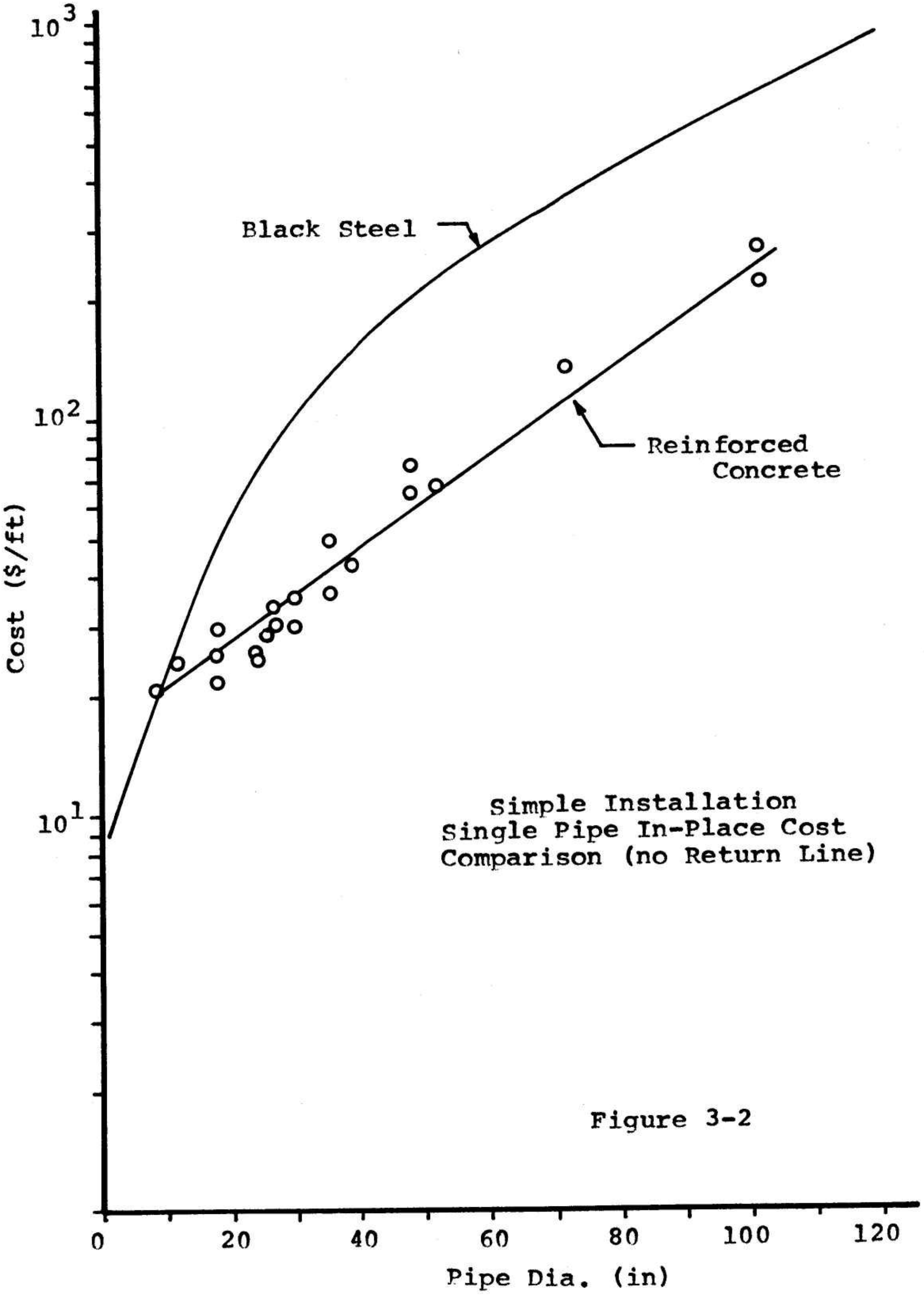
Table 3-2 (continue)

Locale	Discription	Sucessful Bid	Nonsimple Piping Cost %	Notes
Chesire, Conn.	4.2 miles of sanitary sewer	$816,550	53.9%	14.4% rock excavation 9.2% pavement replacement 8.6% building connections
Highland, N.Y.	7 miles of gravity & force mains	$1,559,824	45.8%	17.6% rock excavation 9.9% pavement replacement 6.8% manholes 5.4% pump station
Barrington, R.I.	9.6 miles of sewer lines	$1,747,380	36.6%	13.0% pavements 8.2% precasted concrete manholes 5.7% dewatering and draining
Chanhasseu, Maine	12.4 miles of sewer and water lines	$1,258,203	35%	9.5% fire hydrants 7.6% lift stations 5.6% manholes

simple installation cost range from a low of 10.8% to a high of 59.7% of the total cost. The major contributing items are tunneling for the crossing of streams, railroads, and highways; and manholes, rock excavation, and pavement replacement.

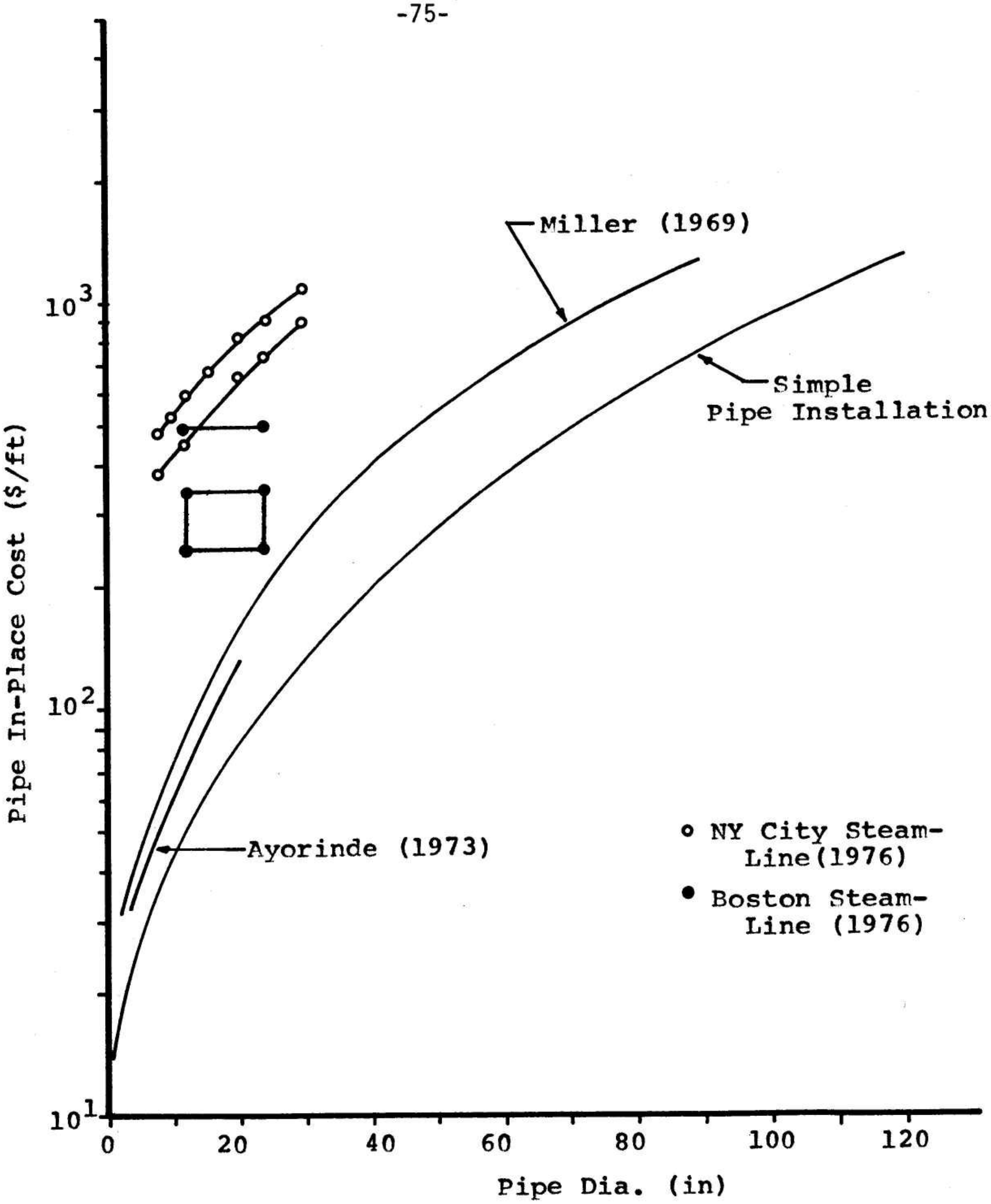
It is desirable to apply a percentage factor to the simple installation cost formula to account for the above-noted items and the remaining miscellaneous items. However, the bids were mostly for sewers which use predominantly reinforced concrete piping. A study of the cost breakdowns for reinforced concrete piping under similar burial conditions as for the warm water system yields the cost curve shown in Figure 3-2. For comparison purposes, a cost curve for a single steel pipeline (no return) is shown from which one concludes that the steel pipeline is significantly more expensive. Since this is so, the application to the steel pipeline of cost increase percentages equal to those determined above for the concrete pipeline would result in higher cost for equivalent items not covered by simple pipe installation cost. Assuming that 60% of the concrete pipeline's cost is due to other than simple installation, then equivalently 33% of the steel pipeline's cost would be due to other than simple installation. This is arrived at by proportioning the total cost with the higher cost for steel pipe installation. In conclusion, a reasonable total network cost may be estimated by using a 1.5 multiplier on the simple installation cost.

Figure 3-3 shows various other piping costs for comparison. The striking variances in magnitude point out the difficulty in deter-



Simple Installation
Single Pipe In-Place Cost
Comparison (no Return Line)

Figure 3-2



Piping Cost Comparison

Figure 3-3

Note: All curves are for high pressure pipelines (300-400 psi) while simple pipeline curve is for 150 psi piping.

mining a "typical" piping cost. The Ayorinde cost curve(6) for 1973 was derived from steampipe cost data in the District Heating Handbook, updated by a factor of 1.65. Miller's 1969 cost curve was determined locally (Oak Ridge, Tenn.) for dual high temperature hot water piping. Boston and New York steam line cost provided by Boston Edison and Consolidated Edison are current. It is remarkable that even between two large congested cities, pipeline cost for the downtown areas can vary significantly.

The problem of determining a "typical" piping cost still remains. It is noted in the Miller, et al. report(1) that the cost for installing high temperature water (HTW) pipelines for Oak Ridge is purported to be approximately the national average. The general specification for the HTW pipeline is 400 psi, 350°F and 6 ft soil cover. The general specification for the warm water system is 150 psi, and less than 100°F with the same soil cover. For a direct comparison, the cost of 400 psi piping is calculated using the simple pipe installation formulation. No account is taken for insulation. The calculated cost is then increased by a factor of 1.5 to account for non-piping cost and the result is plotted in Figure 3-4, along with the Miller curve updated by a factor of 1.5. The factor is determined by a reported cost figure of $210/ft for 24 inch steam lines for downtown Boston (~ 1969) compared to approximately $300/ft for the same size in 1976, as reported by Boston Edison. One notes that despite the crude calculations, the two costs are roughly equivalent. In con-

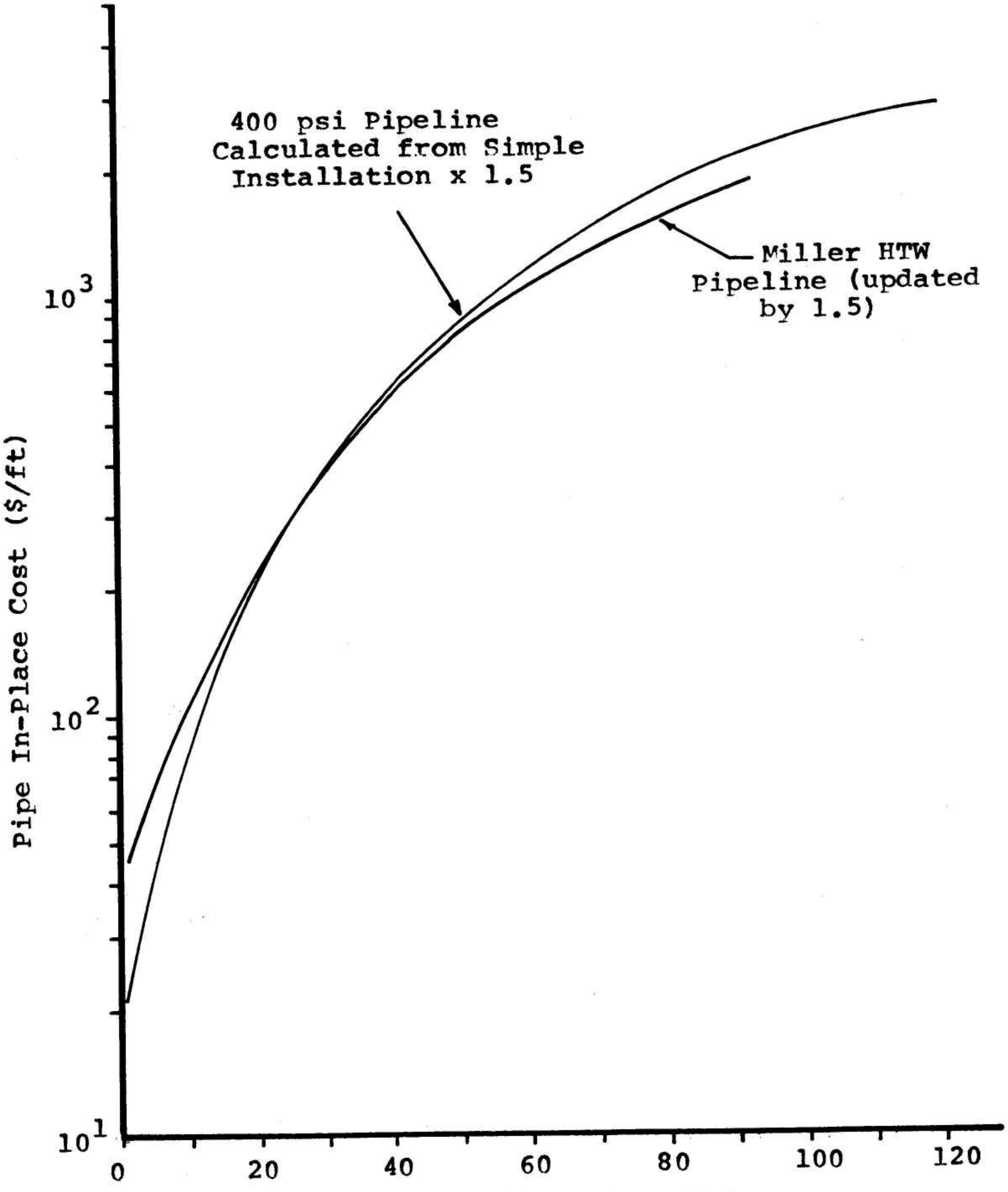


Figure 3-4
Cost Comparison
Miller Cost with Calculated
Cost for 400 psi Pipeline

clusion, when compared to some existing pipeline data, the previously described method for pipeline cost estimation is reasonably "typical" for the purpose of this study.

3.2 Water Pumps

Engineering data for high capacity centrifugal water pumps were obtained from the DeLaval Turbine Corp. (Trenton, N.J.). Capacity ranges from 20,000 to 45,000 gpm. These pumps are $50.00 per horsepower, exclusive of driver. A delta P of 100 psi was selected as a reference to establish capacity. Pump selection was based on performance in the 85% or greater efficiency range.

Electric open frame motors were selected to drive the pumps. Prices for motors in the thousand hp range (see Figure 3-5) were supplied by Reliance Electric Co. (Wellesley, Mass.). A 15% increase based on driver cost was used to allow for gear reduction to match driver speed to pump speed (720 rpm).

The installation of the combined pumping unit is priced at 10% of total capital cost, according to J. F. White Contracting Co. The resulting total purchase and installation cost is plotted in Figure 3-6.

3.3 Cost of Valves

Using gate valves as a reference, costs for valves in the range of 2" to 48" were supplied by the Mueller Co. (Chattanooga, Tenn.). Valves are American Water Work Association (AWWA) rated and

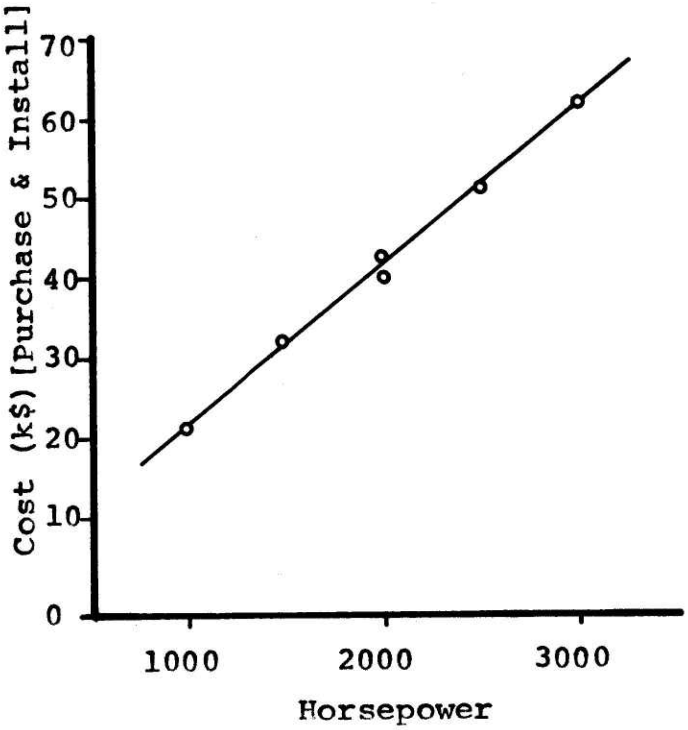


Figure 3-5

Cost of Electric
Drive for High Capacity Pumps

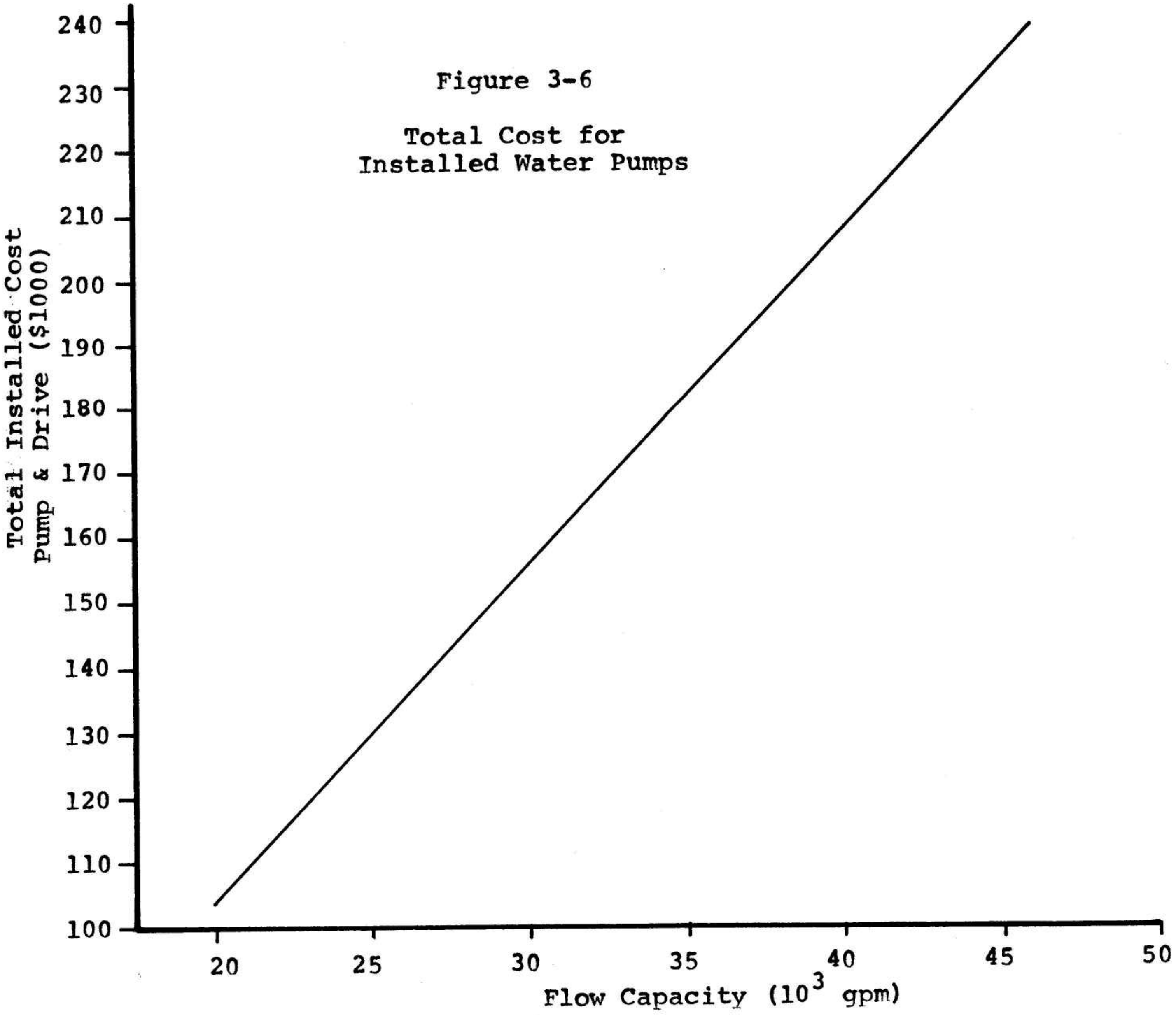


Figure 3-6

Total Cost for Installed Water Pumps

are intended for service at 150 to 200 psi. The installation cost is $100 for each twelve inch valve and under, $300 each for sizes between twelve inches and twenty-four inches, and $30 per inch diameter for sizes beyond twenty-four inches. J. F. White Contracting Co. supplied the above estimates. Total inplace cost for valves is plotted in Figure 3-7.

3.4 Water/air heat pumps

The scope of this study is limited to present day water/air heat pump technology. No effort will be made to project probable future heat pump developments. Climate Master (Utica, N. Y.) water/air heat pumps are used as being typical of present day water/air units, based on availability of engineering data for a wide range of capacities and the upper source temperature limit of approximately 100°F. A listing of various commercial water/air heat pumps can be found in reference (33). Based on an indoor dry bulb temperature of 70°F, the performances of Climate Master heat pumps are shown in Figures 3-8 to 3-12. The coefficient of performance (COP) is defined as heat output per work input. Heating system cost variations with higher COP's are treated in section 4.12.

The costs of various air/air and water/air heat pumps from metropolitan Boston distributors are shown in Figure 3-13. The Air Conditioning and Refrigeration Institute (ARI) references air/air heat pumps at 47°F source air, while water/air heat pumps are referenced at 60°F source water. If air/air units are adjusted to a source tempera-

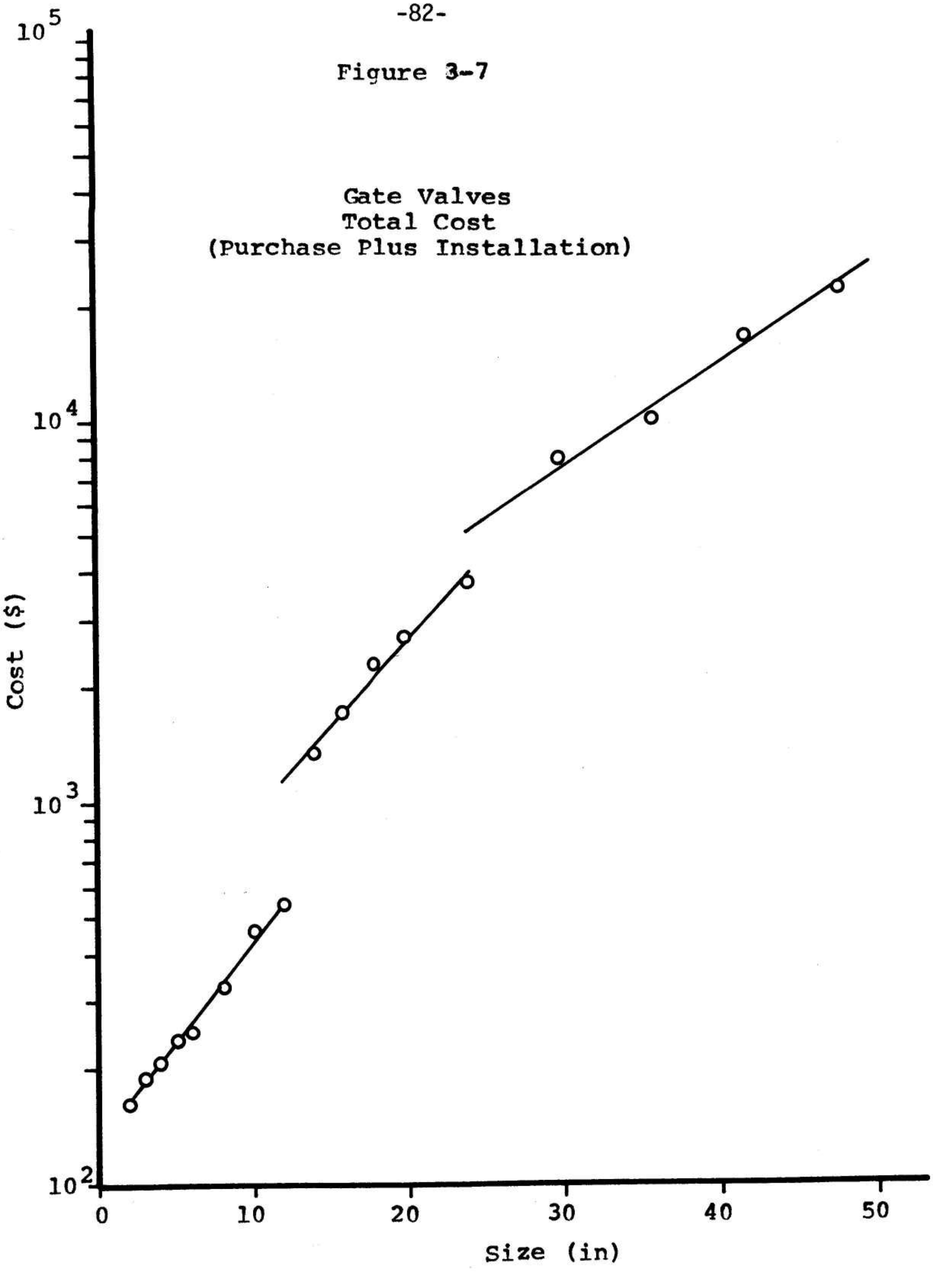
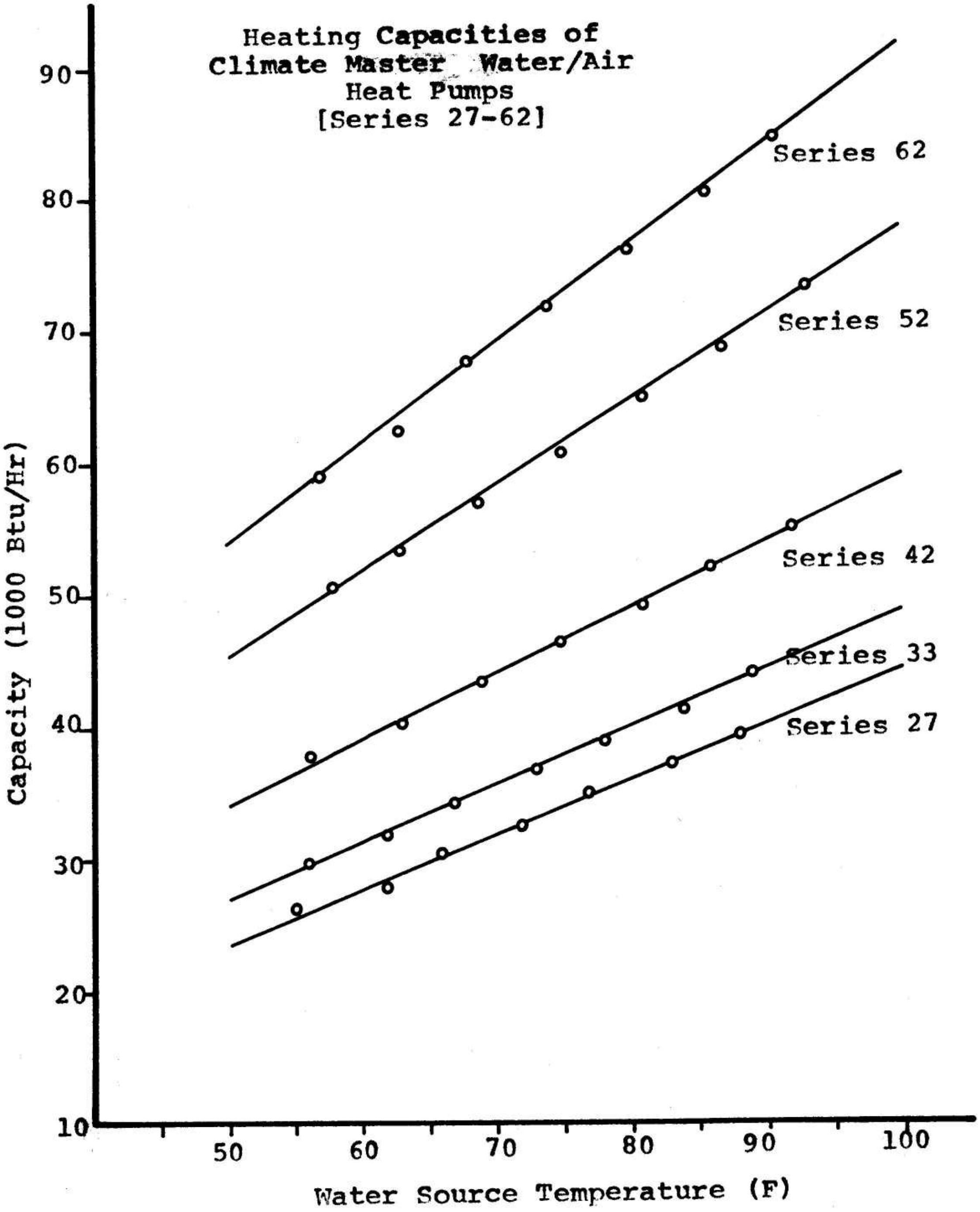


Figure 3-7

Gate Valves
Total Cost
(Purchase Plus Installation)

Figure 3-8



Heating Capacities of
Climate Master Water/Air
Heat Pumps
[Series 27-62]

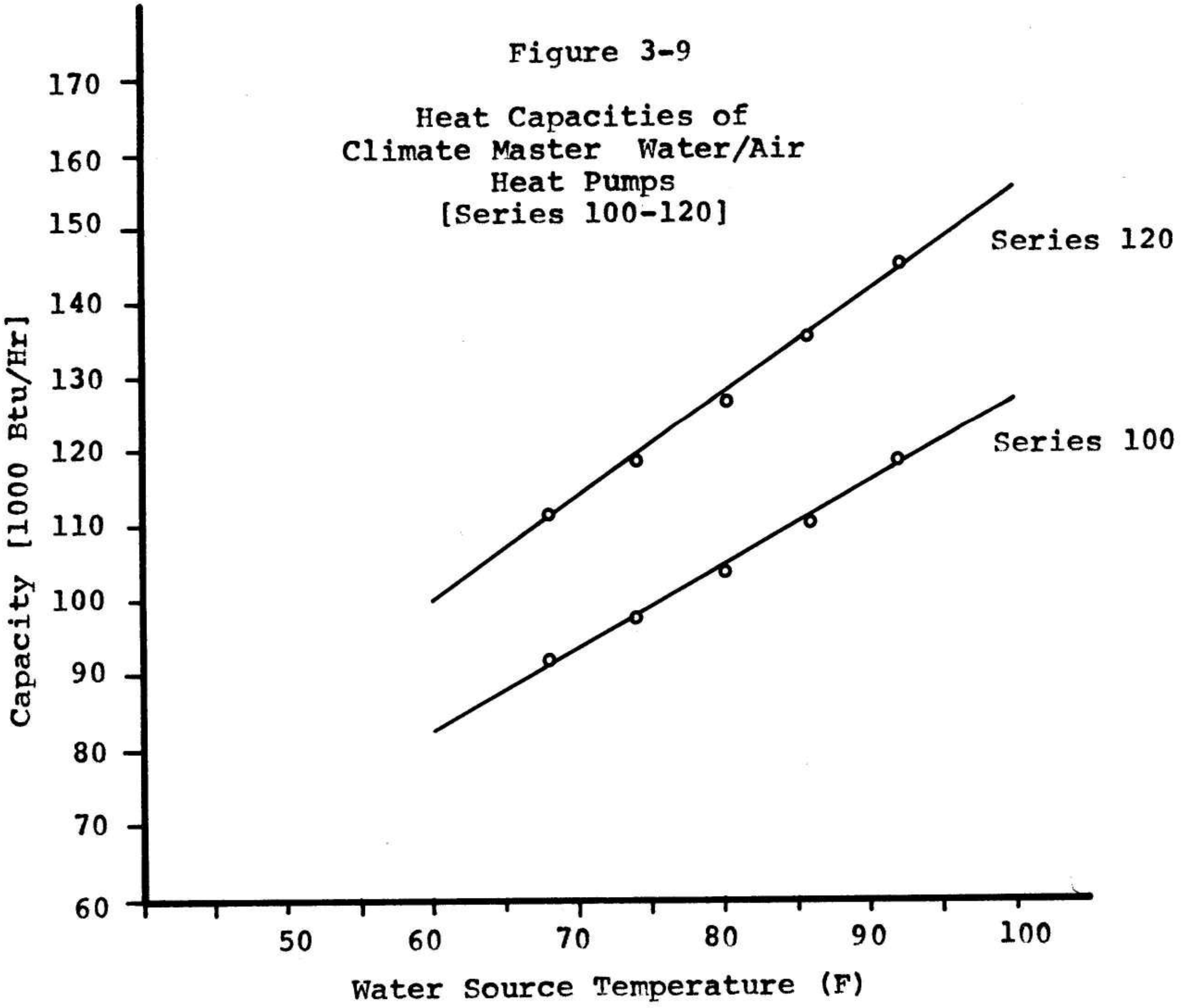


Figure 3-9

Heat Capacities of Climate Master Water/Air Heat Pumps [Series 100-120]

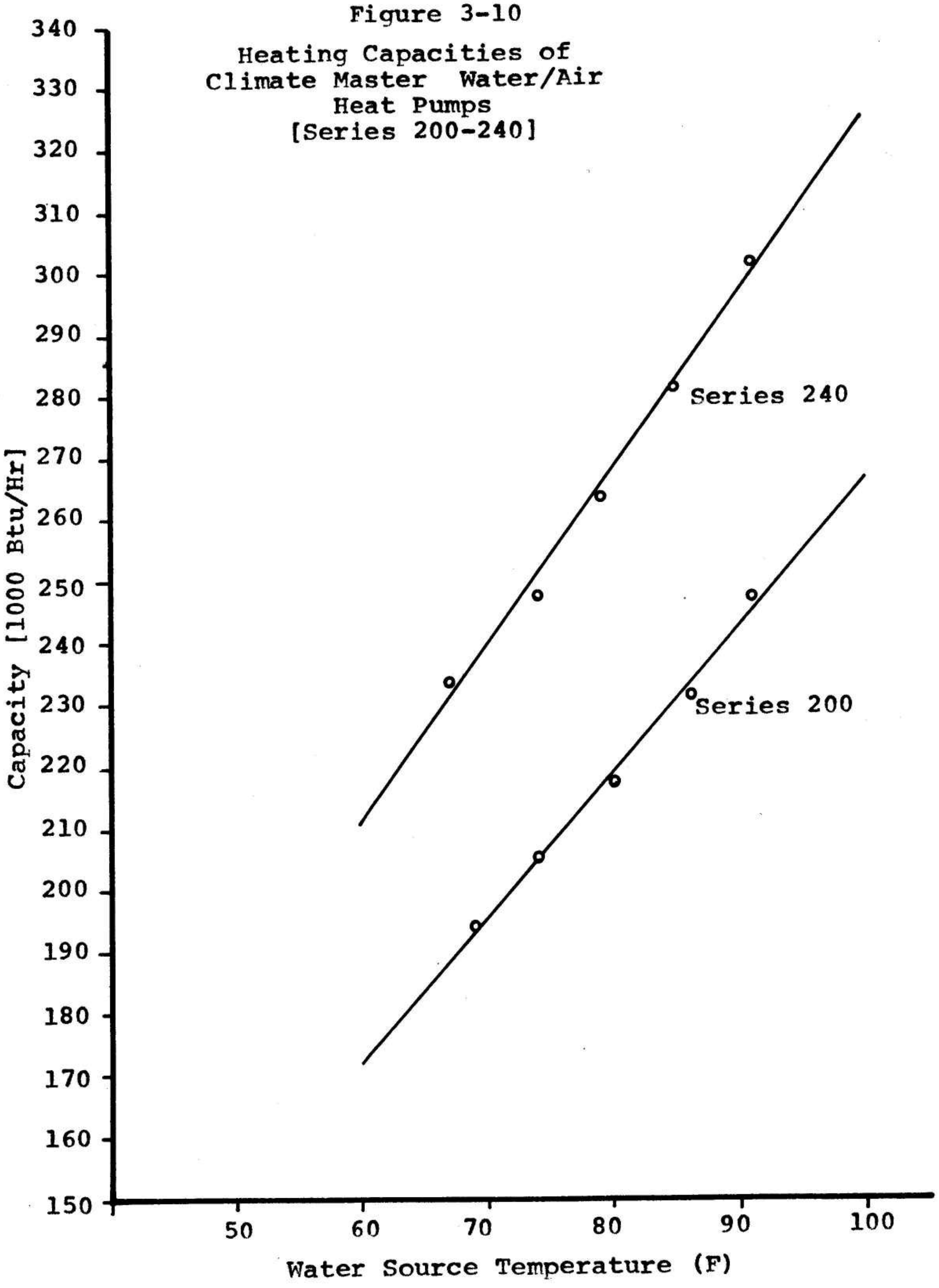


Figure 3-10

Heating Capacities of Climate Master Water/Air Heat Pumps [Series 200-240]

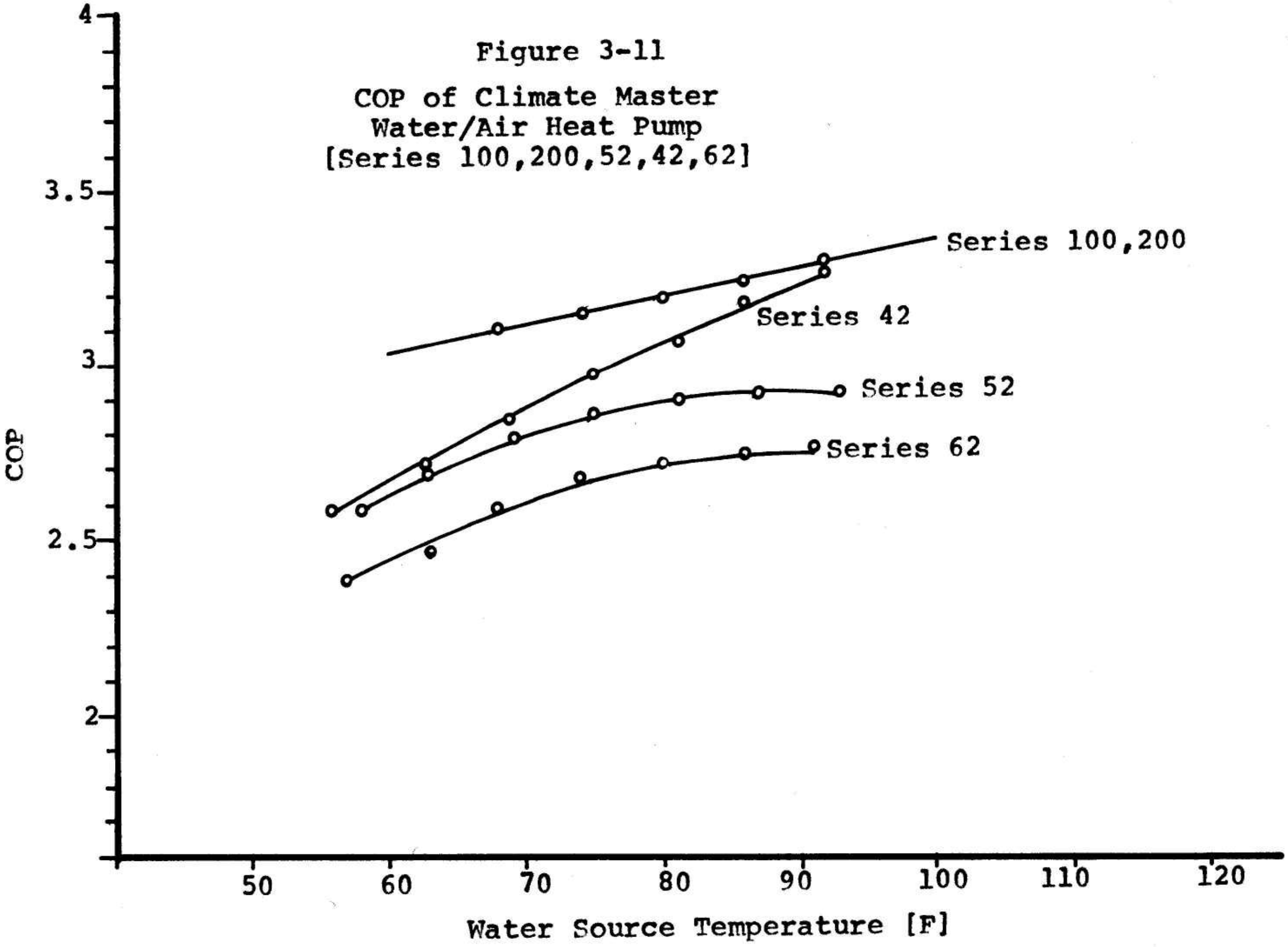


Figure 3-11

COP of Climate Master Water/Air Heat Pump [Series 100,200,52,42,62]

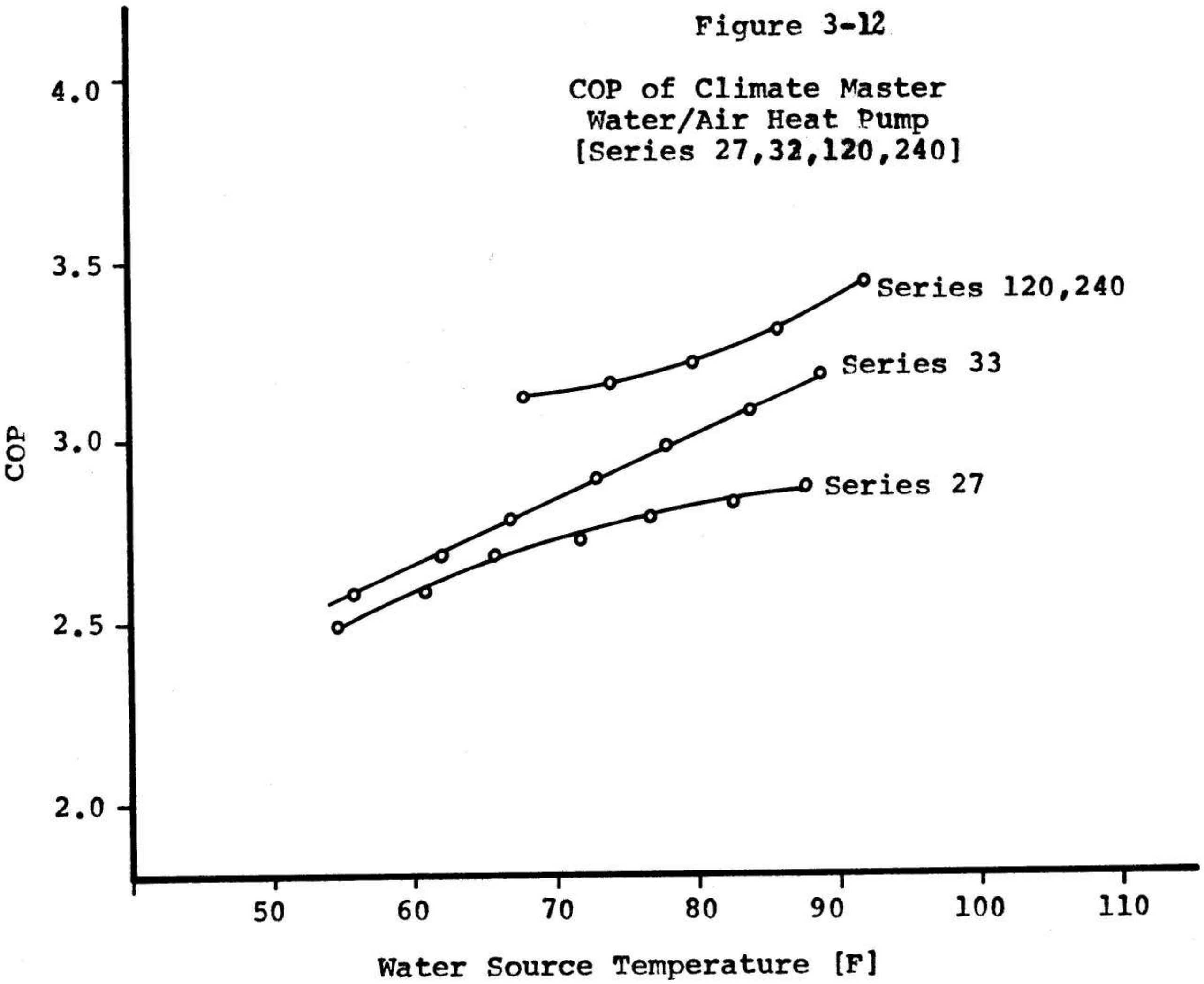


Figure 3-12

COP of Climate Master
Water/Air Heat Pump
[Series 27,32,120,240]

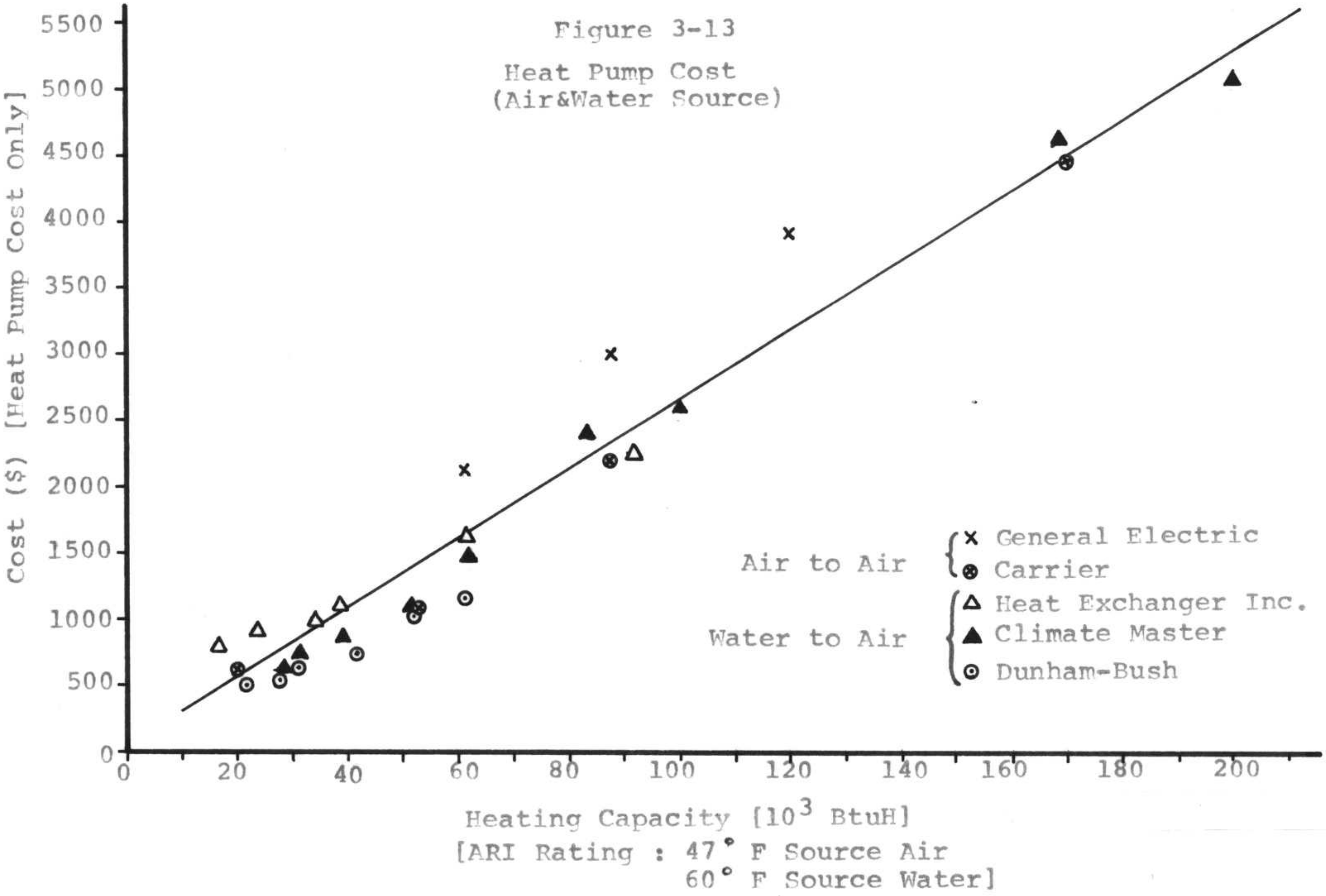


Figure 3-13

Heat Pump Cost
(Air&Water Source)

ture of 60°F, water/air units would cost more. The heat transfer coefficient for water is about an order of magnitude greater than for air and a smaller heat exchanger is needed for the water/air units; therefore one would expect water/air heat pumps to cost less. A possible explanation for this discrepancy is that water/air heat pump manufacturers are relatively small and that these units are not produced in sufficient numbers to enjoy a cost advantage.

For a power plant condenser coolant delta T of 20°F, Table 3-3 summarizes total initial water/air heat pump cost for each of three types of residences. Water temperature drop at each consumer is discussed in section 2.4. The cost for duct work is treated in section 3.6.

For a plant coolant delta T of 40°F, the cost is somewhat different since consumers receive higher temperature water. Because of the gap between heat pump sizes, initial cost for the apartments remains the same but pump performances are better. For single unit homes, however, a range of prices is more applicable since there are four units in series and the first consumer in the series is able to purchase a smaller heat pump, due to the increased capacity at the higher source temperature (Table 3-4).

Cost of heat pump installation is from McNamara & Donnelly, Inc. (Braintree, Mass.) and ductwork cost is treated in section 3.6. Life of a water/air heat pump is better than an air/air heat pump, since its temperature source is essentially constant. Estimated life is about fifteen years. Annual maintenance is estimated at $15/ton, which is equivalent to air/air heat pump maintenance for some southern and mid-

Table 3-3

Initial Heat Pump System Cost for Plant $\Delta T=20^\circ$ F System

	Single Unit Home	Four Unit Apt.	Twelve Unit Apt.
Climate Master Series	52	200	240
ARI Rating (Btu/hr)	51500	164600	200000
Heat Pump Cost	$1448	$4405	$5330 x 2
Installatin/Wiring/ Thermostats	$350	$800	$1400
Ducting and Installation	$2170	$6380	$15880
Total	$3968	$11585	$27940

	Single Unit Homes	
	Low	High
Climate Master Series	42	52
ARI Rating (btu/hr)	39000	51500
Heat Pump Cost	$1122	$1448
Installation/Wiring/ Thermostats	$350	$350
Ducting and Installation	$2170	$2170
Total	$3642	$3968

Table 3-4

Initial Heat Pump System
Cost for Single Unit Homes
Plant $\Delta T=40^{\circ}F$

western states.(14)

3.5 Air/Air Heat Pumps

For overall cost comparison purposes, air/air heat pumps are considered for heating each of the housing structures. Design load for each structure is identical to that for the water/air heat pumps. The balance point for Boston is approximately 32°F and using the engineering data for Carrier air/air heat pumps in reference 11, requirements for each residential type are evaluated and summarized in Table 3-5. For the twelve unit apartment, two heat pumps are used. The cost for air/air heat pumps based on ARI ratings can be taken from Figure 3-13. The cost of auxiliary heat from the Anderson Air Conditioning Corp. (Brookline, Mass.) is shown in Figure 3-14. The average seasonal COP for air/air heat pumps in the Boston area is 2.(17) Estimated life of air/air heat pumps is ten years. Annual maintenance contracts for heat pumps for Boston are about $35/ton (Anderson Air Conditioning Corp.; Brookline, Mass.).

The total installed cost for air/air heat pump systems for each of the residential types is shown in Table 3-6. Installation costs are from McNamara & Donnelly, Inc. (Braintree, Mass.), and ductwork cost is treated separately.

3.6 Heat Pump Ductwork Cost

Estimation of ductwork cost is made difficult by lack of concrete housing details. Based on recommendations from various air

Table 3-5

Air/Air Heat Pumps
for
3 Residential Types

	Heating Load 32 F (btu/hr)	Carrier Heat Pump Series	Auxiliary Heating (Kw)	Heat Pump ARI Rating (btu/hr)
Single Unit	25000	50 DQ 005	8.7	53000
Four Unit Apt.	82000	50 DQ 016	25.7	170000
Twelve Unit Apt.	213000	50 DQ 016	79.5	170000

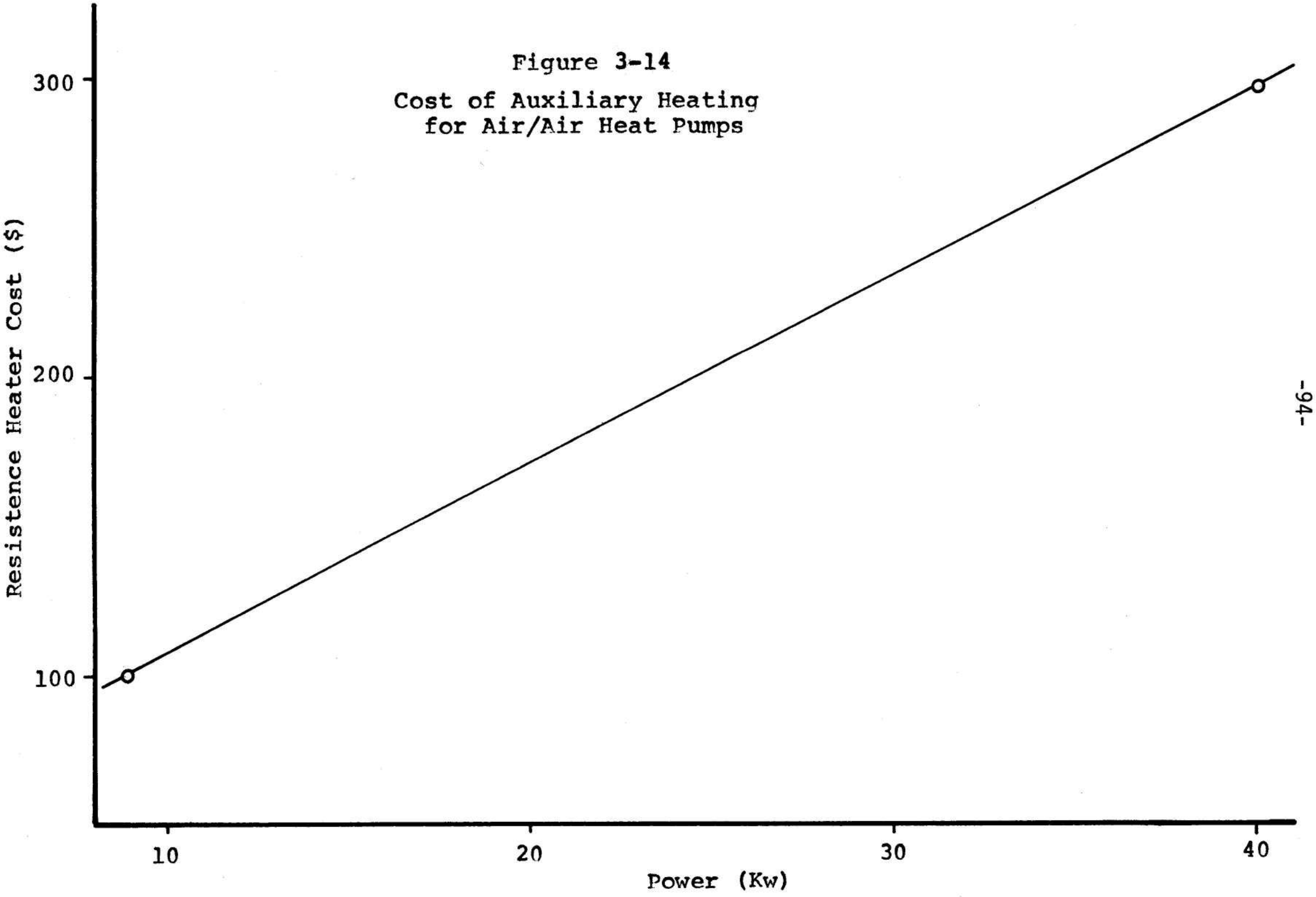


Figure 3-14

Cost of Auxiliary Heating for Air/Air Heat Pumps

Table 3-6

Air/Air Heat Pump Cost for 3 Residential Types

	Single Unit Home	Four Unit Apt.	Twelve Unit Apt.
Heat Pump Cost	$1488	$4546	$9092
Installation/Wiring/ Thermostats	$350	$600	$1400
Auxiliary Heaters	$106	$235	$558
Ductwork and Installation	$2170	$6380	$15880
Total	$4114	$11761	$26930

conditioning and heating contractors, three methods were used to arrive at a "typical" cost. Method I was based on a cost of $\$0.55/ft^2$ of residential surface. Method II used a percentage of 50% of the total cost. Method III assumed an average of $20/ft of ducting. The calculated cost variance is as much as 40% for the single unit house, but only 20% for the twelve unit apartments. Average cost is summarized in Table 3-7. Life of ductwork is estimated at forty years.(17)

3.7 Furnaces

The reference heating mode used for comparison purposes is a gas furnace system. Current prices obtained from the Aspinwall Plumbing and Heating Co. (Brookline, Mass.) are shown in Table 3-8. Estimated life of the furnace is twenty years with annual cost being two percent of original equipment cost.(17) Furnace efficiency is 65%, which is reported to be satisfactorily used for sizing purposes.(19)

3.8 Gas and Electric Rates

Current residential natural gas rates are shown in Table 3-9. The fuel adjustment charge is $0.093/100cf. Using a gas heating valve of 1022 btu/cf(28) and a furnace efficiency of 65%, the integrated average rate for a single unit home is $0.31/100 cf. Addition of the fuel adjustment charge results in an average of $0.403/100 cf.

Current electric rates for all-electric residences are shown in Table 3-10. The average 1976 (January-April) fuel adjustment charge

Table 3-7

Average Ductwork Cost

Single Unit	$2170
Four Unit Apt.	$6380
Twelve Unit Apt.	$15880

Table 3-8

Average Costs for Gas Furnaces

Furnace Rating (btu/hr)	Equip. Cost	Total Cost Installation & Baseboards
49000	$450	$1800
160000	$700	$2600
400000	$1300	$3500 - $4000

Table 3-9

Residential Gas Rates*
(Boston Gas)

↑ 100 cf	$2.95
+ 900 cf	$0.452/100 cf
+ 1500 cf	$0.33/100 cf
+ 5000 cf	$0.285/100 cf
+ 12500 cf	$0.255/100 cf
+ 20000 cf	$0.235/100 cf

symbols

↑=up to
+=increment

*Rates are exclusive of fuel adjustment charges.

Table 3-10

Electric Rate for All-electric Residences*
(Boston Edison Co.)

↑ 15 Kwhr/mon	$1.94
+ 35 Kwhr/mon	5.6¢/Kwhr
+ 50 Kwhr/mon	4.3¢/Kwhr
+ 50 Kwhr/mon	3.5¢/Kwhr
+ 234 Kwhr/mon	2.0¢/Kwhr
+ 616 Kwhr/mon	2.5¢/Kwhr
+ on up	1.4¢/Kwhr

symbol

↑=up to
+=increment

* Rates are exclusive of fuel adjustment charges.

is \$0.0186/Kw Hr. By a calculation similar to that done for the gas rate, an integrated average rate of 2.1¢/Kw Hr is obtained. Adding on the fuel adjustment charge, the total rate is 3.96¢/Kw Hr or approximately 4¢/Kw Hr.

Assuming that residential electric rates also apply to electricity used for pumping water through the piping network, an average of 1.5¢/Kw Hr is used. With the fuel adjustment charges, the electricity rate for water pumping is 3.36¢/Kw Hr.

CHAPTER 4

Feasibility Study

The system model as described in Chapter 2 will be used with cost data from Chapter 3 to study the economics of a heating system involving heat pumps and power plant coolant water. First, the piping network cost is calculated and then the total cost of space heating with this system is compared to that of other modes. In addition, primary energy utilization will also be compared. Various parameters such as interest rates, heat pump COP, fuel cost and load factor will be adjusted to determine cost sensitivity. Finally, possible modifications of the proposed concept (single pipe system, combined heating and cooling, multiple heat sources and a system with auxiliary heating) are included.

4.1 Basic Networks

There are thirty basic piping networks with housing densities varying from 8000 to 1000 units per square mile (see section 2.1 for definition of a "unit"). The networks are further differentiated by housing types and overall temperature drop of the source water. For more detail, the reader is referred to sections 2.2, 2.5, and 2.8. The cost of each network is calculated by the method described in section 2.10. A summary of annual network cost and pumping energy is presented in Table 4-1 and Table 4-2. Each 36 square mile density network is

Δ T=20° F DENSITY NETWORK SUMMARY**

Table 4-1

Unit Structure	Unit Density	Sq. Mile	Annual Cost ($M)	Pipe Cost %*	Valve Cost %*	Pump Cost %*	Electric Cost %*	Pumping Power 106 (Kwhr/yr)	Annual Cost per Unit	Annual Pumping Energy per Unit (Kwhr/yr)
12	8000	1	0.987	53.1	0.7	2.0	5.2	1.538	123.4	192.3
		36	57.94	48.7	0.7	2.5	11.9	205.0	201.2	711.8
	6000	1	0.893	53.8	0.7	1.8	4.5	1.193	148.9	198.9
		36	50.64	49.8	0.7	2.3	10.4	156.5	234.4	724.6
	4000	1	0.626	53.9	0.6	1.6	4.8	0.903	156.5	225.6
		36	36.16	48.6	0.6	3.0	11.4	122.5	251.1	850.5
	2000	1	0.442	55.7	0.3	1.0	3.1	0.411	220.8	205.4
		36	24.00	51.1	0.4	2.2	8.7	62.37	333.3	866.3
	1000	1	0.309	56.5	0.3	0.7	2.5	0.233	309.0	233.1
		36	16.23	52.5	0.3	1.6	7.7	37.10	450.7	1031.
4	8000	1	1.967	54.9	0.9	1.3	2.9	1.717	245.8	214.7
		36	97.84	51.2	0.9	1.9	8.3	240.9	339.7	836.4
	6000	1	1.507	55.1	0.8	1.3	3.0	1.332	251.1	222.1
		36	75.75	51.4	0.7	1.8	8.3	188.2	350.7	871.4
	4000	1	1.224	55.7	0.5	1.0	2.8	1.033	306.0	258.2
		36	60.29	51.4	0.5	2.3	7.9	141.9	418.7	985.6
	2000	1	0.724	56.2	0.3	0.8	2.7	0.573	362.2	286.7
		36	35.22	52.3	0.4	2.0	7.2	75.35	489.2	1047.
	1000	1	0.607	57.1	0.2	0.5	1.9	0.335	607.4	335.0
		36	27.88	54.3	0.3	1.2	5.3	43.77	774.6	1216.

*Cost percentage of total annual cost.
**Cost calculated according to Sections 2.9 and 2.10.

Table 4-1 (continued)

Unit Structure	Unit Density	Sq. Mile	Annual Cost ($M)	Pipe Cost %*	Valve Cost %*	Pump Cost %*	Electric Cost %*	Pumping Power 10^6 (Kwhr/yr)	Annual Cost per Unit	Annual Pumping Energy per Unit (Kwhr/yr)
1	8000	1	3.336	56.4	0.4	0.9	2.1	2.038	417.0	254.7
		36	151.4	53.5	0.5	1.4	6.0	268.7	525.8	933.0
	6000	1	2.669	56.4	0.3	0.8	2.3	1.839	444.9	306.5
		36	120.5	53.7	0.4	1.4	5.8	208.1	558.0	963.5
	4000	1	1.986	56.8	0.3	0.7	1.8	1.083	496.6	270.7
		36	89.44	54.0	0.4	1.2	5.5	147.6	621.1	1025.
	2000	1	1.679	57.6	0.1	0.4	1.2	0.620	839.7	309.9
		36	71.42	55.1	0.2	1.1	4.1	87.43	991.9	1214.
	1000	1	0.989	57.7	0.2	0.3	1.2	0.359	989.3	358.8
		36	42.21	55.3	0.2	0.9	4.1	51.55	1172.	1432.

Δ T=40° F DENSITY NETWORK SUMMARY** Table 4-2

Unit Structure	Unit Density	Sq. Mile	Annual Cost ($M)	Pipe Cost %*	Valve Cost %*	Pump Cost %*	Electric Cost %*	Pumping Power 106 (Kwhr/yr)	Annual Cost per Unit	Annual Pumping Energy per Unit (Kwhr/yr)
12	8000	1	0.833	55.3	0.3	1.2	3.6	0.900	104.1	112.5
		36	43.59	50.4	0.4	2.5	9.4	122.4	151.4	425.0
	6000	1	0.746	55.9	0.3	1.0	2.8	0.626	124.3	104.4
		36	38.22	51.7	0.4	2.3	7.7	87.45	176.9	404.9
	4000	1	0.528	56.1	0.3	0.9	2.8	0.442	131.9	110.4
		36	27.11	51.9	0.4	2.0	7.9	63.48	188.2	440.8
	2000	1	0.387	57.3	0.2	0.5	1.6	0.180	193.3	90.2
		36	19.02	53.6	0.3	1.3	6.2	35.20	264.1	488.9
	1000	1	0.280	57.4	0.2	0.3	1.8	0.150	279.5	150.2
		36	13.40	54.4	0.2	0.9	5.8	22.98	372.3	638.3
4	8000	1	1.386	56.1	0.4	0.9	2.5	1.033	173.3	129.2
		36	66.13	52.1	0.5	2.1	7.2	141.9	229.6	492.9
	6000	1	1.250	56.6	0.2	0.7	2.2	0.815	208.3	135.8
		36	58.30	53.0	0.3	1.8	6.5	112.1	269.8	519.0
	4000	1	1.025	56.9	0.2	0.6	2.0	0.605	256.4	151.2
		36	46.50	53.8	0.3	1.5	5.7	78.67	323.2	546.3
	2000	1	0.605	57.1	0.2	0.5	2.0	0.357	302.4	178.5
		36	27.79	54.3	0.2	1.2	5.4	44.56	386.0	618.9
	1000	1	0.448	57.8	0.1	0.2	1.1	0.152	448.0	151.6
		36	19.94	55.2	0.2	0.8	4.6	27.2	554.0	755.7

* Cost percentages of total annual cost.

** Cost calculated according to Sections 2.9 and 2.10.

Table 4-2 (continued)

Unit Structure	Unit Density	Sq. Mile	Annual Cost ($M)	Pipe Cost %*	Valve Cost %*	Pump Cost %*	Electric Cost %*	Pumping Power 10^6 (Kwhr/yr)	Annual Cost per Unit	Annual Pumping Energy per Unit (Kwhr/yr)
1	8000	1	1.984	56.6	0.4	0.7	1.9	1.107	247.9	138.3
		36	89.34	53.9	0.5	1.2	5.6	148.4	310.2	315.4
	6000	1	1.681	56.9	0.2	0.7	2.0	0.997	280.2	166.1
		36	74.71	54.4	0.3	1.1	5.3	117.6	345.9	544.4
	4000	1	1.764	57.7	0.1	0.4	1.2	0.624	441.0	156.0
		36	74.46	55.3	0.2	1.1	4.0	87.58	517.1	608.2
	2000	1	1.148	57.9	0.1	0.3	1.0	0.348	574.0	174.0
		36	47.92	55.8	0.2	0.8	3.6	51.18	665.6	710.8
	1000	1	0.821	58.1	0.1	0.2	0.9	0.213	821.0	212.5
		36	33.75	56.5	0.1	0.6	2.9	29.16	937.4	809.9

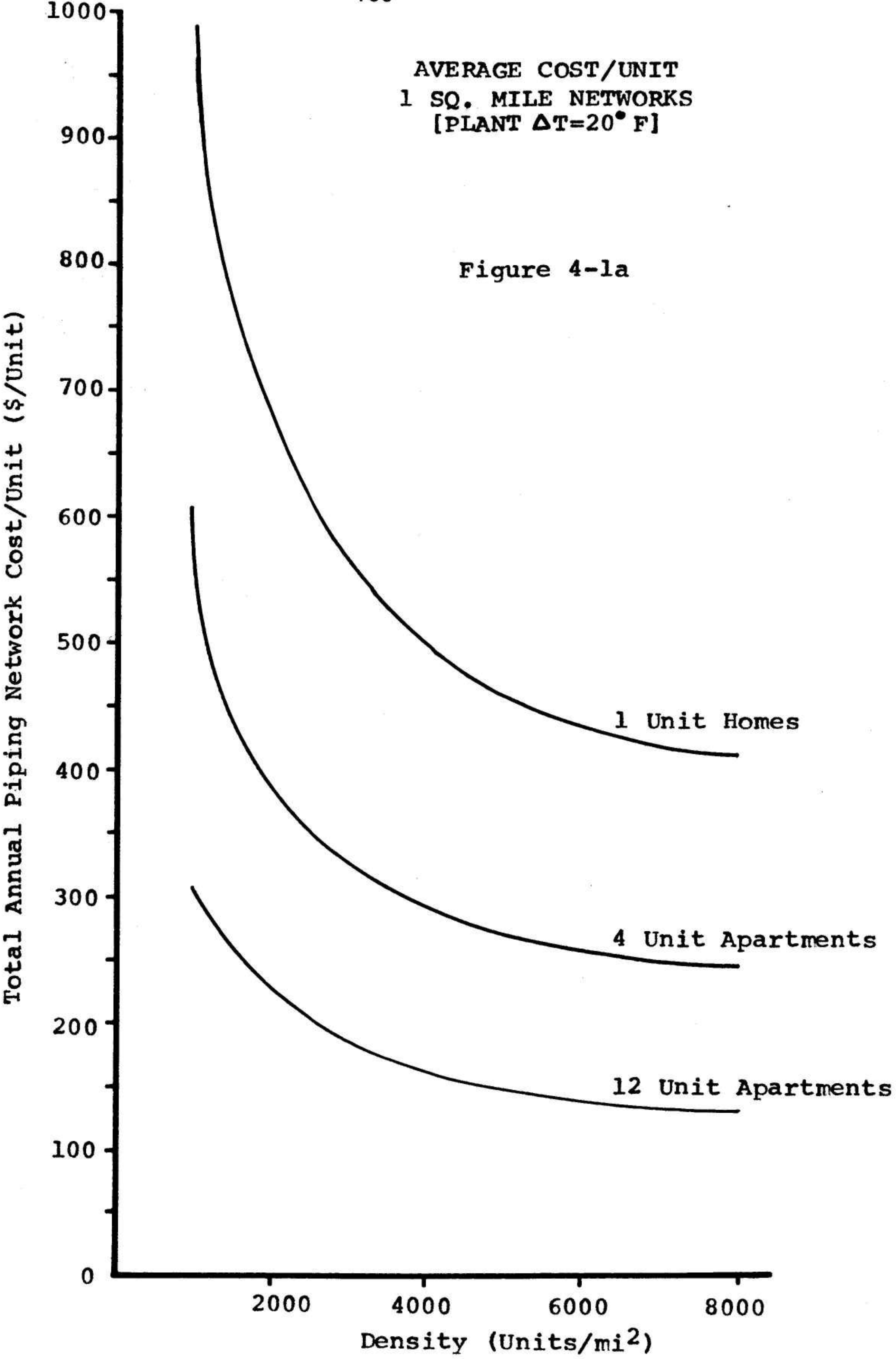
further broken down to show cost and pumping energy for each square mile sub-network.

Examination of Tables 4-1 and 4-2 shows the dominance of the pipe installation component at about 55% of the total piping network annual cost. Cost of valves and pumps is negligible, being on the order of 2.5% combined. Electricity cost for pumping the water is also small, ranging from about 4 to 10% for the 36 square mile networks. Remaining cost items consist of engineering charges for the original system and annual maintenance, which is on the order of 30% of the total annual cost. Cost for lost generating capacity for the delta T = $40^{o}F$ is charged based on the amount of heat used by each residence.

As noted in section 2.5, one of the primary objectives of the system model is to obtain generalized cost-density relationships for each of the housing types and plant delta T's. Cost data from Tables 4-1 and 4-2 are plotted and shown in Figures 4-1 and 4-2. Curves for annual pumping energy as a function of density are shown in Figures 4-3 and 4-4. It is noted that the sum of the annual cost per unit for the square mile networks makes up 65-80% of the total annual cost for the 36 square mile network. The remaining 35-20% is due to the distribution network connecting the square mile networks.

4.2 Metropolitan Boston Tracts

The annual cost and pumping power for each tract of the Metropolitan Boston area are estimated by interpolating and ratioing from



AVERAGE COST/UNIT
1 SQ. MILE NETWORKS
[PLANT ΔT=20° F]

Figure 4-1a

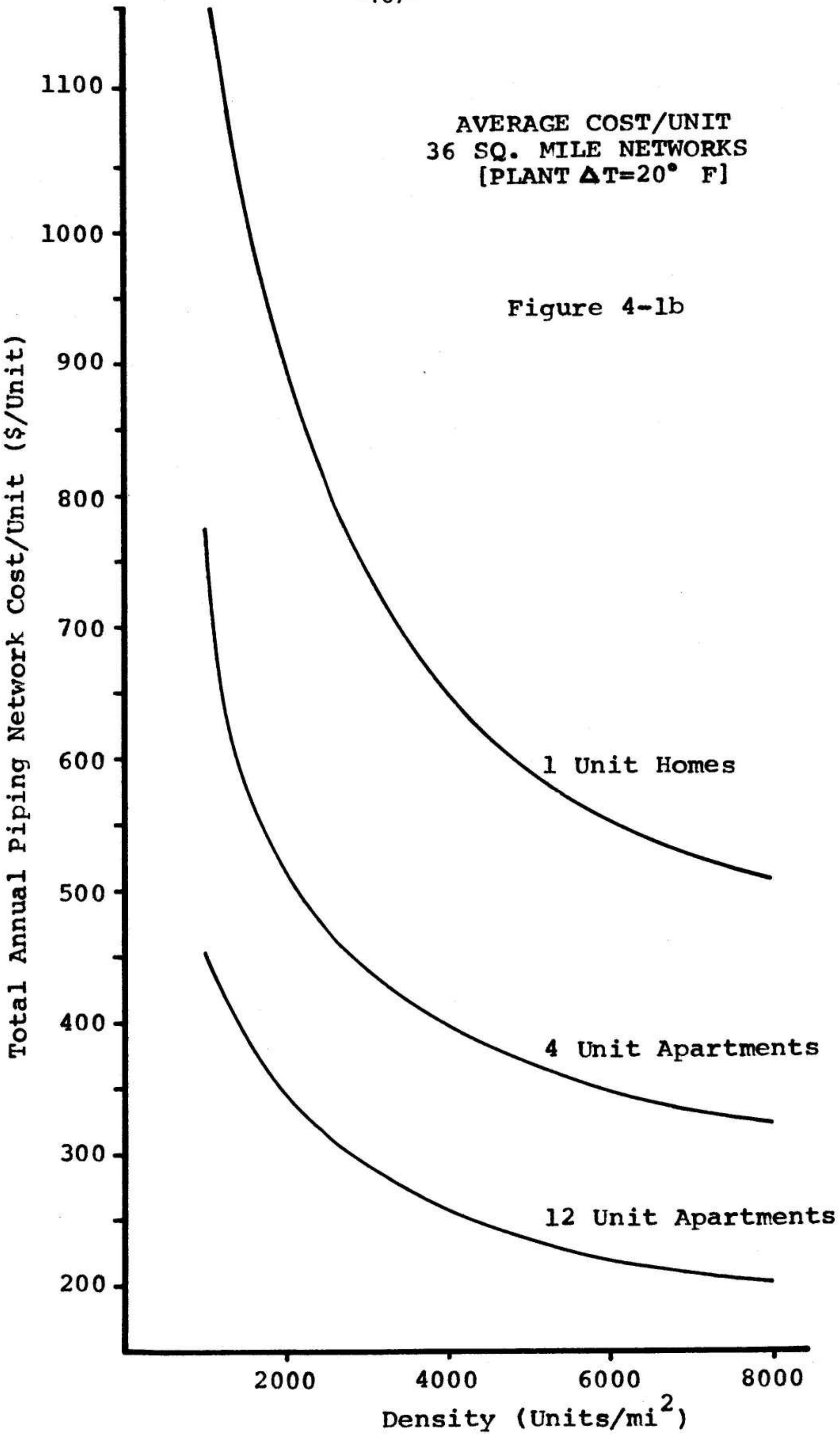
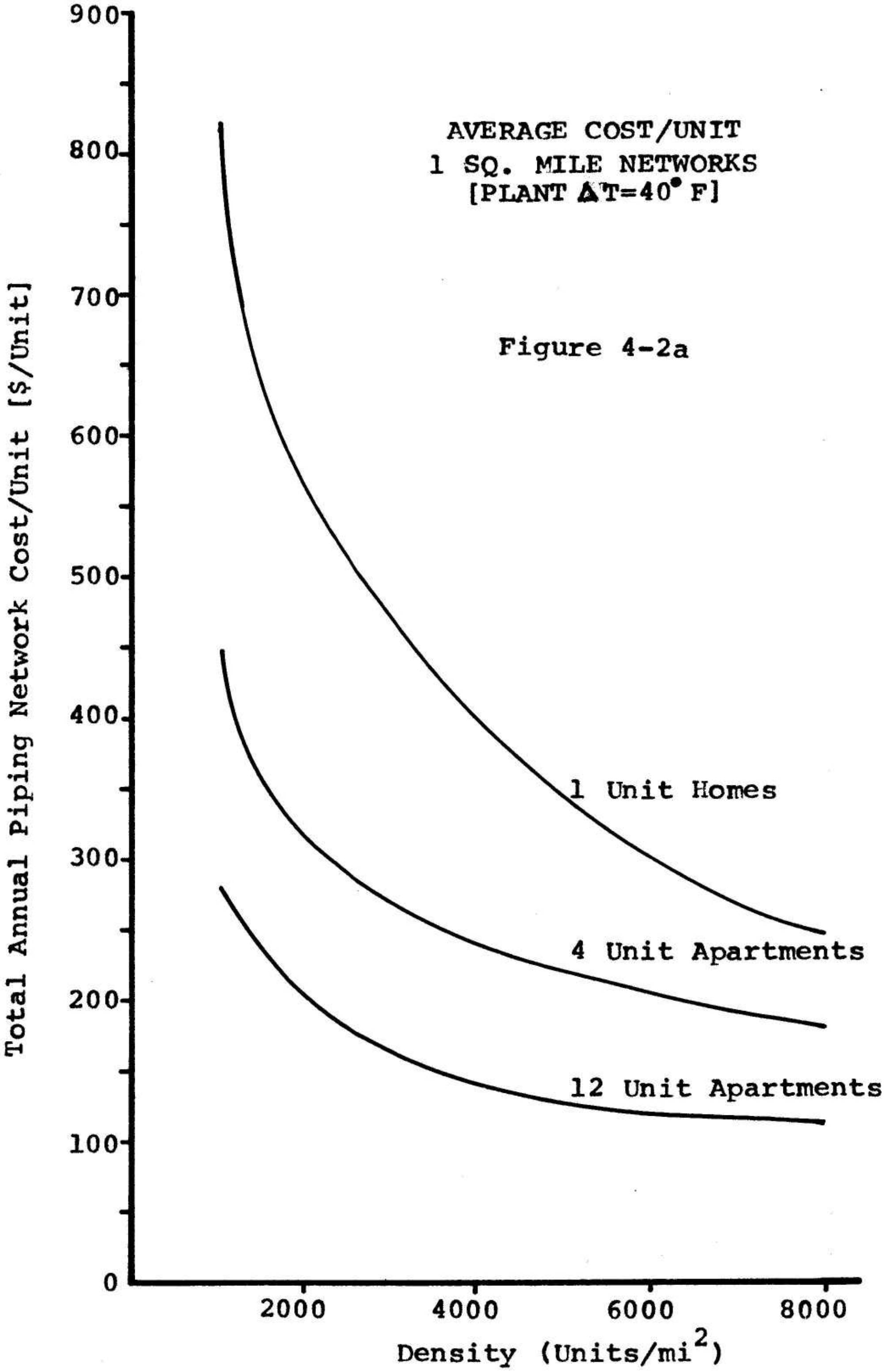

AVERAGE COST/UNIT
36 SQ. MILE NETWORKS
[PLANT ΔT=20° F]
Total Annual Piping Network Cost/Unit ($/Unit)
1100
1000
900
800
700
600
500
400
300
200
1 Unit Homes
4 Unit Apartments
12 Unit Apartments
2000
4000
6000
8000
Density (Units/mi²)

Figure 4-1b


AVERAGE COST/UNIT
1 SQ. MILE NETWORKS
[PLANT ΔT=40° F]
Figure 4-2a
Total Annual Piping Network Cost/Unit [$/Unit]
900
800
700
600
500
400
300
200
100
0
2000
4000
6000
8000
Density (Units/mi²)
1 Unit Homes
4 Unit Apartments
12 Unit Apartments

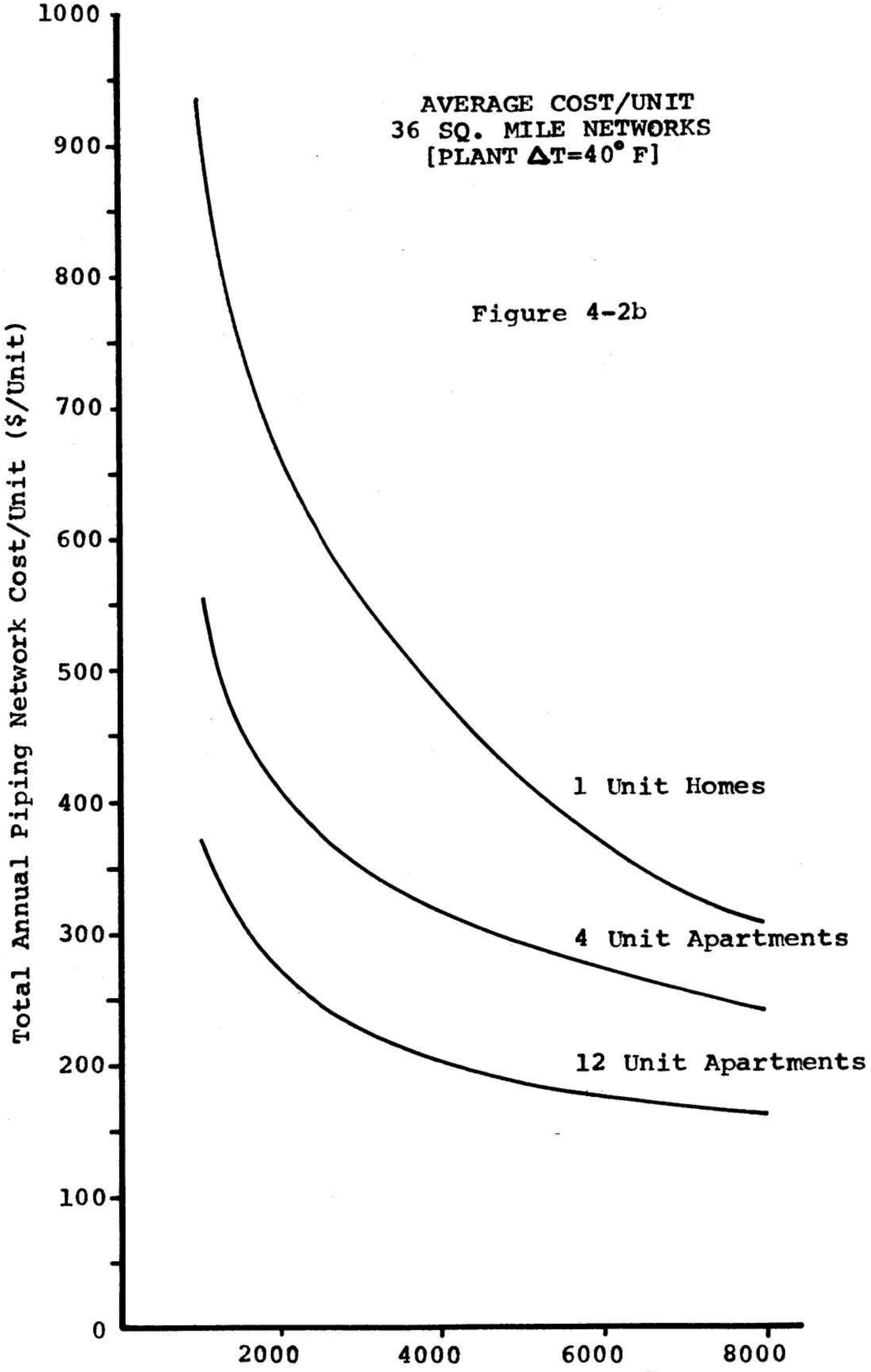

AVERAGE COST/UNIT
36 SQ. MILE NETWORKS
[PLANT ΔT=40° F]
1 Unit Homes
4 Unit Apartments
12 Unit Apartments
Total Annual Piping Network Cost/Unit ($/Unit)
1000
900
800
700
600
500
400
300
200
100
0
2000
4000
6000
8000
Density (Units/mi²)

Figure 4-2b

Figure 4-3

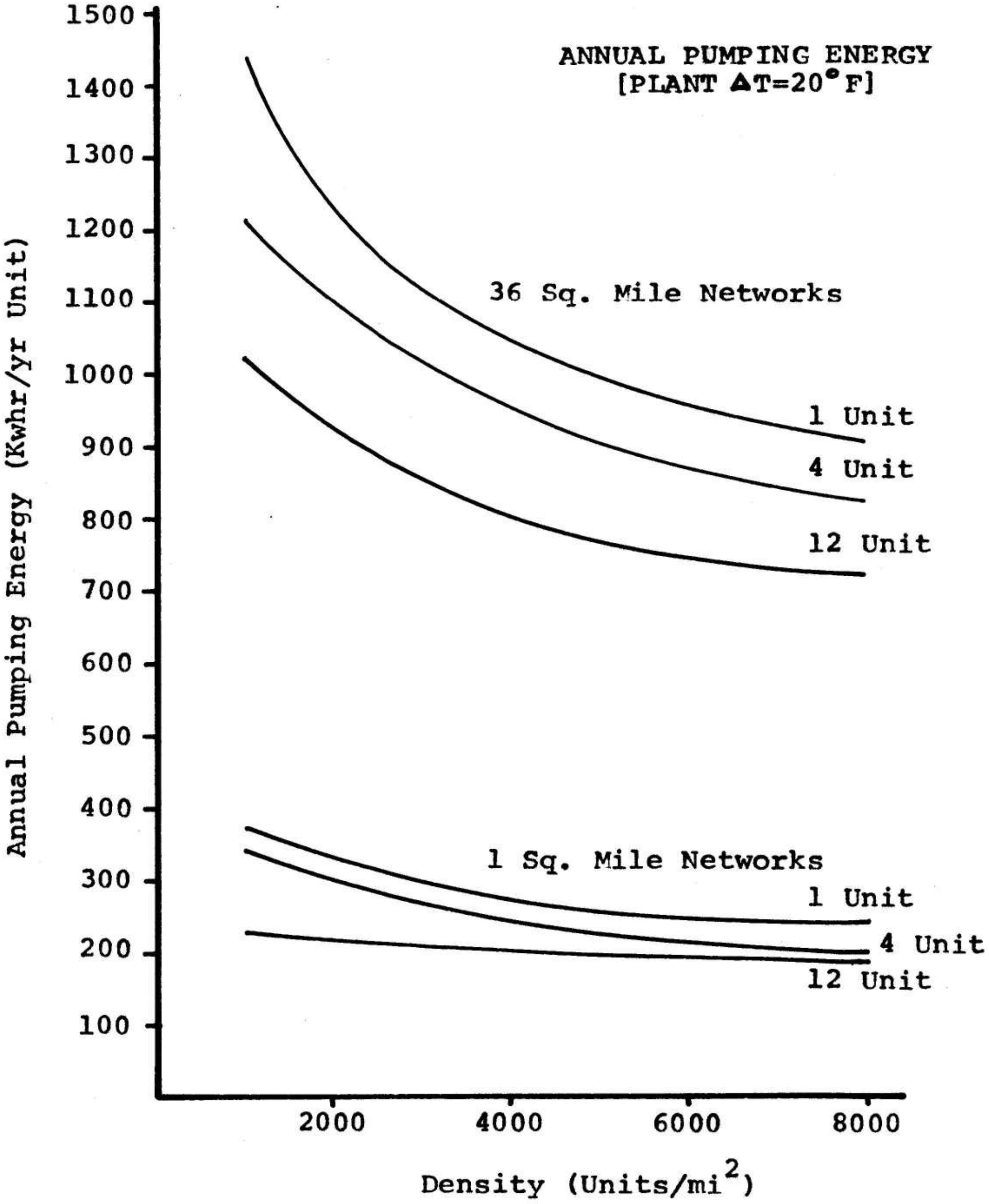
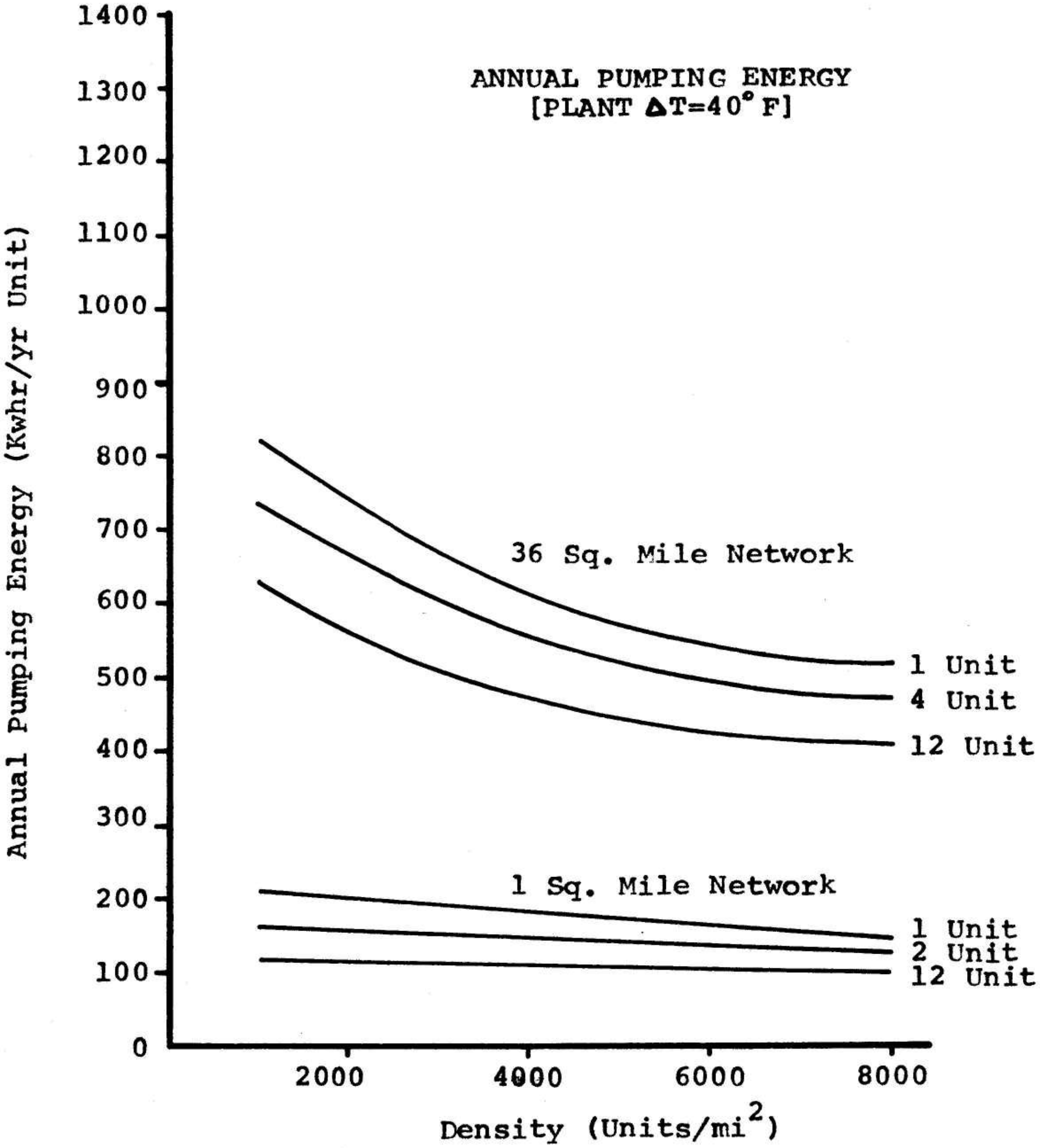

ANNUAL PUMPING ENERGY
[PLANT ΔT=20° F]
36 Sq. Mile Networks
1 Unit
4 Unit
12 Unit
1 Sq. Mile Networks
1 Unit
4 Unit
12 Unit
Annual Pumping Energy (Kwhr/yr Unit)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
2000
4000
6000
8000
Density (Units/mi²)

Figure 4-4


ANNUAL PUMPING ENERGY
[PLANT ΔT=40° F]
Annual Pumping Energy (Kwhr/yr Unit)
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
36 Sq. Mile Network
1 Unit
4 Unit
12 Unit
1 Sq. Mile Network
1 Unit
2 Unit
12 Unit
2000
4000
6000
8000
Density (Units/mi²)

the basic network data of the previous section (see section 2.11). Each tract network is assumed to be independent of the other tract networks. The tracts are linked together by a distribution network which originates from the power plant. A summary of each tract is presented in Table 4-3. A lower limit of 1000 units per square mile is used.

The tracts are linked according to a density criterion. The N1 and N3 networks include all tracts with at least 1000 units per square mile (refer to Figure 4-5). The N1 network is for a system delta T of 20^{0}F, while the N3 is for a delta T of 40^{0}F. The power plant, or energy center, is assumed to be located on a site which is approximately 11 miles from the downtown area. The N2 and N4 networks (Figure 4-6) include those tracts with at least 2000 units per square mile. The N1 and N3 networks each contain a total of 658,750 units or approximately two million people, while the N2 and N4 networks each contain 445,710 units or about 1.3 million people. Cost summary for the system networks is presented in Table 4-4 and the pumping energy per network is shown in Table 4-5. It is to be noted that the tract distribution network makes up only 18-26% of the total annual cost.

For simplicity, it has been assumed that all the source water originates from one site. To supply peak space heating needs for the N1 and N3 systems, an energy center with a total electrical generating capacity of 3000 MW(e) is needed. For the N2 and N4 systems, a 2000 MW (e) generating complex is needed. A dual plant system is treated in section 4.14.

Tract #	Density ($Units/mi^2$)	Area (mi^2)	Total Units	Annual Network Cost ($M)		Pumping Energy (10^6 Kwhr/yr)		Flow Req. (10^3 gpm)	
				Δ T=20	Δ T=40	Δ T=20	Δ T=40	Δ T=20	Δ T=40
20	1068	36	38450	35.48	27.12	49.46	29.21	123.6	61.8
28	1154	36	41540	38.90	29.63	53.18	31.11	135.7	67.8
29	1217	36	43810	36.51	27.47	53.58	31.72	138.7	69.4
33	2331	36	83920	49.85	37.06	88.70	51.54	261.8	130.9
38	2088	36	75170	48.19	34.89	80.34	46.83	232.9	116.5
43	1554	36	55940	42.55	31.20	64.84	38.20	177.7	88.8
44	925	36	33300	34.76	27.43	45.80	26.74	109.6	54.8
62	3870	9	34830	15.89	12.51	34.41	19.34	107.1	53.6
63	3175	9	28570	14.61	11.33	29.03	16.58	89.2	44.6
64	2368	9	21310	10.74	8.26	22.00	12.75	64.5	32.3
65	6357	9	57210	19.61	14.30	48.29	28.30	168.6	84.3
66	7584	9	68260	20.24	14.14	54.23	31.87	192.6	96.3
67	2944	4.5	13250	6.10	4.72	13.20	7.48	39.6	19.8
68	3080	2.25	6930	3.33	2.57	6.87	3.89	20.9	10.5
69	6251	9	56260	20.11	14.7	48.43	28.51	168.8	84.4

SUMMARY of NETWORKS for
METROPOLITAN BOSTON TRACTS

Table 4-3

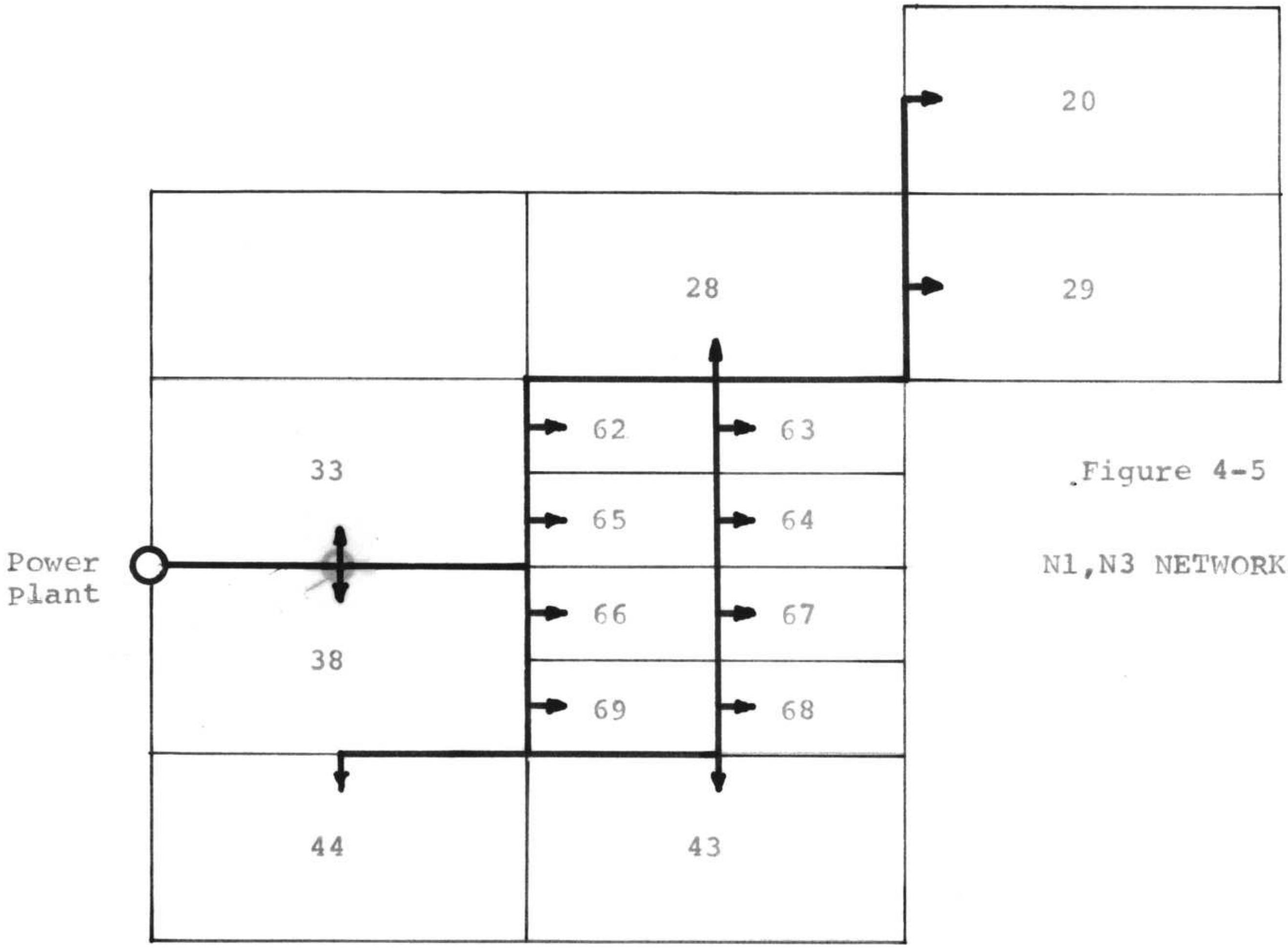
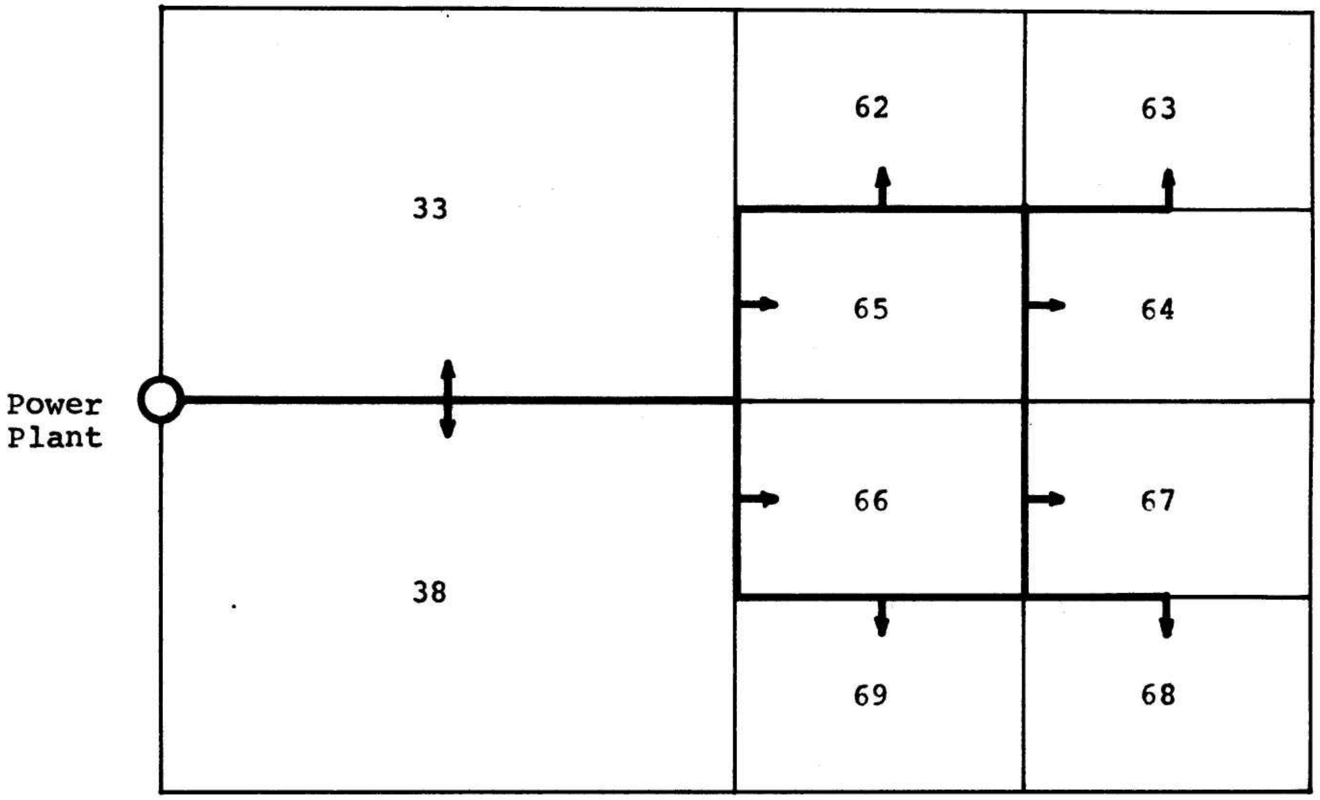


Figure 4-5

N1,N3 NETWORKS

NOTE: Numbers are Metropolitan Boston tracts.
N1 is a $\Delta T=20^{\circ}F$ system. N3 is a $\Delta T=40^{\circ}F$ system.



N2,N4 NETWORKS

Figure 4-6

NOTE: Numbers are Metropolitan Boston tracts.
N2 is a $\Delta T=20^\circ$ F system. N4 is a $\Delta T=40^\circ$ F system.

		Tract Networks ($M)	Tract Distribution Network ($M)	Total ($M)	$\frac{\text{Cost}}{\text{Unit yr}}$
$\Delta T=20°$ F	N1	396.87	134.92	531.79	807
	N2	208.67	59.58	268.25	602
$\Delta T=40°$ F	N3	297.33	70.94	368.27	559
	N4	154.48	32.61	187.09	420

ANNUAL COST of SYSTEM NETWORKS

Table 4-4

		Tract Networks $10^6 \frac{\text{Kw hr}}{\text{yr}}$	Tract Distribution Network $10^6 \frac{\text{Kw hr}}{\text{yr}}$	Total $10^6 \frac{\text{Kw hr}}{\text{yr}}$	Average $\frac{\text{Kw hr}}{\text{Unit yr}}$
$\Delta T=20^\circ F$	N1	692.4	564.9	1257.3	1909
	N2	425.5	286.3	711.8	1597
$\Delta T=40^\circ F$	N3	404.1	318.6	722.7	1097
	N4	247.1	157.3	404.4	907

ANNUAL PUMPING ENERGY of SYSTEM NETWORKS

Table 4-5

4.3 Heating Mode Cost Comparison

The total annual cost for the warm water/heat pump system consists of the average network cost per unit plus the cost of the individual heat pump system. The average network costs per unit are discussed in the previous section, while water heat pump costs are discussed in section 3.4. The total annual heating cost is dependent on the size of the network and the residential type. Air/air heat pump systems using ambient air as a heat source are also included for comparison purposes. The reference heating mode is a gas furnace-baseboard system. Cost for an air/air system is discussed in section 3.5, while the gas furnace is discussed in section 3.7. Fuel and energy rates can be found in section 3.8. A summary of the annual cost for each of the systems is presented in Table 4-6. Cost penalties for lost electrical generating capacity due to a higher than conventional send-out temperature for the delta T = 40^oF system are included for the N3 - N5 networks. The N5 network is identical to the N4, except that tracts 33 and 38 are omitted to obtain a higher overall density for the area covered. Average per unit cost is $383 annually; a nine percent reduction from the N4. However, overall heating system savings is less than three percent.

Exclusive of network costs, heat pump cost for the single unit home averages less for the delta T = 40^oF system than for the delta T = 20^oF system, due to the installation of smaller heat pumps. For the cases of the 4 and 12 unit apartments, where the same size units are installed for both delta T's, improved performance at the

	Single	4 Apt.	12 Apt.
Gas Furnace	857	613	504
Air/Air Heat Pumps**	1031	821	664
Water/Air Heat Pump (Exclude network)	(936)	(683)	(575)
$\Delta T=20^\circ$ w/ N1	1743	1490	1382
w/ N2	1538	1285	1177
Water/Air Heat Pump (Exclude network)	(910)	(700)	(581)
$\Delta T=40^\circ$ w/ N3	1469	1259	1140
w/ N4	1330	1120	1001
w/ N5	1293	1083	964

SUMMARY of ANNUAL COST ($/Unit)
for VARIOUS HEATING SYSTEMS*

Table 4-6

* Cost are calculated at 9% interest using details provided in Chapter 3.

** 1/2 credit is taken on capital cost for cooling function.

Note: Cost of gas is $0.403/100 cf
Cost of electricity is 4¢/Kw hr

higher source temperature for the delta T = 40°F system is offset by the cost of power lost at the power plant. It should be noted that one half of the air/air heat pump capital cost is credited for the air conditioning mode. However, for a given area coverage, the delta T = 40°F networks are less expensive by thirty percent, making annual costs less for the higher temperature systems.

The cost summary shows that at present day fuel prices, neither the air/air heat pump system nor the water/air system can compete with the gas furnace system as heating modes. The warm water-heat pump system's shortcoming is that it couples two high capital cost components, each of which is about the same magnitude as gas furnace cost.

4.4 Primary Energy Usage

The primary energy usage of various heating systems is shown in Table 4-7. Primary energy is defined as the energy derivable from the original fuel. Electricity, for example, is not a primary energy because the efficiency of overall electrical generation must be accounted for to arrive at the primary energy consumption for electrical heating modes (see section 2.12).

From an energy usage standpoint, the warm water-heat pump system is clearly superior. A savings of up to 26% can be achieved for the delta T = 20°F system and up to 30% for the delta T = 40°F system can be saved. The gas furnace is used as the reference energy user.

Table 4-7

SUMMARY of PRIMARY ENERGY USAGE

$(10^6 \frac{\text{btu}}{\text{yr}})$

		Single	4 Apt.	12 Apt.
	Gas Furnace	165.1 [100]*	136.5 [100]	117.9 [100]
	All Electric	325.2 [197]	268.8 [197]	232.3 [197]
Heat Pump Systems	Air/Air	162.6 [98]	134.4 [98]	116.1 [98]
	Water/Air (no network)	(115.6)	(84.8)	(73.7)
	ΔT=20° F w/ N1	135.6 [82]	104.8 [77]	93.7 [79]
	w/ N2	132.1 [86]	101.3 [74]	90.2 [77]
	Water/Air (no network)	(113.3)	(86.55)	(72.9)
	ΔT=40° F w/ N3	125.1 [76]	98.35 [72]	84.7 [72]
	w/ N4	123.1 [75]	96.35 [71]	82.7 [70]
	w/ N5	124.7 [76]	97.95 [72]	84.3 [72]

* Numbers in brackets are percentages based on gas furnace primary energy consumption.

Note: Efficiency of gas furnace is 65%.

4.5 Effect of Increased Fuel Cost

As noted in section 4.3, the warm water-heat pump system is capital cost dominated. The effect of increased fuel cost on overall annual cost would not be expected to be great. On the other hand, the capital cost component for the gas furnace system is small compared to the annual cost; therefore increases in fuel cost would balance the difference between the warm water-heat pump system and the gas furnace system. Table 4-8 shows that network cost increases due to a doubling of electric rates is indeed minor, about 7%. Overall effects of increased electric rates and gas rates are shown in Table 4-9. It can be seen that if gas rates were to double, then the warm water-heat pump system with the N4 network is economically competitive. If electric rates were to double, then gas rates would have to be almost triple for the warm water-heat pump system cost to remain even.

4.6 Effects of Interest Rates

Interest rate effects are most pronounced with the warm water-heat pump system. Based on a 9% interest rate, the N4 network heating system's annual cost variations for interest rates of 7 and 11% are ± 9 percent(since the N4 network system appears to be the best, it will be used for all subsequent analyses and comparisons). Annual cost for the apartments with gas furnaces is almost independent of interest rates, due to the low initial capital cost. Cost varia-

ANNUAL NETWORK COSTS
with DOUBLED ELECTRIC RATE
($/Unit)

		1 x rate	2 x rate
Networks	N1	807	865
	N2	602	647
	N3	559	594
	N4	420	448
	N5	383	411

Table 4-8

Note: Cost includes piping network only.

	2 x rate			3 x rate		
	single	4 Apt.	12 Apt.	single	4 Apt.	12 Apt.
Gas Furnace	1508	1151	969	2159	1689	1434
Air/Air Heat Pump*	1663	1341	1113	2291	1861	1562
Water/Air Heat Pump (no network)	(1382)	(1011)	(860)	(1829)	(1339)	(1145)
w/ N1	2247	1876	1725			
$\Delta T=20^\circ$ F						
w/ N2	2029	1658	1507			
Water/Air Heat Pump (no network)	(1358)	(1046)	(873)	(1806)	(1391)	(1164)
w/ N3	1952	1640	1467			
$\Delta T=40^\circ$ F						
w/ N4	1806	1494	1321			
w/ N5	1769	1457	1284			

ANNUAL COST ($/Unit) of HEATING SYSTEMS with INCREASED FUEL RATES

Table 4-9

* 1/2 credit is taken on capital cost for cooling function.

tions as a function of interest rates are shown in Figure 4-7.

4.7 Effects of Annual Load Factors

Boston's annual load factor is 0.25 (section 2.2). If the load factor were significantly larger, then the operating cost of a gas furnace system would increase more than the operating cost of the heat pump system. Therefore the overall cost difference would decrease. However, a study of the seasonal heating requirements of various American cities(3) shows that maximum load factors are generally 0.3. In cold regions of the U. S., the design temperature is lower than Boston's, such that the load factor does not usually go above 0.3. For this reason, calculation of heating cost with a load factor of 0.5, for example, would be unrealistic. As shown in Table 4-10, the cost ratio between gas furnace heating and warm water-heat pump heating improves with the higher load factor, but not enough to affect basic feasibility.

4.8 Annual Maintenance Cost Estimates

It is uncertain whether an annual charge of 5% initial cost for maintenance is applicable. District heating network maintenance ranges from 5 - 15%, while hot water systems generally use 5%.(4,30) However, in Miller's high temperature water system, 5% of initial cost for annual maintenance was discarded as being too conservative. Instead a 3 percent estimate was used.(1) In view of the fact that the

Figure 4-7

EFFECTS of INTEREST RATES

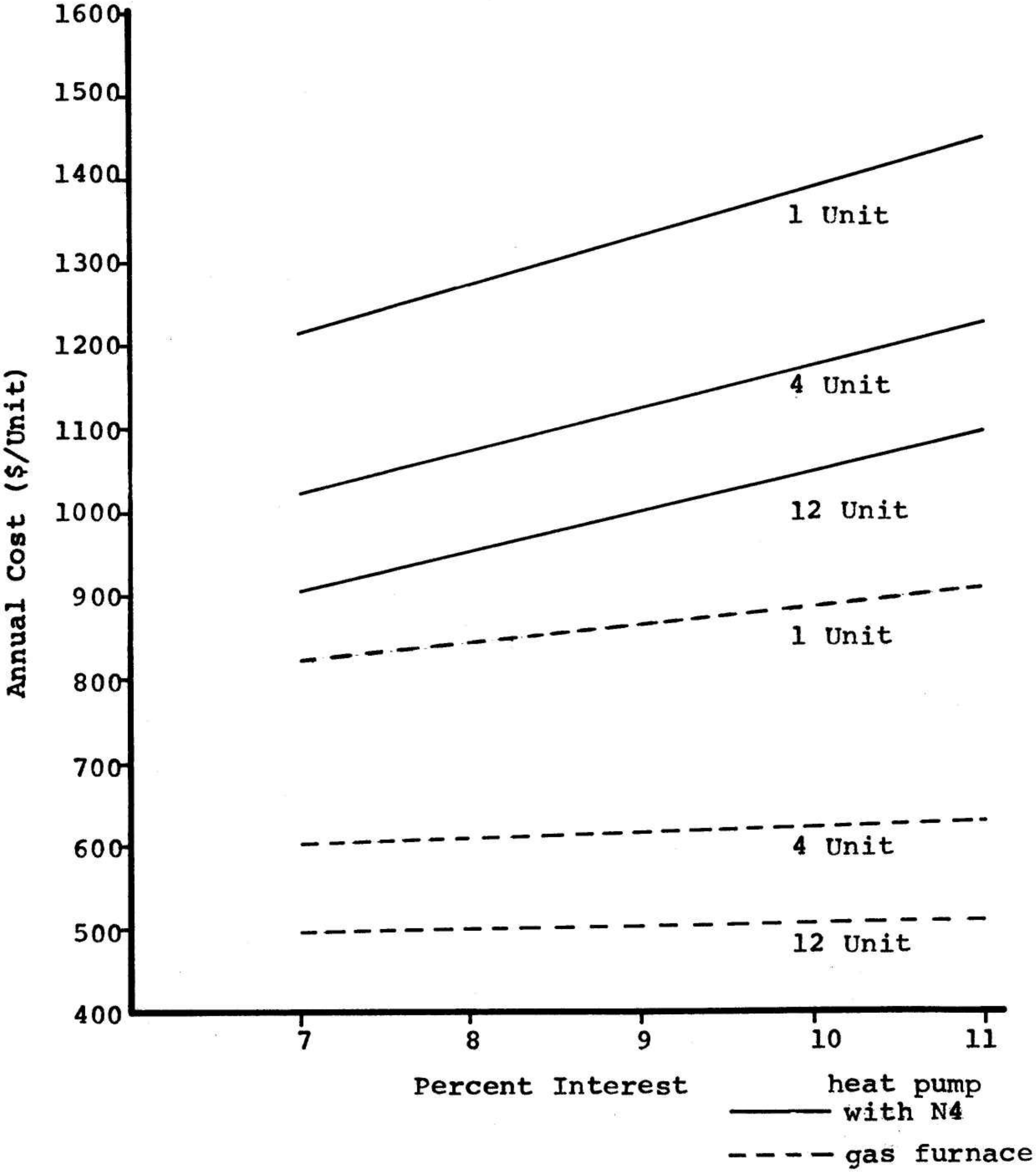


Table 4-10

	Load Factor					
	0.25			0.3		
	single	4 Apt.	12 Apt.	single	4 Apt.	12 Apt.
Gas Furnace	857	613	504	987	720	597
Water/Air Heat Pump (no network)	(910)	(700)	(581)	(999)	(770)	(639)
w/ N4	1330	1120	1001	1419	1190	1059

ANNUAL HEATING COST ($/Unit) with HIGHER LOAD FACTOR warm water networks require no pressurization to prevent water from flashing, a 3% estimate is probably more reasonable. Maintenance cost makes up roughly 30% of the annual network cost. By using a 3% estimate, the overall cost reduction for the N4 network is 12% (see Figure 4-8). The feasibility of the warm water-heat pump system, however, is not significantly affected.

4.9 Effects of Equipment Life Estimates

Revised extended life for some of the key equipment components has negligible effect on the total annual cost for the warm water-heat pump system. Piping is a major cost component, with an estimated life of fifty years. Reference 23 suggests that lifetimes of utility water piping are 100 years. Since the warm water system closely approximates utility water conditions, use of a 100 year piping life may be reasonable. The calculated annual capitalization at 100 years versus 50 years for interest rates of nine percent differs by only 1.3%, so that a revised extended pipe life estimate has a negligible effect.

The water/air heat pumps have estimated lifetimes of 15 years. Using a 20 year life as was done in reference 17 reduced annual heat pump cost by 11.3%. However, the duct work cost component remains unchanged and overall heat pump system savings is only 5%. When coupled with the N4 network, the total cost reduction for network and heat pumps is only 3.5%.

COST of N4 NETWORK
vs. MAINTENANCE ESTIMATES

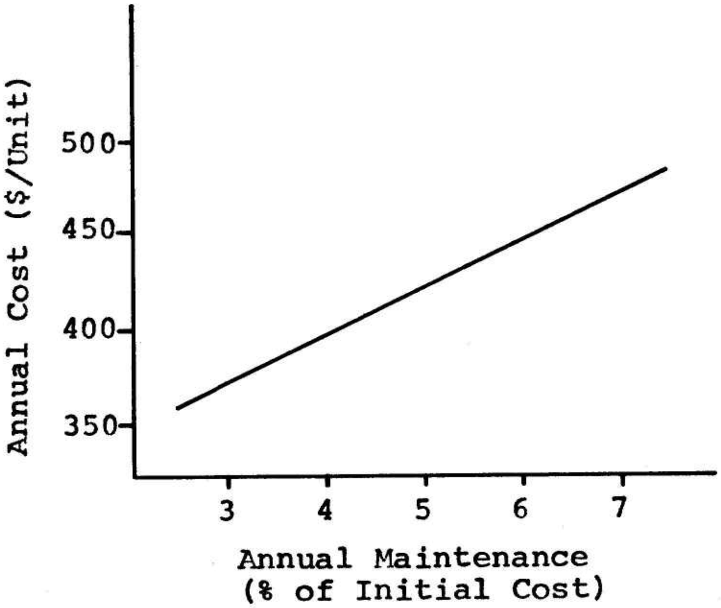


Figure 4-8

4.10 Effect of Localized Load Distribution

Results of a study on the uniformity of housing distribution show that in cases of networks involving low average densities, a significant cost advantage is achieved by clustering. Figure 4-9a is a schematic of a 2000 unit per square mile network, as used in this feasibility study. Figure 4-9b is an alternate design which does not have a uniform distribution of housing structures. Each block for the alternate design is denser than the equivalent block for the original. Calculated cost for the alternate design was less expensive than that for the original by 4% for a system delta T of 20^{o}F. For the case of 1000 units per square mile, the alternate design (Figure 4-10b) costs less than the original (Figure 4-10a) by about 30%. This points out the importance of local density effects, especially in the low average density areas. In communities where homes are clustered and surrounded by open space, a high local concentration may exist, whereas the average per mile density is very low. To deal with this effect would require much more detail than is within the scope of this study. However, it is noted that this effect is weak in areas of high density. Since the feasibility study neglects areas of very low density, the effect of localized concentration may not be overly significant.

4.11 Effects of Residential Block Feedline Configuration

Feedline configuration within a residential block may be an important cost factor. Figure 4-11a shows a standard residential block

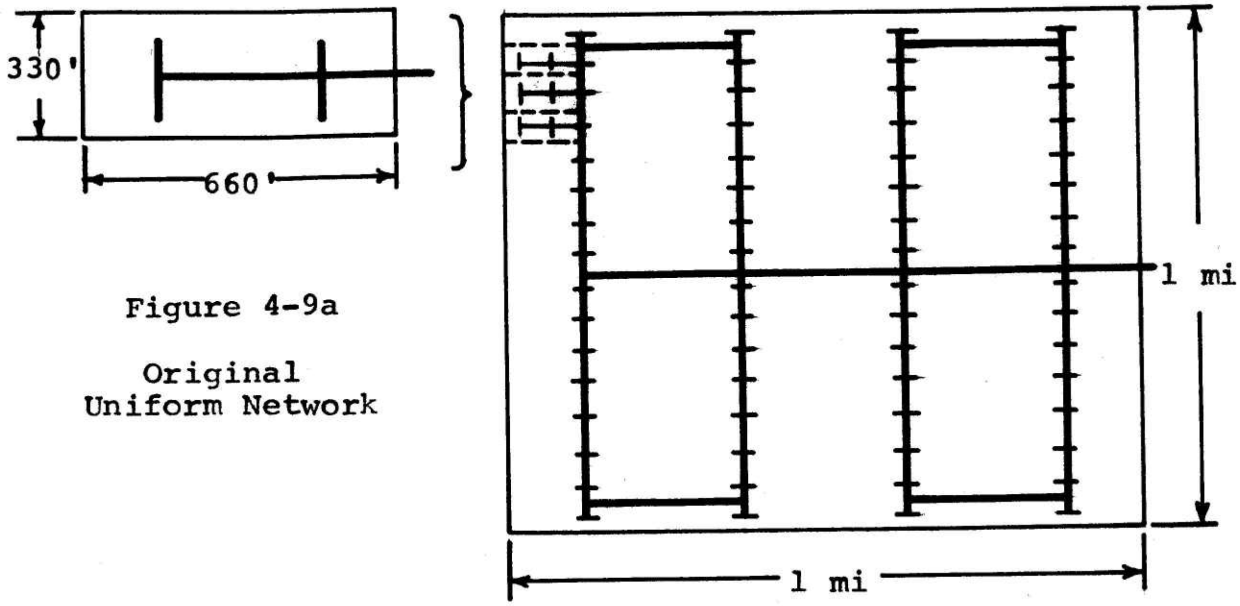


Figure 4-9a

Original
Uniform Network

LOCALIZED CONCENTRATION EFFECTS
2000 UNITS/MI^2 NETWORKS

Note: Feedlines for each block terminates
at a housing structure.

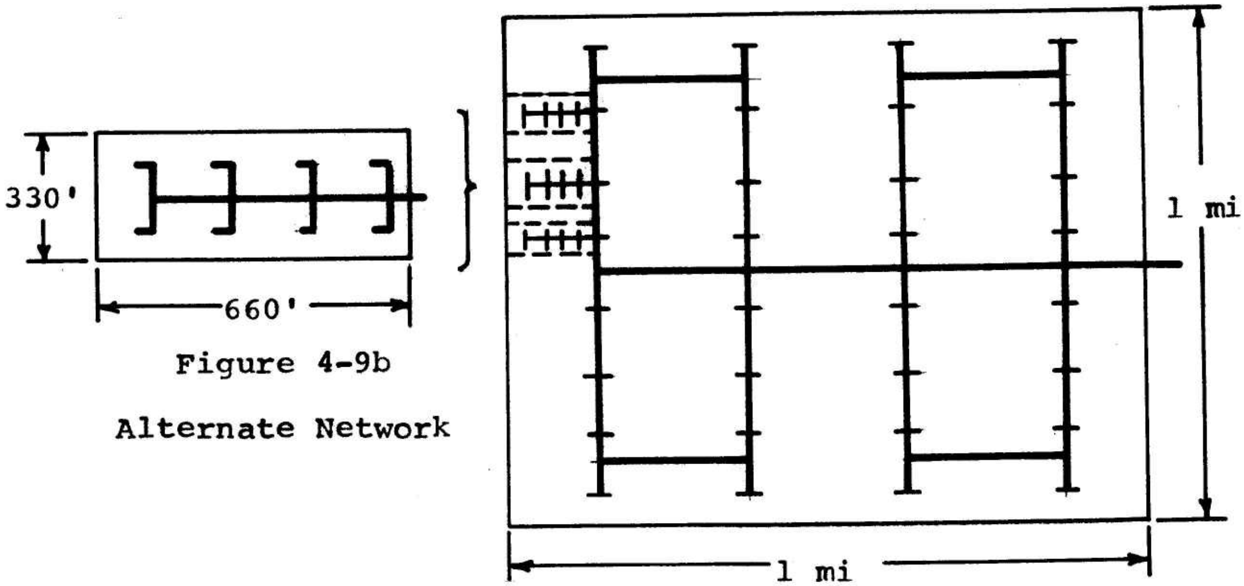


Figure 4-9b

Alternate Network

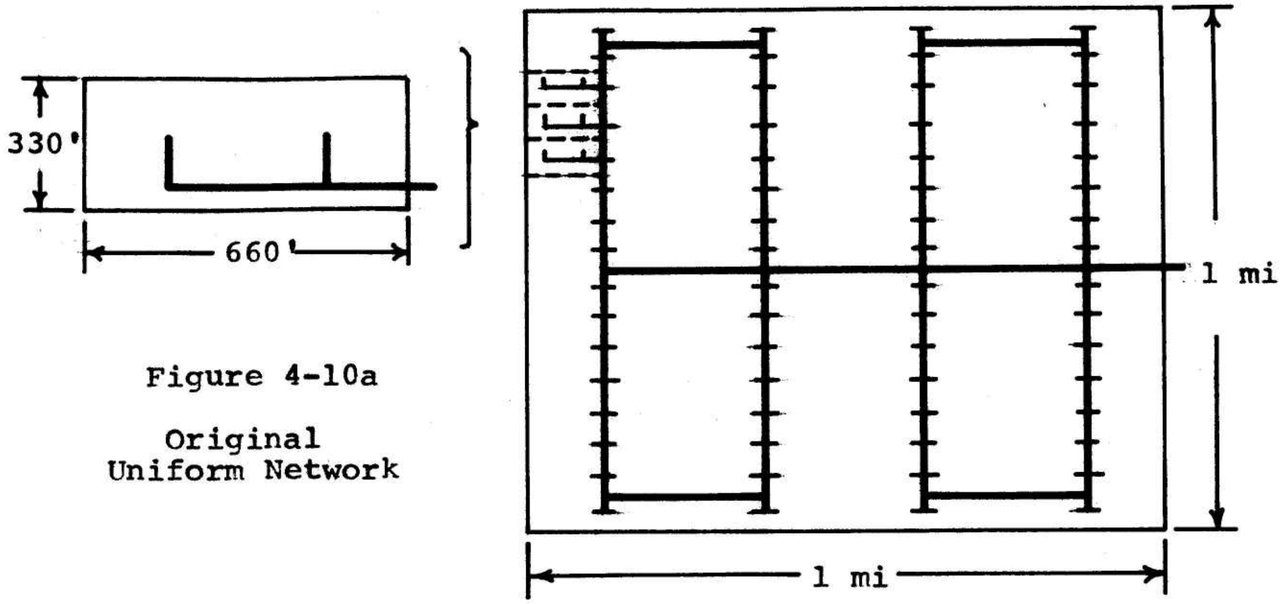


Figure 4-10a

Original
Uniform Network

LOCALIZED CONCENTRATION EFFECTS
1000 UNITS/MI^2 NETWORKS

Note: Feedlines for each block terminates at
a housing structure.

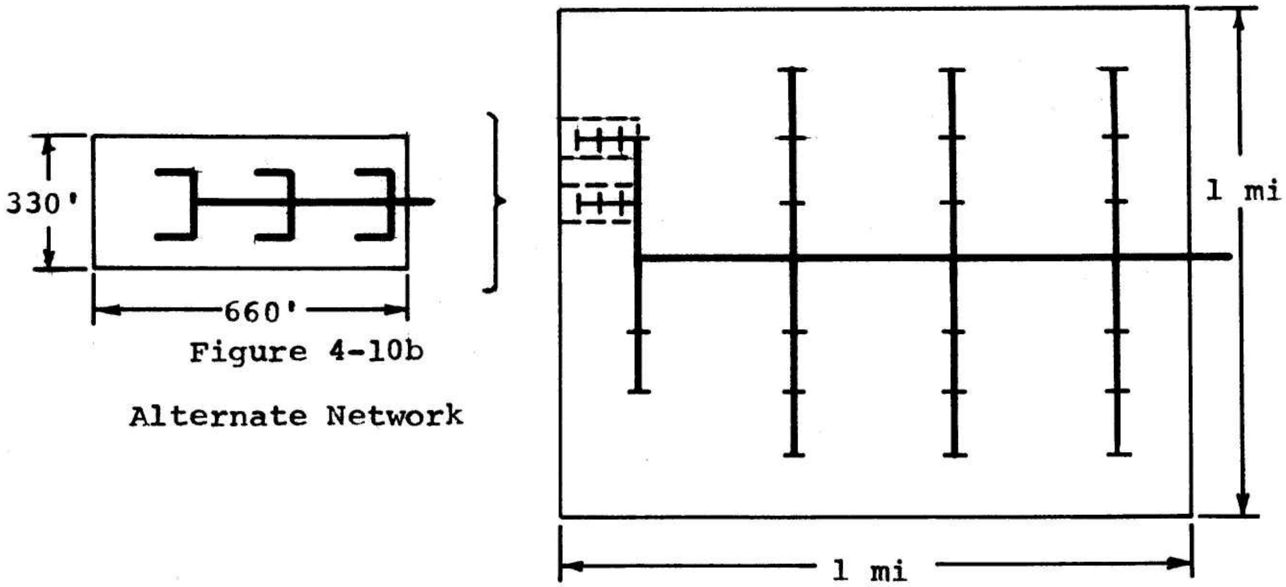


Figure 4-10b

Alternate Network

for the case of single unit homes, system delta T of $40^{o}F$, and 6000 units per square mile. There are four homes in series for each feedline. Figure 4-11b is an alternate layout. It was found that the alternate design cost nearly 40% more than the original design. Actual feedline configuration and cost would depend on the housing arrangement.

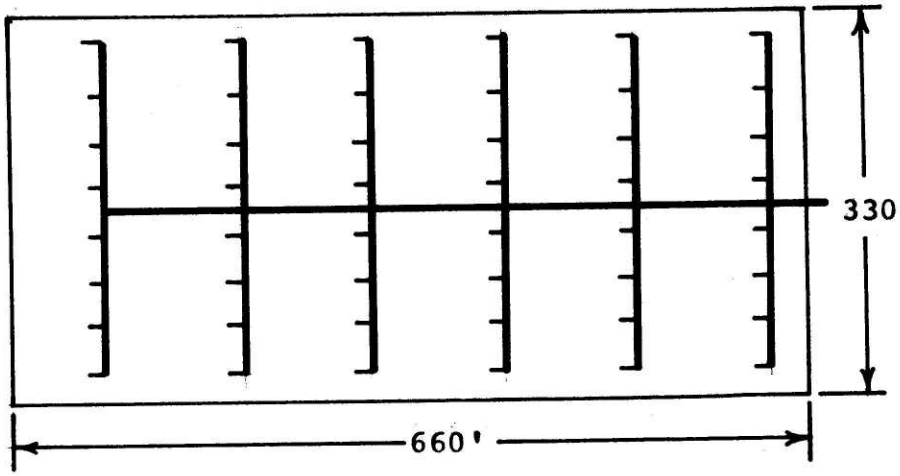
4.12 Effects of Heat Pump COP's

Current water/air heat pumps operate in the warm water temperature range (60^{o} - $90^{o}F$) with COP's of about 3. If the source water network is designed for higher heat pump COP's then the required water flow rates for each housing unit would be somewhat greater for the same system temperature drop, since more heat would be supplied by water. So while improving heat pump performances would decrease that cost component, the water network cost would increase to partially offset the benefit. Figure 4-12 shows annual cost per unit for the N4 network system with various COP's. Despite an infinite COP, the average decrease in annual cost is 23%. On the other hand, primary energy usage improves dramatically. With the gas furnace system as the reference, energy usage decreases of 40 and 50% are possible with COP's of 4 and 5, respectively.

4.13 Single Pipe Network

Since the piping cost for a distribution network is such a dominant component, a single pipe system in which water is not returned may be a viable option. Necessary assumptions for this system are

Figure 4-11a



BLOCK FEEDLINE CONFIGURATIONS

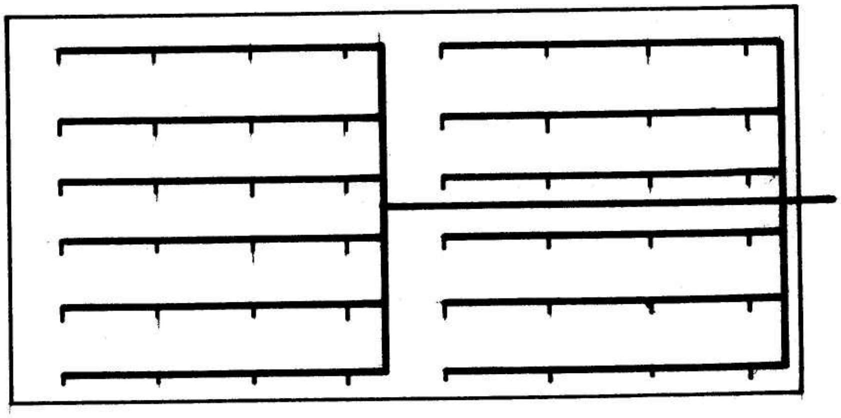


Figure 4-11b

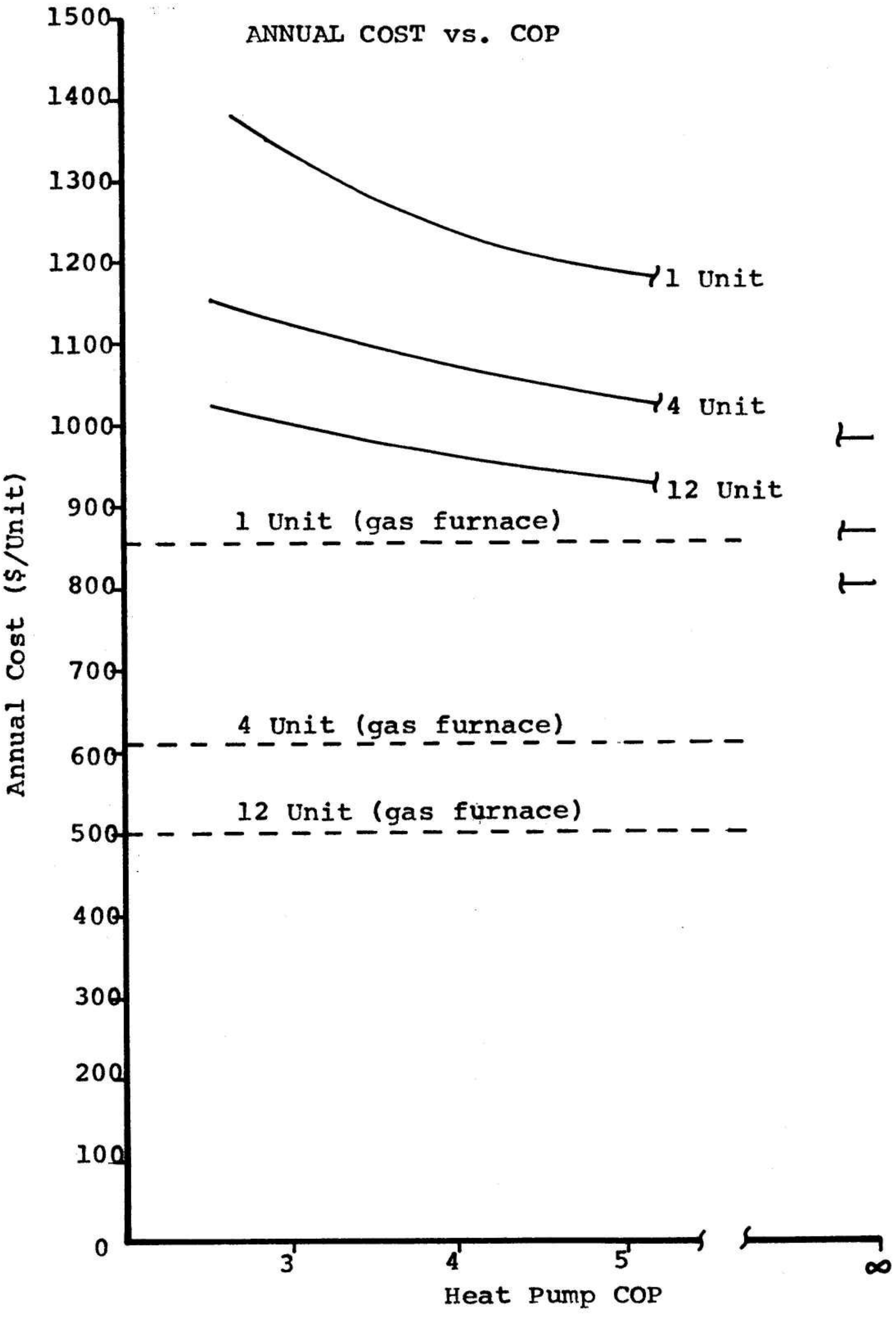

ANNUAL COST vs. COP
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Annual Cost ($/Unit)
1 Unit
4 Unit
12 Unit
1 Unit (gas furnace)
4 Unit (gas furnace)
12 Unit (gas furnace)
3
4
5
∞
Heat Pump COP

Figure 4-12

1. The city sewage system can handle the large quantity of water without modification.
2. The existing waste water treatment capacity is adequate.
3. The required water is availabe.

Estimated cost for a single pipe N4 network is \$95.7 million annually, or a savings of 49% compared to a dual pipe system. The reduction in annual cost per unit is from \$420 to \$215.

The single pipe system introduces another major cost component, water. Table 4-11 shows the cost of water in metropolitan Boston. Water requirements for the N4 network are 1.2×10^6 ft^3/yr, so that the cost of water is \$55.2 million annually. The net savings for a single pipe system compared to a dual pipe system is reduced to 19%. The assumptions made for this system are not realistic. For example, Boston's peak water capacity (according to Boston Public Works Department) is 142.3×10^6 gal/day, while the heating system's peak is 909×10^6 gal/day.

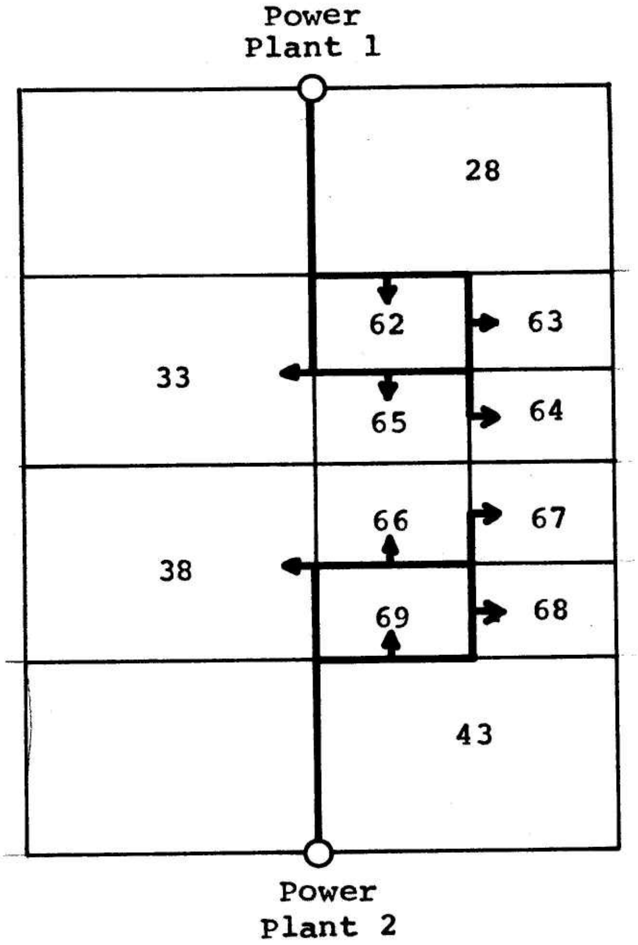
4.14 Cost of Distribution from Two Power Plants

It has been assumed that source heat for the warm water-heat pump system originates from a single electricity generating center. Required size of this center for a distribution of N4 size would be about 2000 MW(e). Perhaps a more reasonable arrangement is two power plants at 1000 MW(e) each, supplying heat to cover a combined area equivalent to the N4 network. Figure 4-13 shows the dual power plant

Table 4-11

COST of PURCHASING WATER
BOSTON RATES

Up to	80000 ft^3/yr	$\$7.65/1000\ \text{ft}^3$
80000 to	4×10^6 ft^3/yr	$\$6.25/1000\ \text{ft}^3$
4×10^6	on up	$\$4.60/1000\ \text{ft}^3$



DUAL POWER PLANT
WARM WATER DISTRIBUTION

Figure 4-13

NOTE: Numbers are Metropolitan Boston tracts.

arrangement. The northern and southern networks' annual costs are \$127.2 million and \$87.4 million, respectively. Combined average cost per unit is \$437 annually, or 4% more than the cost for the N4.

4.15 Combined Heating and Air Conditioning System

The application of a water/air heat pump system for heating only severely limits the device's year round space conditioning capabilities. Adaptation of the water network system to provide for a cooling function during summer months is a desirable and logical step. For this analysis, it is assumed that each of the building types has cooling loads equal to the heating loads, and that the load factor is 0.25. To reject heat during the summer, cooling towers are incorporated into the water network system. The location of the cooling towers is assumed to be at a site close to the energy center. Coolant water for the heat pumps is approximately 70^{O}F if ambient wet bulb temperature is around 60^{O}F. Engineering data for Climate Master heat pumps show that the upper limit for coolant water temperature is about 100^{O}F, so that an effective temperature drop of 30^{O}F is used for the water network system.

Analysis shows that using a delta T = 40^{O}F heating system piping network is undesirable because of large flowrates required for cooling. The large flowrates is a result of the water network having to handle a larger thermal load for cooling than for heating. Equation 1.1

$$Q_h = Q_L + W \tag{1.1}$$

shows that for heating, the thermal load on the water network is Q_L which is less than the heating load, Q_h. During the summer, the thermal load on the water network, Q_h, is a sum of the heat pump work and the cooling load, which is equal to the heating load. Therefore, the water network must handle more heat, necessitating larger water flowrates. Network configuration for the delta T = 20^{O}F heating system is used to minimize the flowrates. Despite a summer temperature drop of 30^{O}F in the water network, the summer flowrates are still greater than winter flowrates by 35%.

For a system coverage equivalent to the N2 network configuration, a peak summer thermal load of 7.78×10^{6} Kw is estimated for the water network. If cooling tower cost is approximately $25 per equivalent Kw(e) generated in a power plant, then cost for cooling towers is about $130 million. Estimated total annual cost is $19.15 million, based on a 9% interest rate, a tower life of 30 years, and an annual maintenance cost of 5% of the initial capital investment. Maximum make up water requirement at the cooling tower is estimated at 2.73×10^{7} lbm/hr. Using data from Table 4-11, the annual cost of make up water is $4.6 million.

Buildings heated by gas furnaces are equipped with air conditioning units for comparison purposes. Costs for air conditioners(34) are $1000, $3440, and $8736 for the single, four, and twelve unit structures, respectively. Ductwork costs are the same as noted in section 3.6. The performances of the air conditioners are measured by an energy efficiency ratio (EER) defined as the ratio of btu/hr per watt input (33). A value of 6.5 is used. Because of the lower sink temperature, the water/air heat pumps have EER's of about 10. A comparitive cost summary is presented in Table 4-12. It is seen that the cost differences between the gas furnace-air conditioning system and the heat pump systems are relatively small. The water system with the heat pump, however, still suffers from a large piping network cost.

4.16 System with Auxiliary Heaters and Concrete Pipes

The warm water-heat pump system is designed for a 65 dd peak. However, during a winter heating season the peak load is not required very often, thus resulting in wasted heat pump capacity. To study the effect of lower design heat loads, a 40 dd peak is used to size the heat pump. The design load is then 30,000, 100,000, and 258,000 btu/hr for the single, four, and twelve unit structures, respectively. To meet higher demands, auxiliary oil fire furnaces are installed.

Using a water network temperature drop of 40^oF, it is found that four single unit homes can be put in series using a flowrate of 4 gpm. Each home is equipped with a Climate Master series 27. Two four unit apartments each equipped with a Climate Master series 100 can be put in series at a flowrate of 7 gpm. The thermal requirements can be met at 10 gpm for the twelve unit apartment using a Climate Master series 240. Note that the lower design peak load reduced water flow requirements to roughly 60% of the flowrates for the delta T = 40^oF system.

Table 4-12

ANNUAL HEATING-COOLING COST COMPARISON
($/UNIT)

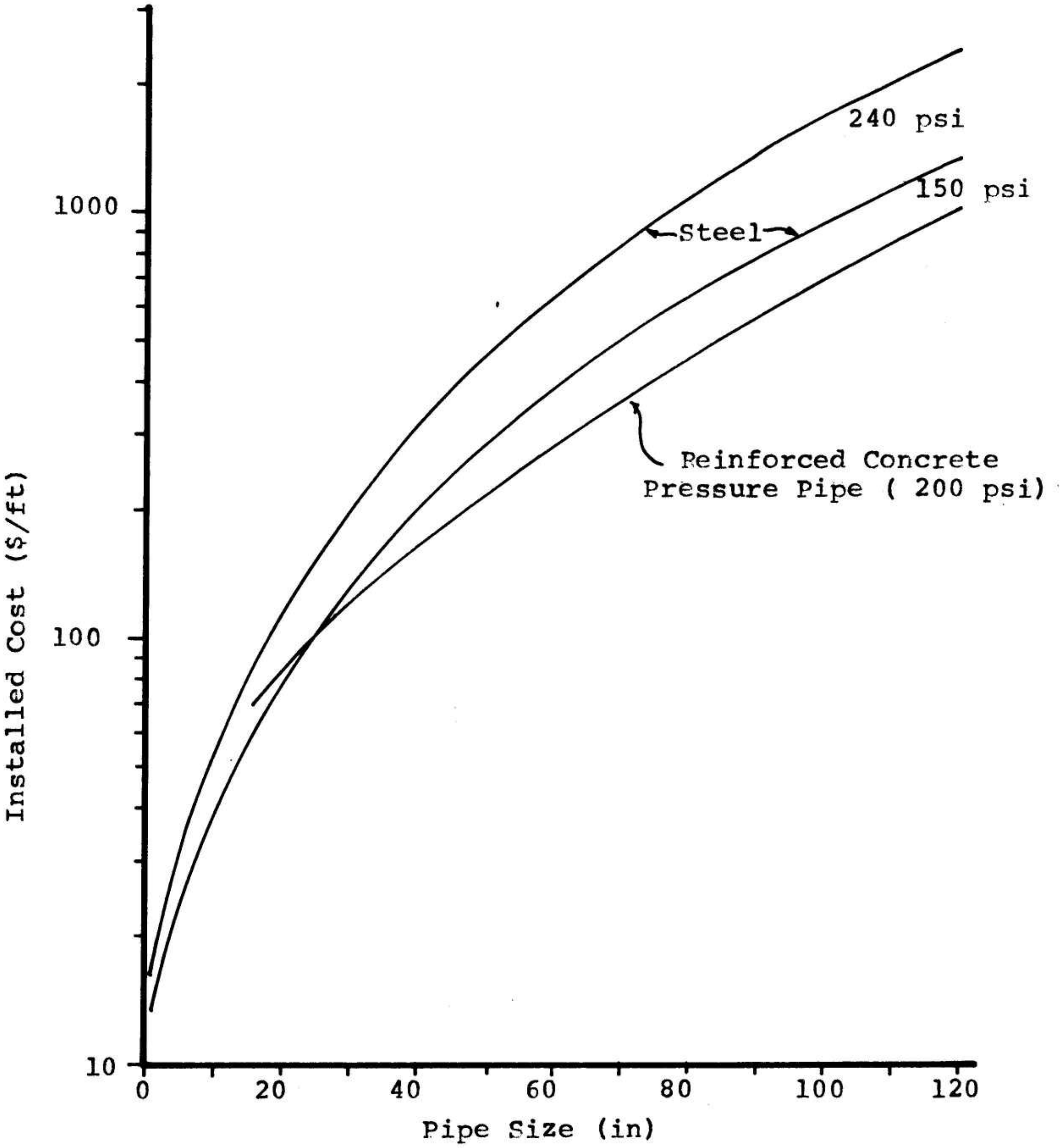
	single	4 Apt.	12 Apt.
Gas Furnace Heating	857	613	504
Electric Air Conditioning	1091	882	752
Total	1948	1495	1256
Water/Air Heat Pump*			
Heating	936	683	575
Cooling	429	355	307
Cooling Tower & Water (Load correspond to N2 configuration)	53	53	53
Water Network (N2 configuration)	697	697	697
Total	2115	1788	1632
Air/Air Heat Pump*			
Heating	1352	1050	839
Cooling	661	546	472
Total	2013	1596	1311

* Heating cost includes total capital cost and maintenance plus electric cost for heating. Cooling cost only includes electric cost for air conditioning.

The cost of heat pumps is taken from Figure 3-13. It is estimated that with mass production of water/air heat pumps, the cost will be reduced by 30% because of smaller heat exchanger requirements for the water source. All other data remains unchanged from section 3.4. To determine the load factor for a 40 dd design, daily Boston temperature statistics for the year 1968(35) were analyzed to show a resultant load factor of 0.39. It is determined that auxiliary heating is needed for 298 dd for the year.

The cost of auxiliary oil fire furnaces plus tanks is from the Fortuna Oil Co.(34) and is estimated at $260, $550, and $1101 for the single, four unit, and twelve unit apartments, respectively. Cost of fuel oil is $0.397/gal as quoted by Exxon Oil (Everett, Mass.). An interest rate of 9% is used along with a furnace life of 20 years.

As seen in Figure 3-2, the cost of reinforced concrete pipes is very much less than steel pipes. However, reinforced concrete sewer pipes are not rated for service above 15 psi. There are reinforced concrete pressure pipes rated for service at about 200 psi and are suitable for use as warm water distribution piping. Figure 4-14 shows the cost comparison (simple installation) of dual concrete pressure pipe versus the equivalent 150 psi steel pipe. The concrete pipe's size range is 16 inches to 120 inches in diameter. For this analysis, cost of pipes under 16 inches will be for steel and above 16 inches will be for concrete. Concrete pressure pipe costs are obtained from the J. F. White Contracting Co. (Newton, Mass.).



COST of DUAL PRESSURE PIPING
SIMPLE INSTALLATION

Figure 4-14

A summary of the system's annual cost with the reduced design peak load, auxiliary heaters, and the steel-concrete piping network is shown in Table 4-13. Comparison with Table 4-6 shows that a cost reduction of about 19% is achieved for the system with the N4 network configuration. This system is still about 45% more expensive than the gas furnace system. For today's prices this heat pump system will break even with the gas furnace system if gas rates increase to 1.5 times the present rate, as opposed to 2.0 times the present rate for an all steel pipe network heat pump system designed for a 65 dd.

4.17 High Temperature Water System

The warm water heating system is modified to obtain a rough cost estimate for a high temperature hot water system. According to reference 5, high pressure high temperature water systems (350^{O}F water) require licensed engineers for operation. This is clearly not practical for the residential homes. To avoid this situation, the network will be divided into primary and secondary networks. The primary network includes piping from the power plant to the square mile networks. It has a temperature drop of 100^{O}F with a high temperature of 280^{O}F. The secondary networks are square mile networks circulating water of 210^{O}F to 160^{O}F. This range was chosen because commercial hydronic equipment for residential use is designed for this temperature range. The system uses 150 psi steel pipes for the secondary network, while 240 psi pipes are used for the primary network. Costs for pipes for

Table 4-13

WARM WATER-HEAT PUMP
ANNUAL COST ($/Unit) with 40 dd DESIGN,
AUXILIARY HEATERS, and STEEL-CONCRETE PIPELINES

	single	4 Apt.	12 Apt.
Heat Pumps			
Capital	313	217	170
Operating	429	303	246
Maintenance	36	26	21
Auxiliary Oil Heater*			
Capital	28	15	10
Operating	23	19	17
N4 Network (Steel & Concrete Pipes)	315	315	315
Total	1144	895	779

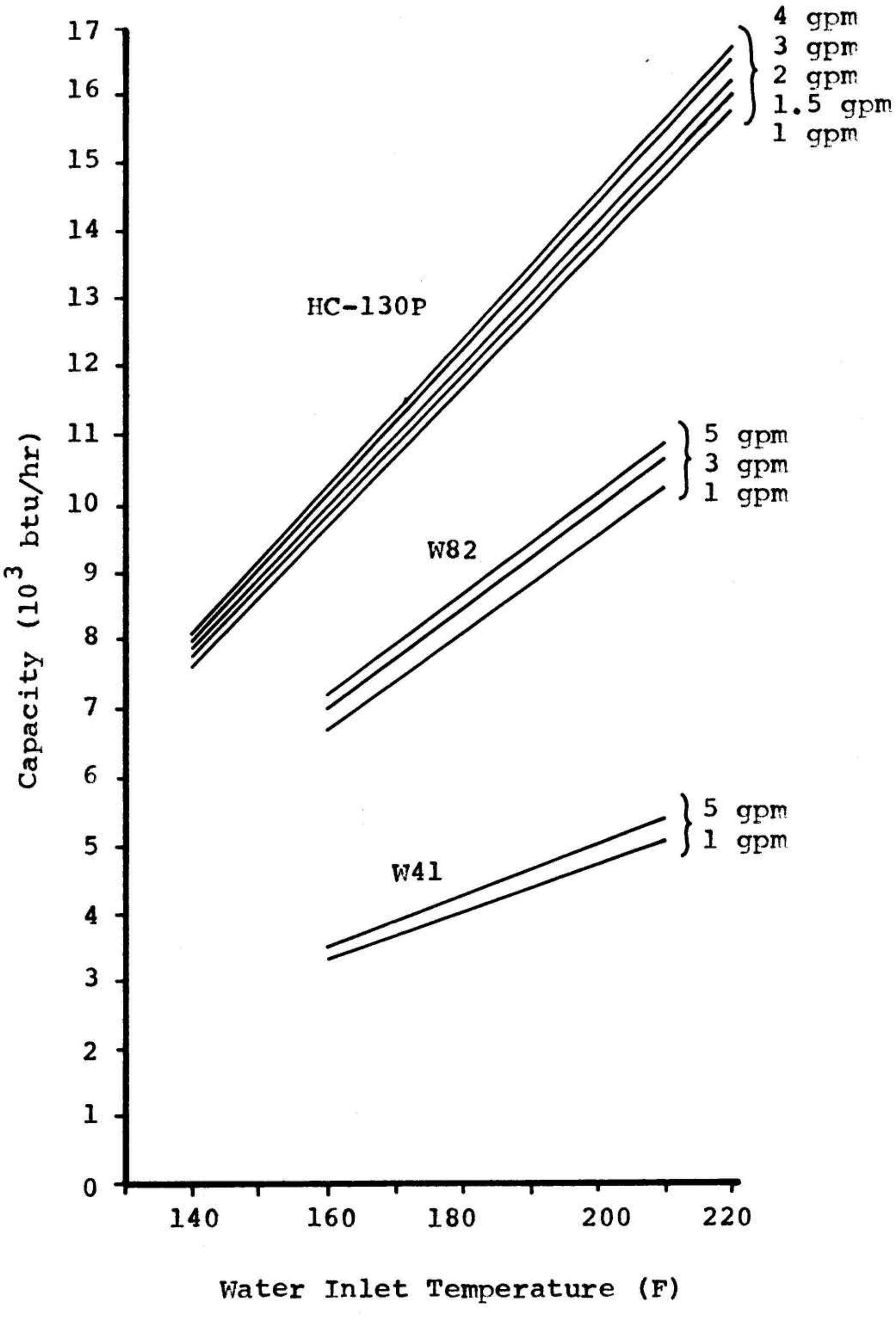
* Maintenance cost of oil heater is neglected because of low furnace usage.

both pressures are shown in Figure 4-14. The 240 psi pipe includes an insulation cost of 15% of the total. It is assumed that cost of heat exchange for the primary-secondary network interfaces and pressurization tanks is small compared with the piping.

The performance of Beacon Morris hydronic heaters* is shown in Figure 4-15. For the temperature range 210°F to 160°F, two houses can be put in series with a flowrate of 4 gpm. A four unit apartment requires 8 gpm, while a twelve unit apartment needs 24 gpm. The piping configuration is identical to the N2 piping configuration, except that each square mile network is closed. Cost of heaters is $300 and $175 for the HC-130P and W82, respectively. Plumbing to hook up heaters to hot water service lines is estimated from reference 36 and heater installation is ten percent of the cost. Total installed costs of the hydronic heaters are $2124, $6336, and $14892 for the single, four, and twelve unit homes, respectively. Annual capital cost is calculated using 9% interest rates and a 35 year expected life. Operating cost consists of electricity for the fan, and annual maintenance is estimated at two percent of equipment cost.

Steam is assumed to be condensed at 320°F at the power plant to heat hot water for the network. Under these conditions, the gross cycle efficiency is about 24% for a typical fossile reheat power plant.(6) The loss of generated electrical power is 6.153×10^{-5} Kw per btu/hr of heat transfered into the water network. A summary of annual costs for the hot water system is shown in Table 4-14. As expected, the piping network makes up a large portion of the total cost. Because of lower

* High temperature water space heaters.



PERFORMANCE of BEACON MORRIS
HYDRONIC HEATERS

Figure 4-15

Table 4-14

ANNUAL COST ($/UNIT)
for HOT WATER SYSTEM

	single	4 Apt.	12 Apt.
Hydronic System Cost	275	210	162
Lost Power Cost	264	218	189
Water Network (N2 configuration)	433	433	433
Total	972	861	784

flowrates the hot water network cost per residential unit is 72% of the identical N2 piping configuration. Consistent with references 4 and 30, annual maintenance cost is estimated at 5% of initial capital. As noted in section 4.8, 5% was also used for estimating annual maintenance cost for the warm water system, although that figure may be somewhat high. It is noted that the lost power cost is a significant portion of the total cost of hot water heating. Comparison of Table 4-14 to 4-6 shows that the hot water system is clearly superior to the warm water-heat pump systems. However, it is roughly equivalent to the modified heat pump system described in the preceeding section. Gas rates have to increase about 1.3 times for this system to break even relative to the gas furnace.

CHAPTER 5

Conclusions

The warm water-heat pump system is characterized by the distribution of large quantities of water. Because the distribution cost goes up with larger flowrates, it is more advantageous to use a system temperature drop of 40^{O}F rather than one of 20^{O}F, despite the cost penalties for the loss of electrical generating capacity at the higher plant condensing temperature. Halving the flowrate, however, does not half the cost. It was found that the dominant component of the annual network cost is piping (roughly 55%), followed by maintenance at about 30%, electricity cost for pumping at about 10%, and approximately 5% for the engineering of the original network. Pumps and valves contribute negligible effects on cost. The total cost of a distribution network was found to be dominated by local distribution (roughly 75%), rather than the network interconnecting the tracts. Based on current prices, it was estimated that warm water could be distributed as a heat source to 1.3 million people in a city with a housing distribution similar to the metropolitan Boston area from a 2000 MW(e) electricity generating complex for about $420 per housing unit. This cost can be reduced to $315 for a heat pumps with auxiliary heaters and mixed steel-concrete piping distribution.

Initially, the reason for considering a warm water-heat pump system is to exploit the higher heat pump performances (COP and capacity) at the constant and relatively high temperature (compared to winter air) of power plant coolant water. However, current cost data show that cost savings are far overshadowed by piping network cost. It is determined that a warm water-heat pump system is not cost competitive with a gas furnace system. For each housing unit, the annual heat pump cost component is roughly 60%, while the piping distribution component is about 40%. The heat pump component alone costs more than the gas furnace's annual cost. The inherent problem appears to be the use of expensive equipment to extract heat from a low quality source, requiring large water flowrates and consequently expensive piping distribution. The study shows that the warm water-heat pump system becomes competitive with gas furnace systems if natural gas rates double or if electricity rates double and gas rates triple.

In an alternate study, it was shown that significant cost savings can be achieved by using concrete pressure pipes and sizing heat pumps for a smaller design load; the peak load being met by use of auxiliary heaters. This system breaks even with gas furnace system cost if present gas rates increase by a factor of 1.5.

Further cost savings can be achieved by abandoning the heat pump in favor of hydronic heaters and designing the network for hot water. While the gas furnace system is still less expensive, gas rates have to increase by only 1.3 times for this system to break even.

It is shown that if air conditioning is also desired, the cost difference between a heat pump system and a gas furnace-air conditioning system becomes small. In this study, the air/air heat pump system becomes very competitive, while the water/air heat pump system still suffers from an expensive piping network.

The major cost variables for the warm water-heat pump system are piping installation cost and the cost of energy. Variations of system cost with interest rates, equipment life, load factor, and maintenance cost were shown to be secondary. Effects of local housing concentrations and block feedline configurations may affect cost as much as 30% in specific circumstances, but the two may offset eachother since one affects the cost favorably and the other does the reverse. The overall effect of all the above considerations is minor compared to piping cost and energy rate effects.

With the likelihood of gas price increases due to deregulation in the near future, it is probable that the warm-water heat pump system can become competitive. Moreover, if such a system is planned for a new city, it may be even more economically attractive since the pipe installation cost would closely approximate cross-country conditions (i.e., simple installation) and hence, overall pipe network cost will be much lower than the figures calculated for this study.

It was found that system feasibility is not a strong function of improved performance (COP's) of the heat pumps. It was estimated that even if the COP is infinite, the annual cost reduction is only 23%. System cost was also estimated for a single pipe system where the source water is not returned to the power plant, but drained into sewers as waste. This scenerio introduced another major cost variable, the cost of water. Despite unrealistic assumptions of zero cost for sewerage and waste treatment capacities, this scenerio was estimated to reduce annual cost by only 19%. Finally, a dual power plant distribution system was compared to the modeled system where all heat is derived from a single energy center. It was found that the dual system is only marginally more expensive than the single source system.

The major advantage of the warm water-heat pump system as compared to the other heating modes is the efficient use of primary energy. Heating with this system saves up to 30% of the primary energy consumed by a gas furnace system. If the water/air heat pump's COP of about 3 is increased to 4, then energy savings is further increased to 40%. Energy conservation potentials,coupled with the possibility of economic competitiveness in the near future, suggest that the warm water-heat pump system warrants further consideration for future urban space heating applications.

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APPENDIX A

Temperature Drop from Power Plant to a Remote Hypothetical Consumer

A preliminary temperature drop study using the calculated underground thermal resistances of Section 2.3 was carried out to obtain an indication of the temperature difference between water at the plant exit and at the consumer inlet. For this study, the power plant is located at the northwest corner of metropolitan Boston tract number 37. The hypothetical consumer is located in the southeast corner of tract number 43, about 31 miles from the plant. Flow requirements are based on an overall load temperature drop of 20° F and an all twelve unit apartment arrangement. Water is assumed to exit the power plant at 100° F. Pipe sizes used were preliminary estimates and are not the result of the optimal study described in Section 2.9. Table A-1 is a summary of the temperature, T_x, at the inlet of each pipe section length leading from the power plant to the hypothetical consumer. The calculations are for two extremes of soil conductivities, k_s (btu/hr ft F). Thermal resistances for pipe sizes 72" and greater are for bare pipes.

Table A-1

TEMPERATURE DROP ANALYSIS*

Pipe Dia (in)	Water Flow (gpm)	Length (ft)	k_s=1.84		k_s=0.33	
			R	T_x(F)	R	T_x(F)
1	8	21	6.56	98.9	12.87	99.6
2	16	41	5.32	99.0	11.44	99.6
2	32	83	5.32	99.1	11.44	99.7
4	64	330	4.08	99.3	9.84	99.8
6	128	165	3.41	99.3	8.87	99.8
6	256	495	3.41	99.5	8.87	99.8
8	572	165	3.00	99.5	8.20	99.8
10	768	1320	2.84	99.6	7.57	99.9
14	1792	1320	2.44	99.6	6.87	99.9
16	3328	1320	2.29	99.7	6.59	99.9
20	5376	660	2.01	99.7	6.03	99.9
30	10752	5280	1.66	99.7	5.02	99.9
30	16128	5280	1.66	99.8	5.02	99.9
36	21504	2640	1.47	99.8	4.60	99.9
42	37600	10560	1.40	99.8	4.22	100.
54	75264	10560	1.18	99.8	3.68	100.
60	112900	10560	1.13	99.8	3.43	100.
72	131700	23760	0.45	99.9	2.53	100.
72	279200	13200	0.45	99.9	2.53	100.
96	472700	13200	0.36	100.	2.01	100.
96	706900	13200	0.36	100.	2.01	100.
120	1265700	73920	0.30	100.	1.69	100.

* Thermal resistances, R (hr ft F/btu), for pipe sizes 72" and greater are for bare pipes.

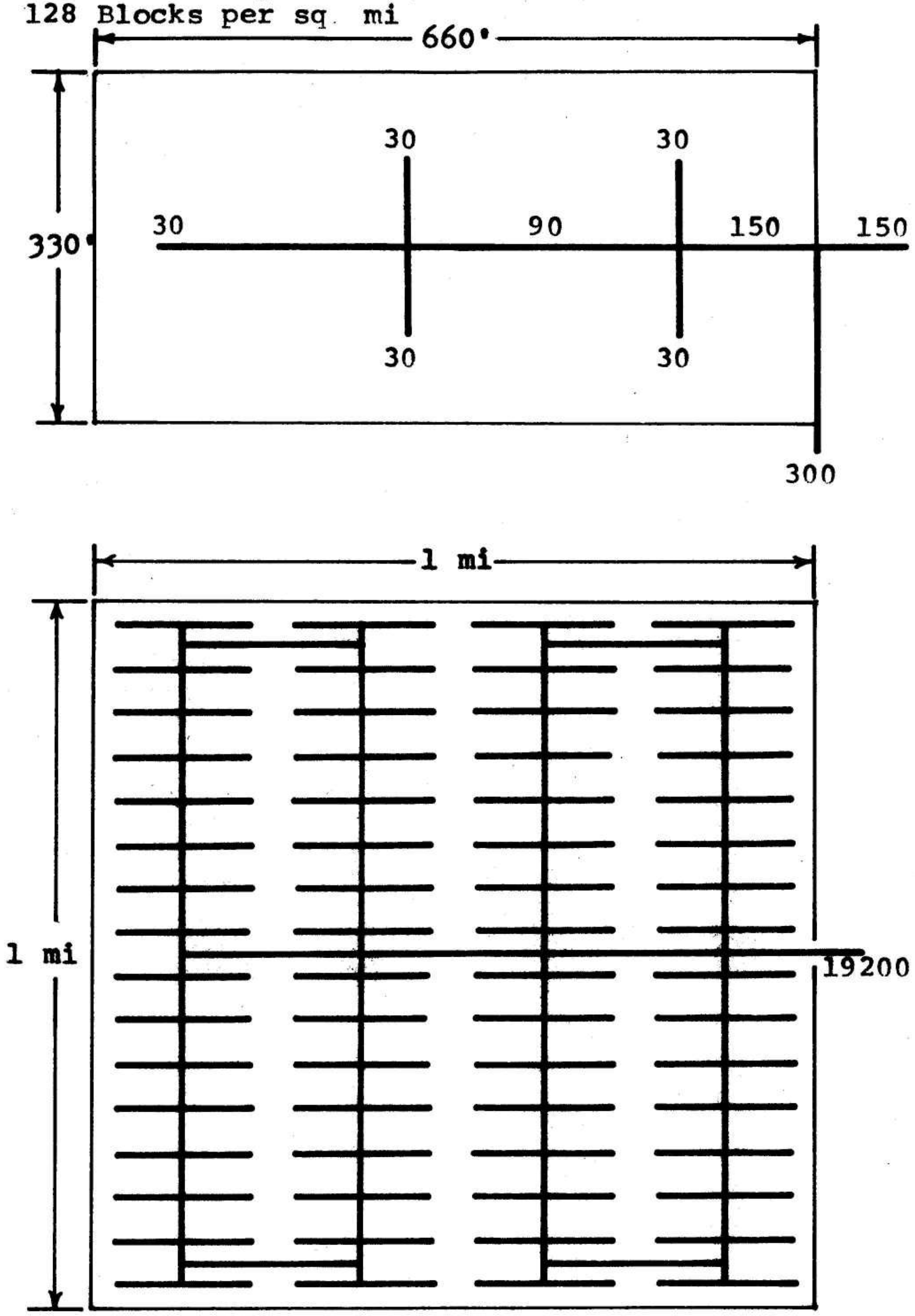
APPENDIX B

WATER DISTRIBUTION NETWORKS

In the following pages are the model networks used in this study to determine generalized parameter-density relationships.

Figure B-1

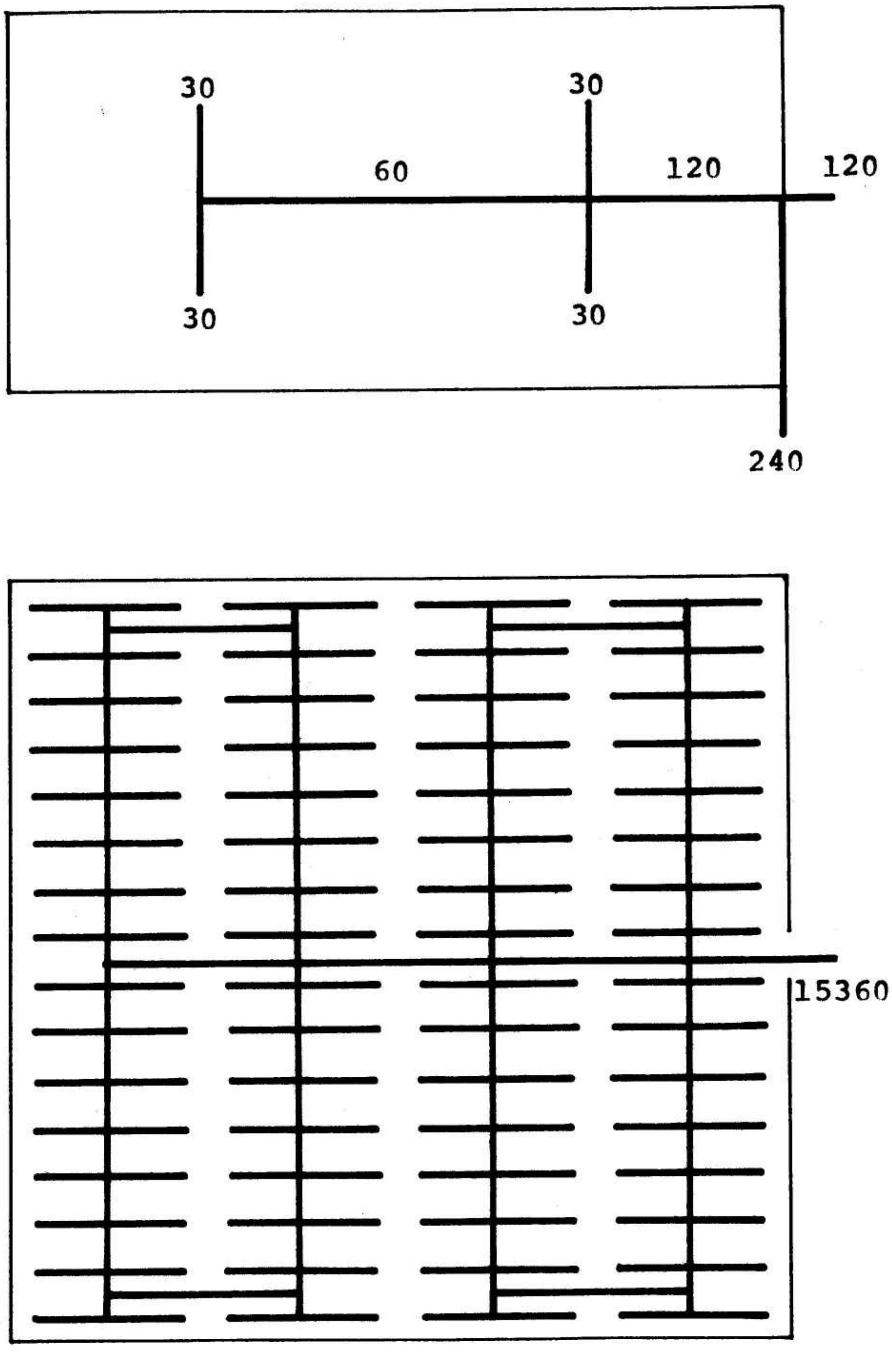
Delta T=20°F
Twelve Unit Apartments
8000 Units/mi^2
5 Structures per block
128 Blocks per sq. mi



Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-2

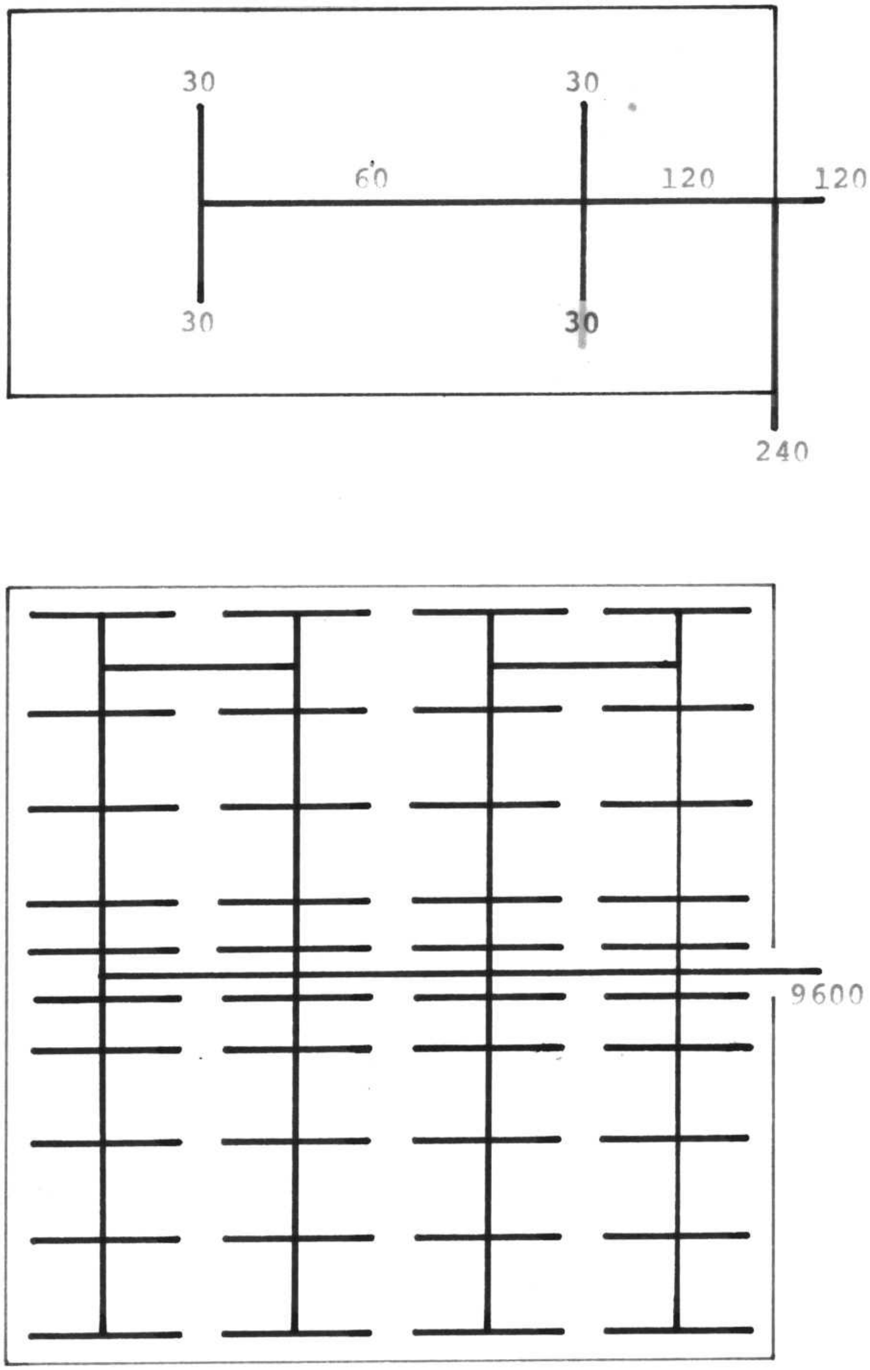
Delta T=20°F
Twelve Unit Apartments
6000 Units per sq mi
4 Structures per block
128 Blocks per sq. mi



Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-3

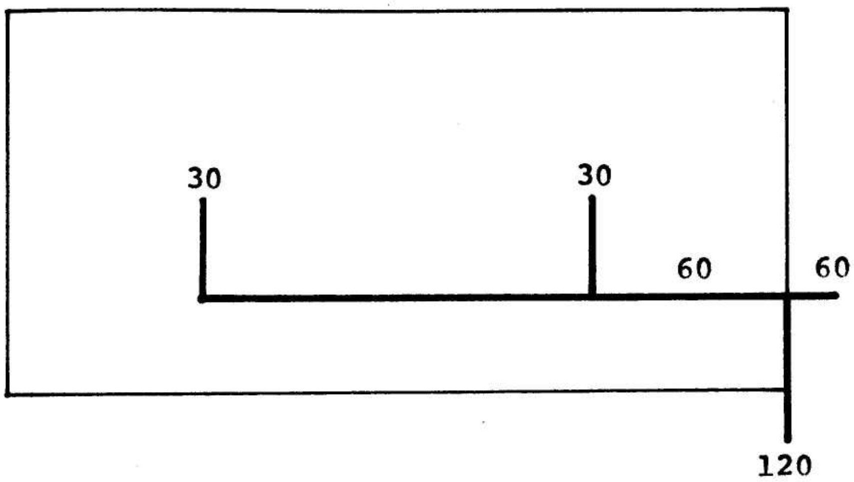
Delta T=20° F
Twelve Unit Apartments
4000 Units per sq mi
4 Structures per block
80 Blocks per sq mi

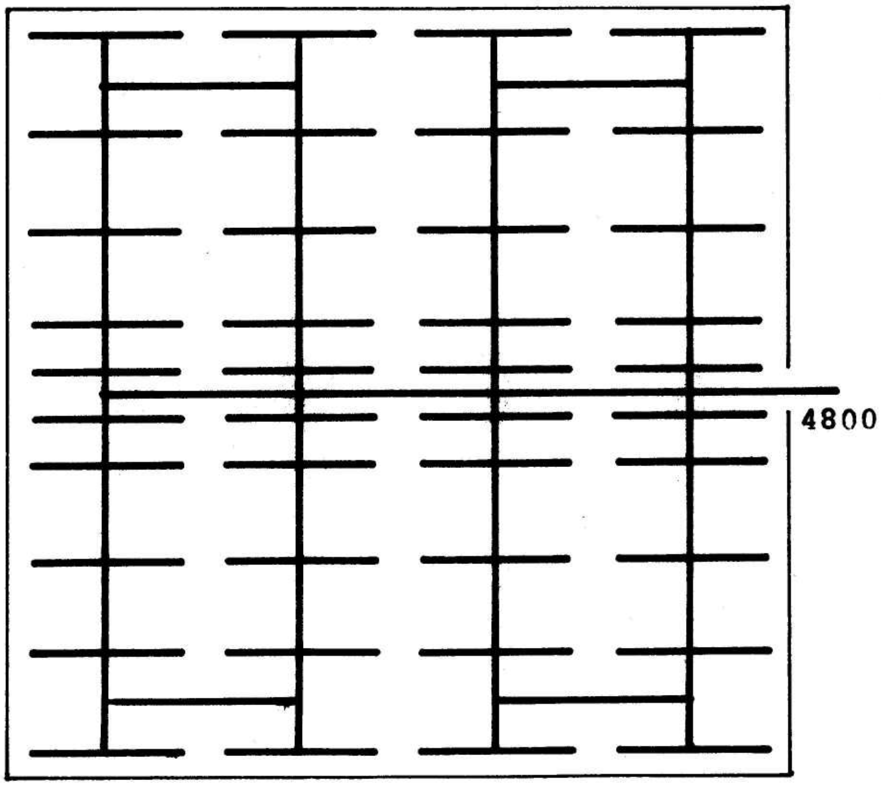


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-4

Delta T=20° F
Twelve Unit Apartments
2000 Units per sq. mi
2 Structures per block
80 Blocks per sq mi

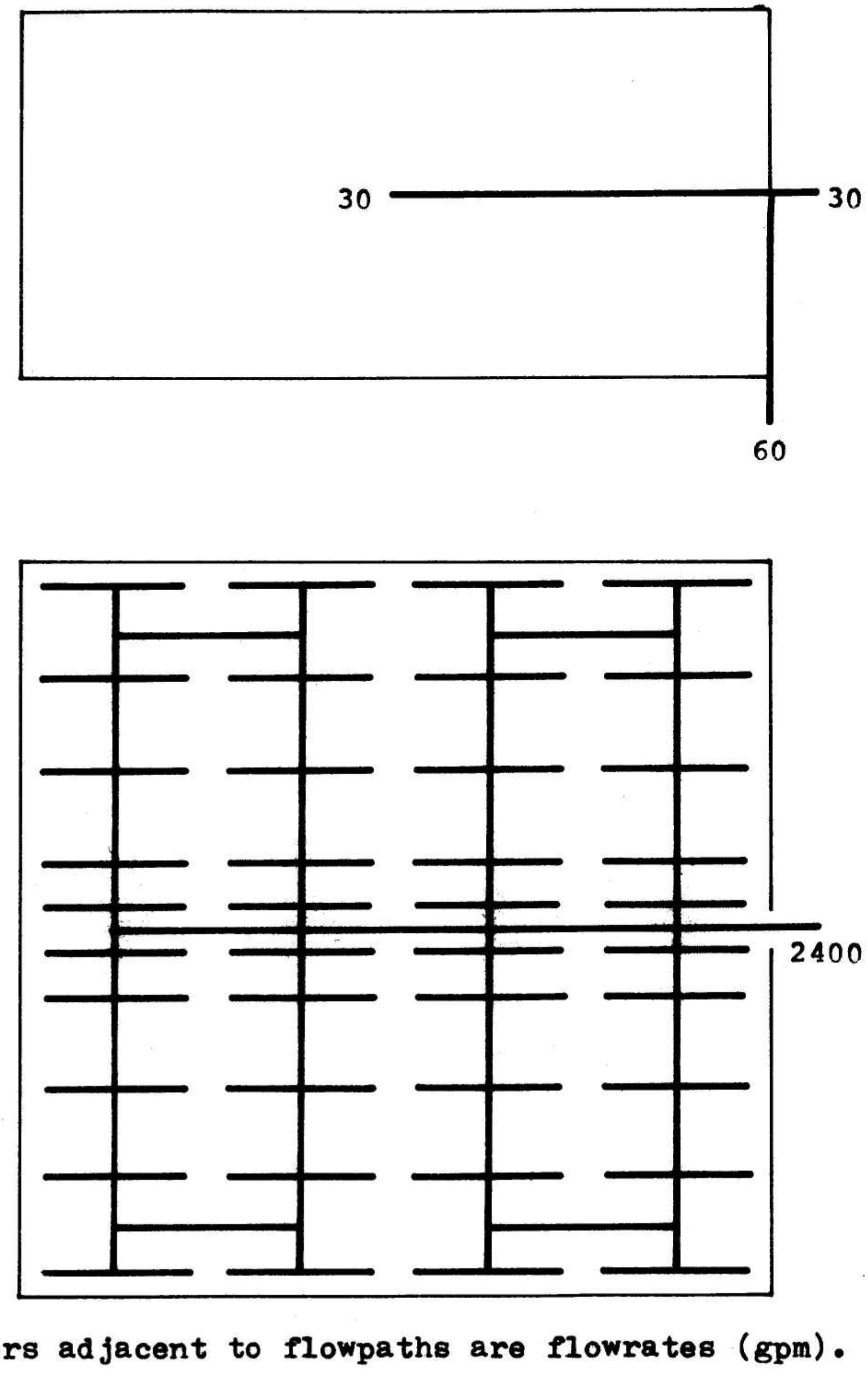




Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-5

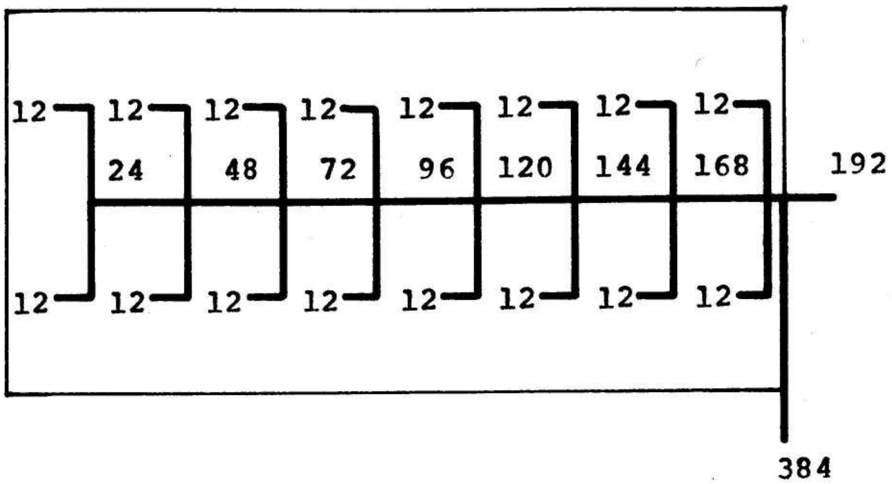
Delta T=20°F
Twelve Unit Apartments
1000 Units per sq mi
1 Structure per block
80 Blocks per sq mi

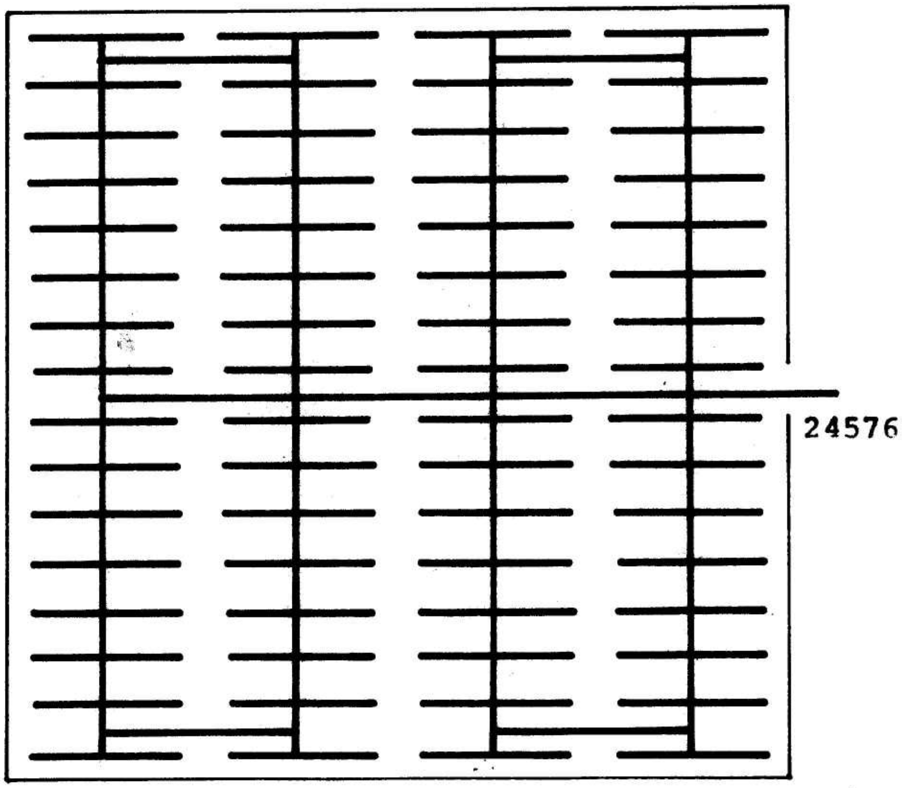


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-6

Delta T=20° F
Four Unit Apartments
8000 Units per sq mi
16 Structures per block
128 Blocks per sq mi

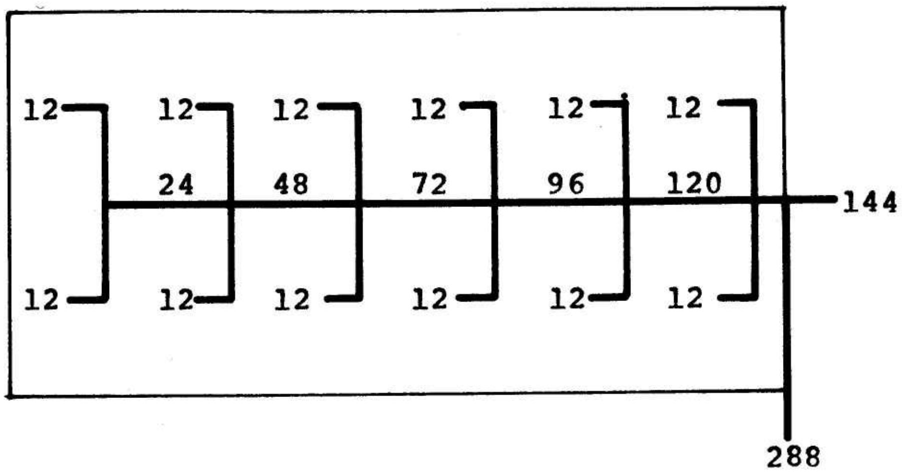


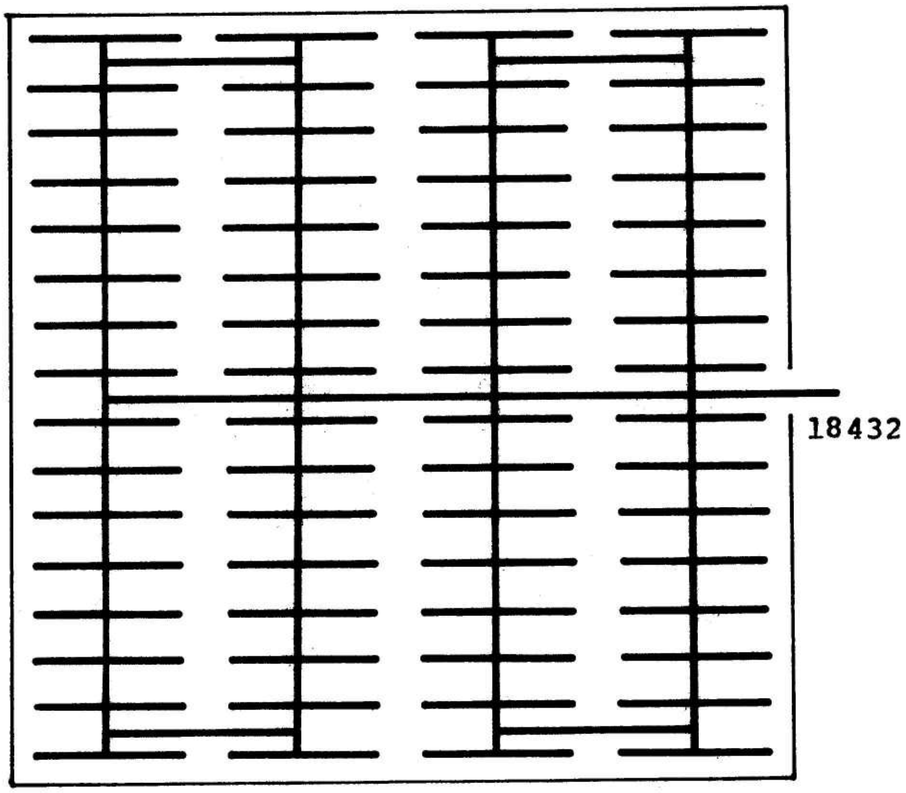


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-7

Delta T=20° F
Four Unit Apartments
6000 Units per sq mi
12 Structures per block
128 Blocks per sq mi

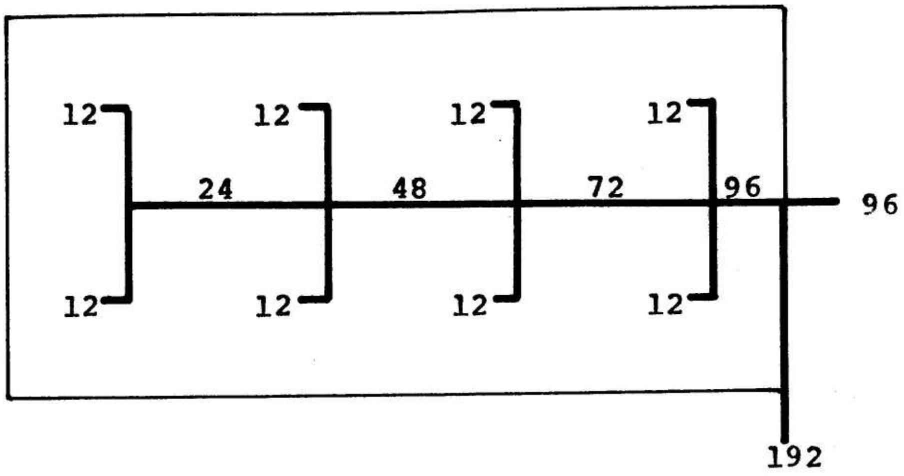


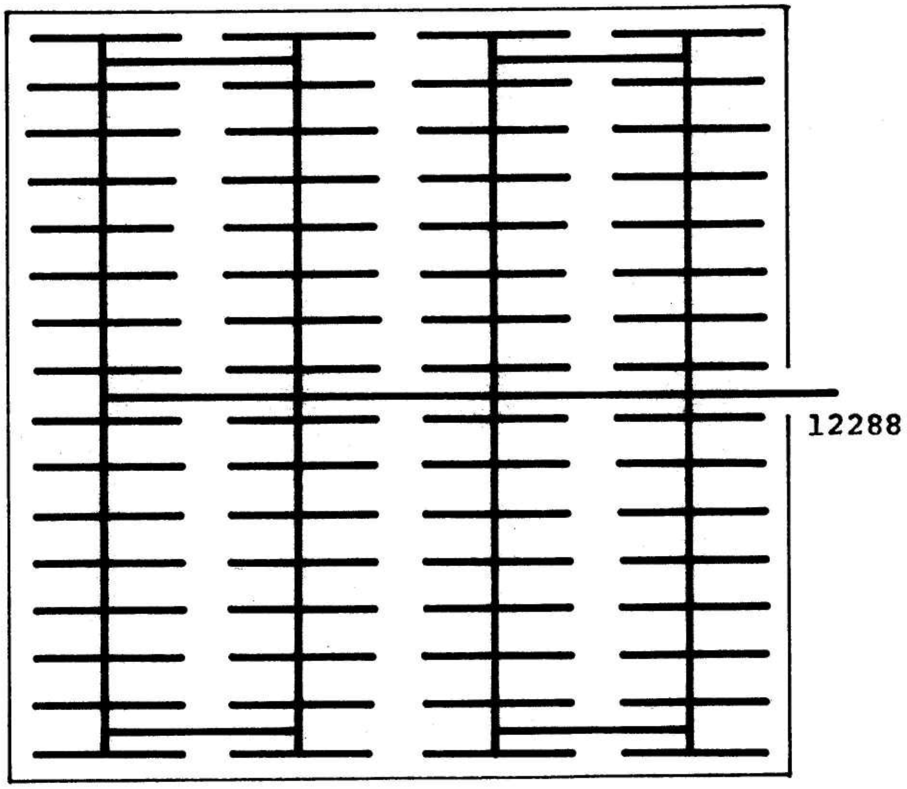


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-8

Delta T=20° F
Four Unit Apartments
4000 Units per sq mi
8 Structures per block
128 Blocks per sq mi

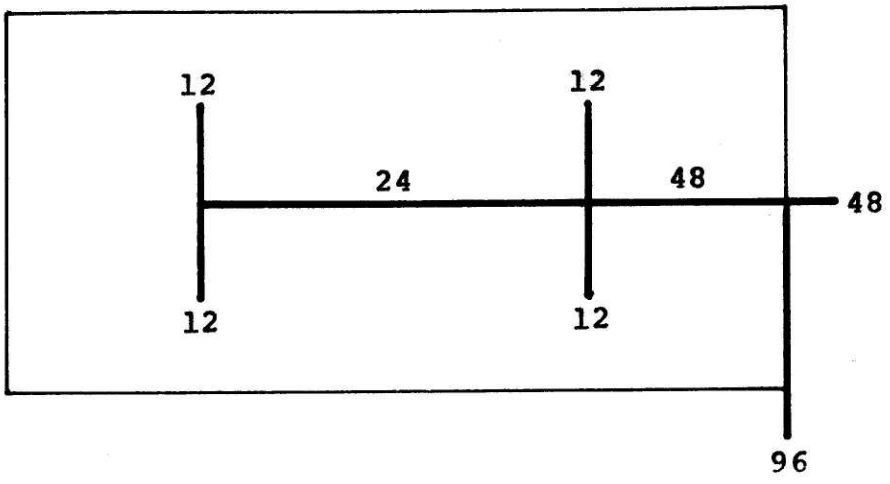


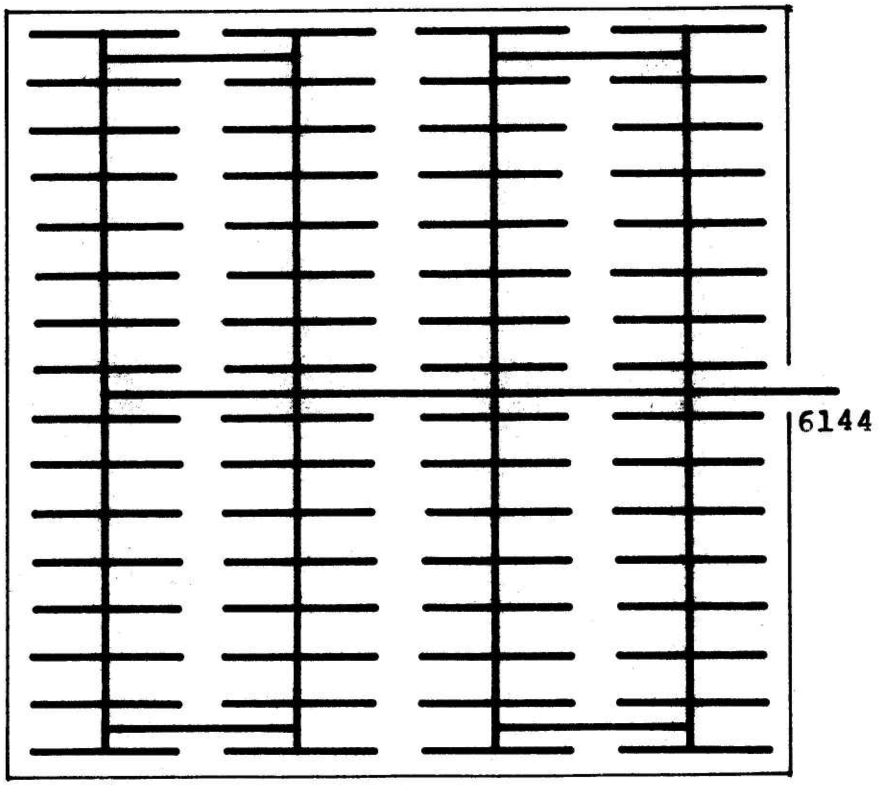


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-9

Delta T=20° F
Four Unit Apartments
2000 Units per sq mi
4 Structures per block
128 Blocks per sq mi





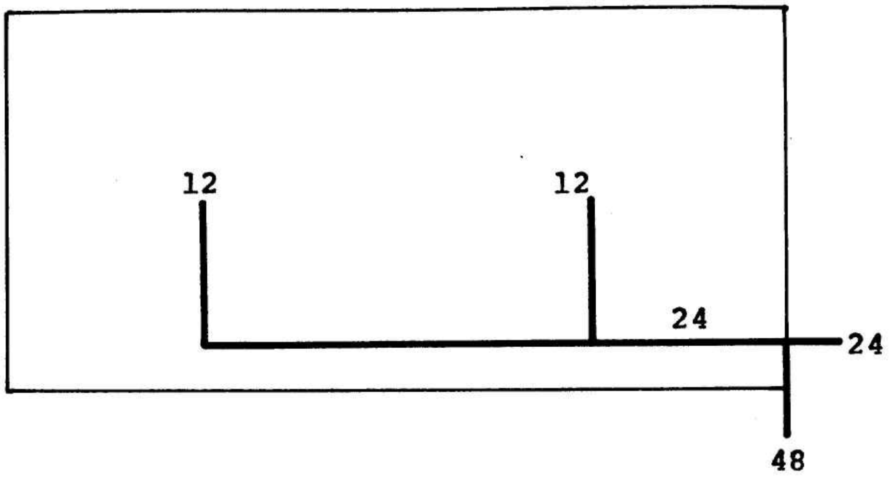
Note: Numbers adjacent to flowpaths are flowrates (gpm).

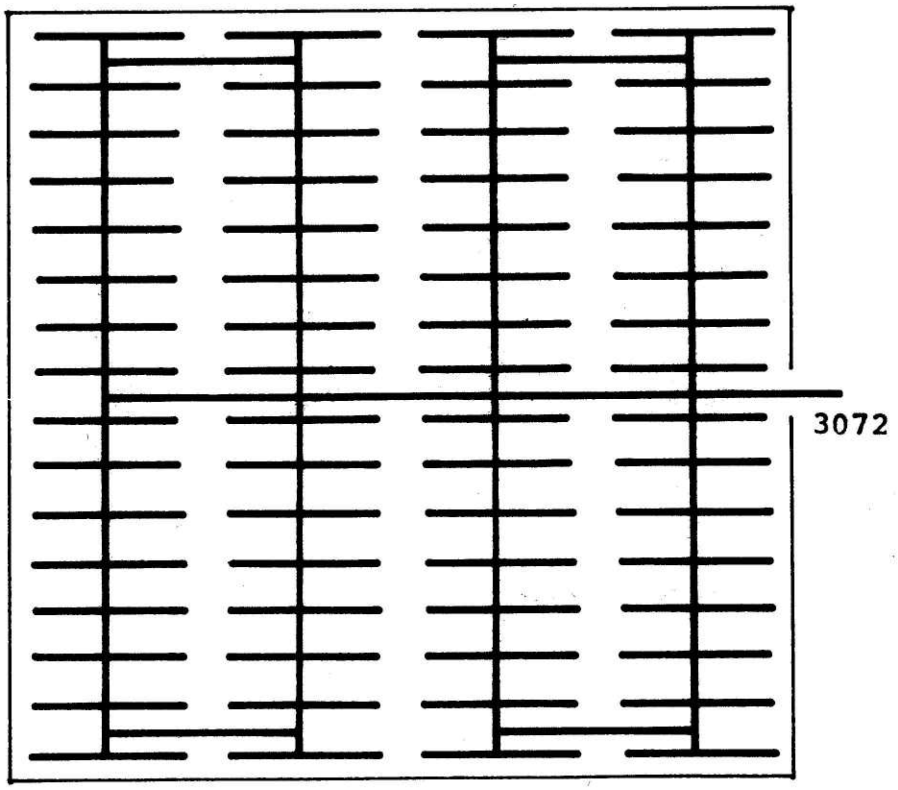
Figure B-10

Delta T=20° F

Four Unit Apartments

1000 Units per sq mi
2 Structures per block
128 Blocks per sq mi

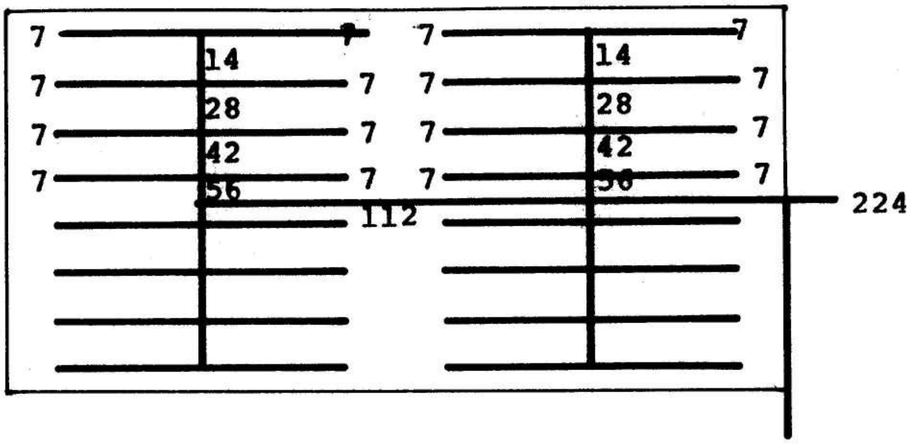


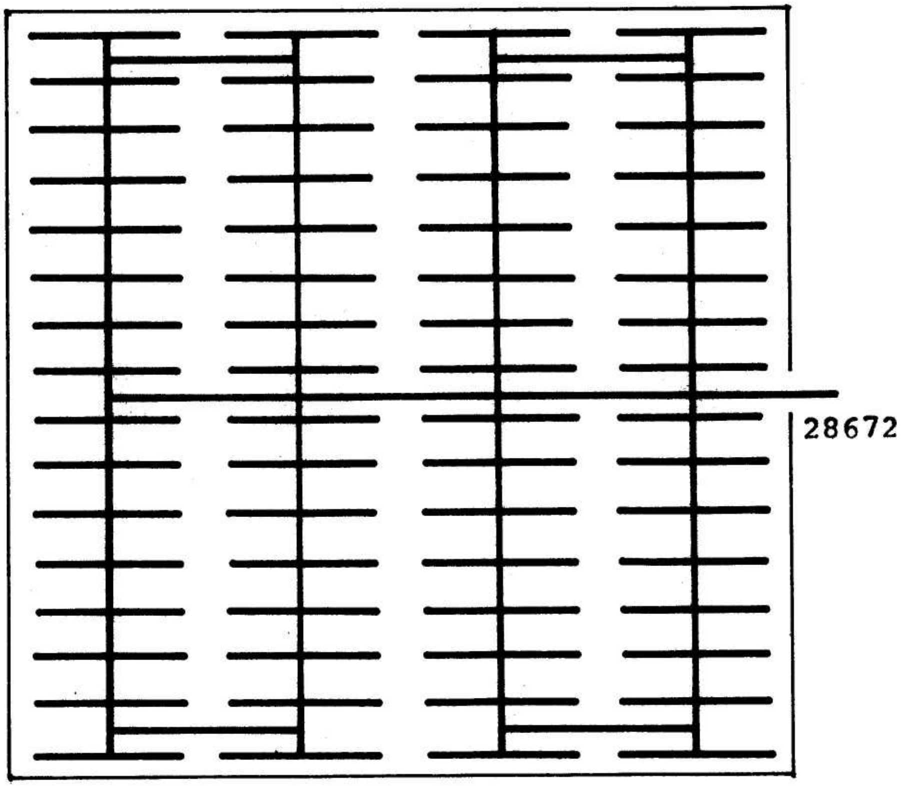


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-11

Delta T=20° F
Single Unit Homes
8000 Units per sq mi
64 Structures per block
128 Blocks per sq mi





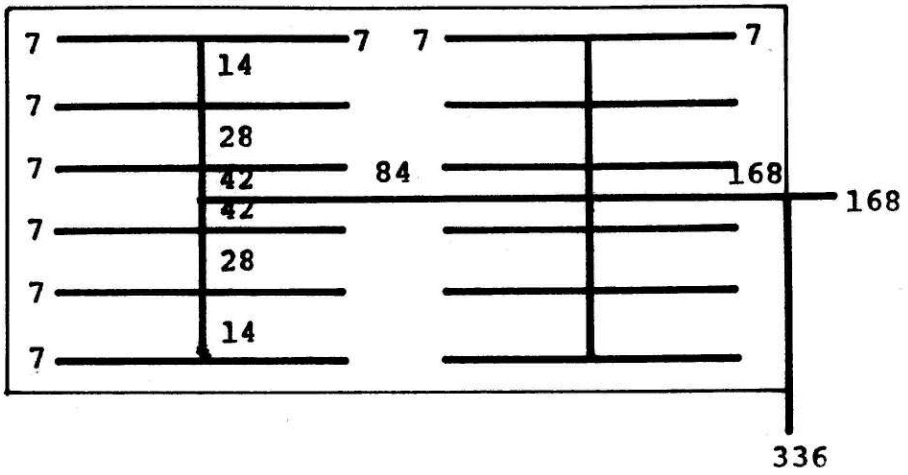
Note: Numbers adjacent to flowpaths are flowrates (gpm).

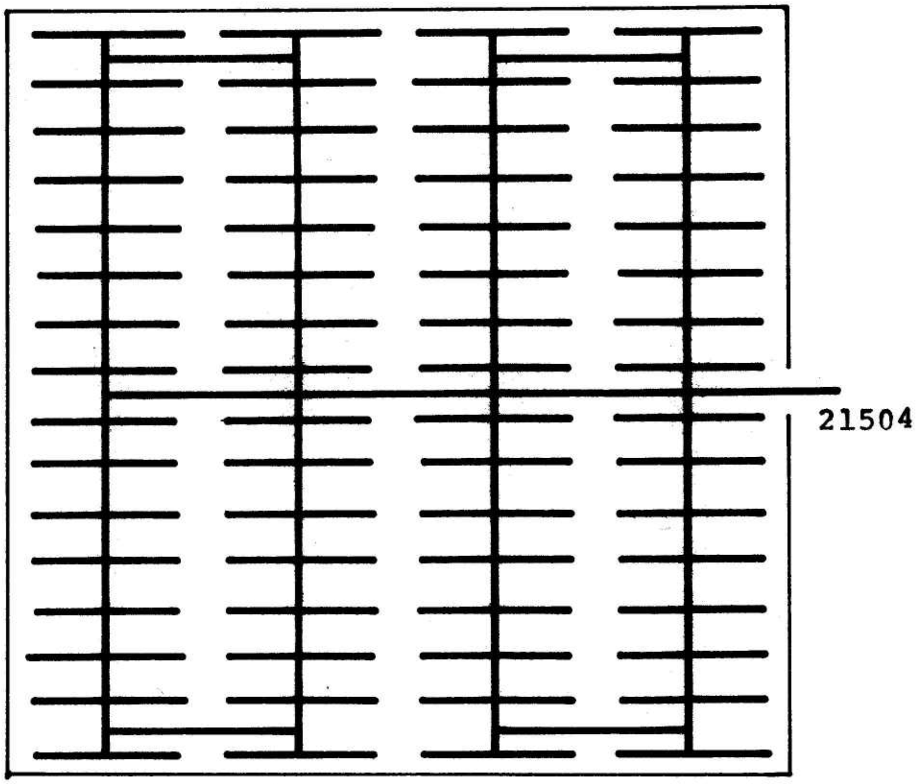
Figure B-12

Delta T=20° F

Single Unit Homes

6000 Units per sq mi
48 Structures per block
128 Blocks per sq mi

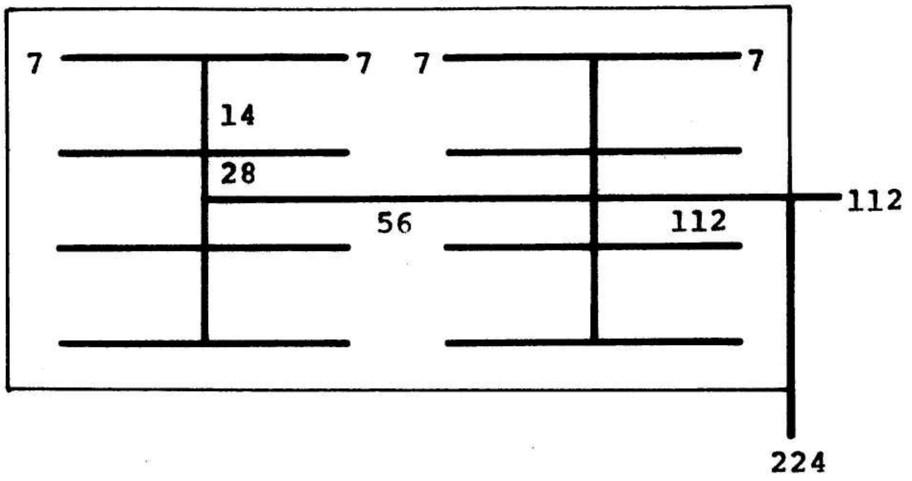


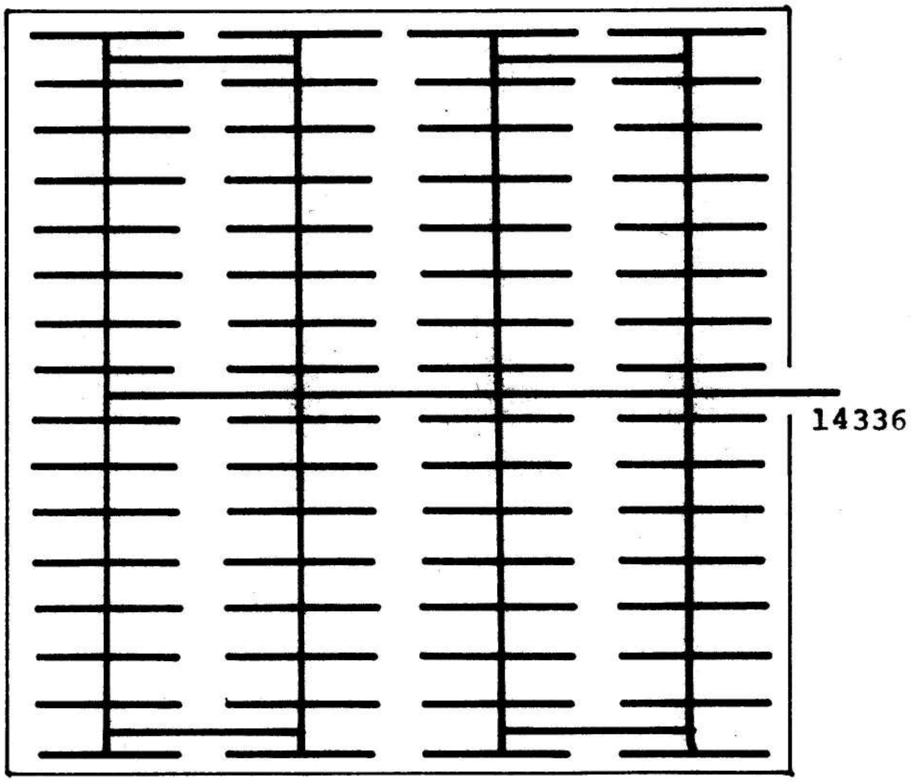


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-13

Delta T=20° F
Single Unit Homes
4000 Units per sq mi
32 Structures per block
128 Blocks per sq mi

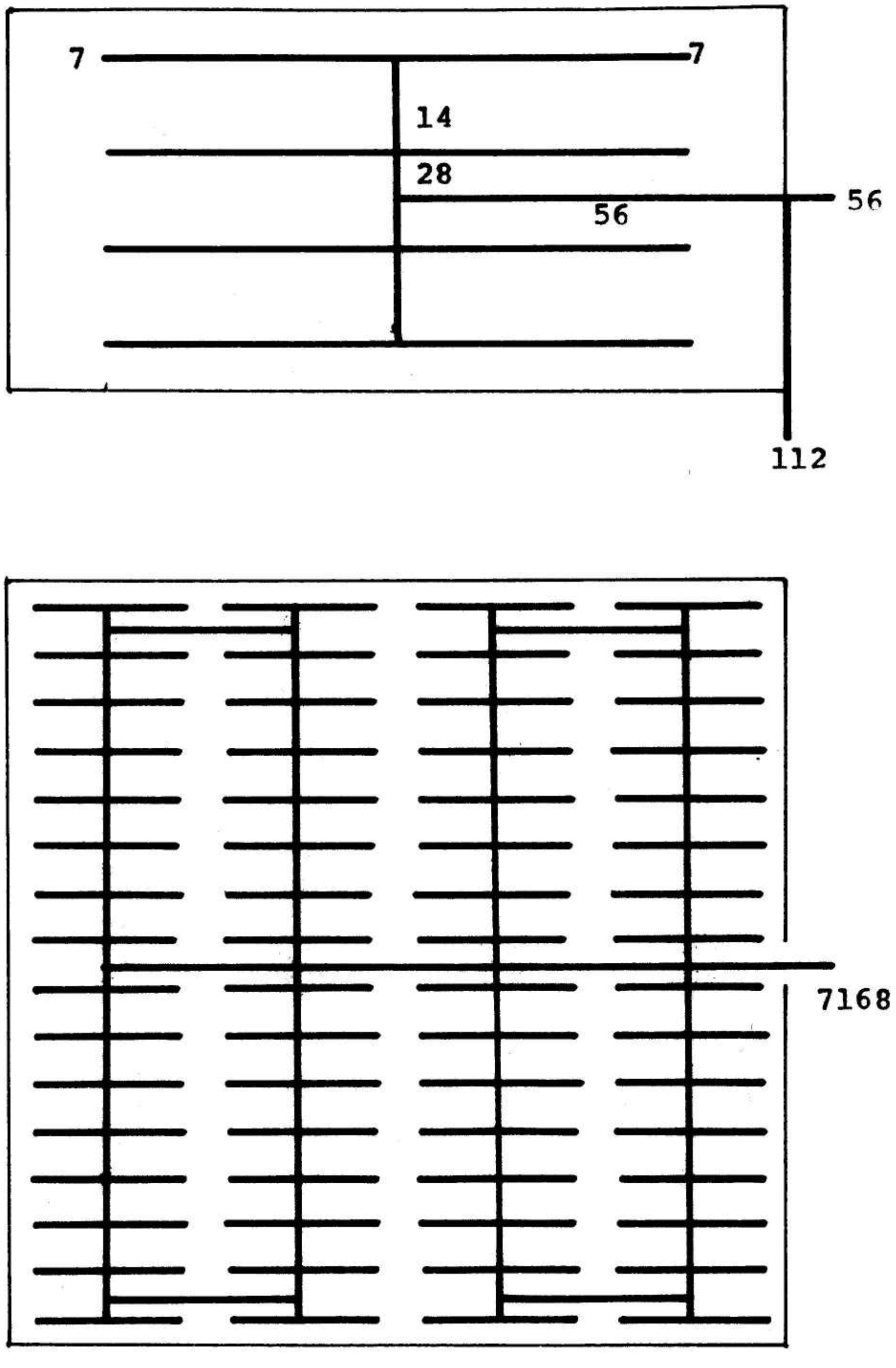




Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-14

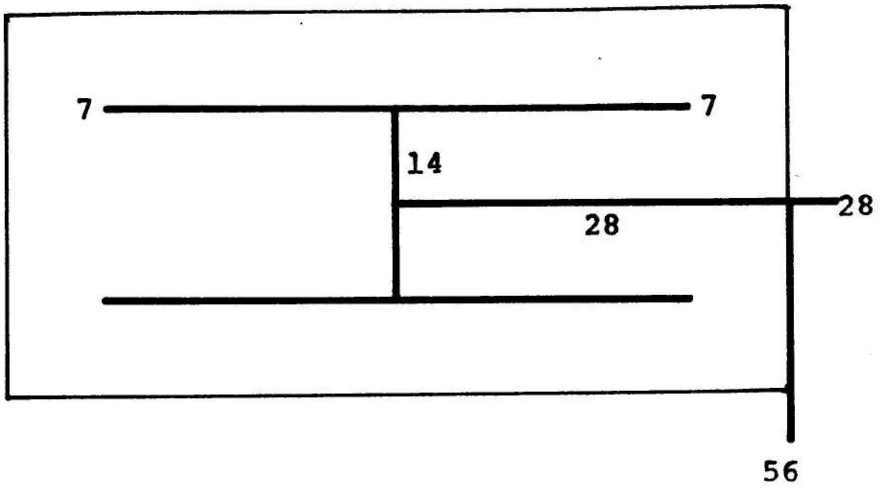
Delta T=20° F
Single Unit Homes
2000 Units per sq mi
16 Structures per block
128 Blocks per sq mi

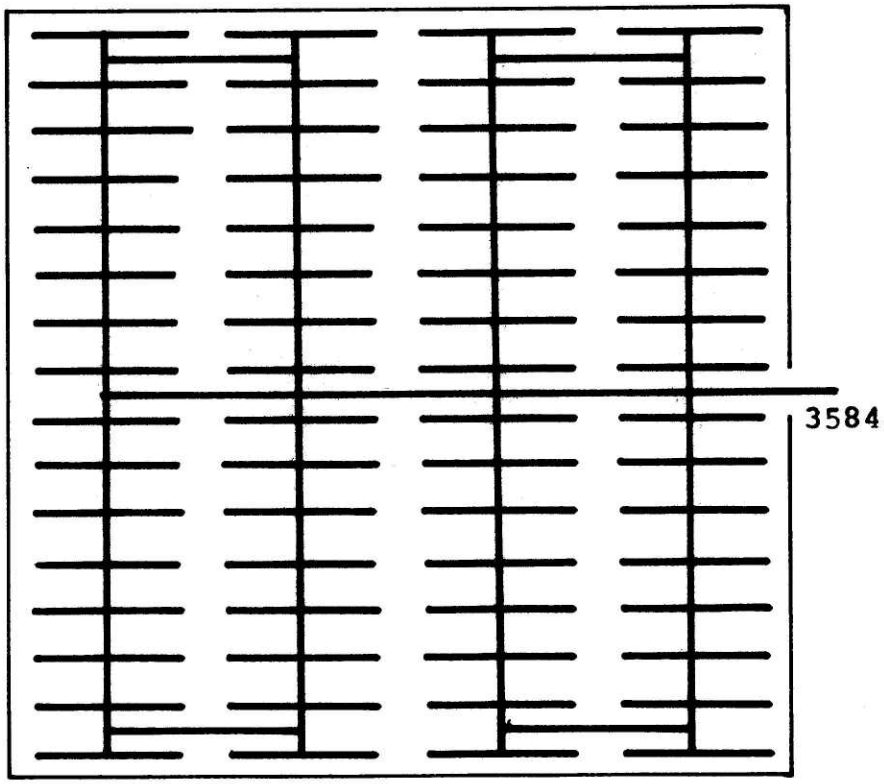


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-15

Delta T=20° F
Single Unit Homes
1000 Units per sq mi
8 Structures per block
128 Blocks per sq mi

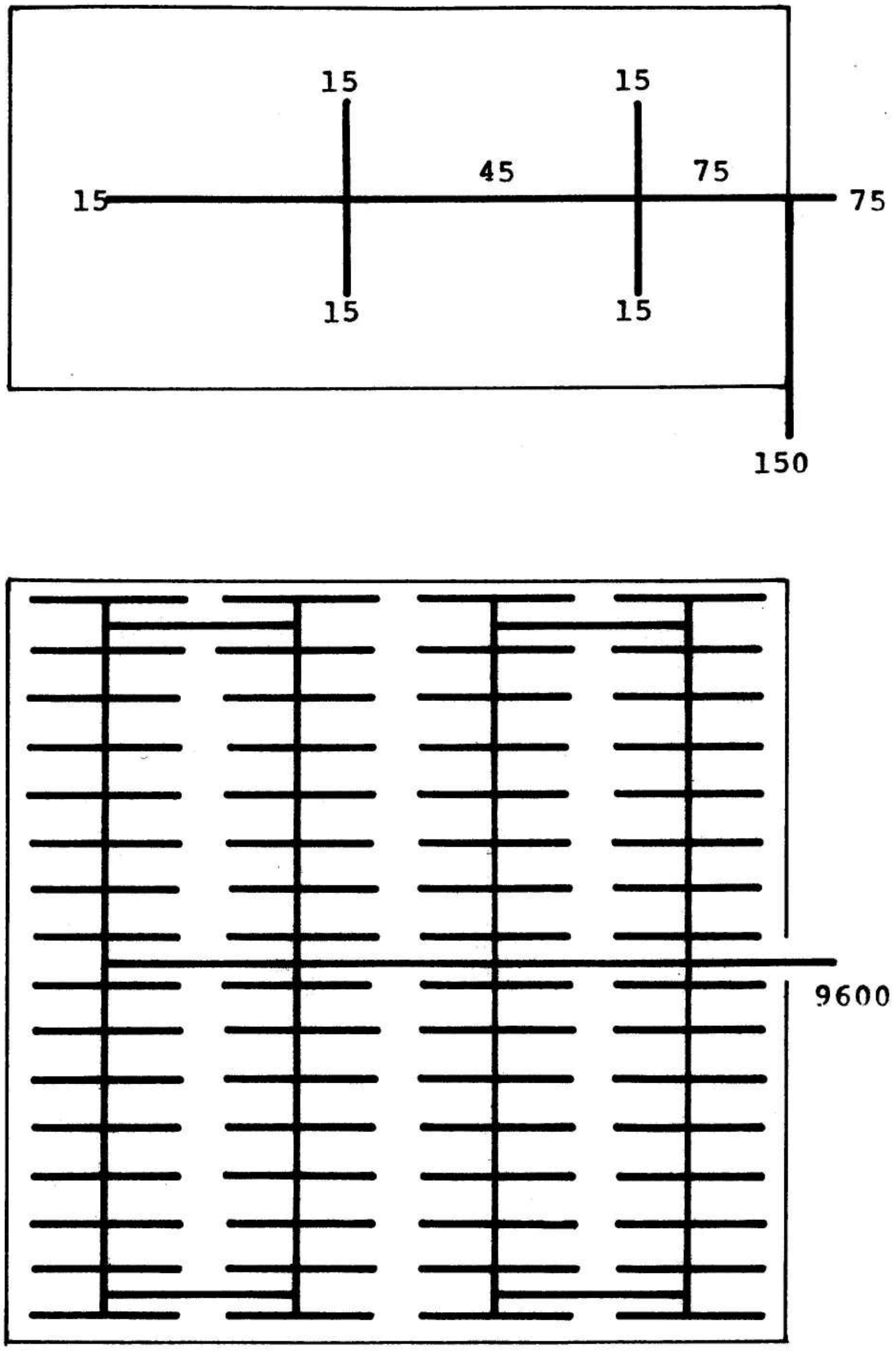




Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-16

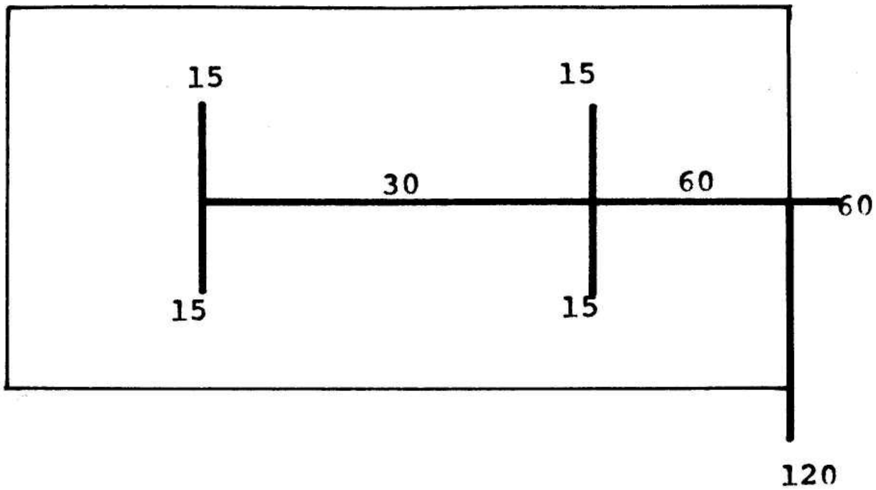
Delta T=40° F
Twelve Unit Apartments
8000 Units per sq mi
5 Structures per block
128 Blocks per sq mi

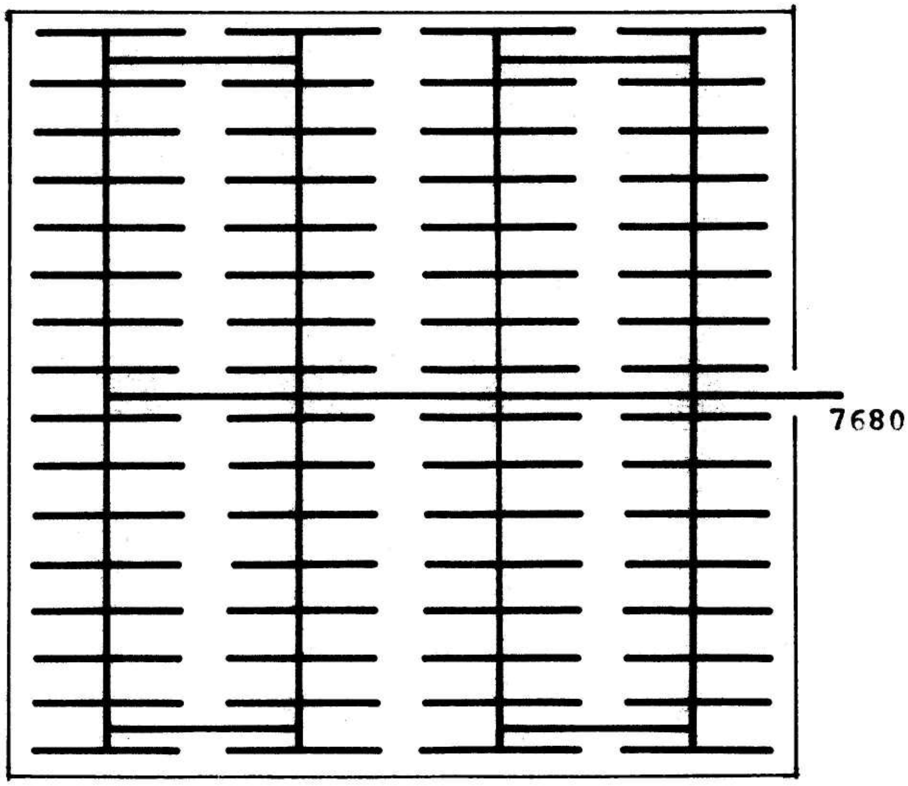


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-17

Delta T=40° F
Twelve Unit Apartments
6000 Units per sq mi
4 Structures per block
128 Blocks per sq mi

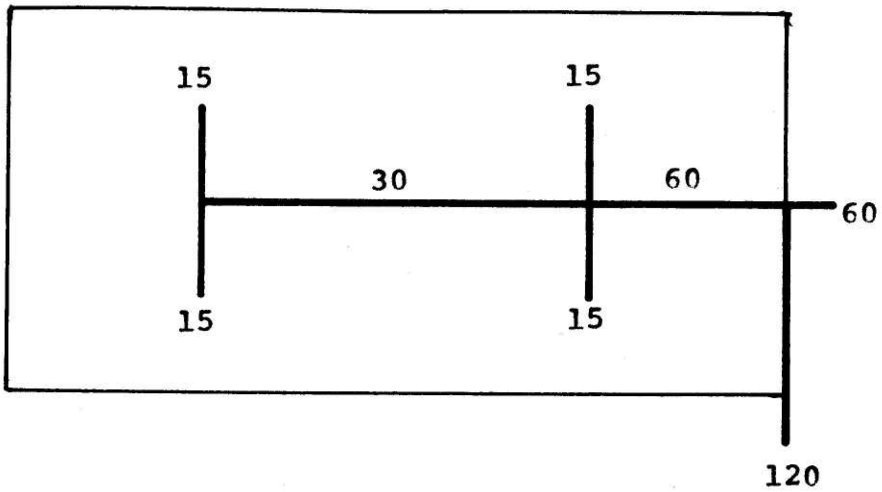


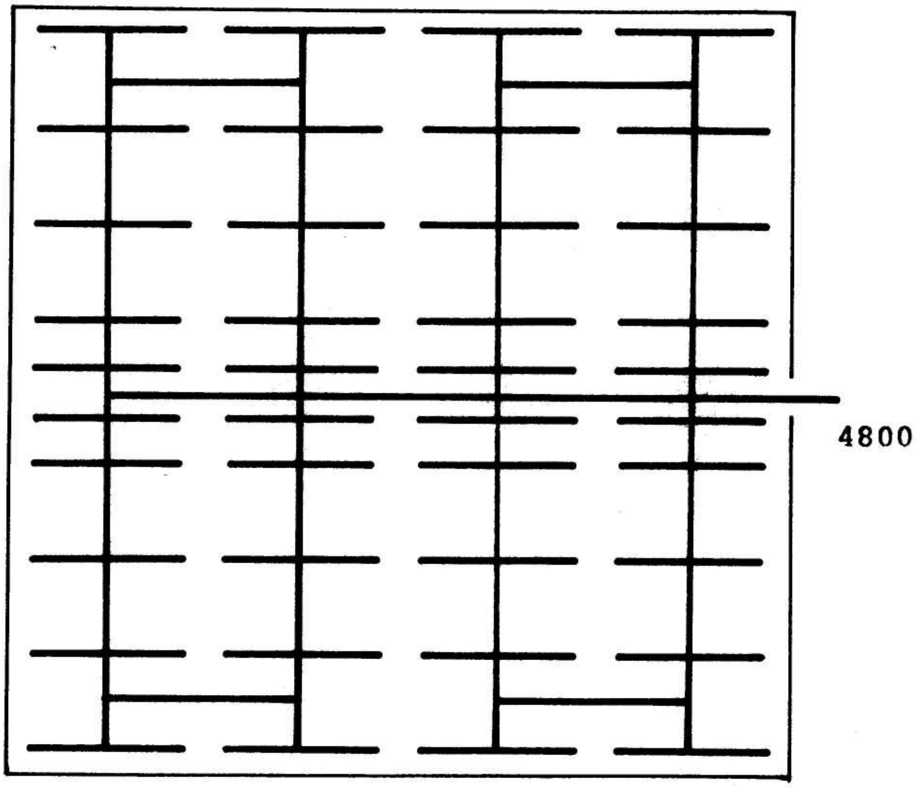


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-18

Delta T=40° F
Twelve Unit Apartments
4000 Units per sq mi
4 Structures per block
80 Blocks per sq mi

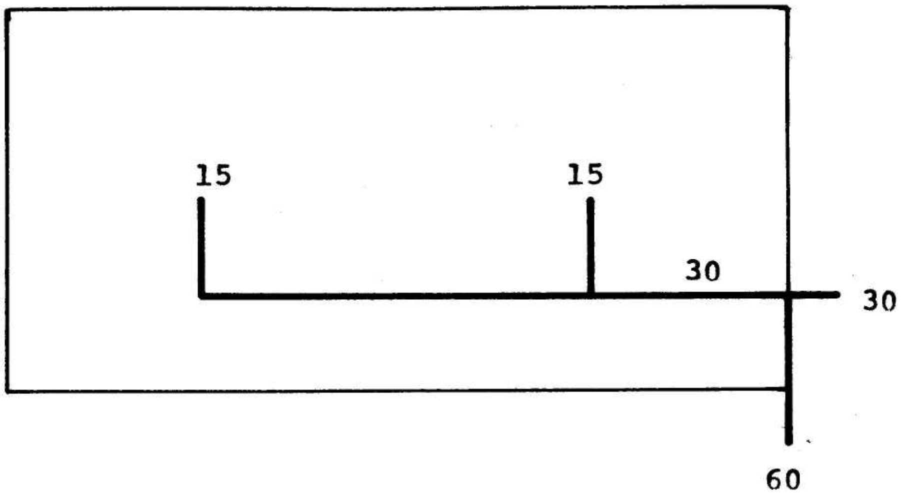


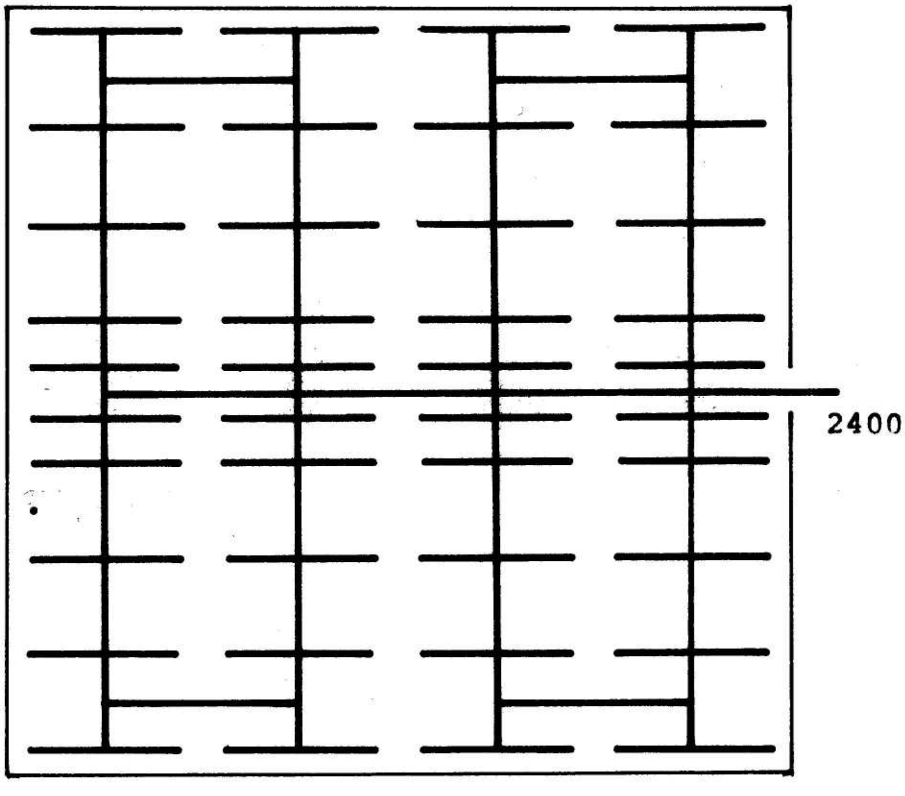


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-19

Delta T=40° F
Twelve Unit Apartments
2000 Units per sq mi
2 Structures per block
80 Blocks per sq mi

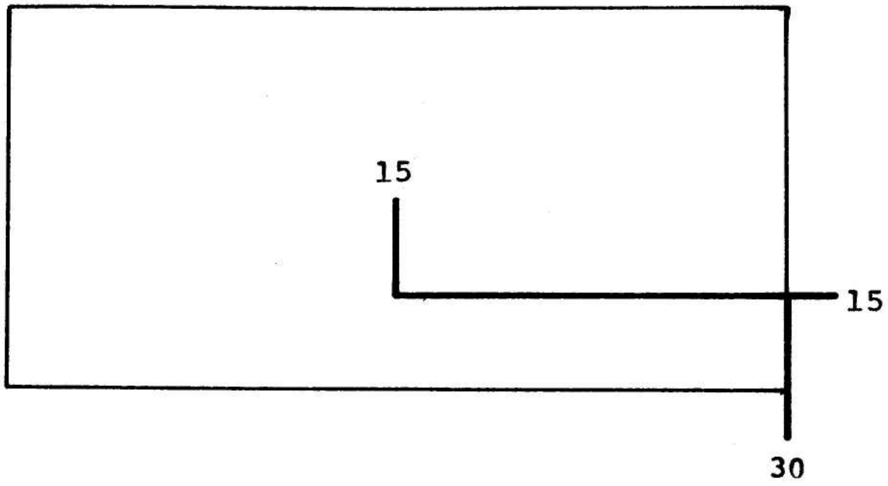


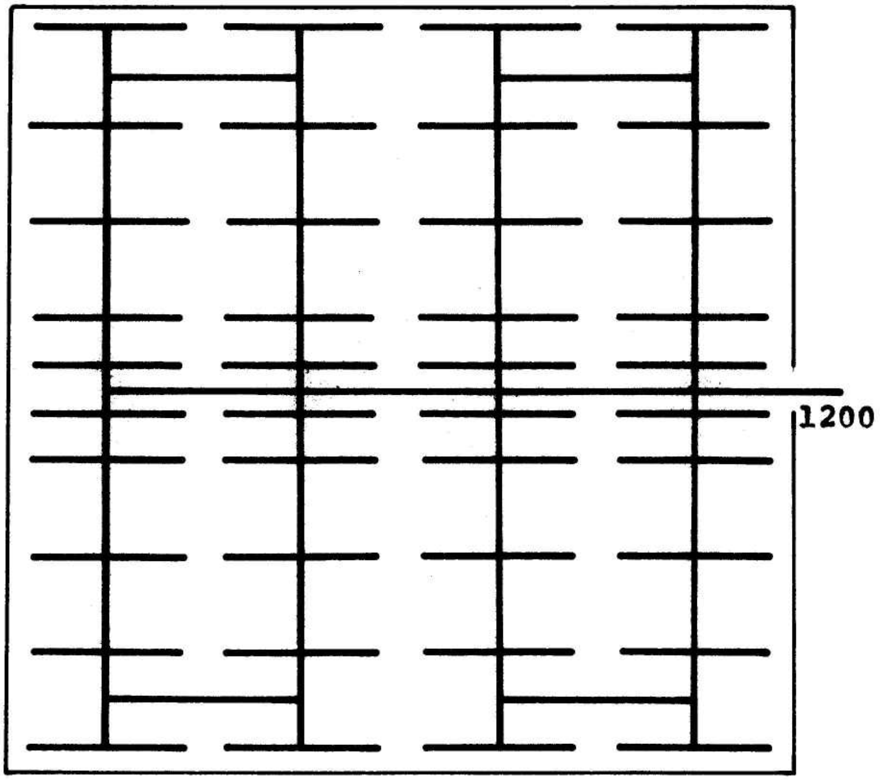


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-20

Delta T=40° F
Twelve Unit Apartments
1000 Units per sq mi
1 Structure per block
80 Blocks per sq mi

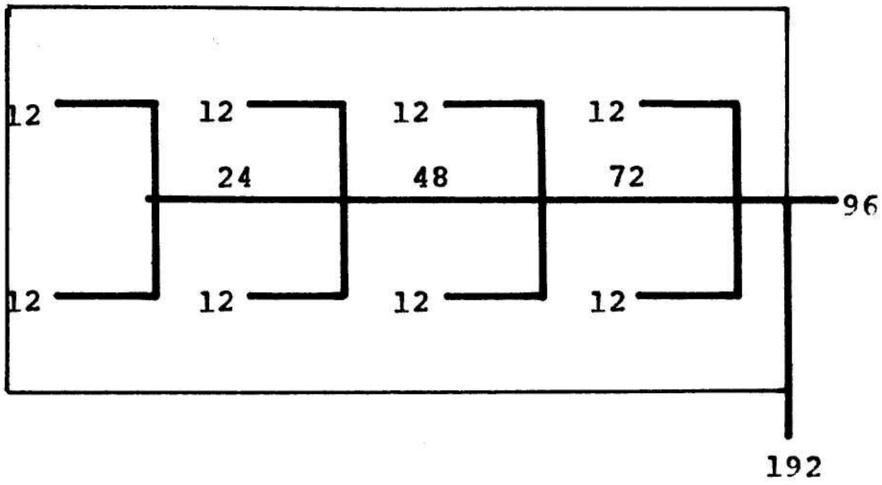


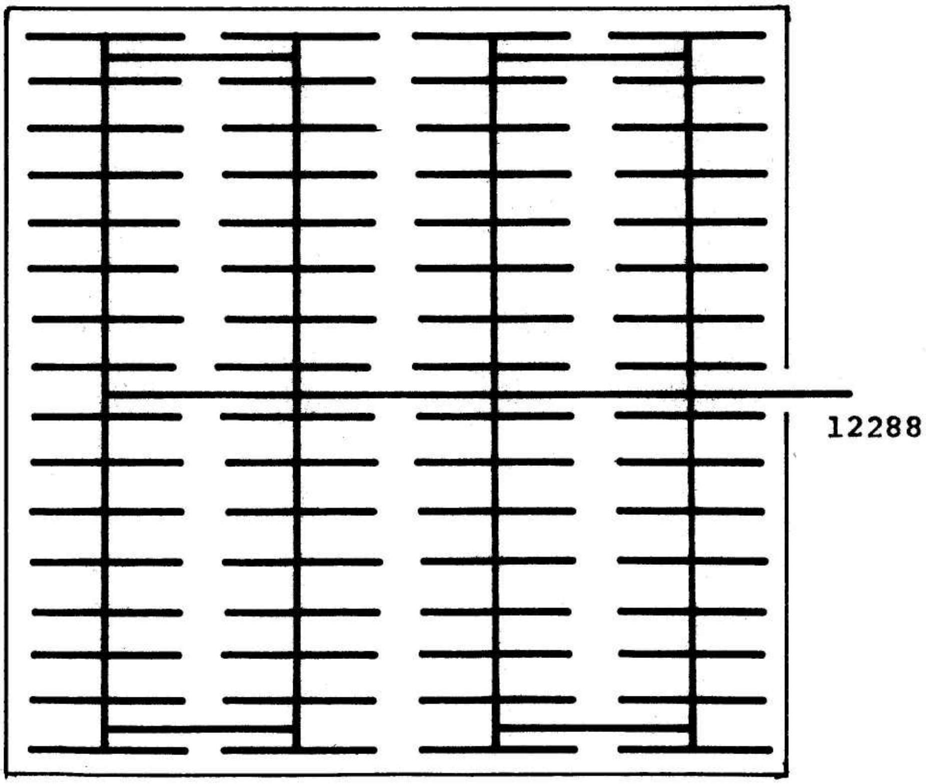


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-21

Delta T=40° F
Four Unit Apartments
8000 Units per sq mi
16 Structures per block
128 Blocks per sq mi

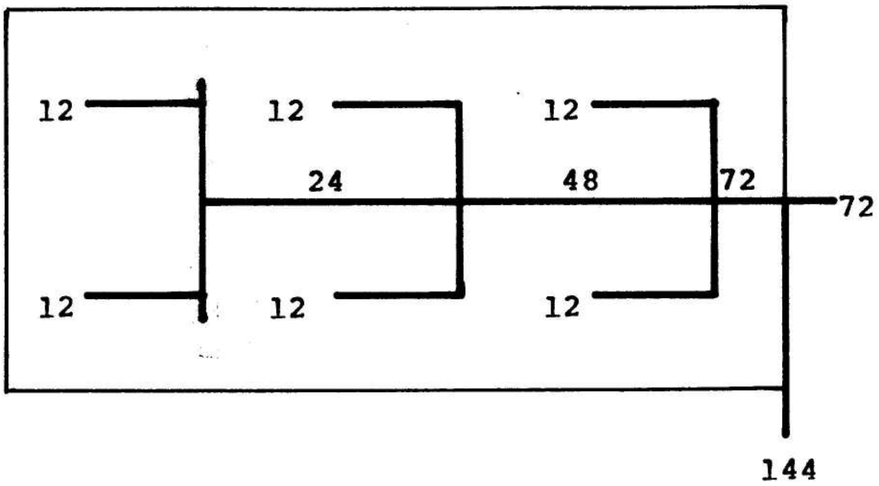


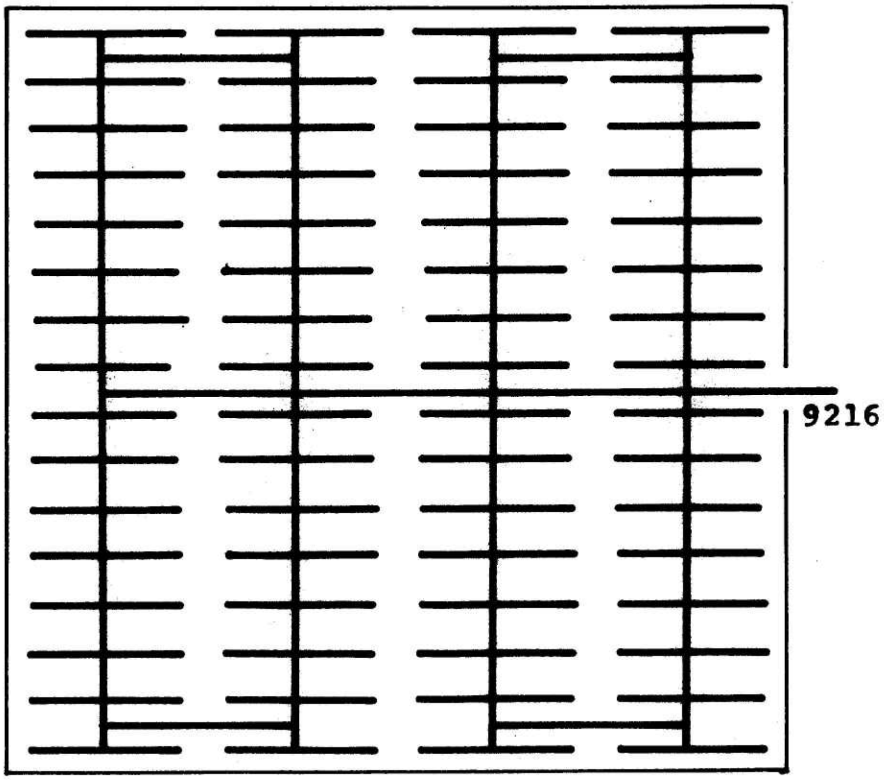


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-22

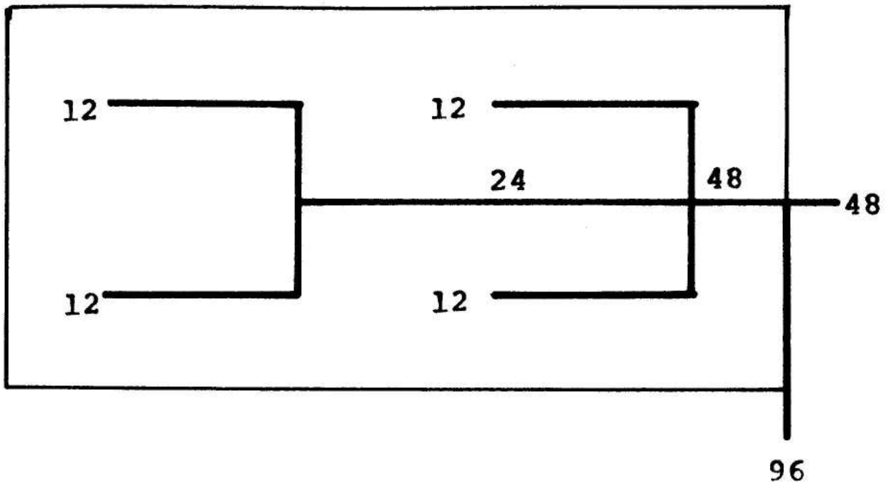
Delta T=40° F
Four Unit Apartments
6000 Units per sq mi
12 Structures per block
128 Blocks per sq mi

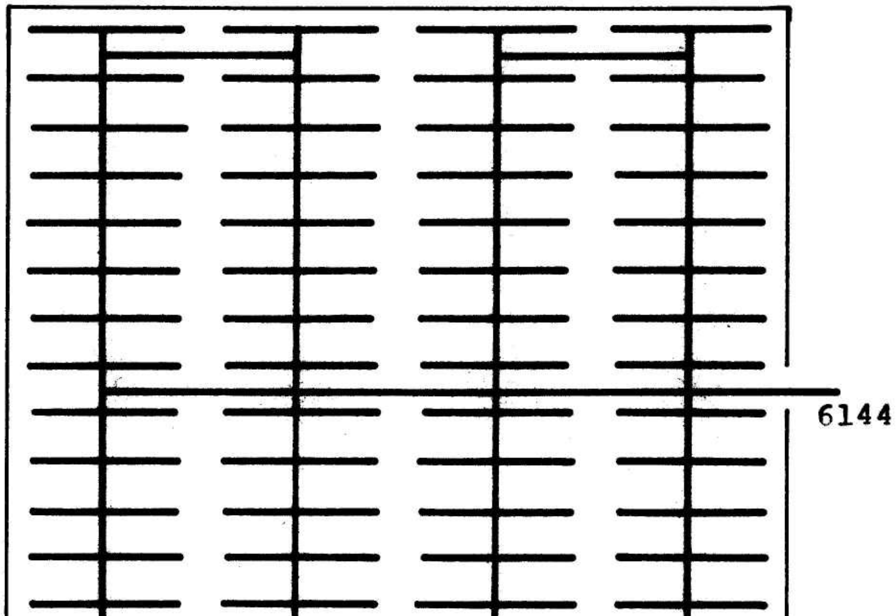




Note: Numbers adjacent to flowpaths are flowrates (gpm).

Delta T=40°F **Figure** B-23
Four Unit Apartments
4000 Units per sq mi
8 Structures per block
128 Blocks per sq mi

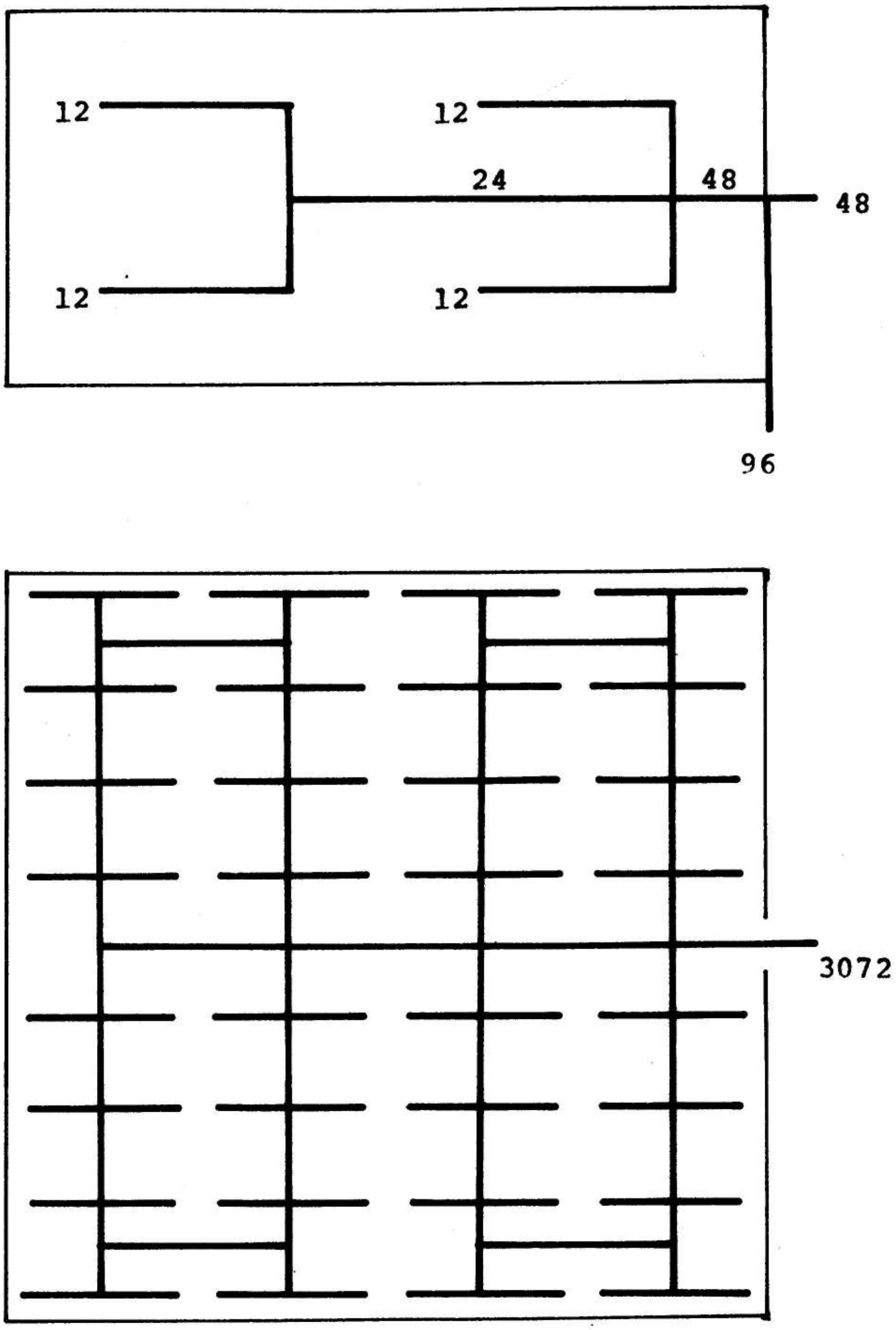




Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-24

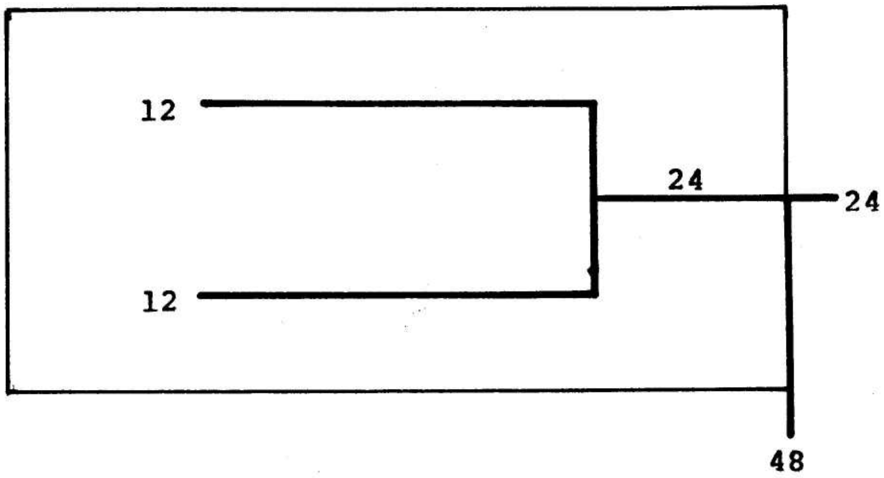
Delta T=40° F
Four Unit Apartments
2000 Units per sq mi
8 Structures per block
64 Blocks per sq mi

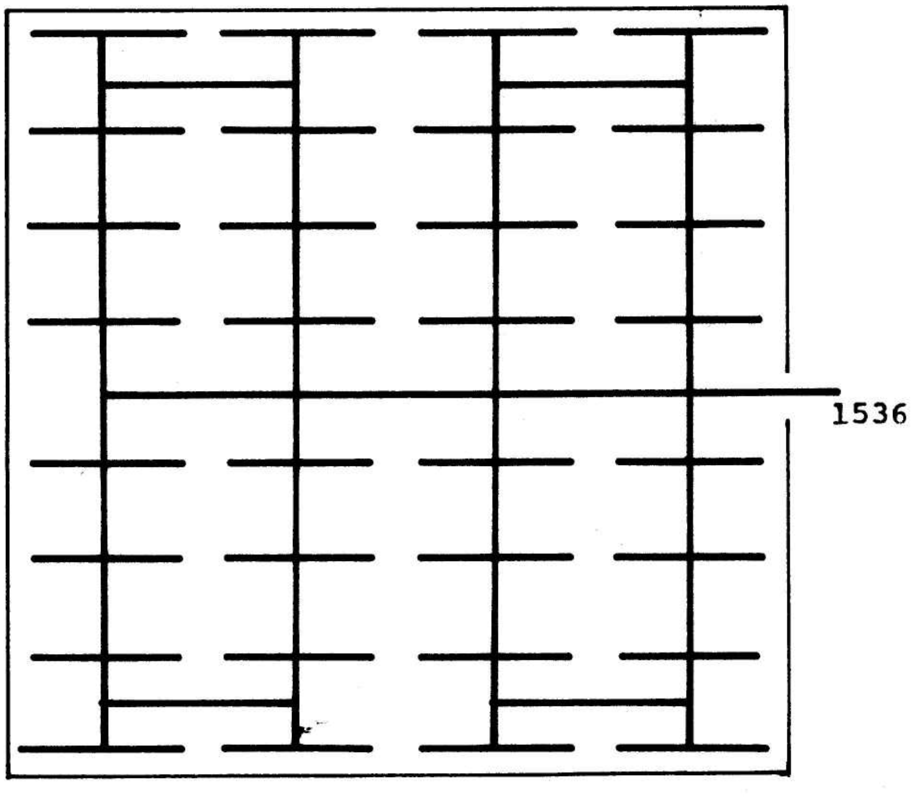


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-25

Delta T=40° F
Four Unit Apartments
1000 Units per sq mi
4 Structures per block
64 Blocks per sq mi

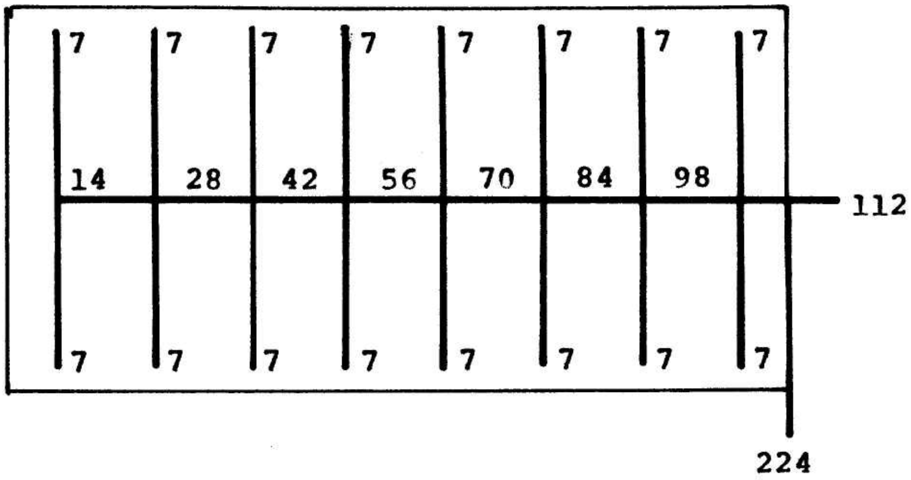


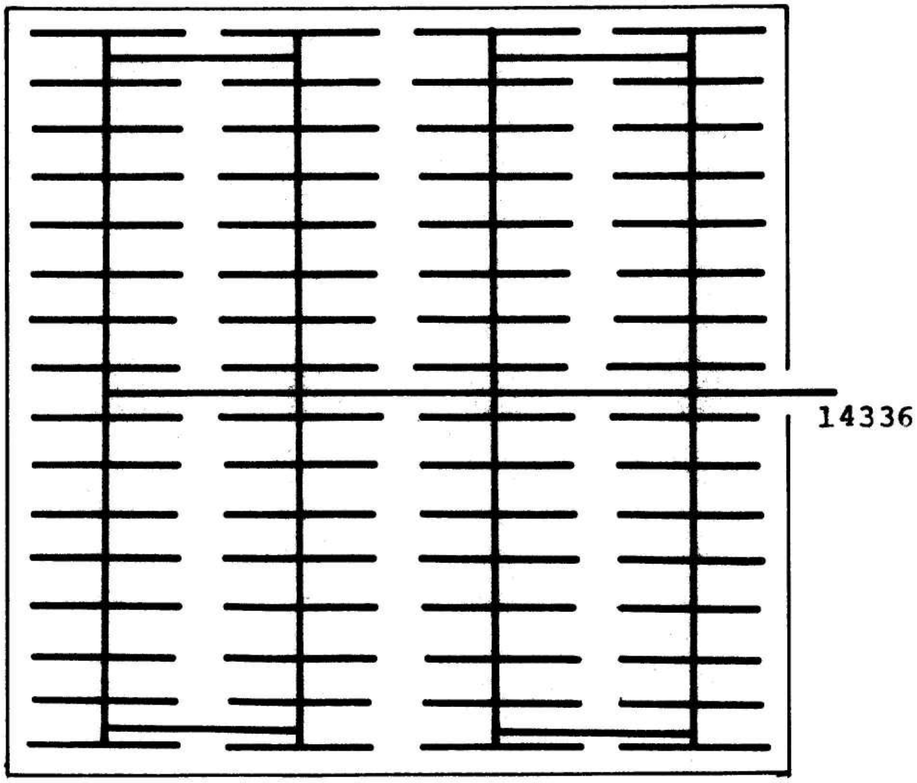


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-26

Delta T=40° F
Single Unit Homes
8000 Units per sq mi
64 Structures per block
128 Blocks per sq mi

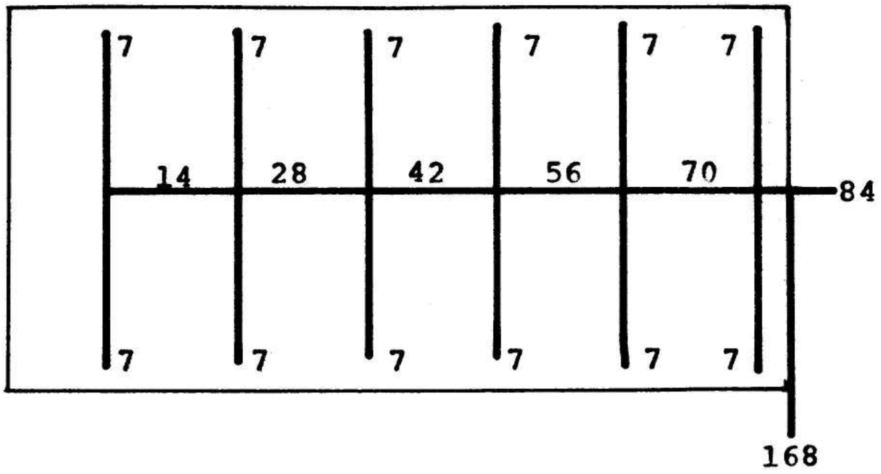


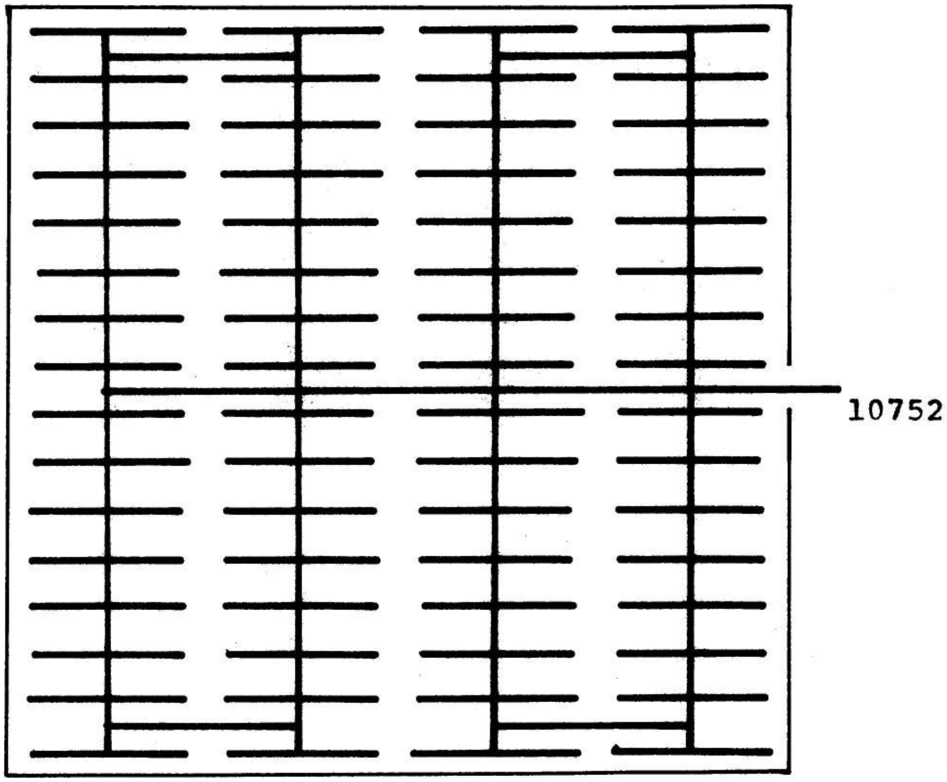


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Delta T=40° F **Figure** B-27

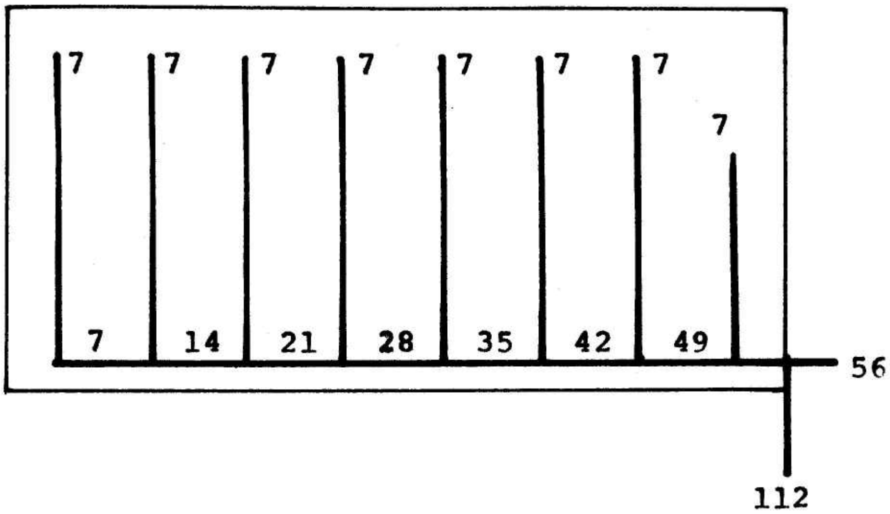
Single Unit Homes
6000 Units per sq mi
48 Structures per block
128 Blocks per sq mi

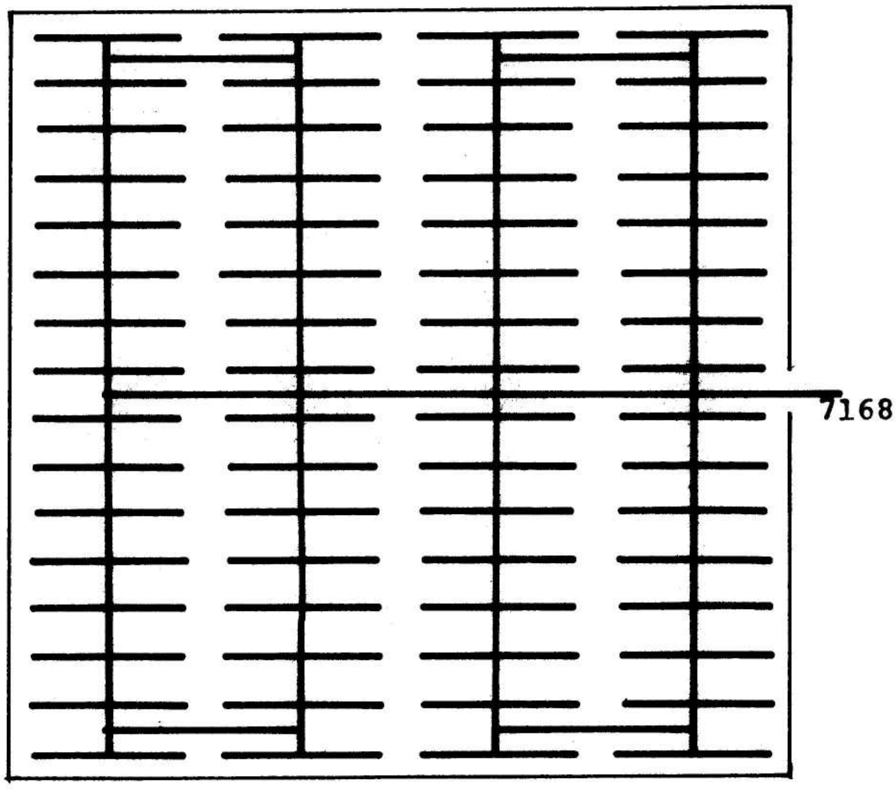




Note: Numbers adjacent to flowpaths are flowrates (gpm).

Delta $T=40^\circ F$ **Figure** B-28
Single Unit Homes
4000 Units per sq mi
31 Structures per block
128 Blocks per sq mi



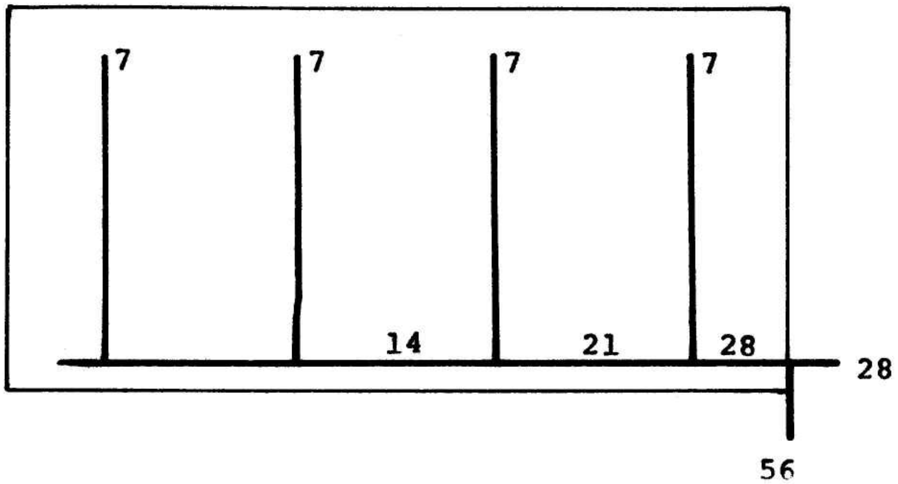


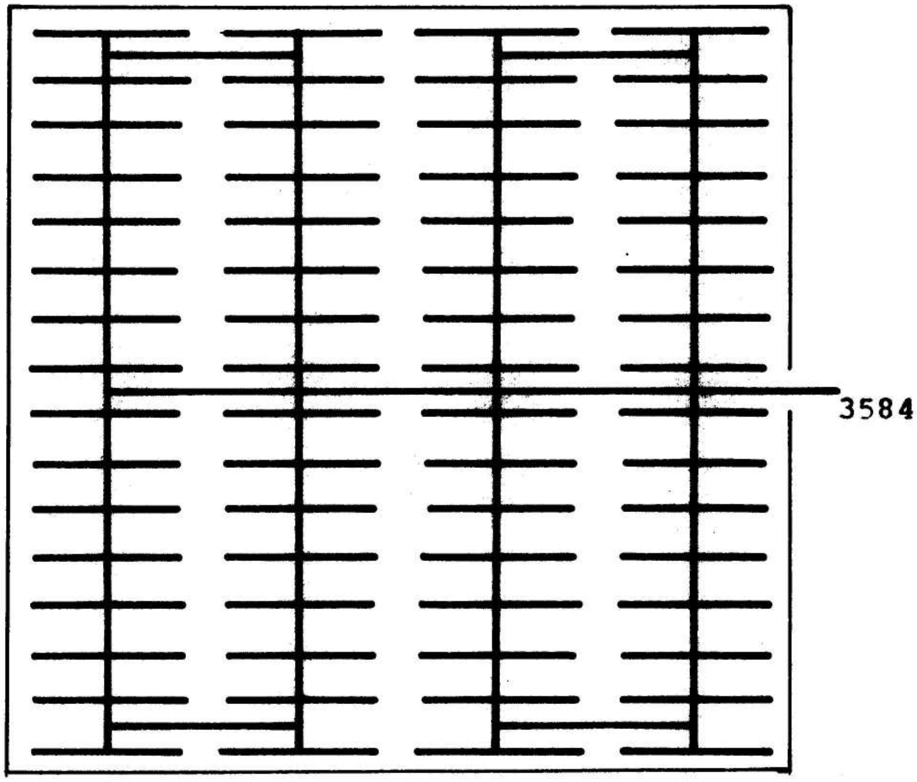
Note: Numbers adjacent to flowpaths are flowrates (gpm).

Delta T=40° F

Figure B-29

Single Unit Homes
2000 Units per sq mi
16 Structures per block
128 Blocks per sq mi

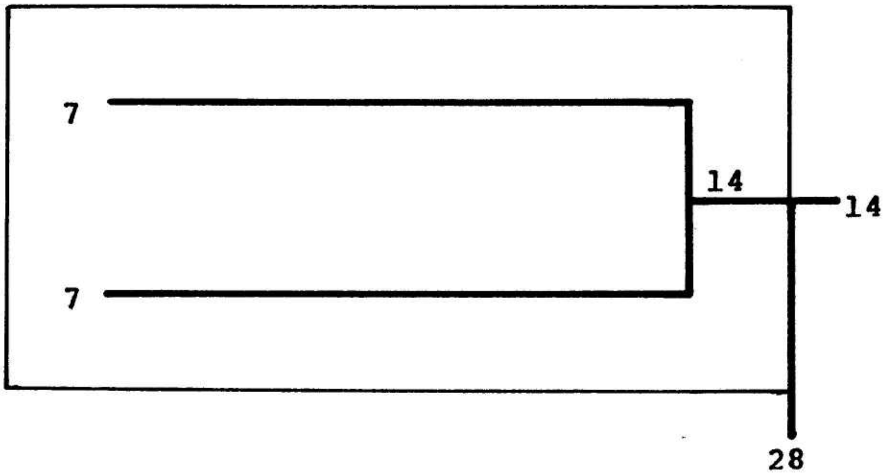


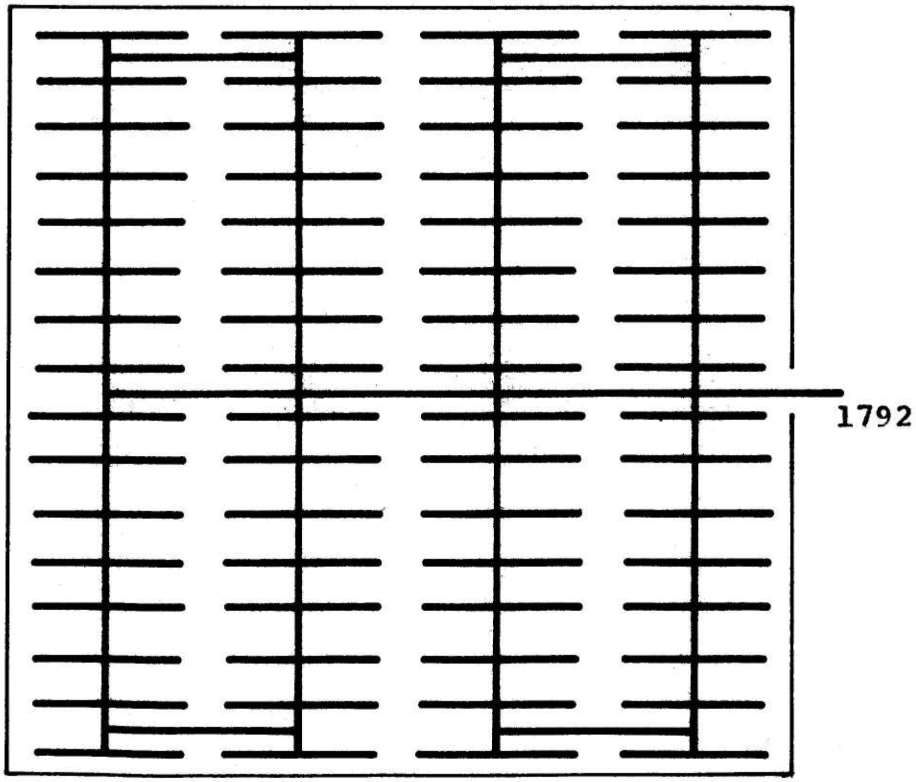


Note: Numbers adjacent to flowpaths are flowrates (gpm).

Delta T=40° F
Single Unit Homes
1000 Units per sq mi
8 Structures per block
128 Blocks per sq mi

Figure B-30

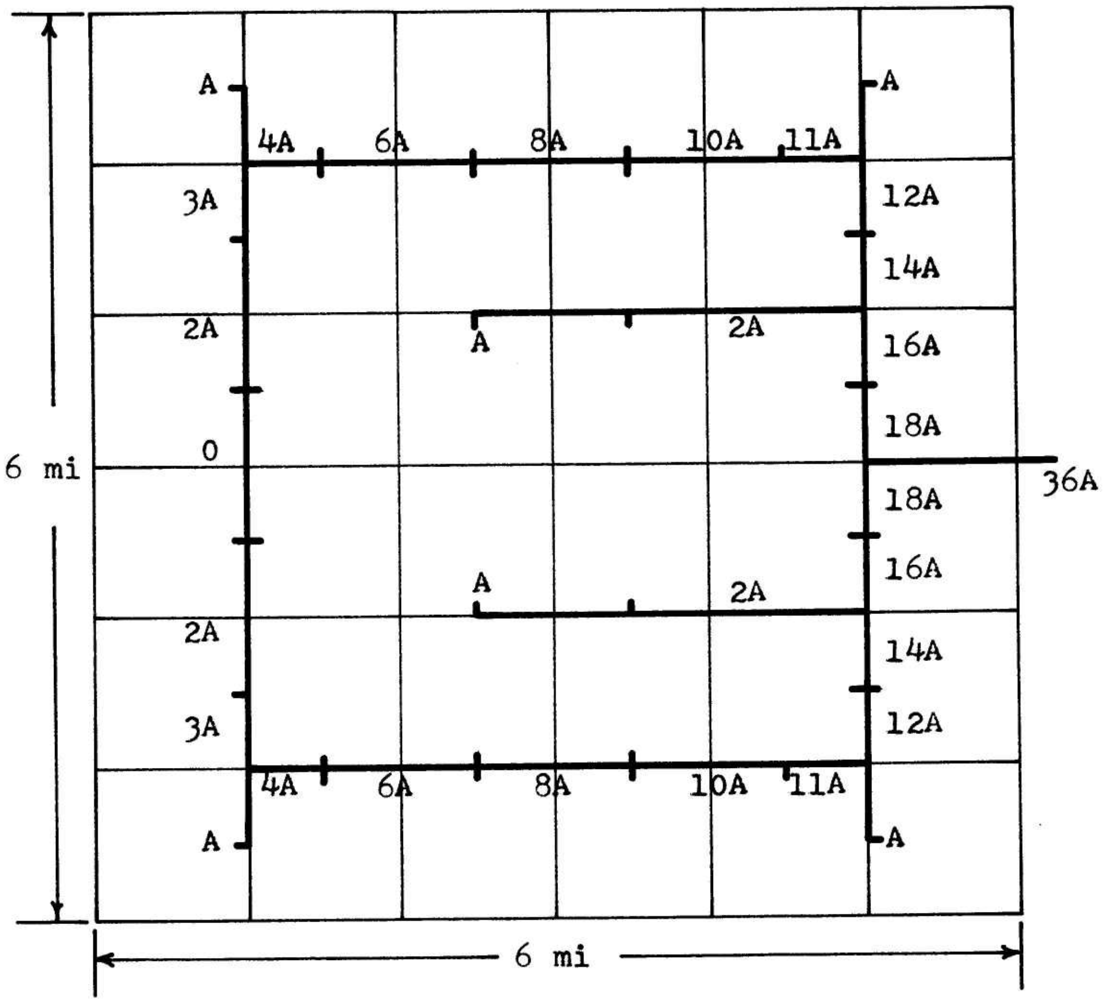




Note: Numbers adjacent to flowpaths are flowrates (gpm).

Figure B-31

BASIC 36 SQ. MILE NETWORK



Note: Each square mile network has flow "A" and the notations by the flowpaths are flowrates.

APPENDIX C

PROGRAM LISTINGS

```
C    PROGRAM FOR CALCULATING OPTIMUM PIPING FOR GIVEN FLOW
      COMMON ROUGH,WTEMP,PIPLIF,PUMLIF,PURATE
      COMMON PIRATE,PUMEFF,DELP,FACT,ERATE
      DIMENSION PQ(30,2)
      DO 200 I=1,30
      READ(8,2) PQ(I,1)
2     FORMAT (F4.0)
200   CONTINUE
      ROUGH=0.00015
      WTEMP=70.
      PIPLIF=50.
      PUMLIF=25.
      PURATE=0.09
      PIRATE=0.09
      PUMEFF=0.85
      FACT=0.25
      ERATE=3.36
      Q=1.
      MM=1
      QQ=1.
1     J=1
      DELDIA=60.
      DIA1=1.
      COST1=PCOST(Q,DIA1,J)
      DIA2=120.
      COST2=PCOST(Q,DIA2,J)
      DIA3=60.
      COST3=PCOST(Q,DIA3,J)
5     IF(COST1.LT.COST2.AND.COST1.LT.COST3) GO TO 10
      IF(COST2.LT.COST1.AND.COST2.LT.COST3) GO TO 20
      GO TO 30
10    DIA3=DIA1
      COST3=COST1
      GO TO 30
```

```
20      DIA3=DIA2
        COST3=COST2
30      DELDIA=DELDIA/2.
        IF(DELDIA.LT.0.01) GO TO 100
        DIA1=DIA3-DELDIA
        IF(DIA1.GT.1.) GO TO 40
        DIA1=1.
40      COST1=PCOST(Q,DIA1,J)
        DIA2=DIA3+DELDIA
        IF(DIA2.LT.120.) GO TO 50
        DIA2=120.
50      COST2=PCOST(Q,DIA2,J)
        GO TO 5
100     J=2
        PRINT=PCOST(Q,DIA3,J)
505     IF(MM.GT.30) GO TO 501
        IF(DIA3.EQ.120.) GO TO 500
        IF(DIA3.GT.PQ(MM,1)) GO TO 502
501     QQ=Q
        DD=DIA3
        Q=Q*1.77827941
        IF(Q.LT.1E7) GO TO 1
        DO 600 I=1,30
C   PRINT OUT MATRIX AND SLOVE FOR VELOCITIES
C   D IS IN INCHES AND Q IS IN GPMS
        IF(I.EQ.1) Q1=1.
        D=PQ(I,1)
        Q=PQ(I,2)
        V1=0.408526*Q1/D**2
        V2=0.408526*Q/D**2
        Q1=Q
        WRITE(5,601) PQ(I,1),PQ(I,2),V1,V2
601     FORMAT(1H ,F4.0,3X,F11.4,3X,F5.2,3X,F5.2)
```

```
600   CONTINUE
      GO TO 9999
502   SL=(DIA3-DD)/(Q-QQ)
      B=DIA3-SL*Q
500   PQ(MM,2)=(PQ(MM,1)-B)/SL
504   MM=MM+1
603   GO TO 505
9999  END
```

```
      FUNCTION PCOST(Q,DIA,J)
      COMMON ROUGH,WTEMP,PIPLIF,PUMLIF,PURATE
      COMMON PIRATE,PUMEFF,DELP,FACT,ERATE
20    DIA=DIA/12.
      PAREA=3.1415926*DIA**2/4.
      WVEL=Q/PAREA/448.8
      WMU=7.3283E-4/WTEMP
      WDEN=EXP(-1.3656E-4*WTEMP+4.14129)
      REYN=WVEL*DIA/WMU
      FRICT=FRIC(ROUGH,DIA,REYN)
      PLOSS=1.4*FRICT*WVEL**2*WDEN/DIA/9273.6
      POWER=4.3502E-4*PLOSS*Q/PUMEFF
      PENGY=8760.*POWER*FACT
      ECOST=2.*ERATE*PENGY/100.
      D=DIA*12.
      IF(D.GE.0.999999.AND.D.LE.120.) GO TO 50
      WRITE(5,60) D
60    FORMAT(55H ERROR]PIPE SIZE OUT OF RANGE.          .DIAMETER(IN)=,
     +F6.2)
50    PIPEC=PIPE(D)
      XX=(1.+PIRATE)**PIPLIF
      PIPEC=PIPEC*PIRATE*XX/(XX-1.)
      PCOST=ECOST+PIPEC
      DIA=DIA*12.
      IF(J.EQ.1) GO TO 100
C   CHECK FOR PRESSURE DROP CRITERIA OF 75 PSI/MILE MAXIMUM
      IF(PLOSS.LE.0.0142) GO TO 10
      IF(DIA.GE.120.) GO TO 10
      DIA=DIA+0.1
      GO TO 20
10    COST=PCOST
```

```
C  PRINTOUT IN SEQUENCE A--J
C  A=Q(GPM)
C  B=DIA(IN)
C  C=TOTAL COST($/FT)
C  F=PIPE COST($/FT)
C  G=PIPE COST(%)
C  H=ECOST($/FT)
C  I=ECOST(%)
C  J=PLOSS(PSI/FT)
       P2=PIPEC/COST
       P3=ECOST/COST
       WRITE(5,2) Q,DIA,COST,PIPEC,P2,ECOST,P3,PLOSS
2      FORMAT(1H ,F11.4,3X,F6.2,3X,E11.4,2(3X,E11.4,3X,F5.3),3X,E11.4)
100    RETURN
9999   END
```

```
      FUNCTION PIPE(D)
      IF(D.LE.6.) GO TO 300
      IF(D.LE.18.) GO TO 302
      IF(D.LE.42.) GO TO 304
      IF(D.LE.72.) GO TO 306
      PIPE=EXP(1.8332*ALOG(D)-1.5564)
      GO TO 56
300   PIPE=EXP(0.42738*ALOG(D)+2.596)
      GO TO 56
302   PIPE=EXP(0.80636*ALOG(D)+1.917)
      GO TO 56
304   PIPE=EXP(1.3082*ALOG(D)+0.46661)
      GO TO 56
306   PIPE=EXP(1.72023*ALOG(D)-1.07324)
56    PIPE=PIPE*1.5
      RETURN
      END
```

```
      FUNCTION FRIC (ROUGH,DIA,REYN)
      Z(A,B,C)=1./SQRT(C)-0.8686*ALOG(A/(1.+18.7*A/(SQRT(C)*B)))-1.74
      RE=DIA/2./ROUGH
30    IF(REYN.LE.2000.) GO TO 10
      XX=REYN**0.871/455.3
      IF(RE.GT.XX) GO TO 20
      FRIC=(1.74+0.8686*ALOG(RE))**(-2)
      RETURN
10    FRIC=64./REYN
      RETURN
20    DELF=0.0375
      F1=0.005
      Z1=Z(RE,REYN,F1)
      IF(Z1.GT.1E-4.OR.Z1.LT.-1E-4) GO TO 60
      FRIC=F1
      RETURN
60    F2=0.08
      Z2=Z(RE,REYN,F2)
      IF(Z2.GT.1E-4.OR.Z2.LT.-1E-4) GO TO 70
      FRIC=F2
      RETURN
70    IF(Z1.GT.0..AND.Z2.LT.0..OR.Z1.LT.0..AND.Z2.GT.0.) GO TO 80
      WRITE(5,75)
75    FORMAT(54H ERROR...NO ZERO SOLUTION TO FRICTION FACTOR.KILL RUN.)
       GO TO 9999
80    F3=F1+DELF
      Z3=Z(RE,REYN,F3)
      IF(Z3.GT.1E-5.OR.Z3.LT.-1E-5) GO TO 90
      FRIC=F3
      RETURN
90    DELF=DELF/2.
      IF(Z1.GT.0..AND.Z3.GT.0..OR.Z1.LT.0..AND.Z3.LT.0.) GO TO 110
      F2=F3
      Z2=Z3
      GO TO 120
```

```
110     F1=F3
        Z1=Z3
120     F3=F1+DELF
        Z3=Z(RE,REYN,F3)
        IF(Z3.GT.1E-4.OR.Z3.LT.-1E-4) GO TO 90
        FRIC=F3
        RETURN
9999    END
```

```
C  PROGRAM FOR CALCULATING NETWORK COST AND PARAMETERS
       COMMON ROUGH,WTEMP,PIPLIF,PUMLIF,PURATE
       COMMON PIRATE,PUMEFF,DELP,FACT,ERATE,PLOSS,ECOST
       DIMENSION PQ(30,2)
C INPUT LIST OF COMMERCIAL SIZE PIPE AND THE OPTIMUL FLOW FOR THAT SIZE
       DO 1 I=1,30
       READ (8,2) PQ(I,1),PQ(I,2)
2      FORMAT(F4.0,E11.4)
1      CONTINUE
C  LIST OF THE CONTROL PARAMETERS
       ROUGH=0.00015
       WTEMP=70.
       PIPLIF=50.
       PUMLIF=25.
       VLIFE=50.
       PURATE=0.09
       PIRATE=0.09
       VRATE=0.09
       PUMEFF=0.85
       DELP=100.
       FACT=0.25
       ERATE=3.36
C  CALCULATION OF CAPITAL RECOVERY FACTORS
C  CR1=PIPE,CR2=VALVE,CR3=PUPP
       XX=(1.+PIRATE)**PIPLIF
       CR1=PIRATE*XX/(XX-1.)
       XX=(1.+VRATE)**VLIFE
       CR2=VRATE*XX/(XX-1.)
       XX=(1.+PURATE)**PUMLIF
       CR3=PURATE*XX/(XX-1.)
C  INPUT...I=UNIT STRUCTURES,NN=#OF DENSITY NETWORKS
13     READ(8,3) I,NN
3      FORMAT(2I2)
```

```
C   CHECK FOR END OF RUN
      IF(I.EQ.0) GO TO 9999
C   PRINTOUT STRUCTURAL UNITS
      WRITE(5,4) I
4     FORMAT(1H1,I2,16H UNIT STRUCTURE)
C   CALCULATION FOR ONE NETWORK AT A TIME
      DO 5 L=1,NN
C   COST SUMMATIONS
      PSUM=0.
      VSUM=0.
      PUMPS=0.
      ESUM=0.
      SUM=0.
      PDROP=0.
C   INPUT..I=TOTAL ENTRIES,JJ=ENTRIES FOR SQ MI,DEN=UNITS PER SQ MI
      READ(8,6) I,JJ,DEN
6     FORMAT(2I2,F5.0)
      WRITE(5,17) DEN
17    FORMAT(1H0,F5.0,18HUNITS PER SQ. MILE)
      DO 7 N=1,I
C   READ NETWORK ENTRIES
      READ(8,8) Q,PL,BRNCH
8     FORMAT(3X,F8.0,F7.4,F5.0)
      XQ=1.
      Q1=Q
C   CHECK FOR FLOW WHERE HALVING Q WOULD MORE THEN HALF THE COST
40    IF(Q1.GT.500000.) GO TO 41
      PL=PL*XQ
      BRNCH=BRNCH*XQ
      GO TO 42
41    XQ=XQ+1.
      Q1=Q/XQ
      GO TO 40
C   IF Q=0 THEN USE PIPE SIZE OF PREVIOUS FLOW RATE
42    Q=Q1
      IF(Q.EQ.0.) GO TO 21
```

```
C  COMPARE Q WITH LIST OF FLOWS FOR OPYIMUM DIAMETER
      DO 10 M=1,30
      IF(Q.LE.PQ(M,2)) GO TO 20
10    CONTINUE
      DIA=120.
      GO TO 21
20    DIA=PQ(M,1)
C  CALCULATE PRESSURE LOSS PER FT
21    PLOSS=PRESS(Q,DIA)
C  AVERAGE PRESSURE DROP PER BRANCH
      PLOSS=PLOSS*PL*5280./BRNCH
C  CUMULATIVE PRESSURE DROP
      PDROP=PDROP+PLOSS
C  CALCULATE PIPING COST
      PIPEC=PIPE(DIA)
C  ANNUAL AMORTIZED PIPING COST FOR THAT SIZE
      PIPEC=CR1*PIPEC*PL*5280.
C  CUMULATIVE PIPING COST
      PSUM=PSUM+PIPEC
C  CALCULATING VALVE COST
      V=VCOST(DIA)
C  ANNUAL VALVE COSTS ALL BRANCHES OF GIVEN PIPE SIZE
      V=CR2*V*BRNCH
C  CUMULATIVE VALVE COSTS
      VSUM=VSUM+V
C  GO TO 1000 CARD SUPPRESSES INTERMEDIATE PRINT OUTS
      GO TO 1000
      WRITE(5,15) Q,DIA,PDROP,PIPEC,V
15    FORMAT(3H Q=,F7.0,3X,2HD=,F4.0,3X,6HPDROP=,F6.2,3X,6HPIPEC=,E11.4,
     +3X,7HVALVES=,E11.4)
C  TEST FOR END OF SQ MI NETWORK
1000  IF(N.NE.JJ) GO TO 7
      Q=Q*XQ
```

```
C     PUMPING ENERGY PER MI**2 PER YEAR
      ENGY=FACT*PDROP*Q*2.*3.8108/PUMEFF
C     ELECTRIC COST FOR PUMPING POWER
      ECOST=(ERATE/100.)*ENGY
C     CALCULATING PUMP COSTS FOR GIVEN FLOW
      PUMPC=PUMP(PDROP,Q)*CR3
C     TOTALS
C     ADD ON 15% ENGINEERING AND THEN 5% INITIAL CAPITAL FOR MAINTANENCE
      SUM=(1.15+0.05/CR1)*(PSUM+VSUM+PUMPC)+ECOST
      WRITE(5,18)
18    FORMAT(1H ,10X,30H***SQ. MILE NETWORK SUMMARY***)
      WRITE(5,16) SUM,PSUM,VSUM
16    FORMAT(1H ,5X,4HSUM=,E11.4,3X,5HPSUM=,E11.4,3X,5HVSUM=,E11.4)
      WRITE (5,19) PUMPC,ECOST,ENGY
19    FORMAT(1H ,5X,6HPUMPC=,E11.4,3X,6HECOST=,E11.4,3X,5HENGY=,E11.4)
      R1=PSUM/SUM
      R2=VSUM/SUM
      R3=PUMPC/SUM
      R4=ECOST/SUM
      R5=SUM/DEN
      R6=ENGY/DEN
      WRITE(5,43) R1,R2,R3,R4,R5,R6
43    FORMAT(1H ,5X,4(F5.3,3X),2(F7.1,3X))
C     EXPAND TO 36 SQ MI AREA
      PSUM=36.*PSUM
      VSUM=36.*VSUM
      PUMPS=36.*PUMPC
      ESUM=36.*ECOST
      PDROP=0.
7     CONTINUE
      Q=Q*XQ
      ENGY=FACT*PDROP*Q*2.*3.8108/PUMEFF
      ECOST=(ERATE/100.)*ENGY
      PUMPC=PUMP(PDROP,Q)*CR3
```

```
C   FINAL TOTALS
        PUMPS=PUMPS+PUMPC
        ESUM=ESUM+ECOST
        ENGY=ESUM/(ERATE/100.)
C   ADD ON 15% ENGINEERING AND THEN 5% INITIAL CAPITAL FOR MAINTANENCE
        SUM=(1.15+0.05/CR1)*(PSUM+VSUM+PUMPS)+ESUM
        WRITE(5,30)
30      FORMAT(1H ,10X,27H***TOTAL NETWORK SUMMARY***)
        WRITE(5,31) SUM,PSUM,VSUM
31      FORMAT(1H ,5X,4HSUM=,E11.4,3X,5HPSUM=,E11.4,3X,5HVSUM=,E11.4)
        WRITE(5,32) PUMPS,ESUM,ENGY
32      FORMAT(1H ,5X,6HPUMPS=,E11.4,3X,5HESUM=,E11.4,3X,5HENGY=,E11.4)
        R1=PSUM/SUM
        R2=VSUM/SUM
        R3=PUMPS/SUM
        R4=ESUM/SUM
        R5=SUM/DEN/36.
        R6=ENGY/DEN/36.
        WRITE(5,43) R1,R2,R3,R4,R5,R6
5       CONTINUE
C   GO TO NEXT STRUCTURAL SIZE
        GO TO 13
9999    END
```

```
      FUNCTION PUMP(PDROP,Q)
      COMMON ROUGH,WTEMP,PIPLIF,PUMLIF,PURATE
      COMMON PIRATE,PUMEFF,DELP,FACT,ERATE,PLOSS,ECOST
      P=1.
20    IF(PDROP.LE.DELP) GO TO 10
      P=P+1.
      PDROP=PDROP/P
      GO TO 20
10    Q1=Q
      A=1.
40    IF(Q1.LE.45000.) GO TO 30
      A=A+1.
      Q1=Q/A
      GO TO 40
30    PUMP=(5.278*Q1-2700.38)*A*P*2.
      PDROP=PDROP*P
      RETURN
      END
```

```
      FUNCTION VCOST(DIA)
      IF(DIA.LT.4.) GO TO 60
      A=1.
      D=DIA
40    IF(D.LE.12.) GO TO 10
      IF(D.LE.24.) GO TO 20
      IF(D.LE.48.) GO TO 30
      A=A+1.
      D=DIA/SQRT(A)
      GO TO 40
10    VCOST=EXP(0.11875*D+4.872)*A
      GO TO 50
20    VCOST=EXP(0.10245*D+5.81)*A
      GO TO 50
30    VCOST=EXP(0.06226*D+7.055)*A
50    RETURN
60    VCOST=0.
      RETURN
      END
```

```
FUNCTION PRESS(Q,DIA)
COMMON ROUGH,WTEMP,PIPLIF,PUMLIF,PURATE
COMMON PIRATE,PUMEFF,DELP,FACT,ERATE,PLOSS,ECOST
DIA=DIA/12.
PAREA=3.1415926*DIA**2/4.
WVEL=Q/PAREA/448.8
WMU=7.3283E-4/WTEMP
WDEN=EXP(-1.3656E-4*WTEMP+4.14129)
REYN=WVEL*DIA/WMU
FRICT=FRIC(ROUGH,DIA,REYN)
PRESS=1.4*FRICT*WVEL**2*WDEN/DIA/9273.6
DIA=DIA*12.
RETURN
END
```

```
C   PROGRAM FOR CALCULATING DATA FOR GIVEN TRACK
C   TK IS TRACK INFO MATRIX...15 TRACKS
       DIMENSION TK(15,6)
       DO 10 I=1,15
       READ(8,1) TK(I,1),TK(I,2),TK(I,3),TK(I,4),TK(I,5),TK(I,6)
1      FORMAT(F3.0,F5.0,F5.2,3F4.3)
C   TK(I,1) TO TK(I,6) CONTAINS TRACK NO.,DENSITY,AREA,RATIOS SINGLE,
C   4 APTS AND 12 APTS
10     CONTINUE
C   READ DATA SET INDEX,M
       READ(8,2) M
2      FORMAT(I2)
       DO 20 I=1,M
       WRITE(5,5) I
5      FORMAT(14H1***DATA SET #,I2,3H***)
C   READ DATA SET IN ORDER APT 12 TO SINGLE,8000 TO 1000
       READ(8,3) A128,A126,A124,A122,A121
       READ(8,3) A48,A46,A44,A42,A41
       READ(8,3) S8,S6,S4,S2,S1
3      FORMAT(5E11.4)
       DO 30 J=1,15
       IF(TK(J,2).LE.2000.) GO TO 100
       IF(TK(J,2).LE.4000.) GO TO 200
       IF(TK(J,2).LE.6000.) GO TO 300
       SL=(A128-A126)/2000.
       B=A128-SL*8000.
       PT12=SL*TK(J,2)+B
       SL=(A48-A46)/2000.
       B=A48-SL*8000.
       PT4=SL*TK(J,2)+B
       SL=(S8-S6)/2000.
       B=S8-SL*8000.
       PT1=SL*TK(J,2)+B
       GO TO 1000
```

```
100     SL=(A122-A121)/1000.
        B=A122-SL*2000.
        PT12=SL*TK(J,2)+B
        SL=(A42-A41)/1000.
        B=A42-SL*2000.
        PT4=SL*TK(J,2)+B
        SL=(S2-S1)/1000.
        B=S2-SL*2000.
        PT1=SL*TK(J,2)+B
        GO TO 1000
200     SL=(A124-A122)/2000.
        B=A124-SL*4000.
        PT12=SL*TK(J,2)+B
        SL=(A44-A42)/2000.
        B=A44-SL*4000.
        PT4=SL*TK(J,2)+B
        SL=(S4-S2)/2000.
        B=S4-SL*4000.
        PT1=SL*TK(J,2)+B
        GO TO 1000
300     SL=(A126-A124)/2000.
        B=A126-SL*6000.
        PT12=SL*TK(J,2)+B
        SL=(A46-A44)/2000.
        B=A46-SL*6000.
        PT4=SL*TK(J,2)+B
        SL=(S6-S4)/2000.
        B=S6-SL*6000.
        PT1=SL*TK(J,2)+B
1000    DATA=(PT12*TK(J,6)+PT4*TK(J,5)+PT1*TK(J,4))*TK(J,3)/36.
        TOTAL=TK(J,2)*TK(J,3)
        X=DATA/TOTAL
        WRITE(5,4) TK(J,1),TK(J,2),TK(J,3),DATA,TOTAL,X
4       FORMAT(8H0TRACK #,F3.0,5X,8HDENSITY=,F5.0,5X,6HMI**2=,F5.2,5X,5HDA
       +TA=,F11.4,5X,12HTOTAL UNITS=,E11.4,5X,8HAVERAGE=,E11.4)
30      CONTINUE
20      CONTINUE
        END
```

```
C  PROGRAM FOR CALCULATION OF ANNUAL COST OF GAS FURNACES
      WRITE(5,4)
4     FORMAT(36H UNITS,CAP,FUEL,UPKEEP,$/UNIT,BTU/YR)
      READ(8,1) BI,HLIFE,EFF,RATE,FACT
1     FORMAT(F5.3,F3.0,F4.2,F5.3,F4.2)
C  BI=BORROWING INTEREST,HLIFE=LIFE(YEARS),EFF=EFFICIENCY,RATE=$/100 CF
       XX=(1.+BI)**HLIFE
      CR=BI*XX/(XX-1.)
      DO 10 I=1,3
      READ(8,2) U,HEAT,COST,UPKEP
2     FORMAT(F3.0,F7.0,F5.0,F3.0)
C  U=UNIT,HEAT=BTU/HR,FACT=LOAD FACTOR,COST=$,UPKEP=MAINTANENCE $
      CAP=COST*CR
      GAS=HEAT*FACT*8.5714/EFF
C  GAS=CF/YR
      FUEL=GAS*RATE/100.
C  FUEL=FUEL COST ($)
      UCOST=(CAP+FUEL+UPKEP)/U
C  UCOST=ANNUAL COST PER UNIT
      ENGY=GAS*1022./U
C  ENGY=BTU/YR/UNIT
      WRITE(5,3) U,CAP,FUEL,UPKEP,UCOST,ENGY
3     FORMAT(1H ,F3.0,5(3X,E11.4))
10    CONTINUE
      END
```

```
C  PROGRAM FOR CALCULATING ANNUAL COST OF AIR/AIR HEAT PUMPS
      WRITE(5,11)
11    FORMAT(29H U,CAP,ECOST,UPKEP,UCOST,ENGY)
      READ(8,1) BI,COP,RATE,FACT
1     FORMAT(F5.3,F2.0,F4.2,F4.2)
C  BI=INTEREST RATE,COP=COP,RATE=¢/KWHR,FACT=LOAD FACTOR
      READ (8,2) Y1,Y2,Y3
2     FORMAT(3F3.0)
C  Y1,Y2,Y3 ARE LIFE OF PUMP,AUXILIARY HEATER,AND DUCT
      XX=(1.+BI)**Y1
      CR1=BI*XX/(XX-1.)
      XX=(1.+BI)**Y2
      CR2=BI*XX/(XX-1.)
      XX=(1.+BI)**Y3
      CR3=BI*XX/(XX-1.)
      DO 10 I=1,3
      READ(8,3) U,HEAT,COST1,COST2,COST3,UPKEP
3     FORMAT(F3.0,F7.0,3F6.0,F5.0)
C  U=UNIT,HEAT=BTU/HR,COST1=PUMP COST,COST2=HEATER COST,COST3=DUCT COST
C  UPKEP= MAINTANENCE COST
      CAP=(COST1*CR1+COST2*CR2+COST3*CR3)/2.
C  CAP DIVIDED BY TWO TO CREDIT HEAT PUMP WITH A/C FUNCTION
      ENGY=HEAT*FACT*8760./COP
C  ENGY =BTU/YR
      ECOST=ENGY*2.93E-4*RATE/100.
C  ECOST=$/YR
      UCOST=(CAP+ECOST+UPKEP)/U
C  UCOST=ANNUAL COST PER UNIT
      ENGY=ENGY/U/0.33
C  ENGY=PRIME ENERGY CONSUMED PER UNIT
      WRITE(5,4) U,CAP,ECOST,UPKEP,UCOST,ENGY
4     FORMAT(1H ,F3.0,5(3X,E11.4))
10    CONTINUE
      END
```

```
C   PROGRAM FOR CALCULATING COST + ENERGY CONSUMPTION OF WATER/AIR HEAT PUMPS
C   DELTA T=20 F
       WRITE(5,11)
11     FORMAT(33H U,COP,CAP,ECOST,UPKEP,UCOST,ENGY)
       READ(8,1) BI,RATE,FACT,Y1,Y2
1      FORMAT(F5.3,2F4.2,2F3.0)
       XX=(1.+BI)**Y1
       CR1=BI*XX/(XX-1.)
       XX=(1.+BI)**Y2
       CR2=BI*XX/(XX-1.)
       READ(8,2) N
C   N=NUMBER OF CALCULATION SETS
2      FORMAT(I2)
       DO 10 I=1,N
       READ(8,3) U,HEAT,COST1,COST2,UPKEP,COP
3      FORMAT(F3.0,F7.0,2F6.0,F5.0,F4.2)
       CAP=CR1*COST1+CR2*COST2
       ENER1=HEAT*FACT*8760./COP
       ECOST=ENER1*2.93E-4*RATE/100.
       UCOST=(CAP+ECOST+UPKEP)/U
       ENGY=ENER1/0.33/U
        WRITE(5,4) U,COP,CAP,ECOST,UPKEP,UCOST,ENGY
4      FORMAT(1H ,F3.0,3X,F4.2,5(3X,E11.4))
10     CONTINUE
       END
```

```
C   PROGRAM FOR CALCULATING COST + ENERGY CONSUMPTION OF WATER/AIR HEAT PUMPS
C   DELTA T=40 F
        WRITE(5,11)
11      FORMAT(33H U,COP,CAP,ECOST,UPKEP,UCOST,ENGY)
        READ(8,1) BI,RATE,FACT,Y1,Y2
1       FORMAT(F5.3,2F4.2,2F3.0)
        XX=(1.+BI)**Y1
        CR1=BI*XX/(XX-1.)
        XX=(1.+BI)**Y2
        CR2=BI*XX/(XX-1.)
        READ(8,2) N
C   N=NUMBER OF CALCULATION SETS
2       FORMAT(I2)
        DO 10 I=1,N
        READ(8,3) U,HEAT,COST1,COST2,UPKEP,COP
3       FORMAT(F3.0,F7.0,2F6.0,F5.0,F4.2)
        CAP=CR1*COST1+CR2*COST2
        ENER1=HEAT*FACT*8760./COP
        ENER2=HEAT*(1.-1./COP)*FACT*8760.
        ECOST=(ENER1*2.93E-4+ENER2*1.0548E-5)*RATE/100.
        UCOST=(CAP+ECOST+UPKEP)/U
        ENGY=ENER1/0.315/U
        WRITE(5,4) U,COP,CAP,ECOST,UPKEP,UCOST,ENGY
4       FORMAT(1H ,F3.0,3X,F4.2,5(3X,E11.4))
10      CONTINUE
        END
```