A SIMULATION MODEL FOR FEASIBILITY ANALYSIS OF DUAL-PURPOSE POWER PLANTS PROVIDING THERMAL ENERGY TO URBAN COMMUNITIES

A Dissertation
for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY

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1977

This is to certify that the

thesis entitled

A SIMULATION MODEL FOR FEASIBILITY
ANALYSIS OF DUAL-PURPOSE POWER
PLANTS PROVIDING THERMAL ENERGY
TO URBAN COMMUNITIES

presented by

David Harold Curtice

has been accepted towards fulfillment
of the requirements for

Ph.D degree in Systems Science

Herman E. Koenig
Major professor

Date May 2, 1977

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ABSTRACT

A SIMULATION MODEL FOR FEASIBILITY
ANALYSIS OF DUAL-PURPOSE POWER
PLANTS PROVIDING THERMAL ENERGY
TO URBAN COMMUNITIES

By

David Harold Curtice

Dual-purpose power generation, simultaneous production of steam and electrical energy by an electric power plant (cogeneration), is a technology that offers the potential for high overall energy efficiency. This study details the technical and economic feasibility of using dual-purpose power plants to supply substantial amounts of thermal energy to urban communities during the production of electric energy.

Possible applications of dual-purpose power plants in urban communities requires extensive consideration of the couplings between three basic thermodynamic components; the dynamics of electric power generation, steam transport, and the time-dependent demand for thermal energy by the community. To explore the interconnected dynamic behavior of these urban energy systems, I develop a simulation model for use in deriving energy and economic parameters within the constraints imposed by various community and power plant characteristics.

The laws of thermodynamics constrain the design of the urban energy systems considered. As a result of Second Law analysis,

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parameters of the steam transport components were designed to require low extraction pressures at the power plant, thus minimizing affects on turbine power output. Benefits resulting from this design scheme included; supplying a thermal energy source to the community in the form of low enthalpy steam after producing some electric energy, and reducing the total demand for low entropy energy sources normally used for space heating and cooling, and water heating.

Three generic community components were designed, incorporating estimating techniques for determining their energy use for space heating and cooling, and water heating, to test the dual-purpose technology in a variety of different communities types. The base-load power plant operates to continuously supply the thermal energy demand for any given community constructed from generic components, while exporting electric energy into the local utility grid. Energy and economic results are obtained from small urban communities without industrial steam users. Parameters of capital, materials, and fuel costs were varied over a range potentially applicable to the year 1980.

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DOCTOR OF PHILOSOPHY

Department of Electrical Engineering and Systems Science

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ACKNOWLEDGMENTS

The unrelenting support and encouragement of Dr. Herman E. Koenig is gratefully acknowledged. Thanks also to Dr. Gerald L. Park, a friend indeed, and to Dr. Robert A. Schlueter and Dr. William E. Cooper for their advice and support. Financial support for this study was provided by the National Science Foundation through the project Design and Management Environmental Systems, and the Energy Research and Development Administration.

Finally, this thesis is dedicated, with affection, to my family.

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CHAPTER I

INTRODUCTION

During the past few years the United States has been host to a variety of unanticipated problems; environmental pollution, energy and resource shortages, and a stagnated economy. As a result, numerous individuals have questioned whether our highly centralized and specialized society aggravates an already complex situation and, on some cases, is the root cause of our problems. These students of all aspects of society ponder, what some believe, are more critical structural problems that are manifested as shortages of energy and raw materials. And in light of our current environmental, energy and economic problems, they advocate a decentralized approach to resource utilization with a heavy emphasis on conservation of all our resources.

This study, which focuses on efficient utilization of energy, was borne out of the centralized/decentralized debate. While it does not propose to resolve this debate by some analytic formulation; there are alternative ways to supply energy to society that fall within the scope of either a decentralized or centralized approach. And it is the objective of this study to examine one alternative energy-producing/energy-using technology that is more decentralized in nature than the existing centralized technology currently employed by society.

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attributes of both a decentralized approach to power generation and high energy efficiency. Decentralized in the sense that a greater number of locally placed dual-purpose power plants, many of smaller size because of space considerations, could generate electric power at higher overall efficiencies instead of a few large plants located far from load centers. Although studies in the past have shown dual-purpose plants as feasible systems, their focus has been on large population areas or industrial complexes, more or less an extension of the large centralized power plant approach. Instead of connecting a multitude of steam heat users to the plant, e.g., greenhouses, sewage treatment plants, industrial parks, and examining a grand urban/industrial community, this study focuses on small urban communities to determine the technical and economic feasibility of dual-purpose power plants supplying thermal energy to residential and commercial complexes.

Toward that end, Chapter II presents our energy situation with respect to residential/commercial and electric power. It provides an overview of how we arrived at our current energy short-fall and future scenarios with respect to availability and use. Since a simulation model is used to analyze the feasibility of using dual-purpose plants, Chapter III reviews energy modeling with emphasis on methodology and scope. Chapter IV presents past applications of the dual-purpose technology, a description of activity by district heating companies, and a discussion of the efficiency of energy production comparing conventional and dual-purpose power plants.

Chapter V examines the techniques used to estimate energy use in the residential and commercial sectors of society. Of particular importance is energy used for space heating, air conditioning, and water heating.

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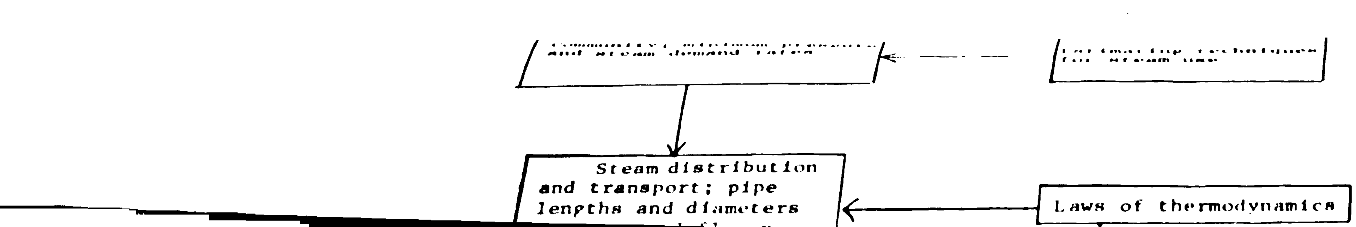
The critical link between the power plant and the community, the steam distribution system, is presented in Chapter VI. And then the building blocks or test cases for the feasibility study are presented in Chapter VII, which include three different communities that will be connected in the simulation model to derive economic parameters of cost associated with operation of the system.

Chapter VIII brings together the preceding chapters in a description of the simulation model. All prior chapters provide the basic tools for analyzing complex problems not directly related to the test cases presented in Chapter VII. The simulation model in Chapter VIII provides a way to vary many parameters of the problem and determine the economic feasibility of different community configurations. Chapter IX presents the test results of economic feasibility for dual-purpose plants operating in small urban communities and generalizations that can be drawn from the results.

For those readers desiring to do a feasibility analysis of a similar energy system Figure 1.1 indicates schematically the sequence of steps required to use the simulation model. The remainder of this introduction is addressed to these readers.

There are three basic components of the energy system, the community, steam transport and distribution, and the dual-purpose power plant. Each component requires analyzing a variety of information, making design decisions, and finally bringing together a finite set of alternatives for each component for use in the simulation model.

Starting with the community, Chapter V details methods for estimating energy use by urban communities with reference to space heating and cooling, and water heating. These three energy uses represent a



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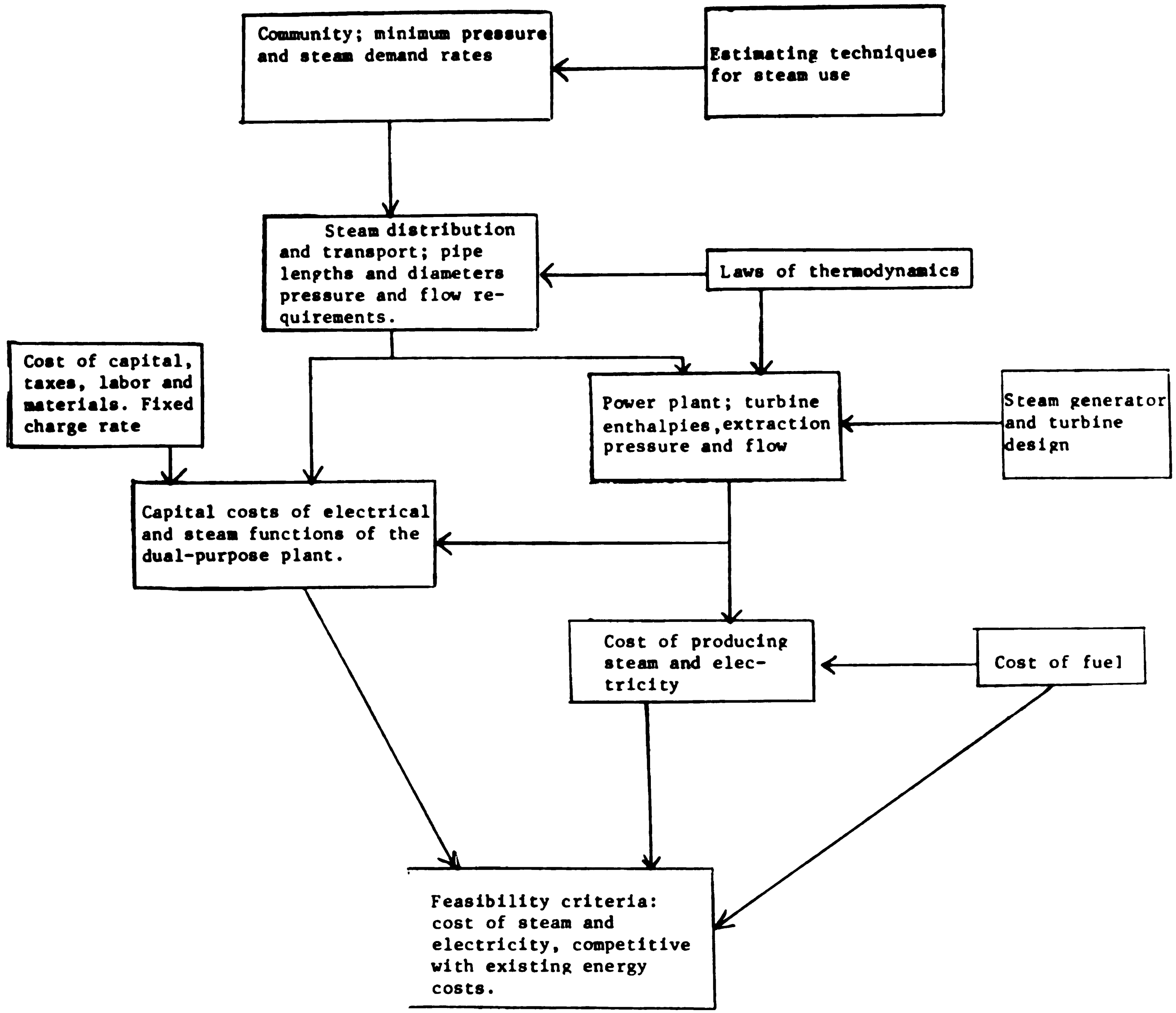

Figure 1.1 Urban Energy System Components

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substantial part of the energy picture for urban communities. Estimates can be made more exact if the community is already established. In this case, collecting energy bills from potential users of the energy system should be used to develop time dependent demands for steam. For communities not yet constructed, estimating techniques provide minimum steam energy needs and must be tempered with worst seasons case, i.e., coldest or warmest day and longest period. Consideration should also be made for the type of task for which steam is to be used. Some laundries, restaurants, etc., potentially located in the community, will require large amounts of steam, these possibilities must be considered.

The community places one important constraint on the operation of the steam distribution system, and the power plant. Minimum pressure requirements must be maintained at all possible points of steam use. Knowing the energy tasks for which steam is to supply the energy source sets these limits for pressure drop in steam lines placed in the community, and the pressure needed at the plant to maintain these pressures. Chapter VIII describes a program for finding pipe diameters, and pressures for the steam distribution and transport component given minimum pressure and flow rates. The coupling between the community and the distribution is strong, this program can be used to examine a variety of pipe diameters, and pressures.

I have placed one more constraint on the design of the steam distribution system not generally considered in the past. The Second Law of thermodynamics was used in the specification of the pressure demanded at the plant. Since extracting high-pressure steam from the turbine and throttling it through the steam transport and distribution system has the benefit of requiring smaller pipe diameters and thus lower installation cos

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installation costs, many systems in the past were designed in this way to decrease first costs. But as a result of this approach power delivered to the generator is reduced, increasing electricity costs. I chose to design the steam distribution and transport system to require the lowest reasonable pressure at the power plant and take full advantage of the work producing ability of high-pressure steam. This resulted in larger pipe diameters, on average, and higher costs for the steam distribution and transport component, but had the advantage of using high-pressure steam to do shaft work instead of throttling steam to lower pressures. In the final analysis this may have made it difficult for some communities, e.g., communities of single-family dwellings, to be economically supplied with steam.

The pressure-drop program for determining pipe diameters in the steam transport and distribution system, detailed in Chapter VIII, requires the spatial layout of the community. This means that distance between potential steam users must be known along with minimum-pressure needs, and flow rates. Inside pipe diameters, minimum pressure, length of pipes, and a table of average steam densities are all that is required to use the program. The designer can then chose pipe diameters and find the initial pressure required at the plant to maintain pressures, or given an initial pressure at the plant find the pipe diameters needed to satisfy minimum pressures in the community. Simple modification to the program to eliminate flows to steam users and the program can be used to specify the transport steam lines.

To determine the final time dependent steam demand to be supplied from the power plant, it is necessary to compute steam losses from the steam transport and distribution system during full-year operation.

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Chapter VI shows the procedure for using results from the pressure drop program to determine steam losses. Two methods are shown, one of which is drawnfrom the operating experiences of District Heating companies and is used in this study.

With the total time dependent demand for steam, and the pressure required at the plant now determined, the feasibility of dual-purpose power generation for a given design can be determined. Chapter VIII describes the simulation model in detail. From it the final break-even cost of steam and electricity can be determined. These costs are dependent upon plant size, cost of fuel, and whether the plant is a single or multiple unit. The analysis in this study considers mainly single unit plants, as it generally represents the more costly alternative.

The model separates costs of producing steam and electricity and the capital costs associated with each to insure that steam users do not subsidize electricity users and vice versa. In the single unit plant case, an extra steam generator is added to the steam function costs to insure adequate steam supply during maintenance of the electrical function of the plant, along with additional water treatment capabilities for water returned to the plant from the community. Also, the steam function of the plant must pay for modifications to the turbine and controls to facilitate extraction.

The cost of producing steam for any given plant size is a function of extraction pressure at the plant, flow rates, and fuel costs. Chapter VIII details the thermodynamic variables that must be known from turbine size and how to use them to determine the final cost of producing steam and electricity. Varying plant size, and the cost of fuel, the model ca

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the model can be used to examine optimal plant size for a given community, and steam transport and distribution system.

Capital costs are determined by use of standard economic analysis used by utilities. The steam function of the plant incorporates direct, indirect, contingency, and an escalation factor to determine the total capital costs of the steam system. An annual fixed charge and an operation and maintenance cost are used to compute to break-even cost of steam, given the annual output of steam. Economic feasibility for any given design of the energy system is then determined by whether or not steam is competitive with other fuels and if electricity costs are representative of a plant connected into the grid.

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CHAPTER II

OVERVIEW OF THE ENERGY PROBLEM

Over the last ten years the United States has been confronted by a series of crises; environmental pollution, the shortage of energy, and economic decline characterized by high unemployment and inflation. The solution to these problems is usually seen as a set of separate policies; imposing pollution controls, finding new energy resources, and manipulating the federal budget, taxes and interest rates. It is increasingly clear that the problems with the ecosystem, the production system, and the economic system are completely interdependent. And what confronts us is not a separate set of crises, but a faulty design of modern society.

Energy plays a decisive role in the interactions between the ecosystem, the production system, and the economic system. Solar energy drives the ecosystem, and energy derived from fossil-fuels drives the production system. The rate of economic activity is intensified by the increased use of energy to produce greater output. Moreover, the fact that energy is in short supply has repercussions for all three of these systems; the high yield we enjoy from the ecosystem is dependent upon the availability of energy for machines and fertilizer, the production system, where machines have tended to replace human energy, is now almost totally dependent upon energy to maintain high levels of output. And the intensified uses of energy in the ecosystem, and the production system, are associated with the economic difficulties of unemployment and inflation.

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What is offered in this chapter is an overview of the energy problem. It is not exhaustive by any means, but provides a description of the problem as it relates to oil, coal, natural gas, and electric energy. The purpose being,to place in the mind of the reader a context in which the following analysis of an alternative energy producing/using system can be evaluated.

II.1 Oil

Up until the 1960's, the United States was essentially independent of foreign oil, producing and consuming more oil than any other country in the world. Its domestic supplies were plentiful and proven reserves were growing. However, production from older fields peaked and new exploration and development of domestic oil diminished because of the easy availability of less expensive oil found in foreign countries. Oil companies cut back on exploration efforts as the price of oil declined slightly after 1962, and in light of the fact that oil prices were not increasing at the rate of 11 percent per year, like they did in the middle of 1950 (increasing only 4 percent between 1957 and 1962). The oil companies decided to reduce domestic exploratory efforts, following a period of poor economic returns on domestic oil, and follow the higher profitability of foreign operations. Import dependency grew from 18 percent in 1960 to about 43 percent in 1976. Direct imports from OPEC nations now constitute about two-thirds of all oil imports with Nigeria, Canada, Venezuela, Saudi Arabia, and Indonesia supplying most of our imported oil (FEA, 1976).

These rising imports increased the U.S. balance of payments from \$3 billion for foreign oil in 1970 to about \$27 billion (\$125 per capita) in 1975. Increased oil prices, since the Arab oil embargo of 1973, affected all pe

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affected all petroleum products with gasoline increasing 50 percent since 1973 (FEA, 1976).

Higher crude oil prices have now stimulated exploration for domestic oil. The number of oil wells drilled has risen from 26,000 in 1973 to about 37,000 in 1975 (FEA, 1976). More drilling rigs are in use, 1,200 in 1973 to over 1,600 rigs in 1975 (FEA, 1976). However, despite increased drilling activity the domestic oil production continued to decline because of the several years time lag between exploration and production, dropping from over 9 million barrels a day in 1973 to less than 8 million barrels a day in 1975. Even with the addition of about 2 million barrels a day from the Trans-Alaskan Pipeline in 1977, domestic oil production will still only be near the 1970's levels.

Consumption of petroleum products since the 1973 oil embargo fell by 4 percent in 1974 and an additional 2.5 percent in 1975. Without the embargo, demand would have pushed oil consumption to 3 million barrels a day over what it was in 1975 (FEA, 1976). While lower economic activity may have contributed to the slowing of demand there is good reason to believe that consumer response to higher prices was a major contributing factor.

Governmental responses to the oil situation were passage of the Energy Policy and Conservation Act (EPCA) and partial removal of the oil-depletion allowance. The EPCA law provides for a statutory domestic composite oil price of $7.66 per barrel that is escalated by a GNP deflator and other incentives to increase production. The price control authorities convert from mandatory to standby after 40 months. If price controls expire in 40 months and world oil prices are $13 per barrel, the conservation measures in the EPCA would reduce import needs to

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3.4 million barrels a day by 1985. If price controls remain in effect through 1985, imports would be 6.5 million barrels a day. If, on the other hand, natural gas price regulations also continued, imports under these alternative oil price control cases would be 6.2 and 8.3 million barrels a day, respectively (FEA, 1976).

II.2 Coal

Essentially, coal production has remained at a constant level for the last five years. Production in 1970 was about 603 million tons (613 billion kg) and about 640 million tons (650 billion kg) in 1975 (FEA, 1976).

Over the past 20 years coal consumption has declined in the industrial and residential sectors while the use of coal as a primary fuel for steam production has increased. The regulated price of interstate gas, removal of import controls on residual fuel oil and its cheap imported price (until the 1973 embargo), and the development of nuclear power have all combined to limit the growth of coal use. In the late 1960's and early 1970's, state and local air pollution regulations discouraged power companies from burning coal. Reliability and costs of stack gas scrubbers, legislative changes to the Clear Air Act, surface mining reclamation laws and uncertainty about environmental issues are still affecting the growth in coal use.

While oil prices rose dramatically, coal prices on long-term contracts have been relatively stable. Some coal prices rose rapidly to \$32 per ton (\$35 per 1000 kg) in the latter part of 1974 because of a pending coal strike, but have declined since 1975. Contract prices of coal have risen steadily since the end of 1973 reaching \$.75 per million BTU's (\$.71 per giga joule) in 1975 (FEA, 1976).

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II.3 Natural Gas

Approximately 21 trillion cubic feet (595 billion cubic meters) of natural gas were used in 1974. Although pipeline line imports from Canada are important in the Pacific Northwest, they account for less than 5 percent of annual consumption.

Because of its clean burning properties and low regulated price compared to other fuels, demand for natural gas increased dramatically after the 1960's. Marketed natural gas production peaked in 1973 at 22.6 trillion cubic feet (640 billion cubic meters) and dropped significantly in 1974.

After 1968, the United States has been consuming more natural gas per year than producers have been able to find in the form of new wells. Except for the 26 trillion cubic feet (736 billion cubic meters) found in Alaska in 1970, annual additions to reserves have failed to equal marketed production over the last seven years. The Alaskan find will not add to these reserves until the 1980's due to the missing link between wells and the lower 48 states.

Low regulated prices have encouraged consumption and discouraged exploration for new gas for the interstate market. Intrastate prices for natural gas have risen much faster than the regulated interstate prices. As a result, producers have been selling gas under new contracts at an average $1.00 to $1.50 per thousand cubic feet ($.35 to .53 per 1000 cubic meters) in the intrastate market compared to the regulated interstate price of $.52 per thousand cubic feet ($.18 per thousand cubic meter) (FEA, 1976). The main result of the regulated lower price has been the development and sale of natural gas in the state where it is found. Since 1970, 90 percent of all new additions to reserves have been sold to i

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been sold to intrastate markets. Six states, Texas, Louisiana, Oklahoma, California, New Mexico and Kansas accounted for 93 percent of domestic production in 1974 - Texas and Louisiana alone provided for 73 percent. In 1974 nearly 50 percent of domestic consumption was in these six states. Industrial relocation and the use by electric utilities in these states are some of the reasons for this large percentage.

II.4 Electric Power

Higher fuel costs, with already escalating plant construction and operating costs, have forced higher rates for electricity. With today's oil prices and the shortage of natural gas, the economics of new plants has shifted to coal and maybe nuclear power. The higher rates for electricity have also reduced demand and this in turn is likely to reduce future capacity needs. These effects, along with the continuing debate over environmental siting and safety issues, and financial problems in the utility industry have introduced significant uncertainties into the growth of electric power.

In the recent past, electric power demand grew at an annual rate of about 7 percent (as high as 10 percent in some areas). Projected plant additions into the early 1980's were based on a pre-embargo, pre-antinuclear rate of demand growth. In 1974, the growth in the demand for electricity fell to zero and only increased about 2 percent in 1975 (FEA, 1976). The economic slowdown and higher rates are given as the reason for the low growth.

The financial situation of electric utilities has been dramtically affected by higher fuel costs, which necessitated large rate increases and a hardened response to further rate adjustments. At the same time, lower capacity utilization, longer lag times for licensing and construction,

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construction, and high inflation associated with new plant construction required even greater rate increases if utilities were to finance new plants (many already in construction as a result of high growth rates before the embargo). When rates did not increase fast enough, the electric utilities ability to raise equity was impaired and the shortage of money caused cancellation or deferral of many new plants.

The fuels used to generate electricity have shifted in recent years. Nuclear's share of electricity production grew sharply from 4.5 percent in 1973 to about 8.6 percent estimated for 1975 (FEA, 1976). Although nuclear power has the lowest variable operating costs, they require larger capital investment and the longest construction to operation time. Consequently, nuclear power has been the most heavily affected by plant cancellations and deferrals. Since June 1974, over 100,000 megawatts of planned nuclear capacity have been cancelled or postponed. They accounted for almost 70 percent of planned additions. Nevertheless, with the drop in electricity growth and the additions of new plants, reserve capacity is now 34 percent, compared with a traditional level of 20 percent (FEA, 1976). This idle capacity is expensive for consumers, since the carrying and overhead costs must be paid whether or not the equipment is used.

II.5 Our Energy Future - Oil

It seems clear that little can be done between now and the 1980's to alter the supply and demand relationships between OPEC and consuming nations enough to weaken the cartels' exclusive control over world oil prices. And since any analysis of the future domestic oil outlook must be influenced by world oil prices, the possibility of lower oil prices must start with the OPEC nations.

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Political factors and consumer nation's initiation of programs to cope with higher prices, and excessive dependence on foreign oil make forecasting the future very uncertain. But most estimates follow the FEA projections that prices will be in the range of $8 to $16 per barrel for the near future. If current prices continue, total energy demand should increase from 72.9 quadrillion BTU's (77 x 10^{18} joules) in 1974 to 98.9 quadrillion BTU's (104 x 10^{18} joules) in 1985 (FEA, 1976).

Petroleum demand is naturally sensitive to oil prices. This is particularly evident in the electric power generation sector. At $8 per barrel, in 1985, more oil is projected to be used to generate electricity whereas at $13 per barrel, almost 70 percent less oil is used to generate electricity (FEA, 1976). Coal replaces oil at higher import prices because electricity from a new baseload coal plant is cheaper than from an oil-fired plant if oil is above $9 per barrel (FEA, 1976).

The industrial demand for petroleum tends to be relatively insensitive to price since about 30 percent of the demand is for feedstocks where alternative fuels cannot be physically substituted. The transportation sector, accounting for more than half of petroleum demand, may see lowered demand as a result of higher gasoline prices and more efficient automobiles. Different projections for petroleum use as a function of price are given in Table 2.1, and it appears that only the electric generation sector can really respond quickly to changes in oil prices.

II.6 Electricity Consumption

Electricity has grown about twice as fast as the total of all energy sources in the last twenty years, and will probably continue to do so,

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TABLE 2.1

Petroleum Consumption Across Prices

(million barrels per day)

Sector	1974 Usage	1985 demand @ $8/barrel (growth rate)	1985 demand @ $13/barrel (growth rate)
Household/commercial	3.4	4.8 (4.6)	4.0 (2.8)
Industrial	3.1	4.6 (3.8)	4.2 (3.1)
Transportation	8.7	12.4 (3.3)	11.5 (2.1)
Electrical generation	1.5	3.8 (8.3)	1.2 (-2.3)
TOTAL	16.6	25.6 (4.0)	20.7 (2.0)

Reference: National Energy Outlook, 1976. Federal Energy Administration. Report no. FEA-N-75/713. U.S. Government Printing Office, page 17.

although at lower rates. The FEA estimates that the use of electricity will grow at a rate of 5.4 percent per year from 1974 to 1985 if present world oil prices continue. A higher projection is estimated by Pelley et al , they project the growth of electricity demand through 1990 at 6 percent per annum (Pelley et al, 1976).

The large uncertainties with respect to the demand for electricity affect coal, nuclear, oil and gas consumption. But with natural gas shortages and higher petroleum prices, the reliability and availability of electricity make it a premium energy source. Electricity tends to displace direct use of oil and natural gas in households and industry and since nuclear power is constrained by great uncertainties and long lead-times for new plants, the next cheapest source of electric power - coal, becomes the fuel for swing capacity. For each 1 percent change in electricit

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in electricity growth rate from 1974 to 1985, coal consumption is projected to change by 150 million tons (136 billion kg) in 1985, provided coal plants can be completed in time (FEA, 1976).

A strong conservation effort could reduce electricity growth to less than 5 percent annually. Alternatively, if a strong shift towards greater use of electricity occurs, demand could grow at almost 6.5 percent per year (FEA, 1976). Under the latter scenario, coal production can be expected to increase.

II.7 Coal Consumption

The bulk of the projected increase for coal consumption in the 1974 to 1985 period will occur in the electric generation sector (see Table 2.2). The actual coal consumption in the electric generation sector will depend upon environmental standards, availability of coal transportation, surface mining regulations, and the ability of the utilities to obtain capital.

Other sectors are anticipated to have little growth potential for coal. Opportunities for coal consumption by the industrial sector are limited by the cost of complying with air pollution control requirements and the higher cost of handling smaller quantities of coal. Synthetic fuels from coal are not yet competitive at $13 per barrel for oil and are not expected to develop until the late 1980's. (FEA, 1976)

II.8 Natural Gas Consumption

Natural gas usage is projected to change only slightly over the next ten years, assuming deregulation of new natural gas prices. In 1974, about 21 trillion cubic feet (595 billion cubic meters) were produced and in 1985 this figure is projected to be 23.4 trillion cubic feet (665 billion cubic meters) (FEA, 1976).

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TABLE 2.2

1985 Coal Consumption At $13 Per Barrel Oil Prices

(million tons - 10^9 kilograms)

Sector	1974	1985	growth rate (percent/year)
Electric Utilities	390-354	715-649	5.7
Household/commercial	11-10	5-4.5	-6.9
Industrial	94-85	151-137	4.4
Metallurgical	63-57	73-66	1.3
Synthetics	0	16-15	-
Exports	60-54	80-73	2.4
	618-561	1040-943	4.8

Reference: National Energy Outlook, 1976. Federal Energy Adminstration. Report no. FEA-N-75/713. U. S. Government Printing Office, page 21.

Natural gas use is constrained by the very limited availability of inexpensive supply. Much of the more readily accessible domestic supply is already dwindling before imports, synthetic fuels, and Alaskan gas can have much of an impact on resources.

The national trend in the past few years has been a growth in gas consumption in the industrial sector and reduced use in the residential sector. The residential consumption declined in 1972-1975 because gas deliveries to the interstate market declined, while intrastate markets, where a growing industrial market is located in the six producing states, has increased. With industrial users of natural gas in the interstate market on the lowest priority,many industries have voluntarily switched from natural g

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from natural gas to electricity, coal, and in some cases oil to assure a reliable supply of energy.

The effects of higher deregulated natural gas prices will reduce demand as gas prices are expected to increase more than other fuels (FEA, 1976). Since electricity prices are expected to remain relatively constant (in real terms), increasing natural gas prices will probably keep the growth of gas use in the residential/commercial sector very low. Projections to 1985 predict gas consumption will grow in the industrial sector and continue to decline in the residential/commercial sector, continuing the behavior of the last ten years (FEA, 1976).

II.9 The Long-Term

A panel of the Committee on Mineral Resources and the Environment of the National Academy of Sciences has analyzed the numerous estimates of potentially extractable hydrocarbons (oil, natural gas, natural gas liquids) in the United States, including Alaska and the continental shelves. This panel concludes that the hydrocarbon resource base of the United States approximates 113 billion barrels of crude oil and natural gas liquids combined and 530 trillion cubic feet (15 trillion cubic meters) of gas (NAS, 1975). Although the estimate for the ultimate extractable quantity of crude oil is somewhat greater than that estimated by Hubbert, it is nevertheless well within reasonable bounds (Hubbert, 1971). Something like the equivalent of 500 billion barrels of petroleum (oil, natural gas and natural gas liquid eqivalents) appears to be ultimately extractable, of this, somewhat over 40 percent has already been removed.

An appreciation of the significance of these numbers is essential for understanding of the difficult energy situation now confronting the United Sta

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the United States. We are clearly, by anybody's estimate, pushing against the upper limit of our domestic extractable hydrocarbon resources. Alaskan discoveries can be only temporary as reserves are destined to continue their downward path in the long run. Production of hydrocarbons will also continue downward after a brief upsurge following the completion of the Alaska pipeline. There will be another jump upward upon completion of several gas lines about 1979. Since our energy demands are not likely to decrease to any appreciable degree during the next few years we must compensate for the decreased domestic production either by utilizing greater quantities of other energy resources in the United States, like coal, and solar energy, or by importing greater quantities of crude oil and other hydrocarbons from other countries. Suffering by this latter decision the power of the oil cartel and others upon whom we will depend for our energy.

II.10 Coal

One of the principal drawbacks to the use of coal is its sulfur content, and this is particularly troublesome for the future since coal is clearly our most abundant physical energy resource (see Table 2.3).

Pollution from the burning of coal, particulate matter, oxides of sulfur and nitrogen oxides are of great concern. Methods now exist for converting coal to combustible gas, to synthetic hydrocarbon liquids or to methanol (methyl alcohol). Whether or not these technologies can produce an inexpensive product from coal remains an unanswered question. Of course, coal can also be burned directly to generate electricity, but unless the fuel is relatively free of sulfur, special provision must be made to remove the sulfur dioxide formed during combustion. In addition, the partuclate matter formed by the ash must be removed to

TABLE 2.3

Estimated Resources of Shale Oil, Tar Sand Oil, and Coal Compared With Resources of Conventional Hydrocarbons

	United States		World	
	Barrels of oil	Billions equivalent	Barrels of oil	Billions equivalent

TABLE 2.3

Estimated Resources of Shale Oil, Tar Sand Oil, and Coal
Compared With Resources of Conventional Hydrocarbons

	United States		World	
	Barrels of oil (billions)	Billions equivalent tons coal (metric)	Barrels of oil (billions)	Billions equivalent tons coal (metric)
Conventional Hydrocarbons	500	69	5,000	690
Identified[1] reserves of shale oil	2,000	280	3,000	415
Undiscovered[1] reserves of shale oil	25,500	3,530	340,000	47,000
Incomplete reserves[2] of tar sand oil	30	4	750	140
Minable coal[1,3] and lignite		1,500		7,600
TOTAL		5,380		55,800

Reference: Brown, Harrison 1976. Energy in Our Future. Annual Review of Energy, Annual Reviews, Inc., Palo Alto, California. page 26.

1 U.S. Geological Survey. 1973. United States Mineral Resources, Prof. Pap. 820. Government Printing Office. Washington, D.C.

2 National Academy of Sciences, Commission on Natural Resources. 1975. Mineral Resources and the Environment. National Academy of Sciences. Washington, D.C.

3 Hubbert, M. K. 1969. In, Resources and Man, National Academy of Sciences. Freeman, San Franciso. pp. 157-239.

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prevent pollution of the atmosphere. These problems appear to be solvable since scrubbers now collect over 90 percent and the natural environment is capable of handling a given amount of gases given off by coal-fired electric plants. Thus, coal appears to be a possible alternative for the long term.

One possible danger associated with the expanded use of coal lies in the fact that the carbon dioxide in the atmosphere equilibrates very slowly with the bicarbonate of the deep oceans. Apparently, as a result of the combustion of fossil fuels, the carbon dioxide concentration in the atmosphere has increased. Theoretical studies indicate that a doubling of the concentration could effect an increase of the temperature near the earth's surface by about $4^{o}F$ ($2^{o}C$). Such a change could trigger other mechanisms, possibly leading to irreversible climatic effects.

This single aspect of greatly increased consumption of fossil fuels should be monitored very closely. Any clear physical or theoretical indication of emerging adverse effects may make it advisable to lessen substantially the global rate of fossil fuels consumption.

No matter how you analyze the problem, fossil fuel use will start declining. It is too early to say whether this change will come about because of decreasing availability of fossil fuels in the ground, because of prohibitively high costs (both monetary and energy) of mining and conversion, or because of adverse environmental effects or a combination of all three. But even before we reach that time, it seems probable that we will be using solar energy or nuclear power, or perhaps both, on a very large scale.

II.11 Nuclear Power

Any casual student of the nuclear power issue will quickly recognize that not one of

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that not one of the processes involved in the nuclear fuel cycle is free from attack for one reason or another.

Estimates of the resource availability for nuclear power question the ability of nuclear power to have a real impact on the total energy situation. Some more pessimistic forecasts see the possiblity that yellow cake, U_3O_8, could be seriously limited by the year 1980 if expansion of nuclear electric power proceeds as planned (Lieberman, 1976). As only about 1 percent of the total energy available in the uranium is utilized, the quantities of uranium needed for nuclear power are large. Quantities of uranium that can be obtained for $14 per pound ($30 per kilogram) or less, are no more than one million tons (907 million kilograms) (Brown, 1976). Perhaps, an additional five million tons (4536 million kilograms) could be obtained at costs under $45 per pound ($90 per kilogram) (ITC, 1971). It is likely that for as long as nuclear technologies are employed that make use of such a small fraction of the total energy available, the spread of nuclear power will be basically limited by the cost of uranium.

Breeder reactors, advocated by the Energy Research and Development Administration as the long-term solution to limited uranium - 235 resources, will be able to feed on plutonium derived from the most common isotope of uranium (uranium 238), releasing as much as 60 percent of its available energy. However, there are numerous problems that must be solved if breeder reactors are to play a role in energy production. There are problems of waste disposal, since huge quantities of radioactive by-products will be generated. Last, but by no means least, there are problems of preventing plutonium from falling into the hands of unscrupulous persons. Not much plutonium is needed to make a bomb of substantial explosive force.

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II.12 Alternative Sources

Without a doubt the nuclear/faster-breeder power issue is a complex social and technical problem that has as much to do with the problems of radiation, costs, and capital, etc., as it does with the question of "what ought to be." The uncertainties associated with nuclear power production have spurred new interest in solar energy. Wind generators, solar heating and cooling, photovoltaics and an endless stream of new ideas to use renewable resources of energy have been proposed to help solve the energy crisis.

The potential supply of solar energy is practically unlimited. Its effective utilization suffers from the fact that it is of relatively low intensity, variable in its availability, and not available in any one location for the entire day. In spite of these difficulties, the prospects for the use of solar energy on a large scale seem reasonably hopeful.

II.13 Summary

Oil and natural gas are clearly going out of the long-term energy picture. Electricity consumption is expected to continue to grow with coal-fired and nuclear-fired plants being built to meet demand based on a complex set of environmental, safety and economic issues. The nuclear power impact is very difficult to measure at this time. After so many years of debate, nuclear power is still problematic. The impact of solar energy is not likely to come about until after the 1980's. Even then, its replacement of other fuels will be slow to develop. The real hope for solar energy is in the very long term.

United States has coal reserves amounting to more than three times the energy contained in the Middle East oil. This coal reserve is approximately 9

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approximately 90 percent of all proven United States energy reserves. Yet over the last 75 years, the United States has shifted away from the use of coal for 90 percent of its energy needs to dependence upon oil and natural gas for 75 percent of its energy. Thus, the nation now uses energy which is least abundant in the United States and for which imports have made us almost totally dependent upon the OPEC nations.

The availability of the expensive Middle East oil served to decrease the exploration and production of domestic oil, which peaked at 9.6 million barrels a day in 1970 and now stands at only 8.2 million barrels a day. Meanwhile demand continued to grow at 4.6 percent in the 1960's and early 1970's in response to low prices, environmental constraints on the use of coal, and the growing dependence on automobiles. By 1975, thirty-seven percent or 6 million barrels a day of imported oil made up the difference between demand, and domestic supply. After the shock of the Arab oil embargo, and the increased price for oil charged by OPEC, the United States paid about $27 billion ($125 per person) for imported oil in 1975 - up from $3 billion in 1970.

The demand for all forms of energy grew in the United States at a rate of 3.6 percent in the 20 years before the 1973 oil embargo. By 1975 the United States used about 73 quadrillion BTU's (77 quintrillion joules) of energy. During this period, electricity grew at an average annual rate of twice the rate of all energy demand (about 7 percent per year). This means that if we continue to demand energy at a rate of 2.8 percent, we will use 98.9 quadrillion BTU's (104.2 quintrillion joules) in 1985.

Lowering the historical growth rate from 3.6 percent to 2.8 percent can be accomplished because the residential/commercial and transportation sectors can make adjustments to higher energy prices. An active

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conservation effort could cut this rate to 2.2 percent through 1985, but it would take a different policy at the Federal level to reduce it much more.

In the near future, between now and 1985, deregulation of oil and gas prices could reduce imports to about 5.9 million barrels a day. Domestic oil production could increase to 12.3 million barrels a day by 1985. All of which depends upon the amount of oil we discover and produce and whether or not prices are high enough to justify production.

Electricity could continue to grow at a rate of 5.4 percent or about twice the expected growth of all energy if coal and nuclear power plants are allowed free access to supply demand. But the future of nuclear power is in doubt and the future growth of coal-fired plants is constrainted by environmental standard, and the availability of capital. The use of natural gas and oil-fired power plants will probably be phased out due to higher fuel costs. Coal can take their place, but this would mean about 700 million tons (635 billion kilograms) would have to be mined in 1985. Whether or not this is possible depends upon environmental as well as Federal decisions.

Conservation, although having no real impact on energy use by the year 1985, in the long run, is man's best policy for all resource utilization. Switching from fossil and nuclear fuels in the future may make the axiom, "less is more" an every day reality. But, between today and the not-so-distant future, the United States will have to exploit resources while moving in the direction of making better use of the abundant resources available. Using these abundant resources so as to produce the maximum amount of work possible while recovering any useful by-products produced to lessen the demand for energy and resources.

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CHAPTER III

REVIEW OF ENERGY MODELING

In the past, only government regulatory agencies developed and used energy models to any great extent. But since energy is now recognized as such a vital part of the economic well-being of society, energy modeling has enjoyed a great boom in interest. For policy makers, people involved in research and analysis, and the many prophets trying to forecast the fate of man, energy modeling provides ways to construct complex integrated sets of technical and economic information.

Energy system models have been formulated using theoretical, analytical methods and data from a variety of disciplines. Engineering, economics, operations research, management science, using the techniques of mathematical programming, with some use of statistics and econometrics, and network analysis, have developed models for regional, national, and international forecasting, and policy formulation and analysis. In this short reveiw we will examine the application and methodology of some selected energy system models.

The fact that a model has been developed for this or that process usually evokes the image of complex mathematical equations and some form of overwhelming complexity that is not understandable to the average person. Sometimes the smallest result of a model can have great impact on society because models are viewed by many as complex and thus, somehow truthful. Yet models may be complex or simple depending upon the needs of the question for which the model is attempting to give an answer.

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Some judgment is always involved in developing a model and in some cases, simple judgmental models can provide good information if only overall performance of a process is needed; in other cases, judgment is kept to a minimum as when deciding optimal allocation of generation mix to provide electricity to a varying electrical load. In these cases, the theoretical description from relevant disciplines and applied mathematics are more appropriate. The choice of theoretical structure, analysis methods, and level of detail are part of the art of modeling as distinct from the science of modeling.

Energy system models have been developed for engineering models of conversion processes, like electric power plants, all the way up to models of international supply and demand of energy in its various forms, and just about everything in between. The nation's economy has been modeled, and the energy sector itself has been modeled for different reasons. Many energy-related models have been developed with the primary interest in ecosystems, or physical processes, they are excluded from this review.

Hoffman and Wood classify energy system models according to the purpose, normative or descriptive analysis and predictive purposes, for which they are employed. When normative analysis is the objective, the impact on the system of changing some element or process, that is an exogenous event in the model, is sought. Whereas, predictive models are used primarily to forecast energy states of supply and/or demand and associated constraints for future time periods (Hoffman and Wood, 1976). In truth, almost all models have both normative and predictive abilities and this type of classification is only useful to indicate the relative objective of a model.

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Validation and the treatment of uncertainty are important for the power of the model and is related to the methodology used. Uncertainty is always present in any real system and how the model handles these events can determine the usefulness of the results. The variety of methods used for dealing with problems of uncertainty are important in evaluating the predictive capability and validating the model. For example, normative* models deal mainly with how the given system should respond to events, given an objective, and validation issues are then usually concerned with the structural grouping of components and specification of input parameters. Whereas, for predictive models, the logical structure of the model and its predictive power are important.

Three levels of predictive capability are identified by Hoffman and Wood. First, there is the ability to predict the direction which the system will take given changes in some factor. Secondly, the ability to predict the magnitude and direction to different policies of some other factor and thirdly, the ability to predict the direction and absolute magnitude to a perturbing factor. Validation on the first two levels is a minimum for any predictive model, while validation on the third level is not always possible or necessary. In fact, many models cannot be validated on the third level, but are quite useful.

III.1 Methodologies

Energy system models are derived using theoretical and analytical descriptions of components taken from a wide range of disciplines; engineering, economics, operation's research, and management science. Generalizing a little bit, economic models tend to deal mainly with the

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behavioral characteristics of policies to produce and/or use energy. Engineering energy models have tended to deal with physical and technical aspects of conversion processes. The objective of behavioral models tend to deal with alternatives, modification, or creation of new technologies that are better then existing alternatives. Lately, see FEA, 1976, energy system models have incorporated both behavioral and process components to provide a more complete description of the system. In the case of FEA, this was done to evaluate the emergence of new technologies, i.e., gasification of coal, oil shale, etc., on the supply/demand and price of energy in the United States.

Methodologies used to implement energy system models ranges from mathematical programming (LP and nonlinear programming), econometrics and statistical methods, to methods related to network analysis.

Mathematical programming methods have been used to describe techniques and engineering details of energy processes with economic factors. In the majority of cases, mathematical programming exhibits the model as a group of simultaneous equations, the variables of which represent the activity of specific processes. Activity variables are grouped in a matrix which defines such things as demand requirements and supply constraints, and other technical descriptions that are intended to represent reality as close as mathematical equations allow. An objective function or performance function is defined, which is minimized or maximized, i.e., cost, profit, supply or demand, and any number of computer algorithms are used to solve the equations.

The most popular of the mathematical programming techniques is linear programming, mainly because LP methods can efficiently solve large-scale problems. Also, the dual problem formulated in terms of prices, associated with any LP problem formulated in terms of quantities, is a direct and att

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direct and attractive link between processes and economics. Other methods, such as LaGrange multiplies, and variational methods are used for generally normative purposes. These later methods can include environmental or regional characteristics, which result in determining optimal strategies for specific objectives.

Input-output methods, that started with Leontief's input-output analysis of the economic system, have been applied using conversions of economic activity into a standard unit of energy, the British Thermal Unit. The basic assumptions for these models include a fix technology and zero price eleasticity. Their primary use is in determining the level of energy use required to reach a certain level of demand for goods and services.

Econometric methods are generally concerned with empirical representation and validation of economic theories (Hoffman and Wood, 1976). The principal method is regression analysis combining the economic model derived from theory with a statistical model of the process from which the observed data are assumed to be generated. Examples include testing the hypothesis that a particular parameter is not significantly different from zero, that parameters in different equations of the model are not significantly different, or that combinations of parameters are equal to some specific value.

The system dynamics approach evolved from the study of industrial operations. These models use simultaneous linear and nonlinear equations to describe components of the model with the use of feedback relationships included in the structure of the model. The biggest problem confronting these models has to do with validation.

The functional relationships between components in system dynamics models, demand that modelers make judgments that are not always shared by other stude

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by other students of the system. Although system dynamic models are powerful, they have been evaluated through a jaundiced eye because of their scope. One of the latest models includes world development in energy, resources, economics, the environment, and population (Mesarovich and Pestel, 1974).

III.2 Energy models

The vast majority of energy system models are of the economic type. This review will consider a few different types of economic models then system dynamic models.

Many of the economic models have as their primary focus, the supply or demand for specific fuels or energy forms. The demand for gasoline, electricity and oil receiving much of the modeling attention. Taylor recently surveyed the econometric demand models of the demand for electricity (Taylor, 1975). He reviewed the special problems associated with modeling the demand for electricity, complicated by the fact that demand is dependent upon the utilization rates of equipment and the effects of the regulatory process and price schedules.

The gasoline demand model developed by Sweeney examined the conservation policies affecting automobiles. Gasoline use is a derived variable dependent upon average miles per gallon and the total number of miles driven. Where real disposal income, unemployment, and cost per mile of automobile travel determine demand for vehicle miles. Other petroleum demand models have been developed by Lay and Verleger.

The study of the need for industrial expansion or the need to understand the impact of different regulatory policies on the energy industry has produced much modeling of industrial markets. For example, Adams and Griffin combined as LP model of the U.S. refining industry with an econometric mo

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econometric model for determining endogenously the prices, quantities demanded, and inventory adjustments for major petroleum products (Adams and Griffin, 1972).

Mathematical programming has been used extensively in the analysis of electric utility operations and expansion plans. Anderson reviewed over 50 models used by that industry and found models using the methods of dynamic programming, linear programming (LP), and nonlinear programming (Anderson, 1972).

Analysis and modeling of the overall energy system were stimulated largely by the need to forecast total demand. Barnett, Dupree and West, used the approach of energy balancing for all energy forms. The emphasis was on quantity flows expressed in a common physical unit, the BTU. As an accounting approach, the energy balance system focuses attention on a complete accounting of energy flows from original supply sources through conversion processes to end-use and the approach accounts for intermediate consumption and losses of energy during conversion processes as well as efficiencies at various points in the energy supply system (Dupree and West, 1972).

When process models are used with the energy balancing approach the model encompasses all alternative fuels and energy sources, and frequently employs network analysis in order to represent technical detail. The network is used to describe the spatial flows of energy as well as the alternative processes and fuels that may be used in specific demand sectors. In addition, these models of energy systems can be augmented with optimization or simulation techniques to examine behavior and options.

Baughman used a system dynamic model to study interfuel competition by simulating the flow of resources like coal, oil, gas, and nuclear fuels

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to the various demand sectors, residential, commercial and industrial (Baughman, 1972). The model is used to simulate interfuel competition and to determine quantities, prices of fuels, and energy sources as demand, and the availability and cost of changing resources.

A system dynamics model of the coal industry has been developed by Naill, Miller and Meadows. The purpose of the model was to study the role of coal in the transition of the U.S. energy system from non-renewable resources to renewable resources up to the year 2100 (Naill, et al, 1974). Time delays associated with R & D and plant construction for the synthetic fuels sector add to the models' realism. Where, the demand for energy and the markets share of various fuels are determined endogenously as a function of price, GNP, and population.

The last type of energy system models covered in this short review are the world or global models championed by the Club of Rome. The first of these energy/society models was developed by Meadows, et al, in 1972. The Limits to Growth was a simulation model using the methods of industrial dynamics developed by J. Forrester. While the energy sector is only a some part of the models developed by Forrester, Meadows and followers, later world models would consider the energy system explicitly. The most significant example of this is the global model of Mesarovich and Pestel. This model encompasses energy, resources, economics, the environment, and population. The energy submodel consists of an energy resource model, a demand model, and an energy supply model. Statistical information on energy resources allowing for uncertainty of the resource and the feasibility of recovery, and a simulation of the production of resources are included in the resource model. The demand model describes the demand for energy as a function of GNP and the supply model covers 13 primary and 7 secondary forms of energy along with the associated conversion process.

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III.3 Summary

This review has examined the methodologies, and applications of some energy system models. Methodologies included mathematical programming, linear programming, nonlinear programming, econometric methods some with statistical methods added, input-output methods, system dynamics, and network analysis. Applications reach from regional analysis, industrial markets analysis to national and world models. All of which suggests that a broad range of possibilities exists for supporting policy and regulatory behavior at all levels with the proper use of energy models. Policy makers, and planners can benefit by the power and precision of energy models.

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CHAPTER IV

THE DUAL-PURPOSE PLANT

The limitation on physical forms of energy, coal, hydrocarbons, and uranium, is clearly a reality (Hubbert, 1971). This means that sometime in the future inhabitants of the space ship earth will have to adjust to many energy related problems, as a result of the way we use energy. Future generations, after examining the industrial society of the 20th century, will surely recognize that one of the greatest tragedies of that era was the almost complete disregard for the efficiency of energy use.

Today our electric power plants convert only 32 percent (based on average heat rate) of the primary fuel burned into electric energy. Diesel engines, considered better then the internal combustion engine used in passenger cars, have efficiencies of around 36 percent. The way we use energy in the house is even more appalling. Incandescent lights are only 5 percent efficient, and an electric clothes dryer 50 percent efficient (not including the efficiency of the plant). The home furnace, while 60 percent efficient in top condition, is probably considerably less efficient in actual operation because of poor maintenance and installation.

There are strict upper levels to efficiency of use for every fuel, as defined by the laws of thermodynamics. But with energy so cheap and seemingly plentiful in the past, we paid little attention, until lately, to the efficiency of energy use. We now face the real prospects of

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prospects of running out of oil and natural gas, and the drastic changes this implies. Can we afford to continue to burn fuels in electric power plants at such low efficiencies? Where should oil and natural gas be used, and what efficiency of use should we expect? Since there are special qualities associated with oil and natural gas, can society continue to use these fuels to generate electricity?

Many proposals to increase the efficiency of energy use involve doing more of what we already do; insulating, recycling, making more efficient air conditioners, etc. Other proposals point to alternative systems and devices. For example, a molecular sieve for separating oxygen and hydrogen is a device idea, possibly opening the way for fuel cells. Whereas, pumping ground water through coils inside a forced air furnace is a system's idea.

The application of heat produced during the production of electric energy is a system's idea which provides possibilities for significant savings in energy use. Heat energy in the form of steam or hot water could be used, after producing some electrical energy for other tasks. As an alternative to large electric power plants located great distances from load centers, smaller dual-purpose plants could be located near load centers providing steam as well as electricity.

In this chapter the activities of the district heating business, the current applications of dual-purpose plants, the turbine systems used to produce electricity, and the energy efficiency associated with a dual-purpose plant are presented.

IV.1 District Heating

District heating is the use of large steam generators (boilers) to provide steam for residential, commercial, and industrial consumers of steam. Toda

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steam. Today, most district heating companies use packaged industrial steam generators to produce steam which is distributed to steam users by the use of underground steam pipes.

For many years district heating was a form of public-utility service that prospered after a slow beginning due to the lack of engineering development. District heating has been popular in the Middle West, with both small and large cities of Ohio, and Indiana receiving the idea favorably. As time passed, electric power companies got out of the district heating business and concentrated on larger power plants to meet a growing demand for electricity. The majority of companies separated electric and steam production, while others got out of the business of trying to supply anything other than cheap reliable electric power.

District heating systems in the United States sold more than 81 billion pounds of steam in 1970, and served almost 15,000 customers (Schuster, 1971). For the 15 years prior to 1950, district heating showed a net gain, but the rate of growth was erratic. After the 1950's, utilities began to promote district heating, and since then steam sales have increased 53 percent (Schuster, 1971). Thus, it appears that there are plenty of tasks for which steam is a useful form of energy. With the growth of district heating proof that many tasks performed with the use of other fuels can be performed with the use of steam, and that there are many potential consumers.

The dual-purpose electric power plant is a technology that can produce electricity, for which electricity is the only form of energy useful, like for lighting, computers, etc., and steam, to provide energy to low-temperature tasks like space heating and cooling, and water heating.

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IV.2 Applications of Dual-Purpose Plants

The dual-purpose plant is a particular type of central electric power station, usually built by the utilities, which also furnishes a significant amount of steam to one or more steam users. When several steam users, typically industrial customers, are grouped near or around the dual-purpose plant it is frequently referred to as an "energy center", or a "nuplex" if the plant is nuclear-fired. Examples of dual-purpose plants can be found in the states of Michigan, Missouri, New Jersey, Ohio, Washington, Indiana, Delaware, Louisiana, and California.

One of the oldest dual-purpose plants was built in 1930 and is operated by the Gulf States Utilities Company. Supplying steam to the Ethyl Corporation and Exxon Company, the plant produces 240 megawatts electric with a total steam generation capacity of 5 million pounds per hour (IECS, 1975).

In New Jersey, the Public Service Electric and Gas Company has been supplying Exxon with steam since 1957. Between one and two million pounds of steam per hour, at 150 psi (1 M newtons per square meter), are furnished with the use of extraction turbines. In exchange for steam, Exxon supplies fuel to the utility.

Public Service Indiana did not originally design the Cayuga station to produce process steam, but in 1975 completed the change over to supply 225,000 pounds per hour of steam to the Inland Container Corporation. By tapping the cold reheat header, process steam is produced with no return condensate received from Inland. Inland Container is located some 9,000 feet (2743 meters) from the Cayuga plant. Steam is supplied through a piping system, much like the system used by district heating companies.

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The first nuclear dual-purpose plant is being built by the Consumers Power Company of Michigan. This company has had more than its share of problems with nuclear power in the past, and problems with the dual-purpose nuclear plant at Midland have delayed it until the 1980's. Expected to come on-steam much sooner, the Midland plant is designed to supply 4 million pounds per hour to Dow Chemical, and generate 1300 MW of electrical power (EICS, 1976).

An agro-industrial complex, designed for developing countries, uses the dual-purpose plant technology. Oak Ridge National Laboratory has helped with studies of agro-industrial complexes for India, Pakistan, Israel, and Egypt (Beall, 1971). A Puerto Rican study done by Burns and Roe, and the Dow Chemical Company for the Atomic Energy Commission - now the Energy Research and Development Administration - planned to use heat from a dual-purpose nuclear plant for petroleum refining, irrigation, and other industrial uses.

The Southern Interstate Nuclear Board and the State of Texas have undertaken studies, the one in Texas supporting a large group at Texas A & M University, to produce conceptual designs of a nuplex. Kentucky and Maryland have done similar studies (Beall, 1971). Many of the resulting studies have concluded that electric-heat, or dual-purpose plants, are an attractive option from economic, conversion, and environmental points of view (Beall, 1971).

Urban applications of dual-purpose plants have been investigated by the Department of Housing and Urban Development. The problems of installing a central heating supply system, pipes, valves and meters, in any existing city was thought to be too difficult and studies were limited to a hypothetical new city. The resulting study by Miller et al postulated a

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postulated a new city of 389,000 people living in a climate similar to Philadelphia's. Sixteen square miles (41 square kilometers) is served by the district heating system using heated water for space heating, water heating, and air conditioning. Within a 5-mile radius (8 kilometers) heated water is supplied to a sewage plant, and 200 acres (81 hectares) of greenhouses. Two hundred fifty-eight thousand of the total population reside within 12 square miles (31 square meters) located about 7 miles (11 kilometers) from the nuplex. This grand study examined the economics of applying a large nuclear plant to other tasks than just the production of electricity. And results indicated that at favorable population densities of 21,000 people per square mile, heated water can economically be supplied to large cities within the design considered.

IV.3 Advantages of the Dual-Purpose Plant

The basic advantage of the dual-purpose plant lies in the increased utilization of energy. Simplified in Figure 4.1, the conventional power plant produces only about 40 percent of the input energy as electric energy, E. Over 60 percent of the primary fuel burned is dissipated to the environment as waste heat at the plant, H. The second design extracts some of the steam, after it has produced some shaft work in the turbine, and sends it into a steam distribution system where the remaining energy is used. In the design shown, 35 percent of the primary fuel is turned into electricity, 35 percent is extracted for other purposes, and waste heat only accounts for 30 percent. The ultimate design would be the last illustration where a back-pressure turbine is used and 30 percent of the primary fuel is produced as electricity, and the remaining 70 percent is used in o

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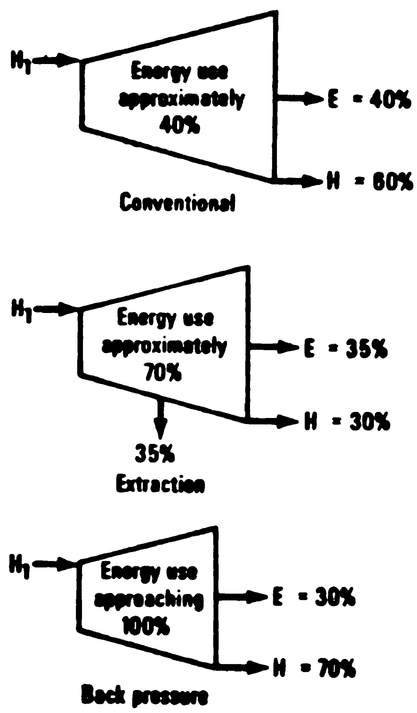

Figure 4.1 Turbine Types

Reference: Beall, S. E. 1973. Total Energy - A Key to Conservation. Consulting Engineer 40 (2): 180.

Considered at the community level, dual-purpose power generation can decrease overall fuel requirements for the generation of electric energy and the supply of low-temperature energy used in the residential, commercial, and industrial sectors. Also the use of very limited fossil-fuel resources like gas, and oil are also removed from the community, substituting hot water or steam. In addition, the misapplication of electricity to provide space heating and cooling, water heating, and other tasks are eliminated, and these terribly inefficient (when plant efficiences are included in the total efficiency calculation) processes are replaced by

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replaced by the use of steam or hot water. Since less fuel is burned in the whole community, the release of combustion products in the urban community is also decreased, and at the plant less waste heat is dissipated to the environment through cooling towers, ponds, etc.

IV.4 Turbine Systems

Three types of turbines can be used to generate electricity in an electrical power plant; condensing, back-pressure, and extraction. The condensing turbine, used in the vast majority of today's power plants, expands prime steam at around 2,400 psia and 1000^{o}F (16.548 M newtons/m^2 and 538^{o}C) through a turbine and condenser. Condenser cooling water, from lakes, rivers and streams, plays an important part in determining the Rankine efficiency of the turbine. Water at ambient temperatures, 40 to 60^{o}F (4 to 16^{o}C), increases the available energy (work producing) by creating low-temperature conditions in the condenser. Where laws prohibit the use of natural bodies of water, cooling ponds or cooling towers are used. Since towers return condensing cooling water at 100^{o}F (38^{o}C) to the condenser, they have the distinct drawback of decreasing Rankine efficiency.

Production of electric energy with the condensing turbine results in 60 to 70 percent of the primary fuel burned ultimately discharged as waste heat to the environment. Putting to practical use this enormous amount of energy has charmed many investigators (Jensen 1971, Miller 1971, Beall 1970) in the past. Only a few low-temperature uses like greenhouse heating, waste treatment, and fish ponds are technically able to use this degraded heat. While uses of this low-temperature heat are rather limited, the low cost and small affects on plant operation ar

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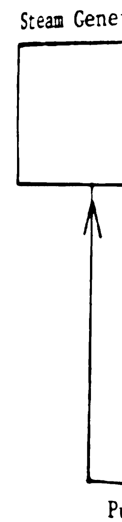
operation and efficiency, make continued economic and technical analysis of possible applications worthwhile.

The back-pressure turbine system is practical in only a limited number of cases. In general, prime steam is expanded through the turbine to a predetermined lower pressure, generating some electricity. Steam is then moved to the rest of the system by pumps where the remaining energy is used by industrial, commercial, and residential users. This arrangement is useful if there is a large demand for steam at high temperatures.

The back-pressure turbine can be designed so that steam expansion can be terminated at almost any pressure and permitted to exhaust into heat exchangers or a piping system at the desired pressure. Since all the steam is exhausted into a system using the remaining energy, ideally no waste heat must be discharged to the environment at the plant site. The only energy loss in this type of system is the result of losses in transport, heat exchangers, etc. The overall efficiency of the system, in terms of energy use, approaches 100 percent (Beall, 1973). The equipment arrangement for a back-pressure turbine system is shown schematically in Figure 4.2.

The back-pressure system works well for both electric power companies and steam users only if the steam users are always ready when steam is produced, and if steam users can be cut-off during power plant maintenance periods. But the constraints of locating steam users close enough to the power plant to be economical, the problems of planning and construction time differences between users and the power plant, make the back-pressure system quite inflexible, and are counted among the many reasons why power companies are not involved in selling steam.



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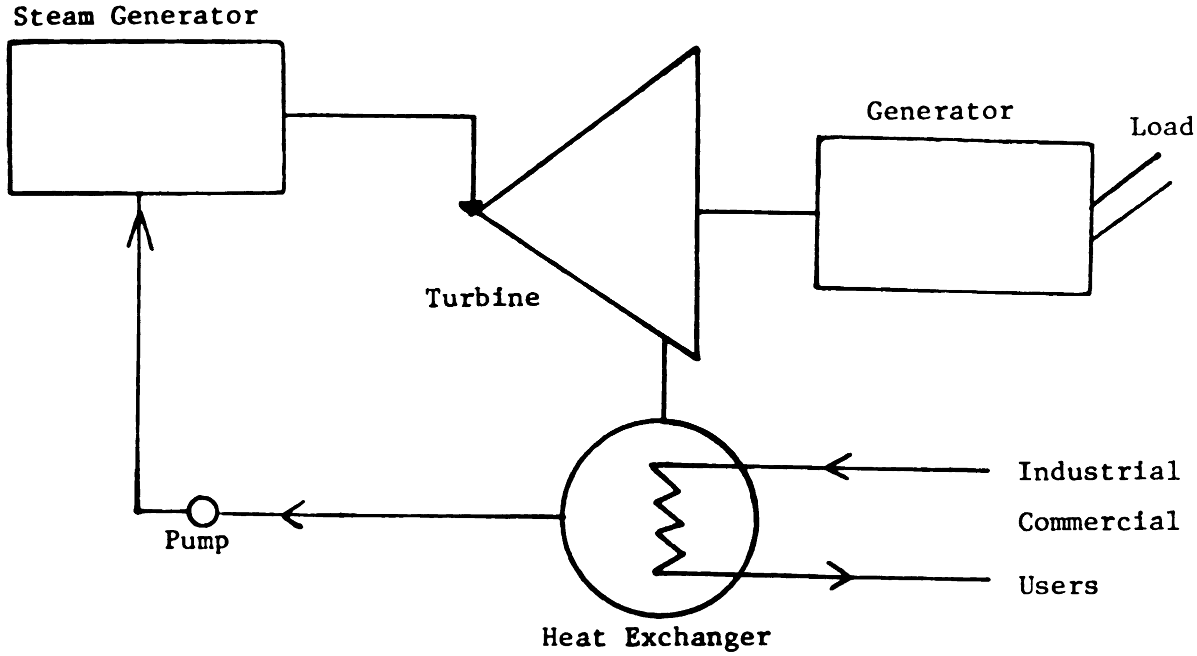

Figure 4.2 Back-pressure turbine

The extraction turbine system by contrast can be used where steam demand is small to moderate. Steam can be taken from the turbine at more than one point enabling industrial steam to be extracted at one point, and steam at lower pressures to be taken at other points. This permits electrical power to be generated by steam expansion through the turbine and removed at the desired pressure instead of throttling high-pressure steam to a lower pressure for some steam users.

Extraction turbines have the flexibility to be designed so that as the steam load decreases, the reduced steam load can be expanded through the turbine, increasing electrical power generation. Figure 4.3 is a schematic diagram of the equipment arrangement for the extraction system.

The extraction system offers the greatest flexibility for increasing the number of steam users in the system, and as the system grows it may justify the

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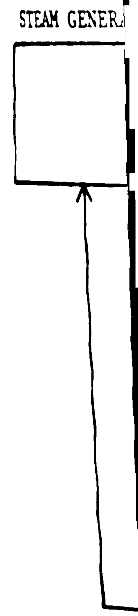

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justify the addition of a back-pressure unit, but in the most general case, the extraction turbine is the most useful.

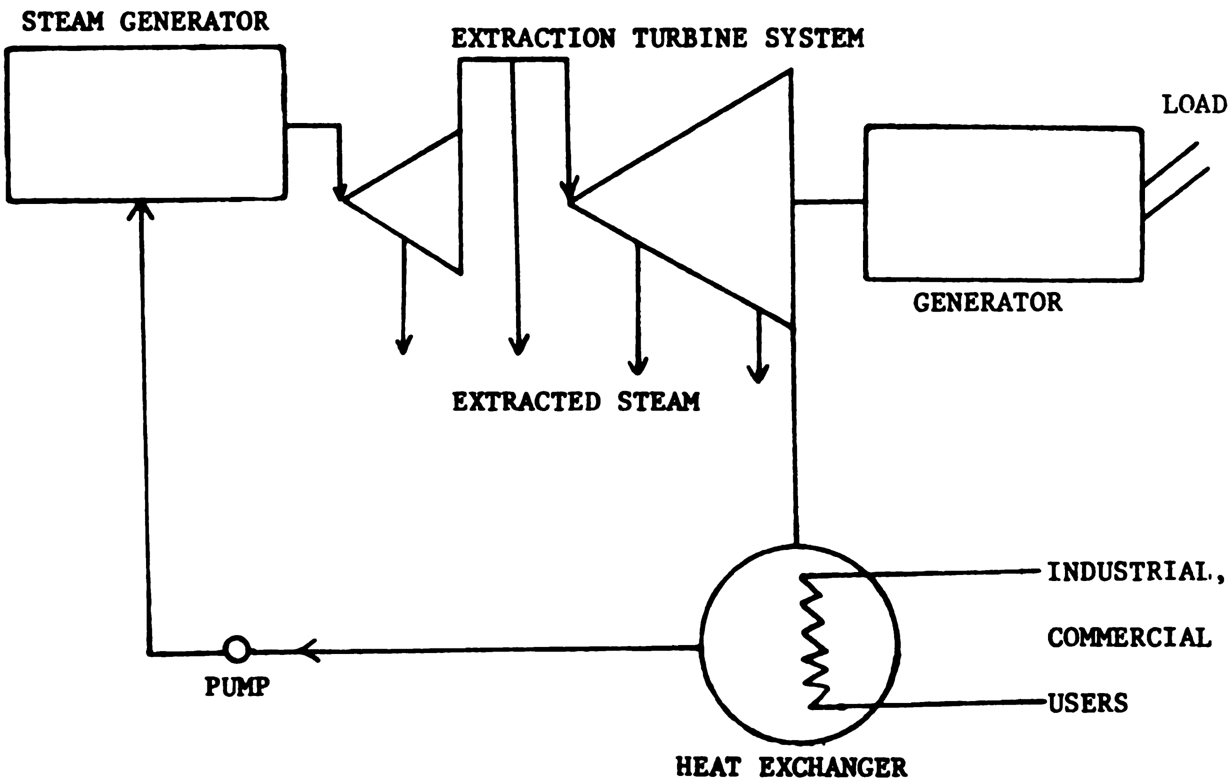

Figure 4.3 Extraction Turbine System

IV.5 Automatic Extraction

Automatic extraction units bleed off part of the main steam flow at one, two or more points. Valved partitions between selected turbine stages control extracted steam pressure at the desired level. When extracted steam flows through the turbine does not produce enough shaft work to meet demand, more steam flows through to exhaust, increasing the electrical output. These turbines are put between the steam supply and process steam headers, diagrammed on the following page, Figure 4.4. Automatic governing systems correlate steam flows, pressures, shaft speed and shaft output for any one unit.

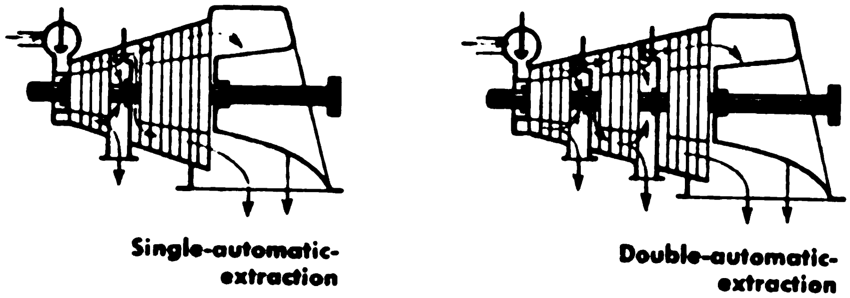

Figure 4.4 Automatic Extraction Turbine

The extraction turbine has advantages over the back-pressure turbine system because it allows steam to be withdrawn at any needed pressure. Back-pressuring turbines also have no flexibility if the heat-users are temproarily removed from the system. The power plant can not economically operate if there is a chance that the heat-users are unable to use the steam produced. Therefore, the extraction turbine is considered a better choice for the system under consideration since it can be expanded to meet demand from new heat-users added to the system.

The extraction turbine reduces the amount of steam reaching the last stages of the turbine, thus, it also decreases the amount of waste heat produced, see Figure 4.5. The efficiency of electrical energy production is decreased, but overall efficiency of energy use is increased.

IV.6 Energy of Steam and Electric Power

The energy available in steam is the maximum work-producing capability of steam when exhausted to a cold heat sink. In steam turbines the available energy of the steam is the work produced by the steam between the initial steam conditions from the steam generator to the level of the lowest attainable turbine exhaust pressure. In general, steam at the outlet is not capable of producing useful work unless a colder sink is used.

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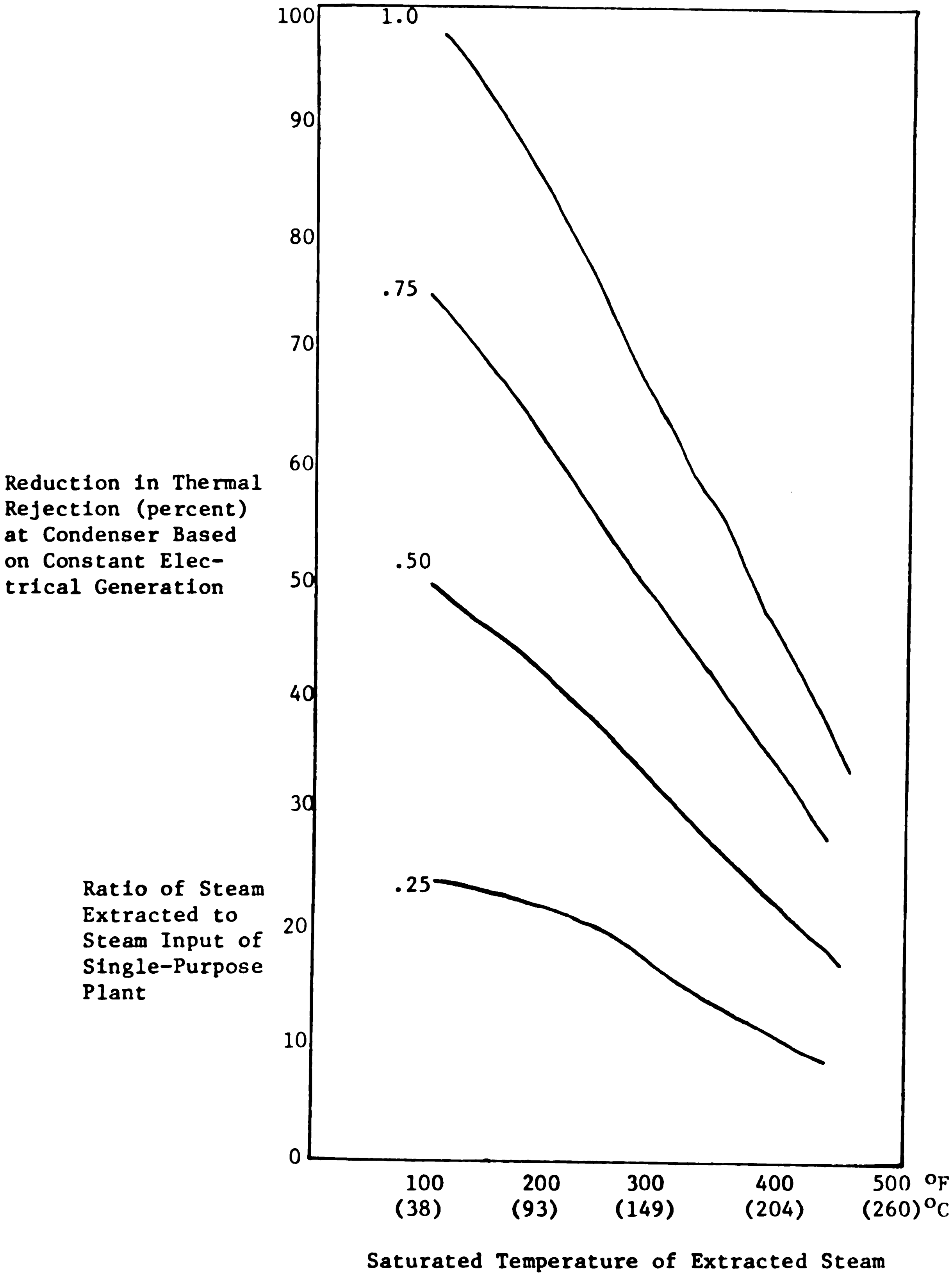

Figure 4.5 Reduction in Thermal Rejection

Reference: Miller, A. J., et al. 1971. Use of Steam-Electric Power Plants to Provide Thermal Energy to Urban Areas. Report no. ORNL-HUD-14, UC-80 Reactor Technology, Oak Ridge National Laboratory, U. S. Department of Housing and Urban Development, Washington, D.C.

Ideal Rankine cycle work assumes that the steam is expanded through the turbine abiabatically to the condenser with no change in the entropy. In real processes, the expansion of steam must be accompanied with an increase in entropy, see Figure 4.6. Therefore, the useful work per unit mass of steam expanding in the turbine per unit time is:

Turbine Work = hi - hf' where sf' > si and,

$$\text{Electrical Power} = \frac{hi - hf'}{3414} = \text{kw, where kw} = 3414 \text{ BTU/hour}$$

Because extracted steam is not available for electric power generation, an extraction turbine has the same maximum work producing capacity as a single-purpose turbine, when no steam is extracted.

When no steam is extracted, the maximum electrical output Ec and the mechnical output of the turbine, W max, would be:

$$Ec = \frac{W\ max}{3414} = \frac{mi\ (hi - hf')}{3414}$$

where,

mi = mass flow rate of steam generator, pounds per hour

hi = initial enthalpy, BTU's per pound

hf'= final or exhaust enthalpy, BTU's per pound

If steam mx is extracted, the actual output of the turbine is:

$$Ea = \frac{W\ actual}{3414} = \frac{mi\ (hi - hf') - mx\ (hx - hf')}{3414}$$

The energy lost to electric power generation by the extracted steam is the difference between Ec and Ea,

$$Ec - Ea = \frac{mx\ (hx - hf')}{3414} = Ex$$

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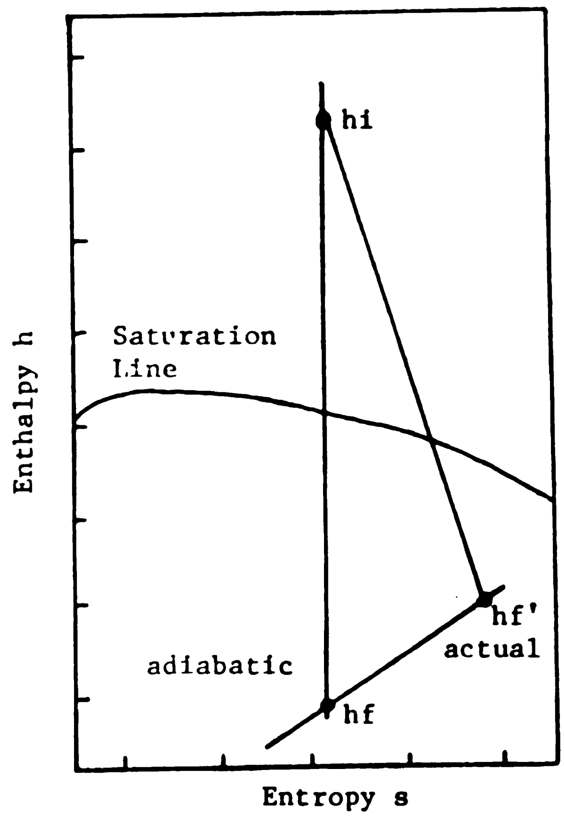

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Figure 4.6 Turbine Expansion Curve

For example, the dual-purpose plant shown in Figure 4.7 has throttle conditions of 4,000,000 lbs/hr. (504 kg/sec.) at 2400 psia (16.548 m newtons/m^2). Process steam is extracted in the amounts of 1,000,000 lbs/hour (126 kg/sec.) at 335 psia (2.310 M newtons/m^2) and 2,000,000 lbs/hour (252 kg/sec.) at 150 psia (1.034 M newtons/m^2). The later could be used for district heating and the former for industrial processes. Another 500,000 lbs/hour (63 kg/sec.) is extracted at 35 psia (.241 M newtons/m^2) for low-pressure district heating and chillers producing cooling water for the community, and another 500,000 lbs/hour (63 kg/sec.) at 35 psia (.241 M newtons/m^2) is used in the deareator and feedwater cycle. The steam generator has a first law efficiency of 91 percent.


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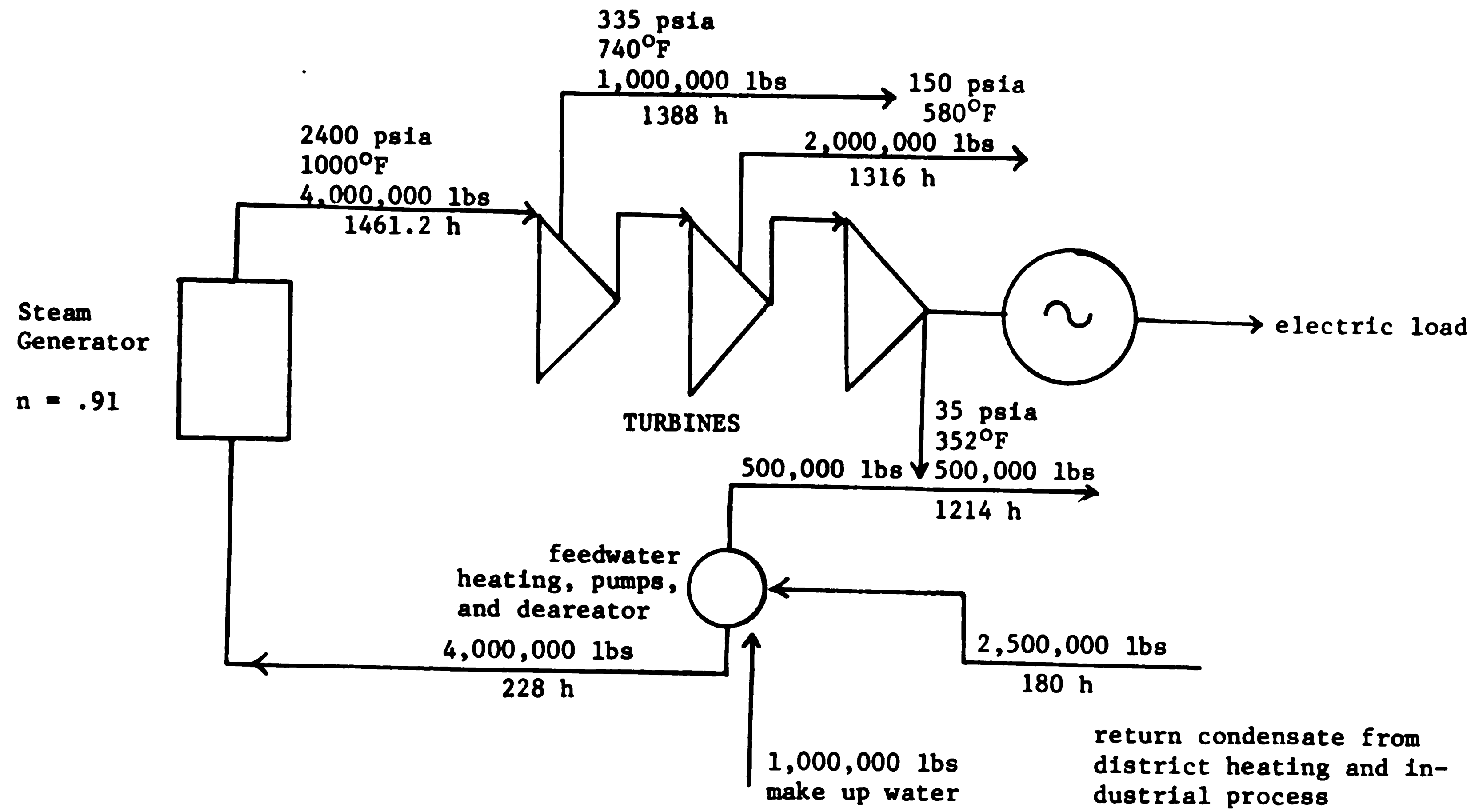

Figure 4.7 Dual-purpose Turbine Heat Balance

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If a condensing turbine was used instead of the extraction system, an attainable condenser back-pressure of 1.75 in Hg (604.28 kg/m^2) is assumed. The exhaust enthalpy, hf', is 1,032 BTU/lb. (.398 M joules/kg), and final feedwater enthalpy is 228 BTU/lb. (.530 M joules/kg).

Computation:

Ultimate electrical output for the condensing (non-extraction) turbine:

$$Ec = \frac{4{,}000{,}000\ (1461.2 - 1032)}{3414} = 502{,}870.53 \text{ kw}$$

Electrical output of the extraction turbine:

$$\begin{aligned} Ea = [&1{,}000{,}000\ (1461.2 - 1388) \\ &+ 2{,}000{,}000\ (1461.2 - 1316) \\ &+ 1{,}000{,}000\ (1461.2 - 1214)]\ \frac{1}{3414} = 178{,}910.37 \text{ kw} \end{aligned}$$

The loss of energy for electric power generation by the extracted steam is the difference between:

$$Ec - Ea = 502{,}870.53 - 178{,}910.37 = 323{,}960.16 \text{ kw}$$

The efficiency of electric energy production from the extraction turbine is decreased. While the non-extraction turbine would convert nearly 30 percent of the prime steam energy, in this example, into electric energy, only 10 percent is converted to electric energy by the extraction turbine. The overall efficiency is quite different since extracted steam is used for other tasks. The extraction turbine system has an overall efficiency of nearly 70 percent since extracted steam is used for other energy requiring tasks, increasing the total useful output of the system.

To compare the efficiencies of the convertional, and extraction turbine it is necessary to introduce the concept of available energy or active e

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or active energy. Available energy is a second law of thermodynamics concept which specifies only harnessable work, not work done on the atmosphere. Work is the highest "quality" form of energy, and work is the best overall measure of the capacity for doing any task.

If we measure the available energy and the useful work output of the conventional power plant with that of the dual-purpose plant, the result would indicate that the dual-purpose plant was not as efficient in the second law measure, as the conventional plant. What is needed is a concept which measures not only the available energy input to the system, but also the utilization of energy by the system. To do this, we define the following ratio.

$$U \triangleq \frac{y}{A}$$

where U = the utility of the system

y = utilization, W useful + Q applied (useful work + heat energy applied)

A = availability

The utility of a system as defined above, is a meaningful measure of the total benefit derived from a system in comparison with the ideal maximum which might be obtained and the utility measure provides a way to measure the effect of cascading energy systems. The conventional power plant has a utilization measure, y, that is electrical energy output. Whereas, in the case of the cascaded system of the dual-purpose or extraction turbine system, y is electric and heat energy output. Thus, not only has the utility concept included the work output, but it has also taken into consideration the use of energy in other connected systems.

The available energy A of the steam inputted to the turbine is a theoretical measure of the maximum work producing quality of energy.

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Assuming a cold heat sink of atmospheric conditions, the available energy can be found from the following relation

$$A = Q\,\frac{(TH - Tc)}{TH}$$

where, A = available energy

Q = heat energy added

TH = hot input temperature

Tc = cold sink temperature

The available energy of the system in Figure 4.7 is 5.44×10^{9} BTU's (5.73×10^{12} joules).

The utility, u, of the non-extraction or conventional turbine is simply the work, electric energy output divided by the available energy A.

$$u = \frac{y}{A} = \frac{1.72 \times 10^{9}\ (1.81 \times 10^{12}\ \text{joules})}{5.44 \times 10^{9}\ (5.73 \times 10^{12}\ \text{joules})} = .32$$

The utility of the extraction turbine is the sum of the electric energy plus the usefully applied extracted steam,

$$u = \frac{y}{A} = \frac{.61 \times 10^{9}\ (.64 \times 10^{12}\ \text{joules}) + 2.80 \times 10^{9}\ (2.95 \times 10^{12}\ \text{joules})}{5.44 \times 10^{9} (5.73 \times 10^{12}\ \text{joules})} = .63$$

The utility of the extraction or dual-purpose plant can be nearly twice that of the conventional non-extraction system. To increase the utility of the dual-purpose plant, it would be best to extract steam at the lowest possible pressures. Thus increasing the electric energy output (useful work) and using the extracted steam for low-temperature tasks like space and water heating where useful work is not important.

IV.7 Summary

Chapter IV has presented the activities of the district heating business, and has shown a desire on the part of consumers to use steam.

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Although past applications of dual-purpose power plants has been mainly in the area of supplying steam to industrial uses, some research has been done to consider uses of the dual-purpose plant technology. The efficiencies of these plants is quite high, when compared to conventional plants, and with the added affect of reducing the use of limited energy resources and the inefficient use of electricity to provide low-temperature heat energy, the total efficiency of energy use in a community using a dual-purpose plant can be greatly increased.

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CHAPTER V

ENERGY USE IN THE UNITED STATES

The energy revolution in the twentieth century has transformed America within a lifetime. Over twenty million Americans still remember reading by an oil lamp, gas lamp or candle, splitting wood or carrying coal to feed a pot-bellied stove. Storing perishables in the cool cellar or window box, they used tin basins or tubs to wash in and generally did the tedious time-consuming chores of cooking, washing, and cleaning as everyday necessities.

In 1900, the country farmers, which were most everybody, worked the land with muscle power, human and animal. Wives and daughters scrubbed clothes, beat rugs, cooked in big pots over slow-demanding fires. Children walked to school, and after a few years walked to work. Motor buses and street cars were not common in cities until after the 1920's.

Even though electric power was a reality by the turn of the century, illuminating some wealthy homes in 1880, only 8 percent of all American homes were wired for electricity by 1907, and then only in the larger cities (EPP, 1975). Most Americans were rural dwellers, 60 percent lived on farms and had no electricity and during the next few decades of the century, almost everyone still used kerosene for light, split wood for fires and walked just about everywhere.

Technological changes came swift, making everyone's task easier. By 1925, over half of all homes were wired for electricity, mostly in the cities. Natural gas was common in the thirties, and the number of cars had reached two million in 1920 (EPP, 1975).

In 1943, FDR made his famous fireside chats to the nation by radio and by 1973, virtually every home in America had a television (Makhijani, et al, 1973). By the 1970's, Americans used directly in their homes over 23 quadrillion BTU's of energy (24 x 10^{18} joules) in one year. Considering only electricity, natural gas, and gasoline, they used about 20 quadrillion (10^{15}) BTU's (21 x 10^{18} joules) (EPP, 1975).

Today, energy used in the home, the residential sector, is estimated to be about one-fifth of all energy used in the United States (SRI, 1972). The major uses of energy in the household are shown in Table 5.1. On average, over 70 percent of the total energy used in the household is for space heating and water heating.

TABLE 5.1

Major Uses of Energy in the Household

space heating	57.5%
water heating	14.9%
cooking	5.5%
refrigeration	6.0%
air conditioning	3.7%
television	3.0%
clothes drying	1.7%
food freezing	1.9%
other	5.8%

Reference: Patterns of Energy Consumption in the United States. 1972. Stanford Research Institute. Report no. 4106-0034, GPO: 33.

Air conditioning, shown as 3.7 percent in 1968, is quickly approaching the position of the third largest user of energy in the household. Saturation levels for air conditioners, central and room, rose from 12.8 percent in 1960 to 36.7 percent in 1969 (Makhijani, 1973). With the result that in a typical household energy used by air conditioning is now almost 12 percent of the total.

Despite today's energy servants, it is debatable whether Americans have more leisure time than they did a generation ago. Time spent is housework, for example, is substantial, and has not changed for most American women since their grandparents era (Vanek, 1974).

V.1 Energy Statistics for the United States

Between 1950 and 1970, the United States use of energy resources (coal, hydrocarbons, falling water and uranium) doubled at an average annual growth rate of 3.5 percent, more than twice the population growth rate (EPP, 1974). By 1968, the transportation of people and freight accounted for 25 percent of total energy use, with space heating of homes and commercial establishments using almost 20 percent of the total (SIR, 1972). Industrial use accounted for 41 percent with the remaining 14 percent used in the commercial and residential sectors for water heating, air conditioning, refrigeration, cooling, etc. see Table 5.2.

The growth of electricity use has been increasing at break-neck speed. Between 1960 and 1970, while the use of primary fuels, coal, hydrocarbons, etc., grew by 51 percent, the use of electricity grew by 104 percent (Edison Electric Institute, 1971). In 1970, electric power generation accounted for 24 percent of total energy resource use as compared to 19 percent in 1960 (Hirst, 1973). This increasing use of electricity, much of it by substitution for other fuels, is important when accounting for increased energy growth rates, because of the inherently low efficiency of electric power production.

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TABLE 5.2

Energy Consumed, By Sector and End Use
As A Percentage of National Total*
1968

	Direct	Purchased Electrical Energy	Total
Residential			
Space heating	10.2%	0.7%	10.9%
Water heating	1.9	1.0	2.9
Cooking	0.7	0.4	1.1
Clothes drying	0.1	0.2	0.3
Refrigeration	nil	1.6	1.6
Air conditioning	nil	0.3	0.3
Other	nil	2.1	2.1
Total	12.9%	6.3%	19.2%
Commercial			
Space heating	7.0	nil	7.0
Water heating	0.6	nil	0.6
Cooking	0.1	0.3	0.4
Air conditioning	0.3	1.5	1.8
Feedstock	1.6	---	1.6
Other	nil	3.1	3.1
Total	9.6%	4.9%	14.5%
Industrial+			
Process steam	20.7		
Electricity generation	0.7		
Direct heat	7.0		
Feedstock	3.6		
Total	32.0%	9.2%	41.2%
Transportation	25.0	0.1	25.1
Total	79.5%	20.5%	100.0%

* Including heat wasted in production of electricity

\+ Purchased electricity not allocated separately.

Sources: Bureau of Mines. Stanford Research Institute

Reference: Patterns of Energy Consumption in the United States. 1972. Stanford Research Institute. Report No. 4106-0034, GPO:16.

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End-use of energy in the United States is presented in Table 5.3. From this table it can be seen that many end-uses of energy could alternatively be supplied by the use of steam taken from a dual-purpose electric power plant. Space heating, process steam, direct drive, water heating, some air conditioning, some cooking and refrigeration could use steam as an energy source. This group alone accounts for over 50 percent of the total energy used in 1970.

TABLE 5.3

End-Use Energy in the U.S.

Item	1970 Percent of Total
Transportation	24.7
Space heating	17.7
Process steam	16.4
Direct heat	11.0
Electric drive	8.1
Raw materials	5.6
Water heating	4.0
Air conditioning	2.9
Refrigeration	2.3
Cooking	1.2
Electrolytic processes	1.2
Other	4.9

Reference: Efficiency of Energy Use in the United States. 1973. Hirst, Eric and John C. Moyers. Science, 179 (4080): 1300.

In many communities across America there is great potential for the use of steam extracted from the electric power plants, witness the growth of the district heating business. Space heating, water heating, and in some cases air conditioning in the residential sector, could use steam as an energy source. And the commercial and industrial sectors could make very good use of steam in their processes. In Table 5.4, some of the possible process steam uses are listed for the commercial and industrial sectors.

TABLE 5.4

Major Steam Process Users

Asphalt companies	Plastics company
Chemical companies	Restaurants
Dairies	Snow melting
Flour drying	Soft drink and breweries
Heat treating	Steam cleaning
Humidification	Steam hammers (forging)
Laundry	Sterilization
Leather tanning	Stills
Lumber drying	Tire vulcanizing
Organic fertilizer company	Water heating

One of the real positive benefits of substituting steam for other energy resources used in the residential, commercial,and industrial sectors is that many of these tasks require only low temperatures (500°F, 260°C). To use electricity, natural gas, or oil as an energy source to heat water (150°F, 60°C) or to warm a structure to 70°F (21°C) is a wasteful application of energy. Especially if one looks at the community as a whole unit. For example, in one location, the community's electric power plant wastes about 60 percent of the primary fuel burned, dissipating this low-temperature heat into the environment, and at separate locations throughout the community various potential users of low temperature heat use electricity and natural gas to heat water, warm buildings and to do other low temperature tasks. Clearly, we cannot tolerate this waste in the future. Consider the electric water heater, the first choice for water heaters in the residential sector, after the primary fuel has been burned to produce electricity at 32 percent efficiency the temperature of the water in the water heater is raised to only about 150^{o}F (66^{o}C) and left to sit most of the day. When one adds in the losses incurred in transmission and distribution of electricity, at best this use of energy is only 32 percent efficient. And even then the electricity used provides only the same service, wood, coal or even the sun could have provided. Electricity has unique properties for which only electricity is the energy source. Lighting, running computers, business machines, etc., are tasks that can only be done by electricity and it is a poor choice of energy resources to use electricity to heat water.

V.2 Space Heating

Space heating in the residential sector requires about 11 percent of the total national energy use, while the space heating in the commercial sector uses an additional 6.9 percent of the total (SRI, 1972).

Energy use in home heating is influenced by the design of the dwelling, the climate, and the ways people use their homes. The most significant climatic parameter for energy consumption in the home is average daily temperature. To estimate the amount of heat required to keep the interior of a structure warm, given fluctuations in outside temperature, it is inst

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it is instructive to consider the energy balance of a "standard house" in the temperate part of the United States.

Assume the "standard house" has 1500 square feet (140 square meters) of floor space, with dimensions 25 X 30 X 20 feet (7.6 X 9.1 X 6 M). Assume that the inside temperature is maintained at $70^{\circ}F$ ($21^{\circ}C$), while the outside temperature averages $32^{\circ}F$ ($0^{\circ}C$). To calculate the heat transfer properties of the wall structure, one treats the layers that make up the wall as a set of resistances in series. Wood has a resistivity of about 1 $(BTU/hr\ ft^{2}\,{}^{o}F)^{-1}$ per inch of thickness [.069$(W/m^{2}\,{}^{o}C)^{-1}$ per cm. of thickness]. The thermal resistivity of fiberglass insulation is about 4 times larger. Of course, a more careful consideration would take into consideration the non-uniformities of the studs and air holes in the insulation, but this should give a fairly close approximation. Added to the thermal resistances of the solid materials and trapped air are surface resistances, describing the heat transfer from the wall to the air, which depend on air velocity. Typical values for surface resistances, per unit area, are .8 and .2$(BTU/hr\ ft^{2}\,{}^{o}F)^{-1}$ [.14 and .035$(W/m^{2}\,{}^{o}C)^{-1}$] inside and outside faces of the walls, respectively. The "standard house" has walls with about 2 inches (5 cm.) of insulation and a roof with 4 inches (10 cm.) of insulation. Unit areas of the wall and roof have thermal resistances of 10 and 18$(BTU/hr\ ft^{2}\,{}^{o}F)^{-1}$ [1.8 and 3.2$(W/m^{2}\,{}^{o}C)^{-1}$]. The resulting heat loss through the walls and roof of the "standard house" is 9943 BTU/hr (2912 watts). Conductive losses to the ground add an additional 1875 BTU/hr (555 watts) if floor materials are about the same as wall materials. The effect of a basement is to lower this figure to about 1500 BTU/hr (438 watts). Ground temperature is assumed to be $45^{\circ}F$ ($7^{\circ}C$).

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Window heat losses can be very large if the windows have no curtains or they are left uncovered during the night, even if they have curtains. If 200 ft^2 (18.6 m^2) of wall area is replaced by windows, there is an overall increase transfer of heat to the outside. A typical resistance value for single-pane windows is around $.91(BTU/hr\ ft^{2\,o}F)^{-1}$ $[.16(W/m^{2\,o}C)^{-1}]$. Since the transfer of heat through a window is dominated mainly by the surface resistances of the inside and outside layers, temperature drops across glass are usually only about 1^oF ($.5^oC$), the "standard house", with 200 ft^2 (18.6 m^2) of windows loses an additional 8352 BTU/hr (2446 watts) by conduction through the windows. But the wall area is decreased, reducing by 760 BTU/hr (223 watts) the heat loss through the walls, or a total of 9183 BTU/hr (2689 watts) for the walls and roof.

Air enters the house, called infiltration, through cracks and opening of doors. One air exchange per hour is a reasonable approximation for the "standard house" (ATP, 1975). Since heat must be added to the incoming air to raise it to 70^oF (21^oC), the total air space must be known. The "standard house" has 15,000 ft^3 or 1,100 pounds (500 kg) of air, one air exchange per hour requires another 10,032 BTU's or 10,032 BTU/hr (2938 watts). Assuming that the relative humidity is 60 percent outside and 20 percent inside, the humidity of incoming air must be raised at least 40 percent. To evaporate water, another 2800 BTU/hr (111 watts) is required. We can now examine the total energy lost by the "standard house". This figure, 33,242 BTU/hr from Table 5.5 represents the amount of heat required to keep the "standard house" at about 70^oF (21^oC) with an average outside temperature of 32^oF (0^oC).

Clearly, the effects of insulation and reducing the number of air exchanges experienced by a house can greatly reduce the amount of energy required for space heating. The effect of insulation standards will be examined shortly.

TABLE 5.5

Estimated Energy Requirements for a "Standard House"

	BTU/hr	(watts)	Percental of total
Heat lost through walls and roof	9183	(2,689)	.28
Heat lost to ground	1875	(555)	.06
Heat lost through windows	8352	(2,446)	.25
Heating of incoming air (air exchange)	10,032	(2,938)	.30
Humidication of incoming air	3800	(1,113)	.11
TOTAL	33,242	(9,736)	

V.3 Degree-Day Method

The calculations involved in determining the energy required for space heating just outlined are much too long and cumbersome for whole residential and commercial areas. Another method, called the degree-day method, provides satisfactory results for computing the energy required for space heating.

This method, referred to sometimes as one of the short-cut methods, consists of comparing a given structure to be estimated with a similar structure, the actual steam requirements of which are known. Assuming that steam usage for buildings of the same general type of occupancy, e.g., office buildings, and apartments, will be governed by similar over-all factors, which determine heat losses, i.e., inside temperature, and ventilation, and provided adjustment is made for any difference in size and weather conditions, steam requirements for space heating can be determined.

The degree-day method of estimating steam requirements utilizes a simplified method for measuring temperature differential and time. The unit of measure is called the degree-day. When the temperature is 65°F (18°C) generally no heat is required for space heating; the experience of heating and air-conditioning engineers. And when the mean daily temperature falls below 65°F (18°C) heating requirements tend to vary directly in proportion to the differences between the mean outside temperature and 65°F (18°C).

The number of degree-days in a single day is found by subtracting the average of the high and low temperature for that day from a reference temperature, usually 65°F (18°C). For example, if the high for a single day was 40°F (4°C) and the low 20°F (-7°C), the total number of degree days for the day is 35. The number of degree-days in an interval of several days is then found by summation, including only positive values in the sum. The degree-days, as compiled by the weather service for East Lansing, Michigan are shown in Table 5.6.

The degree-day method for estimating steam requirements for space heating is expressed by the following formula:

$$S = N \times R \times D$$

where, S = steam consumption for the estimate period in pounds

N = experienced steam requirement; load limits expressing the size of the heating load, such as:
- (a) 1,000 BTU of calculated hourly heat loss
- (b) 1,000 cubic feet of heated content
- (c) square feet of connected equivalent radiation surface

R = rate of steam consumption in pounds per degree-day per load unit as expressed by N, usually cubic feet of heated space.

D = number of degree-days in the estimate period.

TABLE 5.6

Mean Degree-Days in Michigan
East Lansing Station

January	1302	July	16
February	1147	August	34
March	986	September	138
April	561	October	415
May	288	November	795
June	75	December	1172

Reference: Climate of Michigan by Stations. 1971. Michigan Weather Service, Revised edition. Michigan Department of Agriculture.

For estimate purposes, in the residential and commercial areas, the degree-day method was used to predict energy use for space heating in terms of pounds of steam. Data from the District Heating Handbook was compiled for the reference area, usually based on Detroit experiences, along with personal contact with the Board of Water and Light in Lansing, Michigan. The coefficients used are presented in Table 5.7.

The "standard house" in the preceeding section can now be estimated using the degree-day method and compared with the results obtained in that section. The month of March in East Lansing has a monthly mean temperature of about 32°F (0°C). The number of degree-days in March from Table 5.6 is about 986. The "standard house" has 15,000 cubic feet of heated space (415 square meters). Using the figure 1.43 pounds of steam per 1,000 cubic feet per degree-day, from Table 5.7, we calculate that in the month of March the average steam requirements for space heating

TABLE 5.7

Steam Consumption for Space Heating in Buildings

Type of Building	average volume of heated space (1000 cu. ft.)	steam required: pounds per degree-day per 1000 cu. ft.
Office	2160	.685
Bank	806	.786
Department stores	3400	.480
Stores, retail	310	.624
Hotel, motel	1795	.990
Apartment building	1425	1.400
Motion picture	1240	.482
Garage	1540	.202
Factory, small	1350	.808
Hospital	3306	1.830
School	1115	.660
Single-family	20	1.430

Reference: District Heating Handbook. 1951. National District Heating Association, 3rd edition, page 343. Data is for Detroit, modified for newer insulation standards. Average annual number of degree-days in Central Michigan is about 6950. Climate of Michigan by Stations. 1971. Michigan Department of Agriculture. Revised edition.

would be about 21,150 pounds. Or about 29.37 pounds of steam per hour. Remembering that a pound of steam has about 1,000 BTU (1×10^6 joules), we calculate that the "standard house" needs about 29,370 BTU/hour (8600 watts). From Table 5.5, the "standard house" required 33,242 BTU/hour (9736 watts) calculated by a heat balance method and the difference can be accounted for by the better insulation required of the "standard house" used in the reference area.

V.4 Insulation Standards

Federal Housing Administration, FHA, minimum property standards of 1965 permitted average heat losses of 2,000 BTU's per thousand cubic feet per degree-day. The "standard house" used in the heat balance estimate of the previous section would require over 41,000 BTU's/hour (12,031 Watts) under these standards. Whereas, from Table 5.5 the "standard house" required a minimum of 1,620 BTU's per thousand cubic feet per degree-day, newer standards have decreased the allowable heat losses considerably since 1965.

Since the majority of houses built in the reference area will be constructed after 1976, they should meet the newer standards. These standards, required by the Housing and Urban Development (HUD) Operation Breakthrough of 1970, were 1,500 BTU per 1,000 cubic feet per degree-day. And the latest requirement, set by FHA, sets the property standards at 1,000 BTU per 1,000 cubic feet per degree-day (Berg, 1973).

The figure used for the reference area represents a compromise between 1,500 and 1,000. The 1,430 figure reflects the fact that new housing has not generally complied with standards, since in 1972 less than 17 percent of new housing complied with FHA requirements (EPP, 1975).

Coefficients used for different buildings in the reference areas, shown in Table 5.7, comply with the newest standards set by FHA, except for the single-family houses as mentioned above. Some commercial buildings are assumed to be well insulated as the coming days of higher energy prices will probably increase the need to lower overhead costs.

V.5 Water Heating

As part of the national energy picture water heating, in 1968, used almost 4 percent of the total U.S. energy budget (see Table 5.2 in the section, Energy Statistics for the United States). By 1968, saturation levels for water heaters reached almost 95 percent with the growth of electric water heaters leading that of natural gas water heaters. But in spite of this faster growth rate, natural gas water heaters still outnumber electric water heaters by almost 3 to 1 (EPP, 1975).

As more households add dishwashers and automatic washing machines to their list of household equipment, both gas and electric water heaters have increased their per unit consumption of energy (SRI, 1972). The amount of energy used by water heaters increased from about 43 million BTU's (45 billion joules) per year to operate an electric water heater, to 46 million BTU's (48 billion joules) in 1969 (EPP, 1975). Now with the increased use of quick-recovery units this figure is nearer 52 million BTU's (55 billion joules) per year. The average natural gas water heater, in 1971, used almost 32 million BTU's (34 billion joules) per year (EPP, 1975).

From an energy convervation standpoint, the general rule that direct burning of fossil-fuel for the production of thermal energy is more conservating than the use of electricity is applicable to the water heater. This rule, however, does not mean that fossil-fuel energy use should not be minimized, because there are many alternative ways to supply thermal energy for water heating.

V.6 Demand for Heated Water

In terms of personal energy use, water heating accounts for nearly 8 percent of the total, see Table 5.8.

TABLE 5.8

Percentage Distribution of Personal Energy - By Use - 1968

Use	Percent
Energy in the home	56
Space heating	32
Water heating	8
Appliances	15
Cooking	3
Refrigeration	3
All other	9
Transportation	44

Reference: Energy Policy Project of the Ford Foundation. 1975. The American Energy Consumer. eds. Dorothy K. Newman and Dawn Day. Ford Foundation, Ballinger Publishing Company, Cambridge, Massachusetts: page 34.

The amount of heated water used by individuals varies greatly according to factors such as socio-economic status, and personal habits. In a recent study done in Michigan communities, families average around 302 gallons (1,144 liters) of water a day (Field, 1974). Nearly half of the water used or approximately 36 gallons (136 liters) per day per person, was heated.

The demand for hot water in the commercial area has been estimated by the American Society of Heating, Refrigeration, and Air Conditioning Engineering and is shown in Tables 5.9 and 5.10. These estimates were used to develop the final estimates shown in Table 5.12. Final figures were arrived at by the use of Miller, et al, because they were from a more recent study (Miller et al, 1971).

TABLE 5.9

Estimated Hot Water Demand for Various Buildings

Type of Buildings	Hot water required per person per day, gallons per day,	(liters)
Residential	40 - 80	(152 - 303)
Commercial	4 - 6	(15 - 23)
Industrial (Factories)	10	(38)

References: ASHRAE Guide and Data Book Applications for 1966-1967. American Society of Heating, Refrigerating, and Air Conditioning Engineers, page 255.

TABLE 5.10

Maximum Daily Requirements for Hot Water in Office Buildings and Hospitals

Type of Buildings	Hot water usage, gallons	(liters)
Office Buildings:		
White-collar worker (per person)	3 - 9	(11 - 34)
Other workers (per person)	4 - 9	(15 - 34)
Cleaning per 10,000 ft^2	36 - 50	(136 - 189)
Hospitals (per bed)	125 - 200	(473 - 758)

Reference: ASHRAE Guide and Data Book Applications for 1966-1967. American Society of Heating, Refrigerating, and Air Conditioning Engineers, pp. 979-980.

TABLE 5.11

Maximum Daily Requirements of Hot Water in Apartments and Private Homes

Number of Rooms	Hot water usage, gallons (liters) Number of Bathrooms 1	2	3	4
1	60 (227)			
2	70 (265)			
3	80 (303)			
4	90 (341)	120 (455)		
5	100 (379)	140 (530)		
6	120 (455)	160 (606)	200 (758)	
7	140 (530)	180 (682)	220 (833)	
8	160 (606)	200 (758)	260 (985)	250 (947)

Adopted from Reference: Megley, J. W., 1968. Heat Pumps Provide Economical Services for Apartment Tenants. Heating, Piping and Air Conditioning 40 (1): 124-131.

TABLE 5.12

Estimated Hot Water Use Rates

Apartments	36* gallons per day per person
Shops and Offices	3 gallons per day per employee
Hospital	100 gallons per day per bed
Hotel	50 gallons per day per room
Public schools and Universities	35 gallons per week per student
Cleaning	30 gallons per day per 10,000 square feet

Reference: Miller, A. J., et al, 1971. Use of Steam - Electric Power Plant Provide Thermal Energy to Urban Areas. ORNL-HUD-14, Reactor Technology, Oak Ridge National Laboratory, page 151.
*Anne Field. 1974. Household Water Consumption, Research Report 249, Agricultural Experiment Station, East Lansing, Michigan.

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Hot water requirements for apartments and homes can present a more difficult problem because other factors can play a part in the final estimated demand. Table 5.11 shows how the number of bathrooms can increase hot water use. The figure for apartment hot water use, shown in Table 5.12, represents the best judgment, given the unknown character of the individuals living in the reference area, tempered with a guess for future hot water use.

V.7 Steam Demand for Water Heating

Estimated steam requirements for water heating can be figured from a known quantity of hot water per unit of time and approximate steam per unit time needed to heat a gallon of water in a water heater. The rule of thumb used was to assume a ground water temperature of $40^{o}F$ ($4^{o}C$) averaged for the year, and since it takes 100 BTU's to raise one pound of water from $40^{o}F$ ($4^{o}C$) to $140^{o}F$ ($60^{o}C$) in a water heater, one pound of steam is capable of raising 10 pounds of water from $40^{o}F$ ($4^{o}C$) to $140^{o}F$ ($60^{o}C$); assuming one pound of steam has about 1,000 BTU's (1,054 k joules). (DHH, 1951).

Insulation of water heaters is assumed to be orders of magnitude better than current standards as a result of higher fuel prices, and heat loss from water heaters used in the reference areas is negotiable.

The amount of steam used for water heating is found by using the following formula:

$$S = G \text{ X } C \text{ X } R$$

where,

S = steam required, pounds per unit time (day, week, month)

G = hot water demanded, gallons

C = constant, 8.3 pounds per gallon

R = ratio constant, 1/10

Table 5.12 contains the estimated hot water demand for per unit of time, G, used to estimate steam requirements for apartments, schools, and commercial establishments.

V.8 Air Conditioning

Several methods have been developed for determining the energy requirements of air-conditioning systems. Most are like the methods outlined in the section on space heating. Hourly weather bureau data are useful for determining the hours of operation based on say, a temperature of 70°F (18°C). Also, cooling-degree hours above a fixed temperature, say 80°F (29°C) is another criterion. When the cooling-degree hours are available, they can be used to determine cooling requirements, and the energy needed similar to the method described in the section on the degree-day method. Cooling degree-days for Michigan are shown in Table 5.13.

Many of the factors outlined in the section on space heating also apply to air conditioning. But, as internal environments of buildings have changed in the last decade, the internal environment has become almost totally separated from the external environment. Increased lightly, more office equipment, computers that require special environments, and controlled climate air flow systems have all combined to increase energy demands for air conditioning beyond the needs measured by climatic variables. Methods used to determine air conditioning needs, like the cooling degree day method, and the modified cooling-degree day method have been replaced by cooling load check figures. Refrigeration for applications in specific classifications are shown in Table 5.14.

All of the previously mentioned methods except the cooling-load check figure, will probably underestimate the requirements for air conditioning since the practice in residential and commercial sectors has been to leave air conditioners on 24 hours a day. Even though the energy crisis

TABLE 5.13

Monthly and Annual Cooling Degree Days Normals

TABLE 5.13

Monthly and Annual Cooling Degree Days Normals

Station	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Adrian	0	0	0	0	36	146	235	200	58	6	0	0	681
Ann Arbor	0	0	0	0	41	154	243	204	56	8	0	0	706
Bay City	0	0	0	0	31	136	226	195	45	10	0	0	643
Detroit	0	0	0	0	33	149	261	225	65	10	0	0	743
Hart	0	0	0	0	19	86	168	138	27	6	0	0	366
Lansing	0	0	0	0	26	111	192	166	34	6	0	0	535
Midland	0	0	0	0	23	119	210	177	33	7	0	0	569
Ontonagon	0	0	0	0	7	24	99	103	6	5	0	0	244
South Haven	0	0	0	0	25	103	190	175	54	9	0	0	556
Three Rivers	0	0	0	0	42	143	222	193	52	8	0	0	660
Watersmeet	0	0	0	0	10	33	80	69	0	0	0	0	192

Reference: Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1941 - 1970. 1973. U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Asheville, North Carolina.

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TABLE 5.14

Cooling Load Check Figures

Classification	Occupancy sq. ft/person			Lights watts/sq. ft.				Refrigeration sq. ft/ton		
	Lo	Au	Hi	Lo	Au	Hi		Lo	Au	Hi
Apartment, High Rise	325	175	100	1.0	2.0	4.0		450	400	350
Auditoriums, Churches, Theaters	15	11	6	1.1	2.0	3.0		400	250	90
Educational Facilities: Schools, Colleges, Universities	30	25	20	2.0	4.0	6.0		240	185	150
Factories: Assembly Areas	50	35	25	3.0	4.5	5.0		240	150	90
Light Manufacturing	200	150	100	9.0	10.0	12.0		200	150	100
Heavy Manufacturing	300	250	200	15.0	45.0	60.0		100	80	60
Hospitals: Patient Rooms	75	50	25	1.0	1.5	2.0		275	220	165
Public Areas	100	80	50	1.0	1.5	2.0		175	140	110
Hotels, Motels, Dormitories	200	150	100	1.0	2.0	3.0		350	300	220
Libraries and Museums	80	60	40	1.0	1.5	3.0		340	280	200
Office Buildings	130	110	80	4.0	6.0	9.0		360	280	190
Private Offices	150	125	100	2.0	5.8	8.0				
Residential: Large	600	400	200	1.0	2.0	4.0		600	500	380
Medium	600	360	200	0.7	1.5	3.0		700	550	400
Restaurants: Large	17	15	13	1.5	1.7	2.0		135	100	80
Medium								150	120	100
Shopping Centers, Department Stores										
Beauty and Barber Shops	45	40	25	3.0	5.0	9.0		240	160	105
Department Stores basement	30	25	20	2.0	3.0	4.0		340	285	225
main floor	45	25	16	3.5	6.0	9.0		350	245	150
upper floors	75	55	40	2.0	2.5	3.5		400	340	280
Dress Shops	50	40	30	1.0	2.0	4.0		345	280	185
Drug Stores	35	23	17	1.0	2.0	3.0		180	135	110
5c and 10c Stores	35	25	15	1.5	3.0	5.0		345	220	120
Hat Shops	50	43	30	1.0	2.0	3.0		315	270	185
Shoe Stores	100	75	50	1.0	1.5	2.0		365	230	160
Malls										
Refrigeration for Central Heating and Cooling Plant										
Urban Districts								475	380	285
College Campuses							400	400	320	240
Commercial Centers							330	330	265	200
Residential Centers								625	500	375

Reference: <u>A Primer of Air Conditioning Types and Methods</u>. 1975. Carrier Air Conditioning, Syracuse, New York.

of 1973 may have made some people more pruent in their use of air conditioning, many residential and commercial buildings have climate control systems that work to remove heat given off by office equipment, lighting, etc. And during some seasons, like fall and spring, both air conditioning and heating systems may be battling it out, confused by solar radiation on one side of the building, shade and cold winds on the other.

The two other variables needed to specify the steam requirements for air conditioning in addition to cooling-load, are the length of season and hours of operation. Hours of operation for properly-sized equipment are shown in Table 5.15. These estimates are probably too low for today's air conditioning use and they were used to give minimum estimates.

Summer in central Michigan, the Lansing area, lasts about 21 weeks. This includes all of June, July, August, and September. Parts of May and October complete the 21 weeks. Hours during which air conditioners will be used are easy to figure in July and August, usually all-day operation can be expected. The remaining months were figured at full-load factors of 45 percent in apartments and 50 percent in the commercial areas. The estimated number of hours in each month are shown in Table 5.16 where the months of September and October are probably overestimated by this method.

V.9 Steam Demand for Air Conditioners

Absorption-type chillers are assumed installed in all those buildings in the residential and commercial areas requiring large quantities of air conditioning. The thermodynamics of an absorption air conditioner demands hot water at about 300°F (149°C) or steam at 14 pounds pressure (200 k newtons/m^2) to produce a ton, removal of 12,000 BTU's (13 M joule),

TABLE 5.15

Full-Load Operating Hours of Refrigeration
Equipment Used for Summer Cooling May 15 to October 15

	Hours open for business	Full-load operating hours of refrigeration equipment used							
		Atlanta	Boston	Chicago	Los Angeles	New Orleans	Philadelphia	St. Louis	Washington DC
Department Stores	490	840	560	610	580	890	720	750	780
Drug Stores	2100	1630	950	1060	980	1790	1330	1420	1530
Offices	1100	1030	660	720	680	1060	880	910	960
Restaurants	2100	1510	820	930	850	1690	1210	1300	1400
Specialty Shops	1090	800	530	590	560	860	690	720	750
Theaters	900	640	420	450	430	650	520	550	580

Reference: ASHRAE Guide and Data Book Application for 1968. 1968. American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc.

TABLE 5.16

Estimated Hours per Month for Air Conditioning*

	MAY	JUNE	JULY	AUGUST	SEPT	OCT
Apartments	123	230	238	238	230	69
Schools	144	270	279	279	270	81
Commercial areas	172	324	335	335	324	142
Hospital	192	700	740	740	360	108

* representing minimum hours of operation, assuming 21 weeks of summer in central Michigan.

of cooling. Single-family dwellings have air conditioners, but not of the absorption type, since absorption systems are not available for small houses.

Using the figures in Table 5.14, the estimated tonnage required for buildings in the reference areas are shown in Table 5.17.

The hours of operation for air conditioning systems were based on 21 weeks of summer. The assumptions for each area were:

1) apartments had a load factor of .45
2) schools full-load operation for 9 hours per day
3) shopping area, 12 hours of full-load operation
4) hospital, .50 load factor 24-hour operation for 3 months
5) office buildings, .50 load factor.

The resulting estimates of steam demand for air conditioning were found by the following formula:

$$S = T \times C \times H$$

where,

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TABLE 5.17

Tonnage of Air Conditioning Required
in Building for the Reference Areas

Type of Building	Tonnage
Apartments	3 tons per apartment
Schools	1,750 tons per building
Shopping area	114 tons per block
Shopping mall	1,522 tons
Office building	214 tons
Hospital	227 tons

where,

S = steam demand for air conditioning, pounds

T = tons of air conditioning, based on Table 5.14 and square feet of space to be cooled, tons

C = pounds of steam required per ton of air conditioning, 18 pounds

H = hours of operation during month, based on length of summer, and load factor.

V.10 Summary

Energy use in the residential and commercial sectors for space heating and cooling, and water heating is substantial. Much of the wasteful use of energy in these sectors is the result of demanding electricity, natural gas, and fuel oil to provide energy to do low-temperature energy tasks. In an average household over 70 percent of the energy used, is used for space heating and water heating and in the commercial sector, nearly 8 percent of the total energy used in the United States is used for space and water heating. The potential application of low-pressure steam extracted from the dual-purpose plant to provide energy to these low-temperature tasks, in any community, is considerable. Also, the effect of lowering the demand for electricity, natural gas, and fuel oil can be substantial for the community using the dual-purpose power plant system.

Energy requirements for space heating and cooling, and water heating can be reasonably estimated by the methods outlined in the preceding sections. The estimates are converted to pounds of steam per hour demanded for different types of buildings. The aggragate steam demand for any given community can then be estimated and used to determine the feasibility of the dual-purpose power plant system.

CHAPTER VI

STEAM DISTRIBUTION

Providing low-temperature heat energy in the form of steam or hot water requires the use of underground piping. In this section, the constraints, and performance of underground steam pipe distribution systems are examined.

VI.1 Components

The fact that a steam pipe distribution system is usually buried in the ground where it is not readily available for enlargement, replacement, and repair, and because such piping must be protected from ground elements and excessive heat losses, complicates the trade-offs in initial design. The cost of later replacing sections of pipe, because of poor design, can quickly surpass any savings incurred in short cutting the initial design.

In general, the components that make up an underground steam pipe system are pipes of various diameters, expansion joints, relief valves for high pressure systems, condensate meters, conduit pipe, insulation materials, man-holes and pumps and the final design of any underground steam pipe system is dependent upon such factors as ground water levels, steam demand, plant location, soil conditions, and economics.

VI.2 Pressure Drop

Once the estimated steam demand has been determined for the community, the various pipe diameters within the distribution system must be sized to insure adequate pressure is maintained. The tasks performed in the community whether space heating, water heating, cooking, or air conditioning, generally require low-pressure systems, below 50 psia (345 k newtons/m^2). Whereas, laundering, pressing, high-temperature cooking, and various other processes, high pressure systems are demanded.

Pressure drop in a given length of pipe is dependent upon steam flow rate, density of the steam, and the diameter of the pipe. Figure 6.1 demonstrates the relationship between pressure drop and pipe diameter for a given pipe length. Increasing the diamter of the pipe decreases the pressure drop. But the longer the length of pipe, the greater the pressure drop at a given pressure, diameter and flow rate. Thus, the optimal location of the steam producing plant is nearest the steam-load center, minimizing pressure drop.

VI.3 Heat Losses

Heat loss is a continuous operating expense for any underground steam distribtuion system. The design problem is to minimze heat losses to an acceptable level without raising the installation costs too high.

Heat loss from steam pipes is dependent upon the specific heat of the steam, its density, flow rate, pipe diameter, the heat transfer coefficient of the insulation material, and ground temperature. Figure 6.2 shows the relationship between conductivity of insulation material and mean temperature. And Figure 6.3 shows heat loss as a function of temperature and pipe diameter.

In addition to heat loss, economic thickness of insulation based on fuel cost, cost of capital, and maintenance must also be considered.

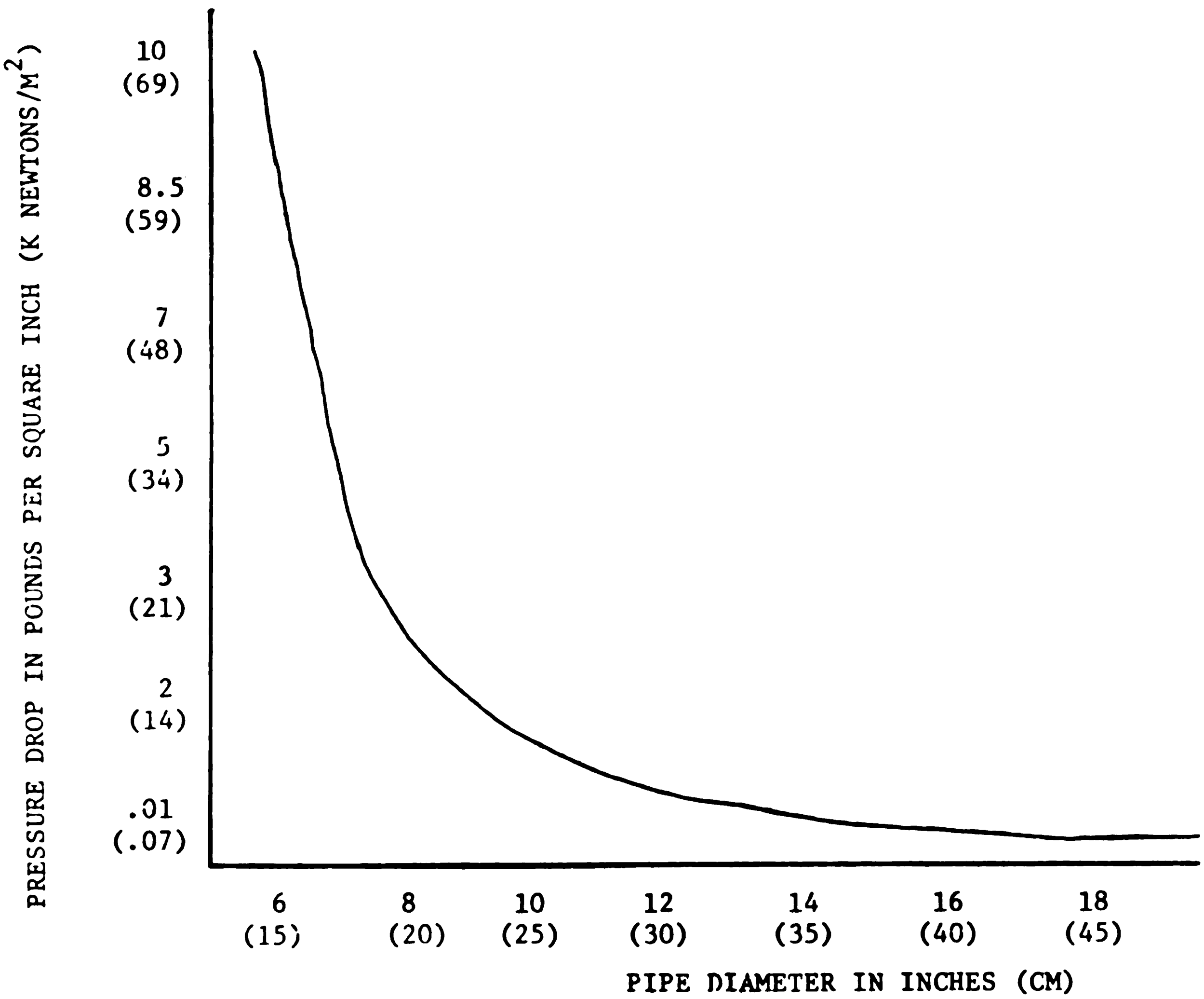


Figure 6.1 Pressure Drop per 1,000 Feet of Pipe for Various Pipe Diameters. Assumes super heated steam at 50 psia and 10,000 lbs/hour flow.

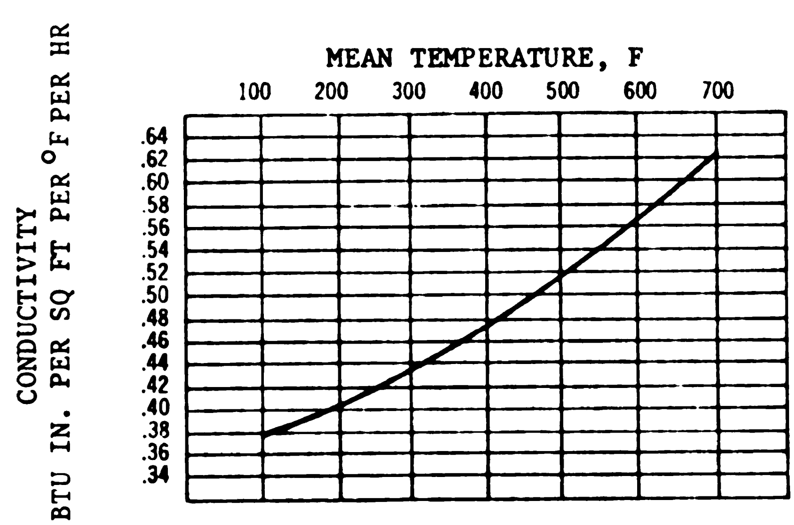


Figure 6.2 Conductivity of Insulation Material

Reference: Insulation Systems. 1976. Johns-Manville, Report on Hydrous Calcium Silicate. Denver, Colorado.

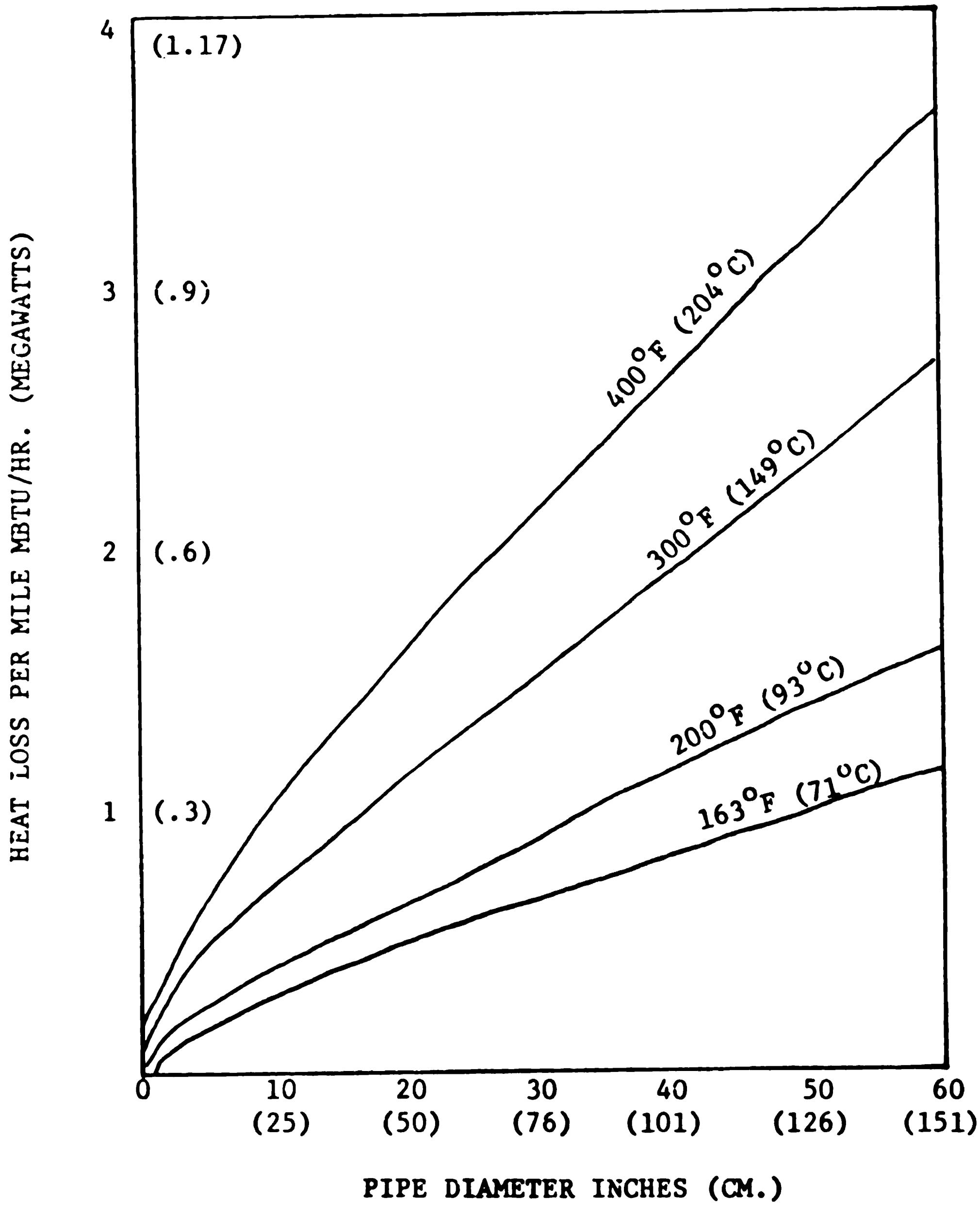


Figure 6.3 Heat Loss from a Single Buried Pipe.

Reference: Miller, A. J., et al. 1971. Use of Steam-Electric Power Plants to Provide Thermal Energy to Urban Areas, Report No. ORNL-HUD-14, Reactor Technology. Oak Ridge National Laboratory, page 142.

Figure 6.4 shows the relationship between cost factors and lost heat cost.

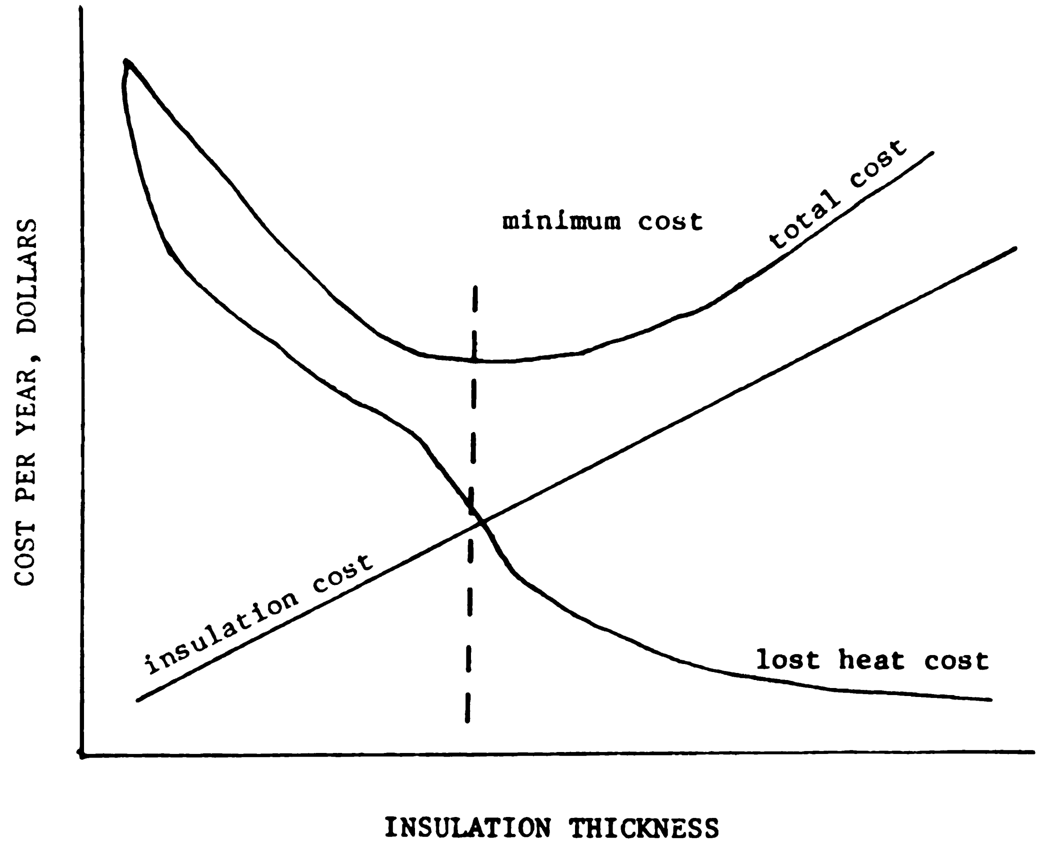


Figure 6.4 Cost Factors of Insulation Material

To get an estimate on the thickness of insulation, we have chosen to use the hydrous calcium silicate pipe insulation. This should give "ball-park" estimates on the cost of insulation based on recommended thicknesses by the insulation manufacturers. The recommended thickness are shown in Table 6.1.

VI.4 Installation Costs

The underground steam pipe distribution system used in all the reference areas were designed with the following assumptions:

1) the pipes are schedule 40 since the design is for a low-pressure system buried 6 feet (1.8 meters) below ground surface.

TABLE 6.1

Recommended Thickness*

TEMPERATURE °F (°C)

Nominal Pipe Size Inches (cm.)	100 (38) to 199 (93)	200 (93) to 299 (148)	300 (149) to 399 (204)	400 (204) to 499 (260)	500 (260) to 699 (371)
2.00 (5.04)	1.5 (3.8)	2.0 (5.0)	3.0 (7.6)	3.5 (8.8)	4.5 (11.3)
2.50 (6.30)	1.5 (3.8)	2.5 (6.3)	3.0 (7.6)	4.0 (10.1)	5.0 (12.6)
3.00 (7.56)	1.5 (3.8)	2.5 (6.3)	3.5 (8.8)	4.5 (11.3)	5.0 (12.6)
4.00 (10.08)	1.5 (3.8)	3.0 (7.6)	4.0 (10.1)	5.0 (12.6)	5.5 (13.9)
6.00 (15.12)	2.0 (5.0)	3.5 (8.8)	4.5 (11.3)	5.0 (12.6)	6.5 (16.4)
7.00 (17.64)	2.0 (5.0)	3.5 (8.8)	4.5 (11.3)	5.5 (13.9)	6.5 (16.4)
8.00 (20.16)	2.0 (5.0)	3.5 (8.8)	5.0 (12.6)	5.5 (13.9)	7.0 (17.6)
9.00 (22.68)	2.0 (5.0)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)	7.0 (17.6)
10.00 (25.20)	2.0 (5.0)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)	7.5 (18.9)
12.00 (30.24)	2.5 (6.3)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)	7.0 (17.6)
14.00 (35.28)	2.5 (6.3)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)	7.0 (17.6)
16.00 (40.32)	2.5 (6.3)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)	7.0 (17.6)
18.00 (45.36)	2.5 (6.3)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)	7.0 (17.6)
20.00 (50.40)	2.5 (6.3)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)	7.0 (17.6)
24.00 (60.48)	2.0 (5.0)	3.5 (8.8)	5.0 (12.6)	6.0 (15.1)	7.0 (17.6)
30.00 (75.60)	2.0 (5.0)	3.5 (8.8)	4.5 (11.3)	5.5 (13.9)	6.5 (16.4)
36.00 (90.72)	2.0 (5.0)	3.0 (7.6)	4.0 (10.1)	5.0 (12.6)	6.0 (15.1)

*Recommended thickness includes cost considerations associated with heat loss, installation, cost of money, etc.

Reference: Insulation Systems. 1976. Johns Manville, Report on Hydrous Calcium Silicate, Johns-Manville. Denver, Colorado.

2) design pressures are in the range of 5 to 150 psi (34 to 1034 kilo-newtons/m^2).

3) supply lines temperature of 400°F (204°C)

4) return condensate at 150° to 200°F (66°C to 93°C) used in all reference areas.

5) installation cost based on digging in dirt and not through road surfaces.

Costs estimates were developed from Miller et al, information from Boston Edison Company, Consolidated Edison Company of New York, and Detroit Edison Company. To get a picture of the costs involved, in 1967 in downtown Boston, 24-inch steam pipe was installed at $210 per linear foot. Outside the downtown area 16-inch steam pipe cost $120 per linear foot to install. An estimate of $180 per linear foot for installation of 8-inch pipe in an unspecified location in New York and $150 per linear foot in Detroit indicates the high cost of installing pipe in an existing city. These costs are almost the same as the costs of installing complete tunnel systems, per linear foot, in a newly expanded part of the steam system at the University of Virginia.

It may be seen from the above data that the installed cost of underground piping in an existing city is sensitive to specific interferences with other underground utilities. In contrast, the cost of underground piping of "new cities" can be estimated as a function of pipe sizes, meter sizes, etc., and information regarding the nature of the earth to be trenched.

Two different "new city" installed underground piping systems are examined by this study. One is the "regular" buried steam pipe system and the other is a modified tunnel system.

The desirability of tunnels for steam distribtuion systems is obvious. Ease of access to all pipes, joints, valves, expansion joints, and supports makes operation and maintenance of these facilities highly satisfactory. Another important aspect of this system is longevity and reliability; less elaborate jackets can be installed initially, very little mechanical damage of insulation is experienced, and dry surfaces minimizes corrosion. Whereas trenched piping systems, like the one mentioned previously, problems of water damage, unknown motion and stresses caused by start-up, and shut-down temperature changes, and protection against ground elements, increase operation and maintenance costs.

The tunnel system is examined because it has possibilities of lower maintenance cost and because the community with a tunnel system would have a certain aesthetic appeal. Underground tunnels could provide space for all services; natural gas, telephone and electric cables, etc., thus removing over-hanging utilities from the community. If the dual-purpose plant technology was adopted by the community, then the other services using the underground tunnels could help make the system economical by paying for the right-of-way. All services using the tunnels would enjoy decreased maintenance costs, which they could pass along to pay for the system. Cost of underground tunnels used in the reference areas are cost accounted to the steam function part of the dual-purpose plant. No discount is included as revenue from other services using the underground tunnels.

The "standard" buried steam pipe system was designed with insulation as shown in Table 6.1, surrounded by about 5 inches (12.6 cm.) of concrete, according to pipe diameter. The thermal conductivity of the insulation is .44 BTU/hr-ft^2-^{o}F per inch of insulation (0.3 watts/m^2-^{o}C per cm.) at about 300^{o}F (149^{o}C). Return condensate lines are buried without insulation in the concrete conduit and are designed to accommodate maximum flow periods.

The network of modified tunnels originates at the power plant. They are routed through major building centers in the commercial area and through as main steam lines in other cases. Inside diameters are 66 inches, 60 inches, and 54 inches (1.7 m, 1.5 m, and 1.4 m). They are a modified walk-through tunnel made of pre-cast concrete which are less expensive then the costly walk-through tunnels.

TABLE 6.2

Estimated Cost of Installed Buried Steam Lines

Pipe Diameter of Main or Supply	Cost in Dollars per Linear Foot ($/m)
2" (5 cm.)	$ 54.41 (178.52)
4" (10 cm.)	56.45 (185.21)
6" (15 cm.)	84.50 (277.24)
8" (20 cm.)	90.69 (297.55)
10" (25 cm.)	104.44 (342.67)
12" (30 cm.)	130.93 (429.58)
14" (35 cm.)	190.38 (624.64)
16" (40 cm.)	221.17 (725.66)
18" (45 cm.)	237.15 (778.09)
20" (50 cm.)	270.39 (887.15)
24" (60 cm.)	315.92 (1,036.53)
30" (76 cm.)	402.68 (1,321.19)
36" (91 cm.)	496.69 (1,629.64)

Cost estimates for "regular" buried steam lines are shown in Table 6.2 All costs include concrete conduit, main or supply steam line, return condensate line, expansion joints, insulation, valves, and labor costs based on trenching in dirt. Miller et al estimated the cost for a similar system in 1969. An 8 inch (20 cm.) pipe, return, concrete conduit, etc., cost $57 per linear foot. Costs estimated in this study are nearly 60 percent higher.

Estimated costs of installing tunnels are shown in Table 6.3 Again, all costs are included - insulation, return condensate lines, anchors, expansion joints, and labor.

TABLE 6.3

Estimated Tunnel Cost*

Pipe Diameter of Main or Supply	Cost in Dollars per Linear Foot ($/m)
4" (10 cm.)	213.90 (701.81)
6" (15 cm.)	232.50 (762.83)
8" (20 cm.)	251.10 (823.86)
10" (25 cm.)	279.00 (915.40)
12" (30 cm.)	297.00 (974.46)
16" (40 cm.)	325.50 (1,067.97)
20" (50 cm.)	390.60 (1,281.56)
24" (60 cm.)	427.80 (1,403.61)
30" (76 cm.)	502.20 (1,647.72)

*estimates were inflated to 1976 dollars.

Reference: University Heating and Utilities Committee Report. 1968. Proceedings of the National District Heating Association. District Heating Association, Pittsburgh, Pennsylvania.

TABLE 6.4

Meter Cost

Meter, Gravity Type - Dollars	Capacity in Pounds per Hour
$ 273.00	250
316.00	500
401.00	750
524.00	1500
841.00	3000
1053.00	6500
1246.00	12,000

Reference: The Cadillac Condensate Meter. 1976. Cadillac Meter Division Central Station Steam Company, Detroit, Michigan.

Meters are installed at each steam energy user. The costs for meters are shown in Table 6.4

VI.5 Steam Losses from an Operating System

Since it is impractical to determine an average value of the manufacturer's rated heat loss for all the different sizes and lengths of steam lines involved, the National District Heating Association recomments using a method which represents steam loss from an operating system (DHH, 1951). This approach includes the theoretical heat loss estimates tempered by actual operating experience of district heating systems. It includes pin hole leaks, outages and other contingencies experienced during full-year operation of steam lines. Winter steam losses are in the range of .04 to .06 pounds of steam per hour per square feet of surface area (126 to 189 W per square meter of surface area) and summer losses are .04 pounds of steam per hour per square feet of surface area, shown in Figure 6.5. These figures were used to estimate the steam losses in the steam distribution systems used in the reference areas.

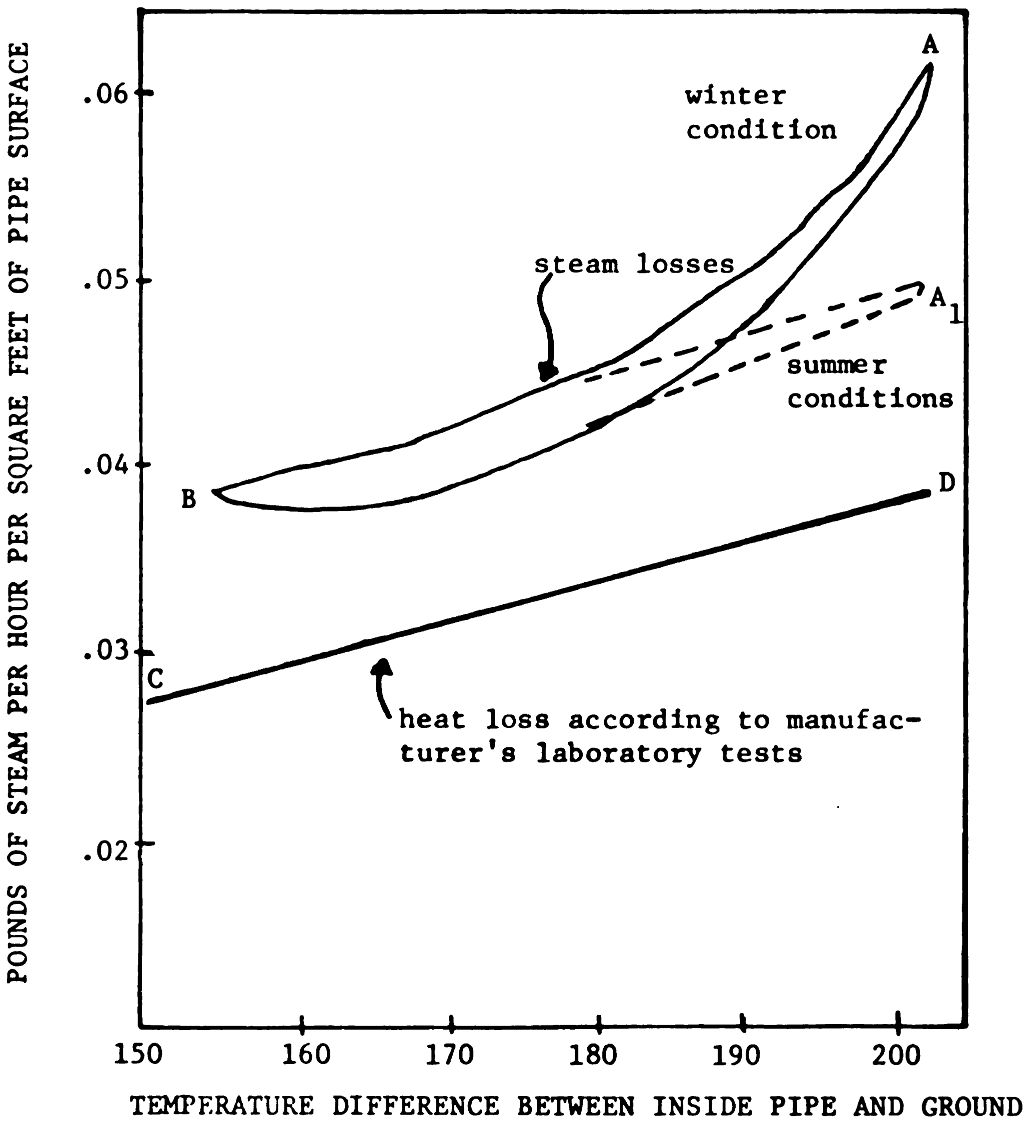


Figure 6.5 Steam Losses From Operating Steam Distribution System.

Reference: District Heating Handbook. 1951. National District Heating Association. Pittsburgh, Pennsylvania.

VI.6 Summary

Steam transport from the power plant and distribution within a given community is dependent upon the steam requirements and spatial organization of steam users. Providing adequate flows and pressures requires analysis of pressure drop and steam losses during operation of the system.

Usually pressure drop in reasonably well selected pipes is minimal, except for very long pipe lengths. Steam losses during operation range between 10 and 15 percent of total output, and is considered a cost of operation. Even with economically sound choices for insulation, taking into consideration fuel costs, capital investment, maintenance, etc., increasing insulation thickness increases the cost of the system without any real decrease in steam losses during operation.

Two alternative systems have been presented. The costs associated with both indicate that distributing steam from the power plant to steam users is very expensive. And at larger pipe diameters, the "standard" buried pipe and tunnels system are equally costly. The difficult design problem is then to use as many small diameter pipes as possible with the shortest distance between the power plant and the steam users.

CHAPTER VII

REFERENCE AREAS

The purpose of incorporating the reference areas is to demonstrate the feasibility of the dual-purpose power plant. The design of the areas is conceptual and provides enough information to test the system as a whole unit. Residential and commercial areas used are more like planned expansion to existing cities than totally new cities per se, since providing steam to an existing city is very problematic. Rights-of-way, other services buried in the street, etc. make retrofitting older cities costly. The reference area presents a good choice to test the system because it is realistic in the demand for steam and provides baseline data with which more complex examples can be approached.

VII.1 Physical Layout of the Reference Areas

Buildings in the residential and commercial areas were developed from general characteristics of the Michigan area and with consideration for energy conservation. Location of buildings as well as increased insulation standards were used to help minimize energy requirements. Also, the central commercial area was designed with many establishments within a collected area to minimize travel to work, home, and recreation. The characteristics and number of commercial services in the reference area reflect the Michigan per capita average for cities of 20,000 or more population. The only simplification imposed was the use of uniform residential and commercial blocks and repetitive square-mile layouts.

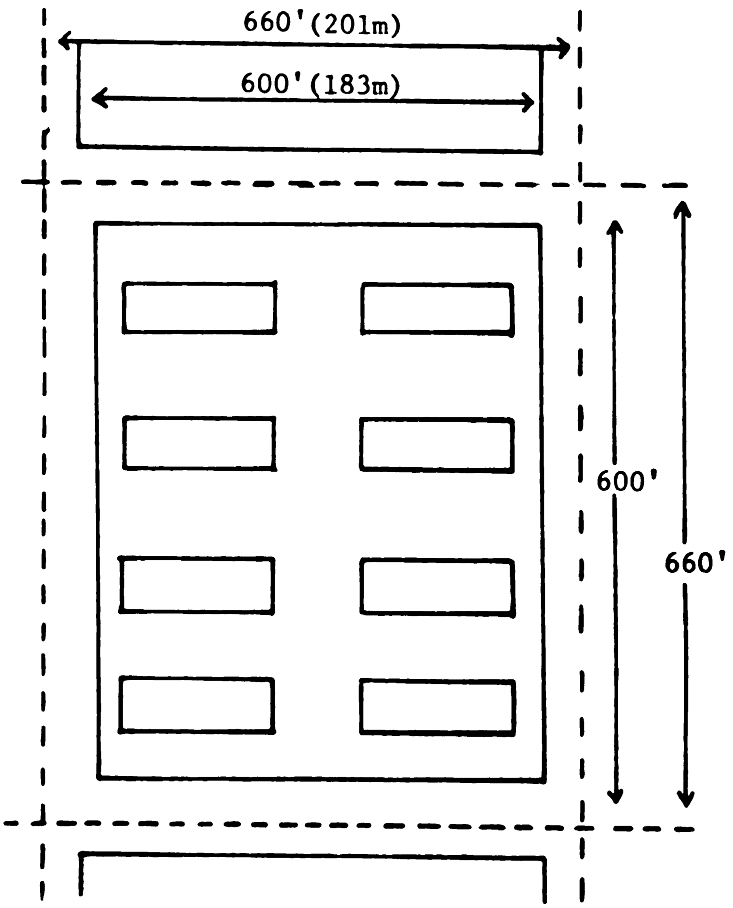


Figure 7.1 Eight Apartment Buildings per Block, Two Stories, Each Building 55' X 175' (17m X 53m).

This was done to facilitate changing the parameters of population, distance from the power plant, and population density.

The physical layout of the multi-family dwellings (apartment complex) is shown in Figure 7.1. Each apartment has 1200 ft.^{2} (111m^2) of usable space or enough room for about 4 people. Apartment buildings are two stories tall with eight apartments per floor. The arrangement of apartments on a residential square mile is shown in Figure 7.2 along with open areas, shopping areas and schools. Schools were sized to provide facilities for the population within the residential square mile. The resulting population density is 16,500 people per square mile (259 hectares). Enlarging the apartments to three stories does not change the physical layout of

Net useable enclosed floor space

Elementary schools 12,750 $feet^2$ (1184 m^2)

Middle and High Schools 647,500 $feet^2$ (60,153 m^2)

Stores 1,000,000 $feet^2$ (9,290 m^2)
apartments 19,250 $feet^2$ (1,788 m^2)

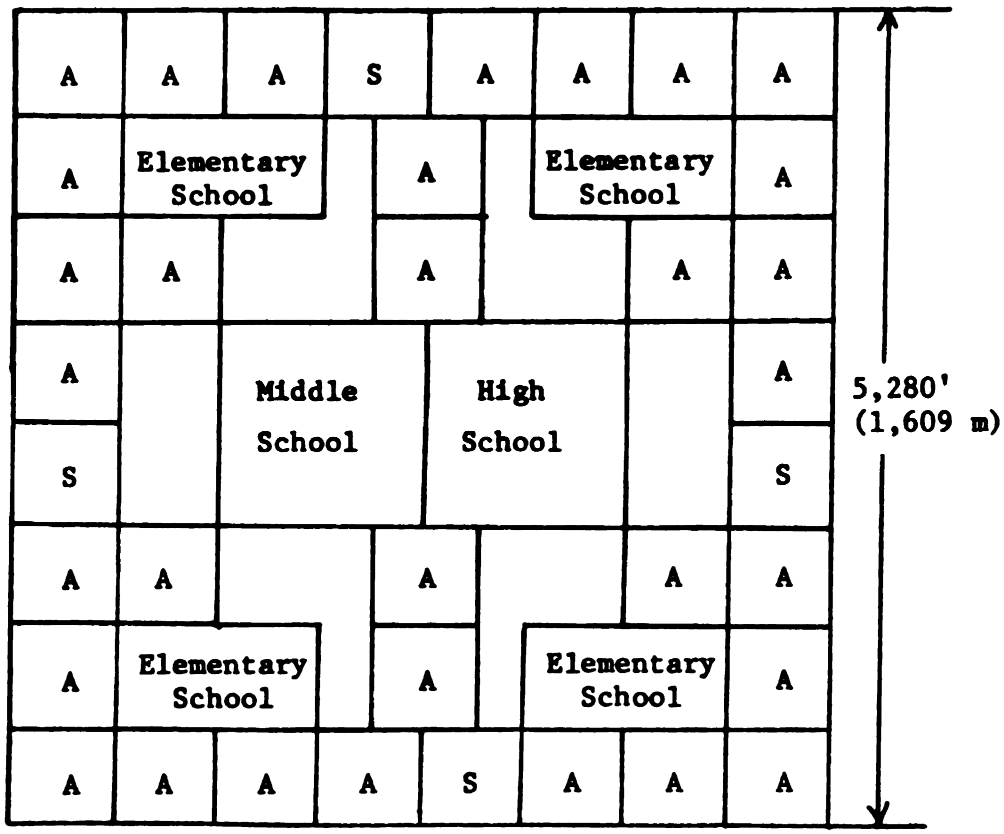


Figure 7.2 Typical Residential Square Mile - Multi-family Dwellings

the shopping, recreation areas or the steam distribution system. The only change is to raise the population density to about 25,000 people per square mile (259 hectares) and increase the steam demand.

The main commercial area has a shopping mall with surrounding office buildings, commercial establishments and a hospital. The services were sized according to the average needs of Michigan residents for a population total of about 20,000. The physical layout of the central commercial area is shown in Figure 7.3.

Extrapolation to large populations is accomplished by repeating square mile blocks, shown above, to create the desired total population level. Increasing population density can be accomplished by raising the height of apartment buildings or decreasing the available space per person from 300 ft.^{2} (28m^2) to a minimum of 200 ft.^{2} (19m^2) per person. Within reasonable limits these variations do not change the physical layout of the square mile reference areas or the steam distribution system.

Although using a "typical" single-family dwelling will probably raise some eyebrows, the necessity of considering an area with only single-family homes was considered more important than trying to find the right "typical" home. The parameters of the single-family dwellings are shown in Table 7.1. They were taken from the Bureau of Census Data for the Northeast region (TES, 1972).

The physical layout of the single-family dwellings is shown in Figure 7.4. Each block has 20 houses, each house on a lot 135' x 60' (41m x 18m). There are 128 blocks in the square mile for a total of 2,560 houses. The population is about 10,240 people per square mile.

Net Usable Space

C_1 - office buildings, banks, federal, city offices.
240,000 ft.^{2} (22,296 m^2) per block

C_2 - auto dealers, garages, wholesale establishments, warehouses, motion pictures.
1,000,000 ft.^{2} (9,290 m^2) per block

S_1 - shopping mall 350,000 ft.^{2} (32,515 m^2) total

S_2 - lumber yard, food stores, large restaurants, motion pictures.
1,000,000 ft.^{2} (9,290 m^2) per block

H - hospital, 75 beds.
50,000 ft.^{2} (4.645 m^2) total

P - park-about 20 acres. (10 hectares)

A - amusement-recreation.
enclosed area 1,000,000 ft.^{2} (9,290 m^2) per block

C_1	C_1	A	P	C_1	A	S_2	S_2
C_1	S_1	S_1	C_1	P	S_2	C_1	C_2
C_1	S_1	S_1	C_2	C_2	P	H	H
C_1	S_1	S_1	C_2	C_2	C_2	H	H

Figure 7.3 Commercial Area

TABLE 7.1

Housing Parameters

House floor area	1500 square feet
House style	two-story
House construction	wood frame
exterior wall construction	
surface	wood shiplap
sheathing	1/2" insulation board
insulation	R-7 batting
inside	1/2" dry wall
ceiling insulation	5" blown-in
basement type	full (unfinished)
attic	ventilated - unheated
window area	12% of floor area
window type	Al casement
storm windows	none
door area (3 doors)	60 ft.^{2}
door type	wood panel with 1/2" ft.^{2} of glass pane
storm door area	40 ft.^{2}
patio door	40 ft.^{2} (single pane)
window covering	70% draped 20% shaded 10% open no awnings
external landscaping	no shading effect
house facing	north
external colors	white roof and walls
roof construction	asphalt shingle
heating system	forced hot-air, natural gas
cooling system	central-electric
garage (enclosed)	attached, slab, unheated
people	2 adults, 2 children

Reference: Total Energy Systems, Urban Energy Systems, Residential Energy Consumption, 1972. Federal Council on Science and Technology. Department of Housing and Urban Development, page 275.

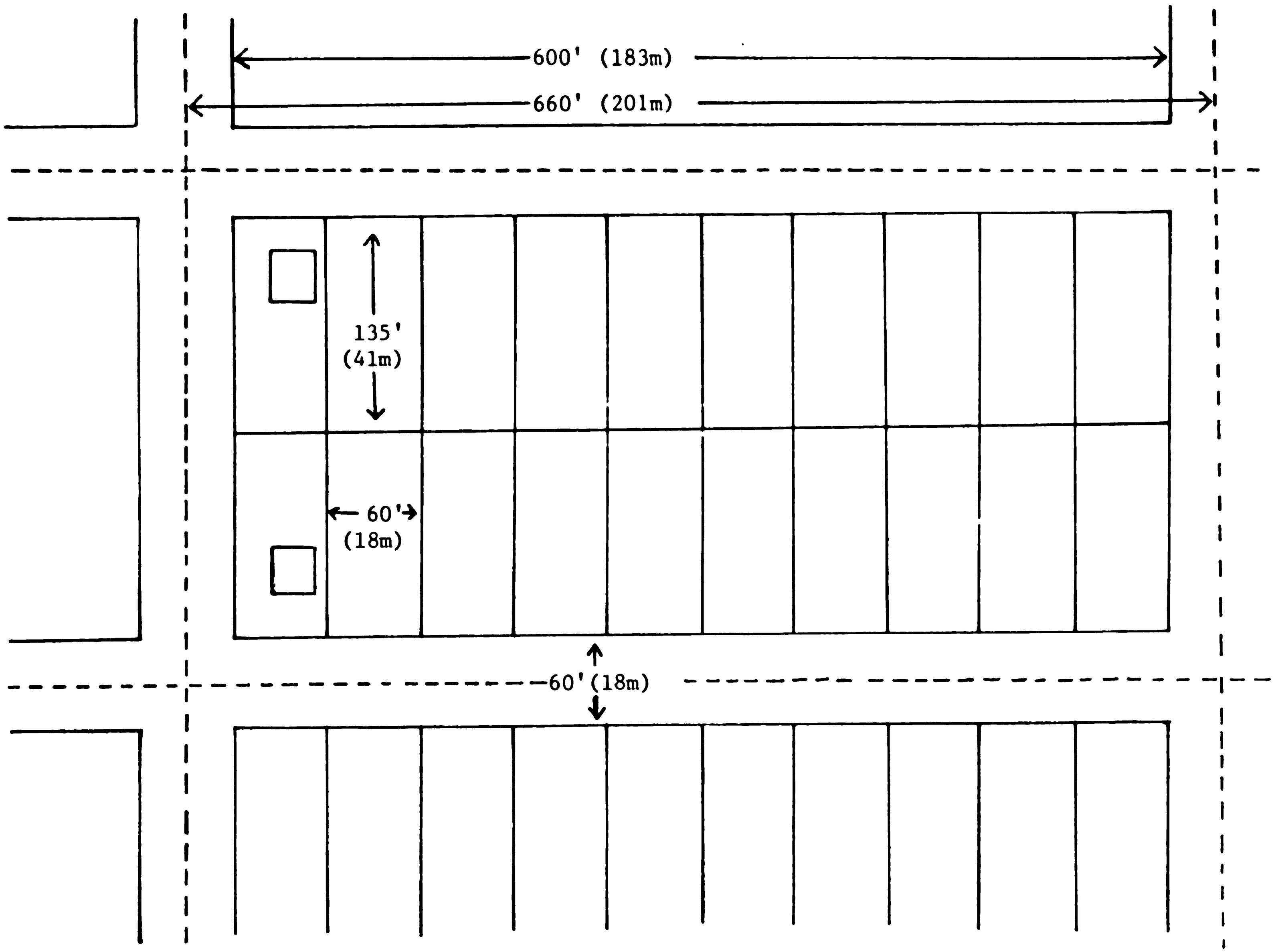


Figure 7.4 Physical Layout of Single-Family Dwellings

VII.2 Steam Consumption in Reference Areas

Energy in the form of low-pressure steam is used in the reference areas for space heating and cooling, and water heating. Steam demand for the single-family dwelling reference area reflects the use of steam for only space heating and water heating.

Estimated steam demand was determined by the methods outlined in Chapter V. The total annual demand for steam is shown in Table 7.2.

TABLE 7.2

Total Annual Steam Demand

(Pounds of steam X10^6)

	space heating	water heating	air conditioning
multi-family dwellings (apartments)	597.559	249.372	249.718
schools (used year round)	31.316	6.824	99.760
commercial area in multi-family dwelling area	6.651	.180	13.362
commercial area	181.396	28.308	339.793
single-family dwellings	380.485	152.986	- - - -

Estimated steam demand was figured on a monthly basis to find maximum and minimum demand periods. The resulting figures for each reference area are shown in Figures 7.5, 7.6 and 7.7. From these graphs, it is clear that without using steam for air conditioning, there is a burden on operation in the single-family dwellings reference area. The single-family-dwellings demand for steam drops nearly 85 percent from maximum demand to minimum demand, remaining at minimum demand for almost four months.

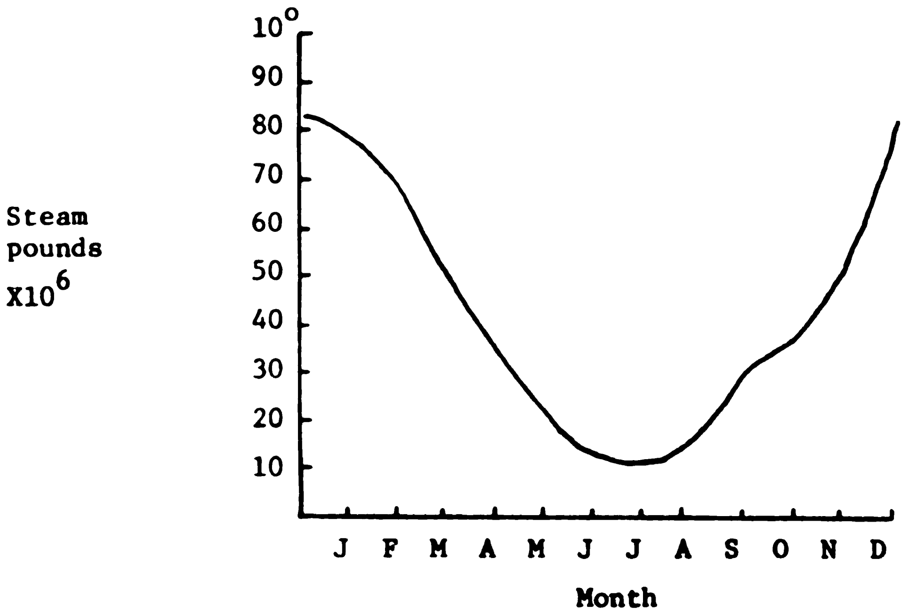


Figure 7.5 Estimated Monthly Steam Demand Single-Family Dwellings

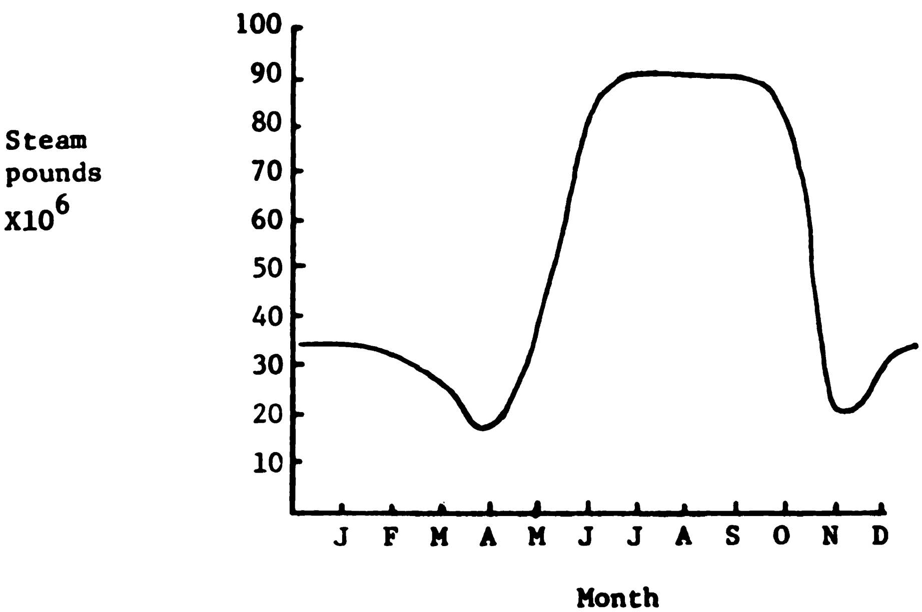


Figure 7.6 Estimated Monthly Steam Demand Commercial Area

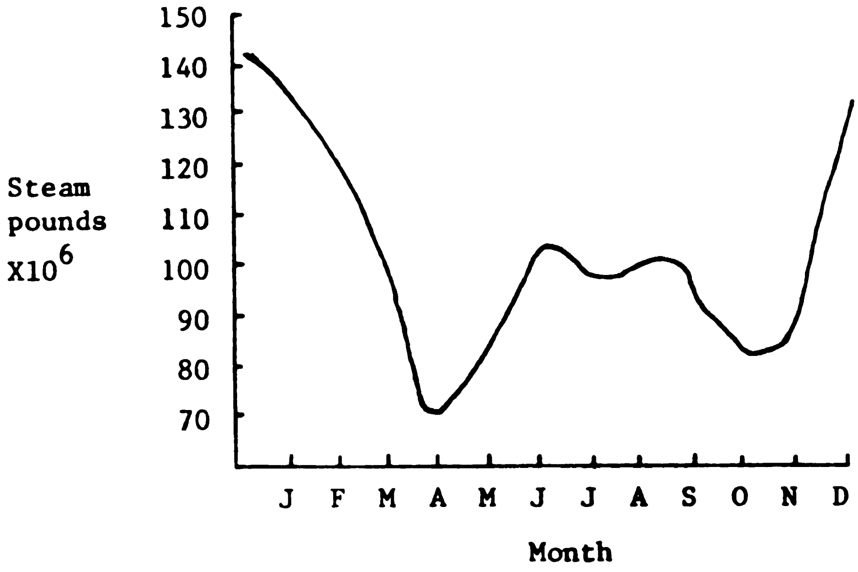


Figure 7.7 Estimated Monthly Steam Demand Multi-Family Dwellings

Steam demand in the commercial area is completely dominated by the use of air-conditioners. As seen in Figure 7.6 during the months of summer, steam demand reaches a maximum.

The separate affects of single-family dwellings and the commercial areas's steam demand for air-conditioning come together in the multi-family dwellings reference area. Steam demand is similar to the single-family dwellings until summer, when the use of air-conditioning increases.

Optimal operation of any system supplying steam would be characterized by almost constant output all year. This might be accomplished if the right mix of single-family-dwellings, commercial establishments, multi-family-dwellings, and industry were located in the community.

VII.3 Summary

The reference areas used to test the dual-purpose power plant have been presented. They are urban communities which show different time demands for steam. Taken together they show that a more diverse community, in terms of residential, commercial, and industrial sectors has a better chance of providing the environment where the dual-purpose plant might work economically. Later we will consider the economics involved in operating a dual-purpose power plant serving these urban reference areas, singularly and in combination.

CHAPTER VIII

DESCRIPTION OF THE MODEL

In preceding chapters we have examined the use of energy in the United States as it relates to urban communities, and developed methods for estimating energy use in the residential and commercial sectors. Later reference areas were designed and estimates were made of the energy required by various communities. The purpose being, to put forth the tools necessary for examining other complex communities and to provide test cases for the dual-purpose plant as a system.

Now that we have energy requirements for various communities with known structural and population characteristics, we now turn directly to considerations of the dual-purpose power plant. To describe the whole system, i.e., the dual-purpose plant with known steam demands from chosen communities, a simulation model of the dual-purpose plant has been developed. This chapter presents the economic and energy relationships of the components of the model and the assumptions incorporated in its development.

VIII.1 Methodology

In order to develop a model of any system, it is important that some theory or theories of behavior exist to explain the interaction between the variables of the model. Since it is the logical structure of the model and the theory used to describe the behavior of its components which finally determines the behavior of the model, the resulting model is only as good as the theory used. And the theory only as good as its ability to explain real world behavior. For example, one might assume that the technologies used by society for the extraction, refining, transport, and utilization of energy resources is fixed, and from an input/output model find the necessary amounts of energy required to produce a given output level of goods and services. The results of this input/output model would be only as good as the assumption of fixed technologies.

Any complex model constructed necessarily forces the modeler to make judgments and simplications. Models are simplified to keep them within manageable bounds and as a result, the final decision on the value of the modeling effort is usually mixed. Some parts are good and accurate and other parts are not so accurate. But if it is realized that a model is just one step in the long attempt to understand which theories best describe the behavior of real world systems, then it is easier to take the modeling exercise with no reservations about its applicability.

The first step in the modeling sequence is to formulate the question, "What behavior do I want the model to explain?" Without first defining this question, modeling can be a very long exercise in boundless futulity. Armed with the answer to this question, one can begin to use or discard variables and relationships between variables, keeping the ones that appear to be important for describing the behavior of the system and discarding the ones with no significance. The ability to know which variables and relationships are most significant and which are not so important is dependent upon knowledge of the system. The greater the knowledge, the easier the modeler's task. Without knowledge about the determinants of behavior, the modeler must make more decisions. Without a clear cut alternative, sometimes the modeler must take an assumption and then later try to validate or destroy that assumption. The final test comes when the model is used to describe the behavior of the real system within the limits of the original assumptions.

The objective of the model developed in this study is to test the feasibility of using small dual-purpose electric power plants to supply low-pressure steam to urban communities. In order to do this, the model must describe the dynamics of a dual-purpose power plant and the effects of changing steam demands on electric energy production. The basic theory used to describe the behavior of the system is taken from thermodynamics. And any simplifying assumptions used in the model are done so as a result of experience gained by practitioners of the technology under consideration. To test the feasibility of the model, different cases, using reference areas developed previously, are examined. The energy flows between the components of the model are handled as an energy balance, or an accounting scheme.

The development of any model of a complex system is an iterative process of construction, simulation, evaluation, modification, construction, simulation, evaluation, modification, etc. With each iteration, the modeler gains new insight into the behavior of the system and, hopefully, a better model emerges. The model presented here describes the results of this process to analyze the dynamics of a dual-purpose power plant supplying steam to small urban communities and the associated economics involved.

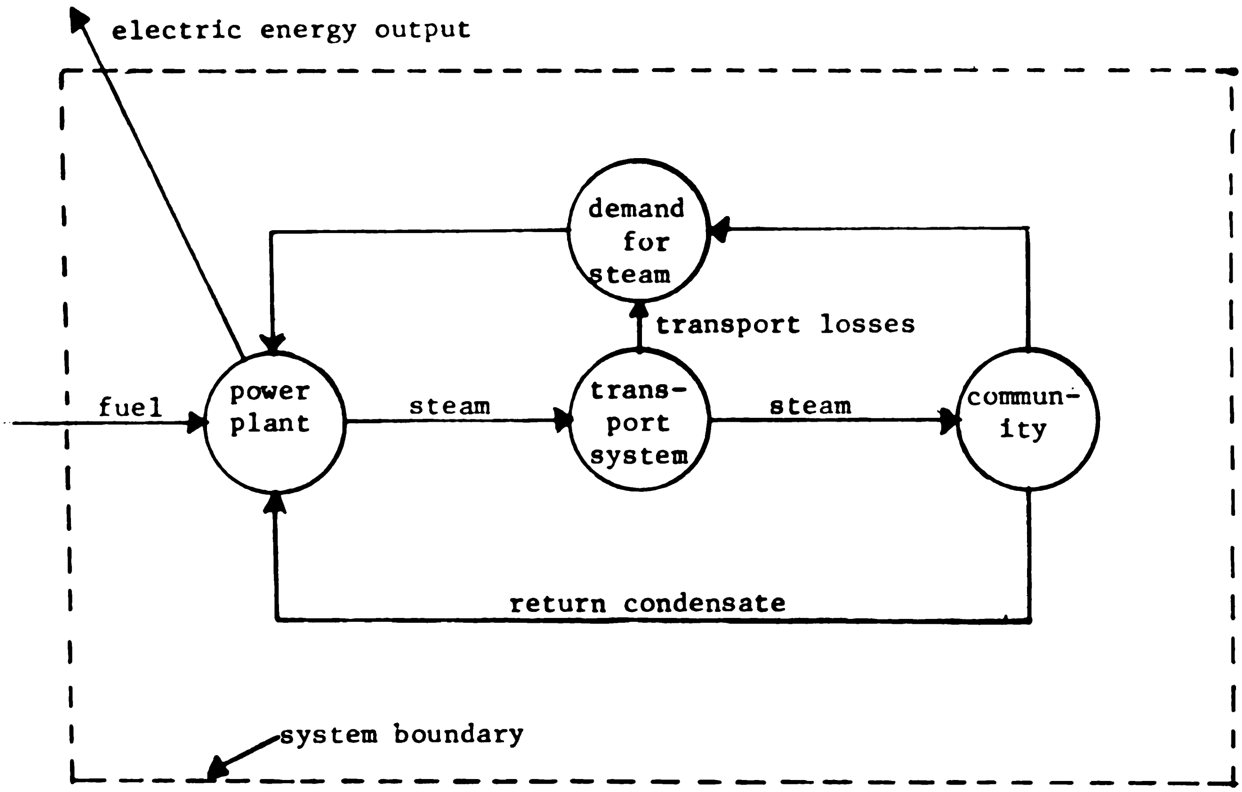


Figure 8.1 General Structure of the Energy Flow System.

VIII.2 Model Boundaries

The purpose of the model is to test the feasibility of using steam extracted from the heat cycles used to produce electricity in an electric power plant for low-temperature energy tasks in an adjacent community. Therefore, the model must contain the interactions between the demand for energy in the community and the power plant. The test of feasibility is a problem of supplying adequate quantities of steam to a given community at reasonable prices for both steam and electricity.

Figure 8.1 depicts important components of the system. Shown are the flows of energy, steam and electric, and demand for steam. The model uses an energy balancing scheme to account for all energy flows within the system.

The boundary of the energy flow and demand system can be easily drawn, since steam demand, as seen by the power plant, includes losses in transport and the demand for steam in the community. Although many individual factors come together to determine the final community demand, a systematic way is available to estimate this demand as shown previously in Chapter V. For the energy demand system then, the complex interactions with the community and the transport component come together to represent an input to the power plant.

The power plant component is a converter of fuel into steam and electric energy. Fuel is an exogenous input variable and electric energy is an endogenous output variable. Since the power plant operates as a baseload plant, electric energy output is a function of steam demand and not related to the demand for electric energy in the community served by the steam system.

VIII.3 Aggragation Level

Steam demand was estimated on a monthly basis and, therefore, the models' results are characteristic of an average year. The method used to find the demand is a function of average fluctuations about $65^{o}F$ ($18^{o}C$) and not directly responsive to exogenous temperature changes. Therefore, the simulation model cannot be used to predict costs and energy output during long hot summers, every cold winter, etc., without recalculating total aggragate steam demand.

Aggragated hourly steam demand is a function of average space heating and cooling, and water heating demand, such that $Y = X_1 + X_2 + X_3$. If X_1 increases by q, and X_2 decreases by q, the model behaves the same. That is, the model cannot be used to directly identify perturbing events in the demand component, whether they are behavioral changes in the way people use energy or exogenous events like extreme temperatures.

Geographical considerations are considered explicitly in the development of materials used in the transport and distribution of steam, and in the type of communities used to test the system. Although the prices for fuels and the cost of construction are not geographically particular to Michigan, they are escalated to cover a range of different capital and operating costs to test sensitivity under other cost's situations.

VIII.4 Pressure Drop Program

Before we get into a detailed description of the energy flow and feasibility model of the dual-purpose plant, an important part of the steam transport and distribution system will be considered.

Three preceding sections on water heating, space heating, and air conditioning detailed procedures for estimating steam requirements of low-temperature energy tasks for a variety of buildings. The purpose being, to provide the necessary tools for estimating steam requirements for any community design, population density, and living style. Once these steam estimated have been made, the next set of questions, i.e., distance trade-offs to the power plant, can the system operate economically, etc., are provided answers through operation of the model.

The distribution system in any community is a critical factor in the feasibility analysis. Because the direct cost of installing steam pipes, condensate return lines, meters, etc., can be very high, it is important that the designer consider alternatives based on accurate information. For this reason, a program was developed to determine pipe parameters for each section of steam line used in the reference areas.

Pressure drop within the underground steam pipe system must be handled such that the end-most user is provided with a minimum required pressure. For example, in the multiple-family dwellings and the commercial area the minimum pressure is constrained by air conditioners - 20 psi (138 k newtons/m^2). Whereas in the single-family dwelling area minimum pressure is not constrained by air conditioners and pressure can drop to 5 psi (34 k newtons/m^2).

Pressure drop in a given length of pipe is a function of the flow rate, steam density, pressure at the sending end of the pipe, and the inside diameter of the pipe. Several formulas have been developed for use in calculating the size of steam pipes to accommodate specified rates of flow. An Urwin chart is a direct and simple method for determining flow rates and pressure drop (DHH, 1951). Another method is to use the Urwin formula directly, providing more accurate results.

The mathematical description, the Urwin formula, for pressure drop is given by the following equation:

$$Q = \frac{0.0001306\ w^2 L\ (1 + 3.6/D)}{Y\ D^5}$$

where, Q = pressure drop, pounds per square inch

w = steam flow, pounds per minute

L = length of pipe, feet

Y = average density of the steam, pounds per cubic feet

D = diameter of the pipe, inches

The Urwin formula is used to calculate the drop in pressure for each length of pipe in the steam distribution system. The calculated pressure drop is used to determine the pressure in the sending end of the next section of pipe. And this process is repeated along the sections of pipe to the last or farthest steam user.

An iterative program has been developed to find the pressure through the system, given pipe diameters, initial pressure, a minimum pressure, and pipe lengths. A description of this program and the information aspects for its use are what follows.

The flow chart of the program is shown in Figure 8.2. The set of steam flows and pipe length are determined by the community being considered, where the spatial arrangement of the community determines the length of pipes needed to connect steam users into the distribution system. The lengths of pipe are inputted as B(KK) where,

B(1) = first length of pipe, feet

B(2) = second length of pipe, feet

⋮

B(N) = Nth length of pipe, feet

B(1) is generally the first steam line in the community nearest the plant, and the B(N)th section serves the farthest steam user from the plant.

It should be noted that the Urwin equation can give pressure drops from 10 to 20 percent above actual if extremely high velocities are used. The Urwin chart is useful here for checking the range of flows in the system and recognizing when the results are overestimated.

The steam demand for each steam user in the community is known via the information presented in Chapter V. The estimated maximum steam demand, in pounds per hour, is converted to the units of pounds per minute. With the sum of the expected maximum demand for all users in the community used to derive the initial steam flow into the circuit. Initial flow required by the total system is reduced by the demand for steam by each user, and steam flow to the first steam user is subtracted

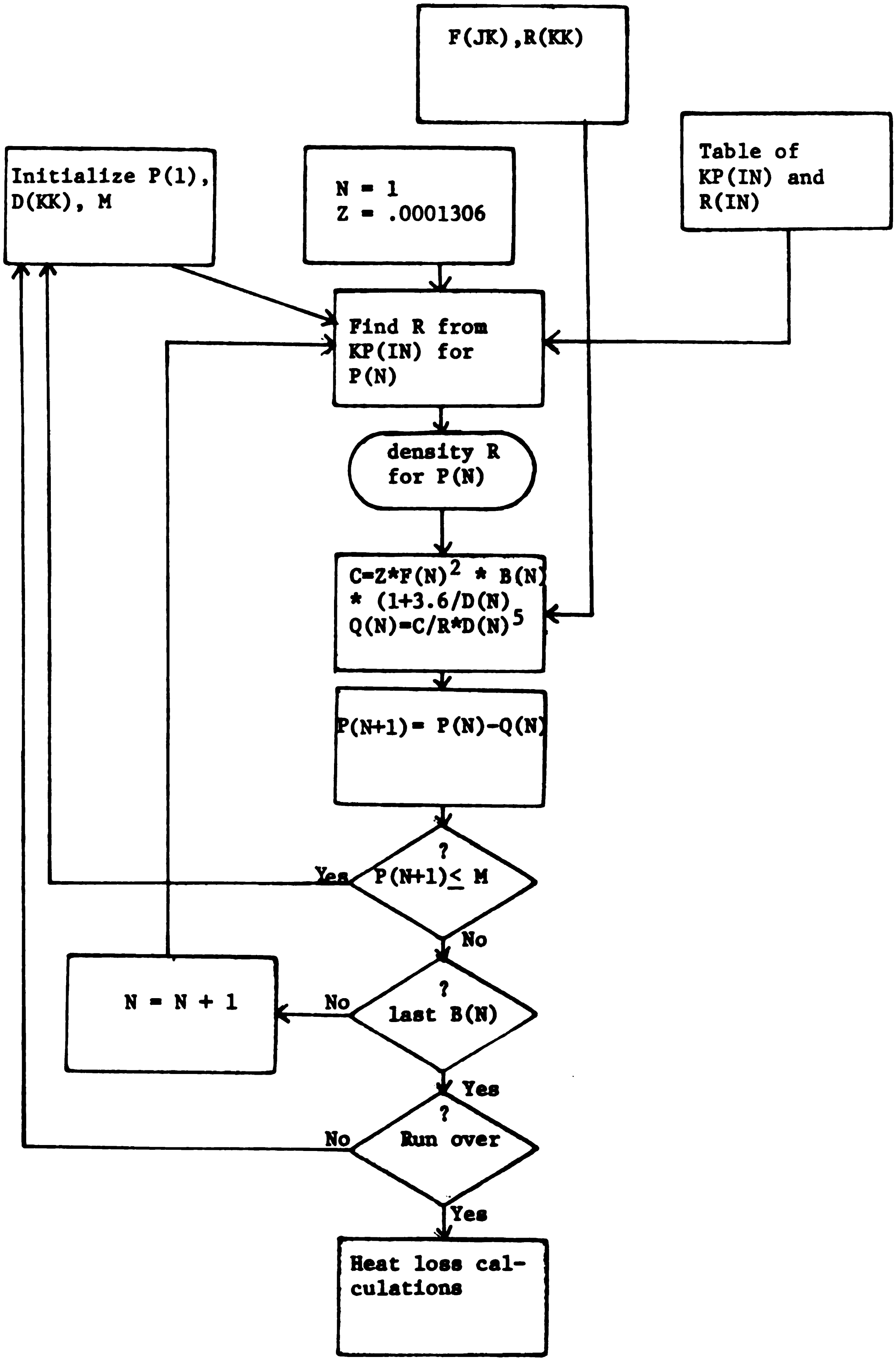


Figure 8.2 Flow Chart of Pressure Drop Program

from the initial flow F(1) to find F(2) for the next section, and F(2) is reduced by the flow to the second user to find F(3), etc.

F(1) = initial steam flow, pounds per minute

F(2) = steam flow in the steam line after the first steam user in the circuit is supplied, pounds per minute

.
.
.

F(N) = steam flow in the last pipe section supplying the steam user farthest from the plant, pounds per minute.

The initial pressure P(1), the pressure at the sending end of the first section of pipe, is selected by the designer. Knowledge of the possible pressures available from the plant and the minimum pressures required by the steam users in the community guide this decision. For example, in this study the multiple-family dwellings and the commercial area, minimum pressure is constrainted by air conditioners, about 20 psi (138 K newtons/m^2). Whereas, in the single-family dwelling reference area minimum pressure can be as low as 5 psi (34 K newtons/m^2).

The minimum pressure M is initialized in setting up the program and is used to find that section of pipe where the pressure was too low. This is done by comparing the derived pressure for each section with M. Where the steam pressure P(J) in any steam pipe section is found by successive reductions of the initial pressure P(1) by the calculated pressure drop in each section preceeding P(J). If the pressure in any section is less than or equal to M, then a new higher initial pressure P(1) is read in, and the series of pressures and pressure drops are re-calculated around the circuit. Or the same initial pressure is used with a new set of pipe diameters, and the pressure and pressure drops are re-calculated for the system.

Figure 8.3 shows the flow, F(KK), and the pipe lengths, B(KK), needed to use the program for the multiple-family dwellings reference

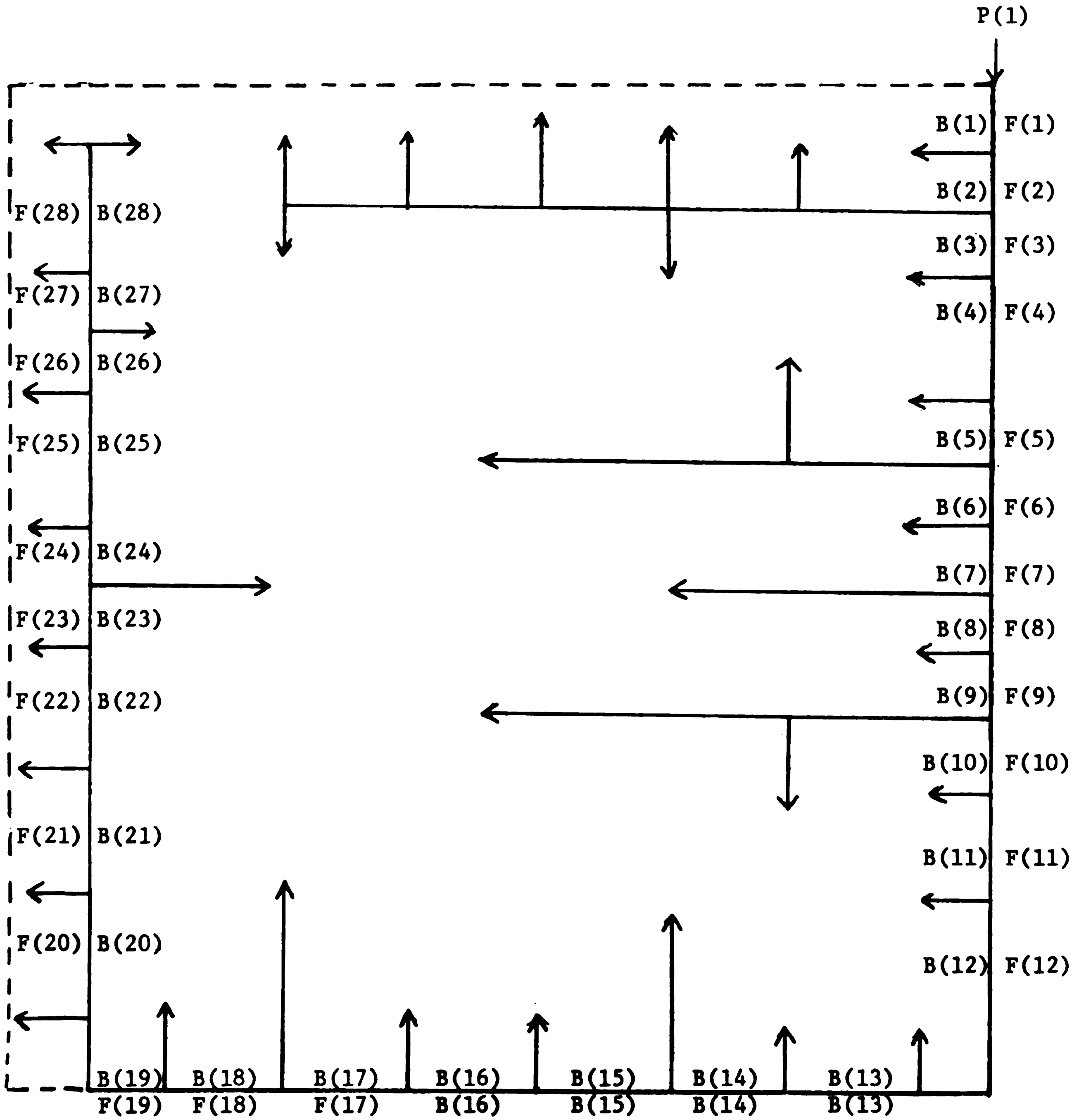


Figure 8.3 Flows and Lengths for Pressure Drop Program (multi-family dwellings)

area. The arrows show the points at which steam flow from the main steam lines are removed for steam users in the community. Generally, the main steam lines are analyzed first and then the shorter steam lines from mains to steam users are checked to insure adequate pressure at all points in the steam distribution system.

The program has either the pipe lengths B(N)'s and steam flows, F(N)'s, read in as data or initialized in the program itself. Pipe diameters D(N)'s, minimum pressure M, and the initial pressure P(1) are read in as data. The program calls for a table of pressures KP(IN) and corresponding steam densities R(IN) tabulated from standard steam tables.

The initial pressure P(1) and all calculated pressures P(N) are compared with KP(IN) values to determine the steam density, R, corresponding to the pressure.

Steam density values, R(IN), vary according to whether or not the steam is saturated or superheated. Extracting from the turbine of an electric power plant generally means steam will be supersaturated. While steam from steam generators used by district heating companies is usually saturated. The corresponding steam density for the pressure in the steam line is labelled R in the program.

Flows, pipe lengths, pipe diameters, and steam density are used to calculate the pressure drop. The program equation is the following:

$$Q(N) = \frac{Z * F(N)^2 * B(N) * (1 + 3.6/D(N)}{R * (D(N) **5)}$$

The output of the program, pipe diameters corresponding with pipe lengths, pressure drop and pressure in each steam line are inputted to the heat-loss program. Where the heat-loss program calculates the expected steam losses during operation of the given steam distribution system. And the feasible pipe diameters are then compared for least steam losses, and a final, smaller, feasible set of pipe diameters is compared for their costs of installation.

Heat loss from buried steam pipes is a function of the specific heat of the steam, steam density, flow rate, pipe diameter, the heat transfer coefficient of the insulation material and the temperature difference between the steam and ground temperature.

The program used to find the heat loss from the steam distribution system follows the method outlined in the section on steam distribution. The method uses a summer minimum, winter maximum steam loss based on operating experience of district heating companies. The technique calculates the steam loss, in pounds per hour, based on surface area of the pipes used.

Since surface area of a pipe is a function of pipe diameter, the program takes pipe diameters derived from the pressure drop program and multiples the corresponding surface area by the length of pipe. The total surface area of the distribution is then multipled by the summer or winter steam loss rate.

$$\text{Steam loss, pounds per hour} = S * C$$

where,

S = total surface area of the steam distribution system, square feet

C = steam loss rate, pounds per hour per square feet of surface area, ranging from .04 to .06 pounds of steam per hour per square feet of surface area.

The flow chart of the programs used to find steam distribution systems that meet minimum pressure requirements and have the least steam losses during operation is shown in Figure 8.4.

The transport of steam from the power plant to the community involves the same set of relationships described in the distribution system. Two

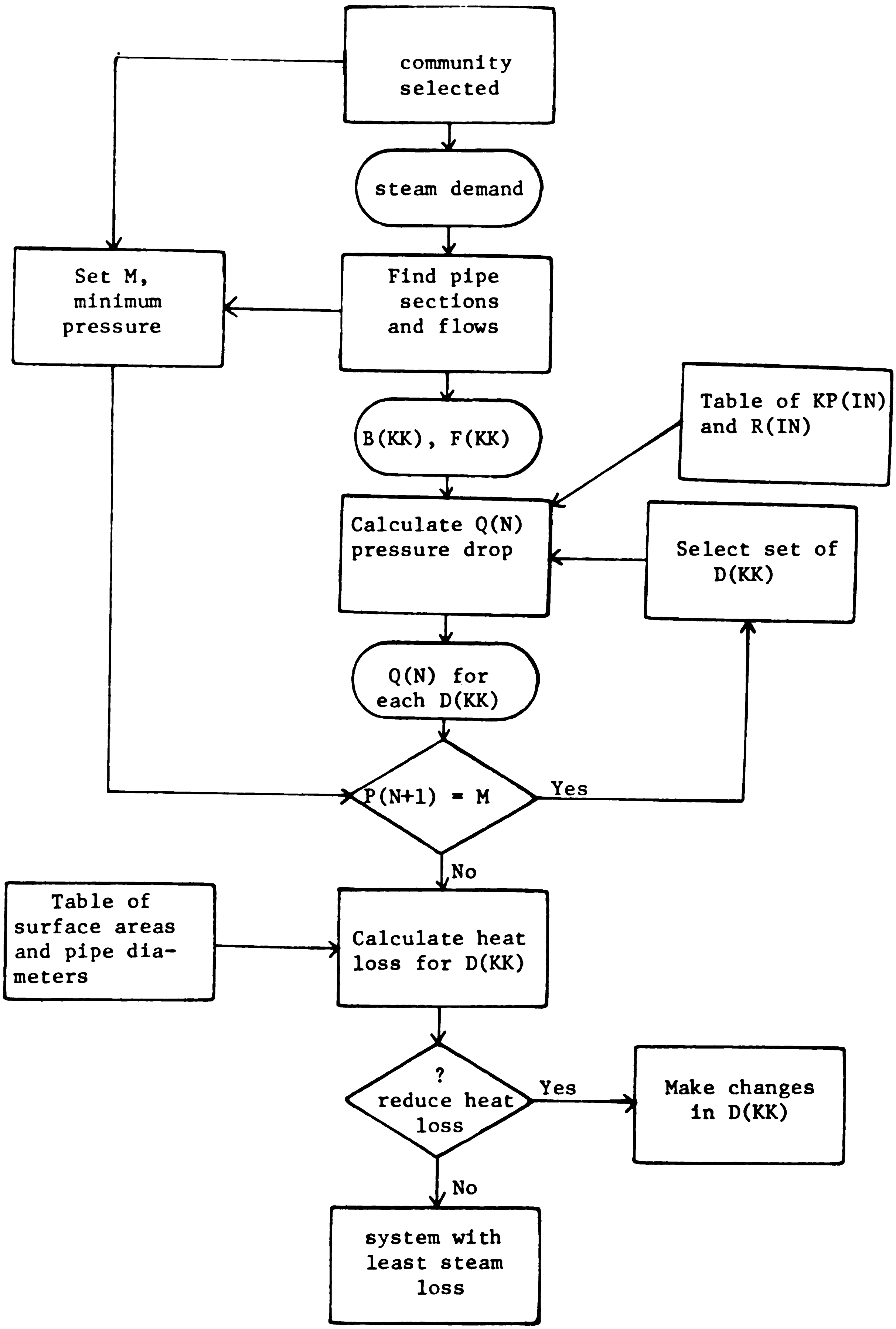


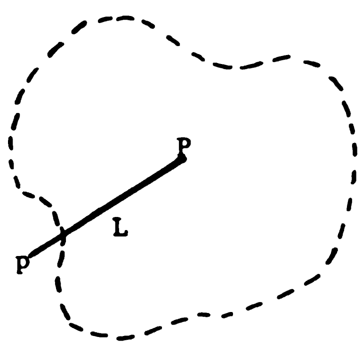
Figure 8.4 Flow Chart of Pressure Drop and Heat Loss Program.

pressures constrain the diameter of pipes used in the transport system; the pressure available at the power plant and the pressure required by the steam distribution system. In general, from studies using all elements of cost, it appears that some advantage is gained by utilizing high pressures for transport (DHH, 1951). For distribution systems, where pressures must be reduced, other factors of cost may make lower pressures more economical.

Pressure influences the extent of an area that can be served economically from a given plant as well as the amount of steam that can be supplied to a given area. The design of the type of distribution is influenced by all three: pressure, area, and steam requirements.

When steam is to be delivered from a given plant and a maximum pressure has been decided upon, a boundary line can be established enclosing the geographical area to be served from the designated plant, inside a radius, see Figure 8.5.

The purpose of the transport component of the model is to define radii for different communities. Since it is possible to increase the pressure P at the plant and extend the radius, a design strategy was developed to limit the total number of possible combinations of plant location, plant pressure, community served, and pressure required.



Dual-purpose plant at P and community at p

Figure 8.5 Transport Radius

The purpose of examining the dual purpose technology is to test the feasibility of using some of the heat cycle used to generate electricity to do low-temperature heating tasks, like water and space heating. If high pressure steam must be reduced after transport for use in the distribution system, the effect of throttling steam is zero efficiency, since high pressure steam has a great capacity for doing mechanical work. Thus, the strategy used to determine transport distances from the plant to the community was to extract steam at the lowest pressure possible. This may cause distribution costs to be high, but the unit cost of low-pressure steam is less than if high-pressure steam was used.

At any given distance, the transport program calculates the pressure drop and steam loss during operation. The feasible set of pipe diameters for given pressures at the power plant and the community are generated in the same way as those in the distribution system. The derived feasible pipe diameters are then compared with respect to steam loss during operation and then to their cost of installation. The initial pressure P(1) used in the distribution system is the lowest pressure required to meet the steam demand of the community and keep the demand for steam pressure extracted from the turbine as low as possible.

Figures 8.6, 8.7 and 8.8 show the main steam lines derived with the used of the pressure-drop programs.

VIII.5 Demand Component

Expected steam demand from any community under consideration can be estimated by the procedures outlined in Chapter V. From the total demand, for any estimate period, the hourly, daily, monthly or yearly steam requirements can be calculated. The approach taken in this study

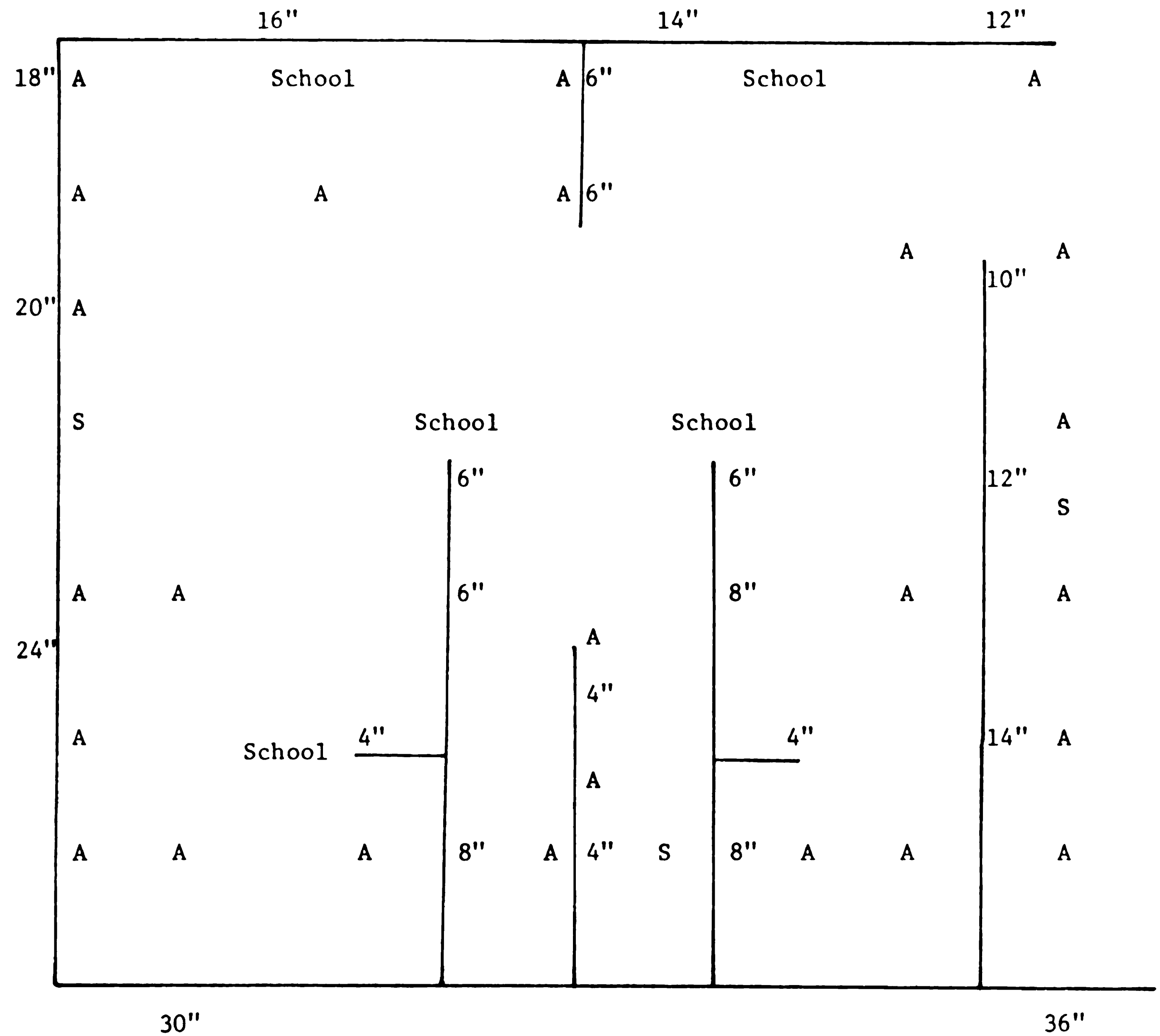


Figure 8.6 Main Steam Distribution - Multi-family Dwellings

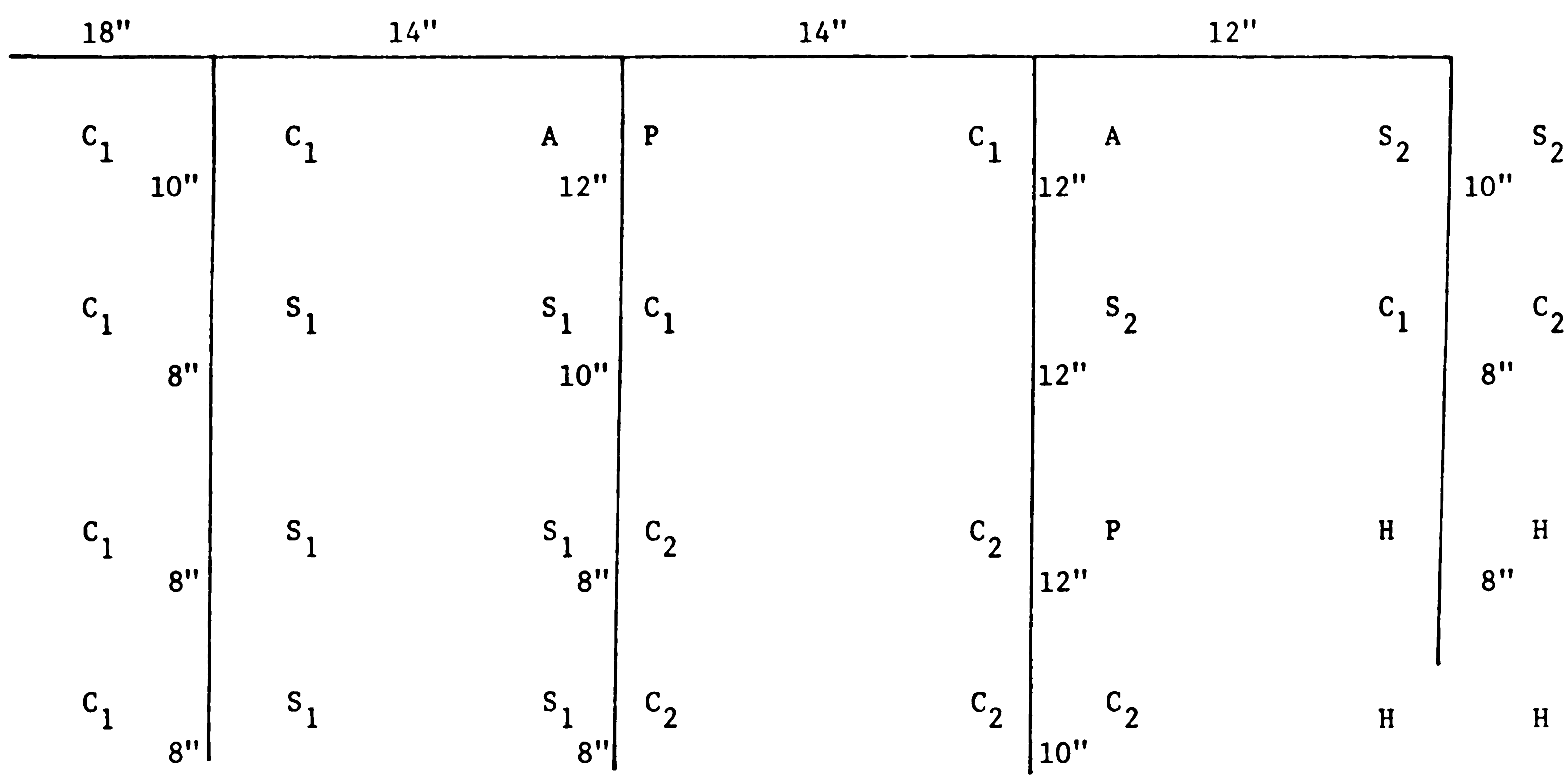


Figure 8.7 Main Steam Distribution - Commercial Area

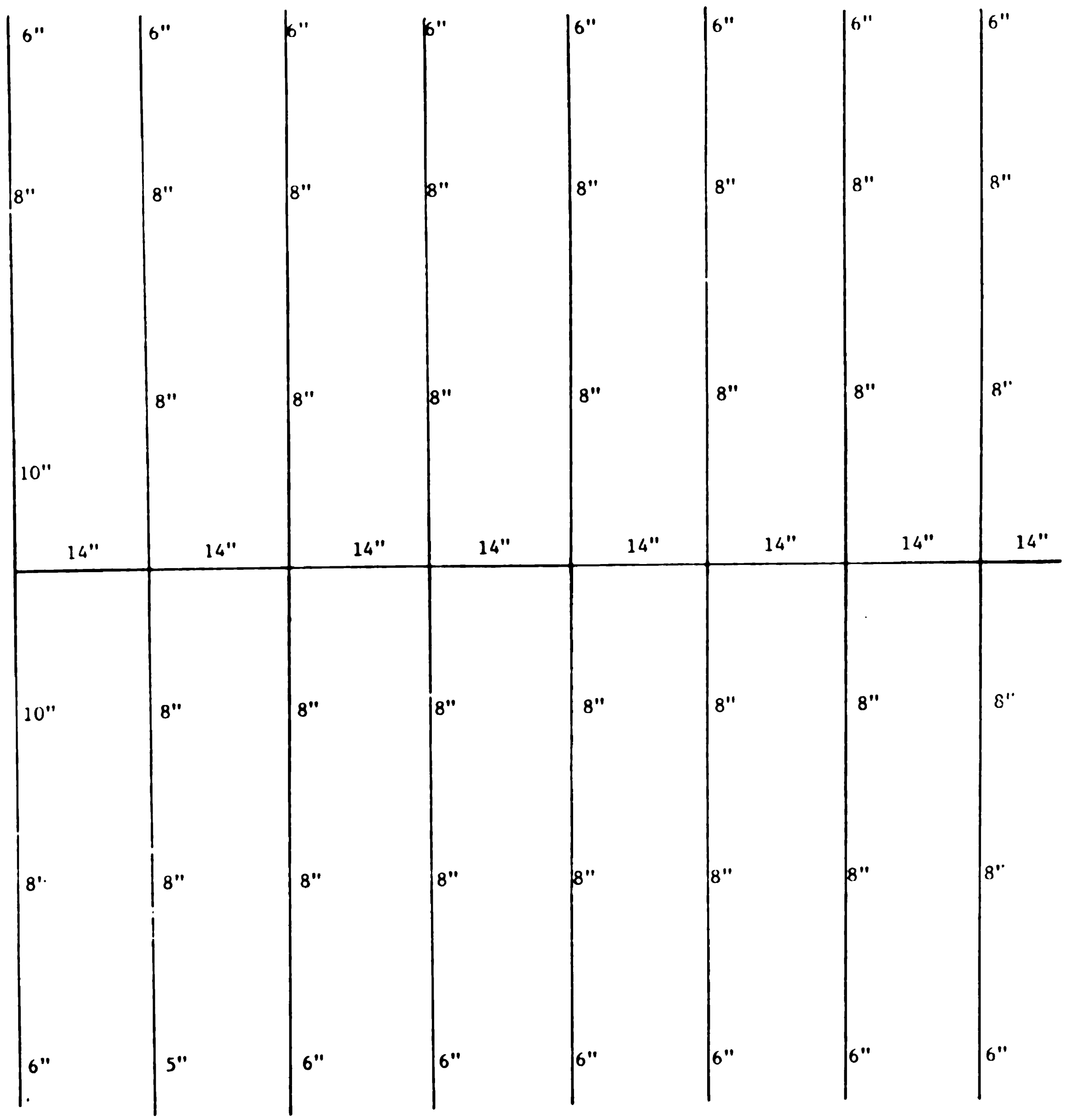


Figure 8.8 Main Steam Distribution - Single-family Dwellings

was to calculate steam requirements on a monthly basis for each reference area. Dividing the total monthly estimates into days and distinguishing between weekday maximums and weekend minimums, from which expected hourly maximum and minimum demands were found.

As will be seen later in greater detail, steam output from a dual-purpose plant decreases the amount of electricity produced. To decide how best to operate the plant on a hourly basis, consider the following figures. Figure 8.9 shows the 24-hour demand curve for electricity for a typical community in the northern part of the United States. Figure 8.10 shows the same 24-hour period for steam demand. It seems fairly clear from these figures that the dual-purpose plant can not supply steam in adequate amounts while supplying the electrical load. Although two or more units with extraction capabilities could operate to supply both demands, one unit operating at a base-load level supplying the steam required can not also supply the electrical load.

The smaller dual-purpose plants, one and two units, considered in this study would have to adopt a strategy of operation to insure adequate supplies of steam on a 24-hour basis. For this reason, the model assumes that the plant operates at base-load supplying steam as in Figure 8.10.

Demand for steam is inputted hourly with minimum hourly demand calculated to supply water heating and space heating requirements assuming thermostats are turned down. Maximum demand occurs during the hours of 8 a.m. to 11 p.m. weekdays and between the hours of 8 a.m. and 8 p.m. on weekends.

In real operating systems, the output of steam is monitored by pressure sensing transducers in the steam distribution system. The general

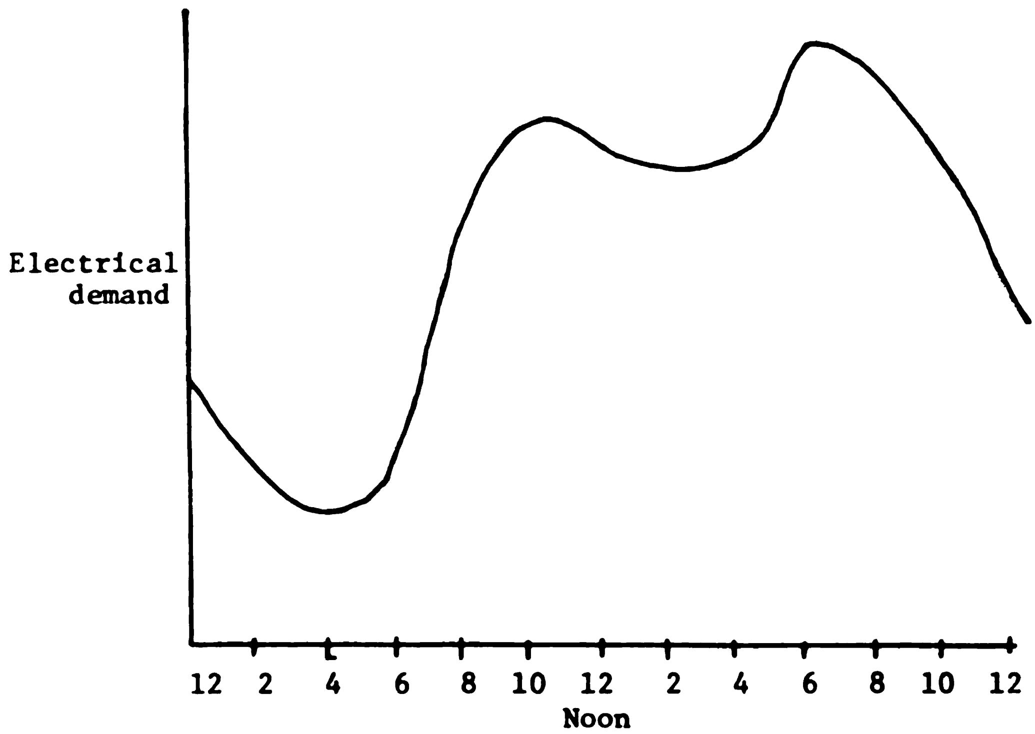


Figure 8.9 24-Hour Electric Demand

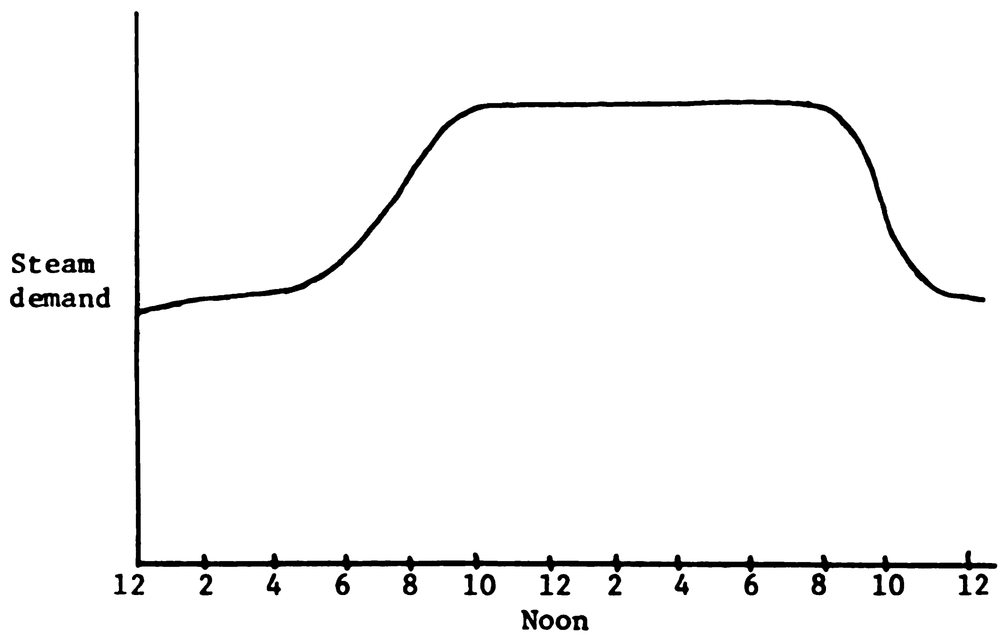


Figure 8.10 24-Hour Steam Demand

shape of the 24-hour curve for these systems is shown in Figure 8.10. The difficulty of modeling such monitored systems dictated the choice of assuming Figure 8.10 as the 24-hour input demand curve. This strategy of operation may have the drawback of overestimating the total yearly demand for steam, but the estimates used for finding the hourly demand for steam assumed no steam demand for services like laundries, laundomats, cooking, etc., in the service areas or the reference areas. Off-setting any overestimates as a result of assuming an input demand for steam based on Figure 8.10.

VIII.6 Dual-Purpose Plant Component

As mentioned previously, the structure of the extraction turbine system used to remove steam from the heat cycle producing electric energy is such that increasing or decreasing steam demand changes the amount of electric energy that can be produced. In this section, we will examine the mathematical relationships in the model used to describe this behavior and the variables used to test the economic feasibility of the system.

As outlined in Chapter IV, the amount of energy extracted as steam for use in the community affects the production of electricity. This "stealing" of electric power is shown schematically in Figure 8.11. As steam demand increases, the production of steam must be increased accordingly. Resulting in a decrease in the production of electricity. Because the energy in steam is used to turn the turbine-generator, extracting more steam reduces the amount of steam passing through the last blading stages of the turbine, reducing the power output. In like fashion, increasing the amount of steam reaching the last stages of the turbine, increasing the power output, necessarily requires that less steam be

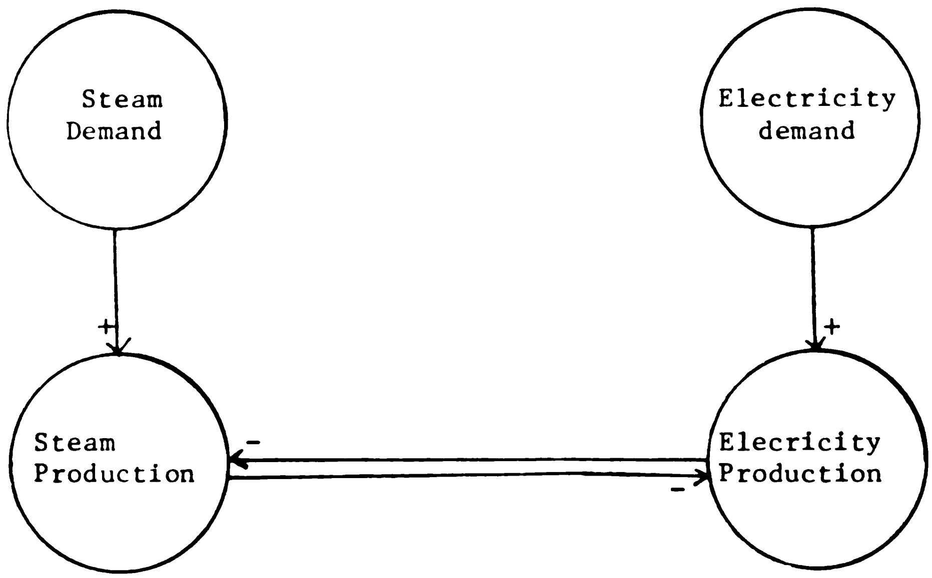


Figure 8.11 Causal Loop Model of the Dual-Purpose Plant System

extracted. This can be done by shutting down the extraction valve at the partition between stages of the turbine.

Steam at high enthalpy levels, higher energy per pound, has the ability to produce shaft work and electric power. At lower enthalpy levels steam has not practical ability to produce shaft work. In order to keep the efficiency of electric energy production at its highest level, steam should be extracted at the lowest possible enthalpy levels. In addition, if we choose to price extracted steam according to its ability to produce electric energy, it is clear that extracting at high pressures, i.e. high enthalpy levels, increases the unit cost of steam. Efficiency and cost considerations prescribe that steam be extracted at lowest possible pressures. The reference areas were designed within these constraints.

The model of the extraction turbine-generator calculates the amount of electric power produced per hour as the demand for steam varies. Demand for steam from the community is inputted per hour and the resulting output of electric power is calculated from the characteristics of the turbine, and the extraction pressure and flow.

The amount of power output from a particular turbine design can be calculated from the mass flow rate, initial and final enthalpies of the steam, and the heat balance relationships for the turbine under consideration. The following equation describes this thermodynamic relationship for a single-purpose turbine-generator with a reheat cycle.

$$\text{Turbine work} = GF * (GFH-GH) + GFR * (GFRH-GRH) \qquad 8.6.1$$

where, GF = steam generator flow rate, pounds per hour

GFH = steam generator enthalpy, BTU's per pound

GH = final steam enthalpy of the power cycle obtainable in the plant, BTU's per pound

GFR = steam generator reheat flow rate, pounds per hour

GFRH = steam generator reheat enthalpy, BTU's per pound

GRH = final steam enthalpy of the reheat cycle, BTU's per pound.

See Figure 8.12, generalized heat balance diagram with relative location of variables.

The amount of electric power is found from dividing equation 8.6.1 by 3414 $\frac{\text{BTU}}{\text{hour}}$ to get kilowatts.

$$\text{Electric power: } \frac{\text{Turbine work}}{3414} = \text{kilowatts} \qquad 8.6.2$$

It should be noted that equations 8.6.1 and 8.6.2 are not the same as the gross heat rate calculation. These equations describe the power cycle of the turbine-generator and not the total heat added to produce a kilowatt-hour of electric energy.

Extracting steam from the turbine has the effect of reducing shaft work and thus electric power output. Extracting at a mass flow rate determined by the demand for steam, DEMAN, from the community, at the enthalpy level, XENTH, determined by the requirements of the steam distribution system, modifies equation 8.6.1 as follows:

$$\text{Turbine work} = GF * (GFH-GH) + GFR * (GFRH-GRH) - DEMAN * (XENTH-GH) \tag{8.6.3}$$

The power output with the effect of extracting steam is then,

$$\text{Electric power} = \frac{\text{Turbine work from equation 8.6.3}}{3414} = \text{kilowatts} \tag{8.6.4}$$

The model calculates the effects on the power cycle of extracting steam by determining the kilowatt equivalence of the extracted steam as follows:

$$ENEXKW = \frac{DEMAN * (XENTH - GH)}{3414} \tag{8.6.5}$$

where, DEMAN = demand for steam from the community, pounds per hour

XENTH = enthalpy of extracted steam determined by the pressure requirements, BTU's per pound

GH = final enthalpy of the power cycle obtainable in the plant, BTU's per pound

ENEXKW = power equivalence of the extracted steam lost from the power cycle, kilowatts.

Extracting at more than one point along the turbine can be simulated by finding the power equivalence of each extraction point from the demand flow rate and the enthalpy of extraction. The sum of the kilowatt equivalence for all the extraction points is the total power lost from the power cycle.

The resulting output of electric power per hour is calculated by subtracting the power lost to extracted steam, ENEXKW, from the non-extraction output, calculated from equation 8.6.2, that is:

$$ENERACT = ENERNON - ENEXKW \qquad 8.6.6$$

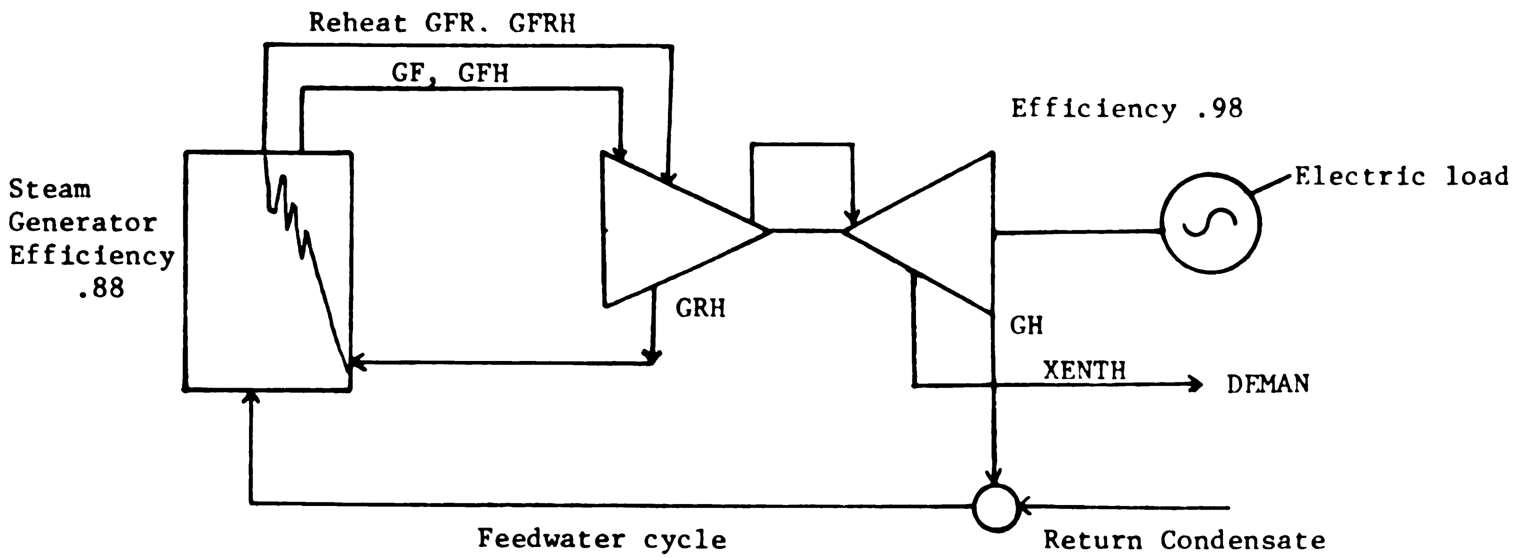
where, ENERNON = non-extraction electric power output, power output if the plant is single-purpose, kilowatts

ENEXKW = power lost to the power cycle due to extracted steam, kilowatts

ENERACT = actual power output of the extraction turbine-generator, kilowatts

The model of the power cycle for the extraction turbine-generator is general enough so that various sized turbine-generators can be simulated. This can be done by substituting the characteristic mass flow, and enthalpy values, taken from heat balance diagrams, for the variables in equation 8.6.1 and proceeding through to equation 8.6.6. See Figure 8.12 for the relative location of variables.

The model of the turbine-generator is not a complete description since it does not include directly the affects of the feedwater cycle, the deaerator or the boiler feed pump. The total auxiliary power required by these and other equipment is on the order of 10 percent of the generating unit rating and does not change continuously during operation of the plant. The results derived from the model deal with the affects on the power producing cycle and efficiencies of conversion



GF = steam generator mass flow rate
GFH = steam generator enthalpy
GFR = reheat mass flow rate
GFRH = reheat enthalpy
GH = final enthalpy obtainable in condenser
XENTH = extraction enthalpy
DEMAN = mass flow rate of extraction

Figure 8.12 Heat Balance Diagram - Extraction Turbine through the system. The affects of auxiliary equipment is considered as a constant reducing the total electric power output of the system. That is, power used in auxiliary equipment is treated as if it were an inefficiency of conversion just like the boiler, which has a first law efficiency of 88 percent.

The model of the dual-purpose plant system provides a vehicle for understanding the dynamics of an alternative design for energy production and use in a community. The physical realization of the system can be simulated under a variety of conditions. We can change steam demand characteristics to represent different community life styles or we can take an existing community and estimate steam demand based on methods outlined in Chapter V. With these parameters we can answer questions with respect to the energy losses, and output of the turbine-generator with respect to steam and electricity.

The physical realization is only one part of the feasibility analysis, now we must examine the behavior and results of the model within economic constraints. Technically, the dual-purpose plant can provide steam to an urban community, and it can be located at just about any distance from the load center. But, can the system operate in the marketplace and what are the trade-offs in plant size, number of units, distance from the load center, and what are the costs of producing and distributing steam? And what is the cost of producing electric energy from these plants?

To answer these questions, and others, an economic model of the dual-purpose plant was developed to predict the cost of producing electricity and steam.

VIII.7 Cost Components

The feasibility analysis of the dual-purpose power plant is literally a test to determine whether the system is of sufficient value to repay the effort and investment. We have seen the physical realization of the system and developed a model to describe its behavior under a variety of different conditions. Now we must add the economic variables to also determine the economic worth of the system. Can this system produce electricity and steam at competitive prices, and what happens to these prices if costs change? These are questions the feasibility model must answer.

The feasibility analysis of the dual-purpose plant includes two separate cost considerations. The capital cost of the total steam system and the total capital cost of the electric part of the plant comprise one of the cost components. The other consideration has to do with the cost of producing steam and electric energy. Together the feasible operation of the dual-purpose plant can be determined under a variety of economic conditions. First, we will examine the cost separation component for producing electric energy and steam of the feasibility model.

There are two ways to cost allocate steam and electricity produced from a dual-purpose plant. One is the energy equivalence method of fuel cost allocation and the other is a fuel cost allocation to steam based on an established electricity cost (Leung, 1973).

The method of energy equivalence of fuel cost allocation was used in the model to determine the cost of producing electricity and steam. Figure 8.13 shows the cost separation component of the model. The method based on an established cost of electricity will also be briefly explained later.

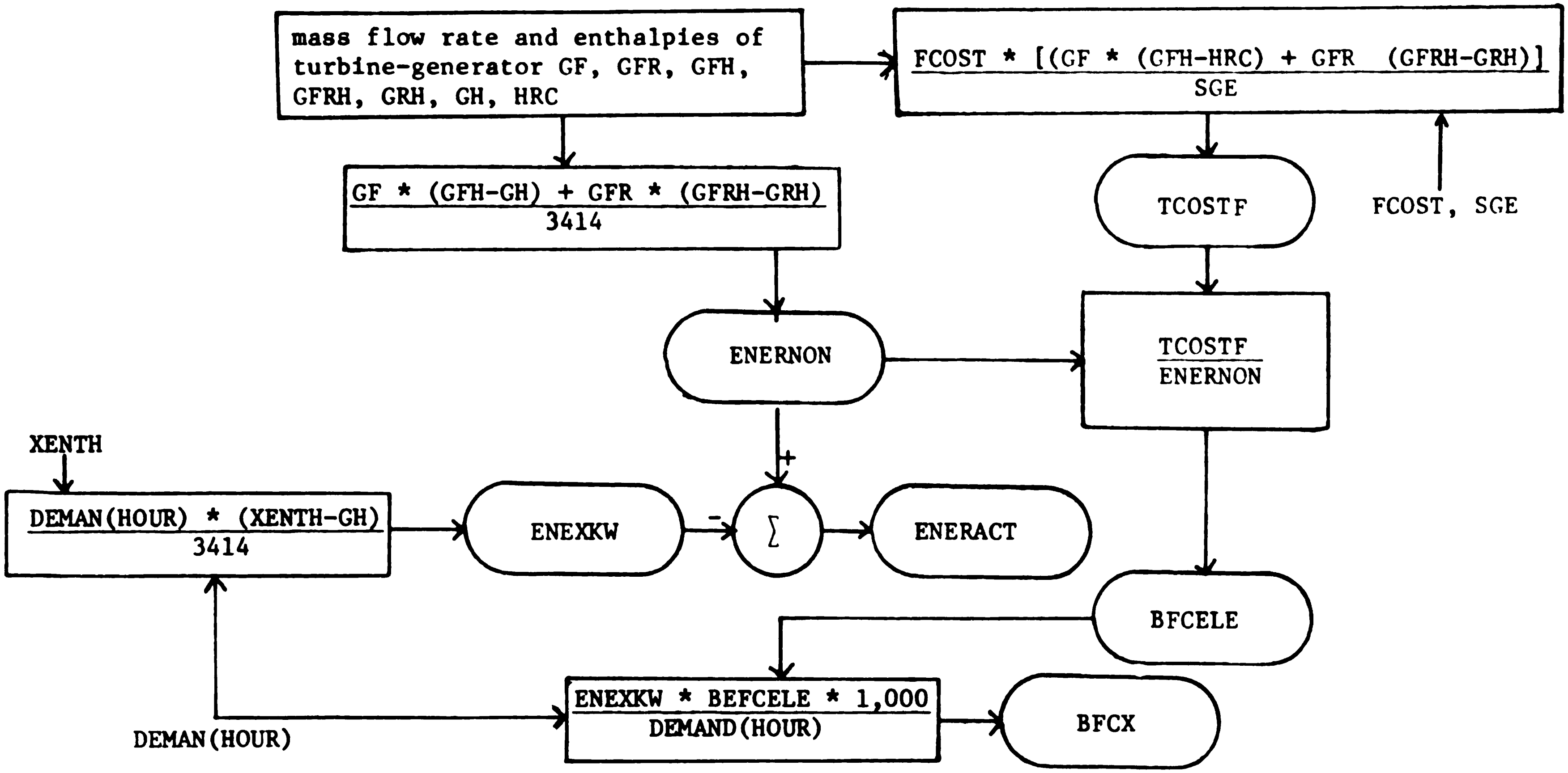


Figure 8.13 Cost Separation Model of Dual-Purpose Plant

Given the characteristics of the turbine-generator, see equation 8.6.1 and Figure 8.12, the method of energy equivalence of fuel cost allocation calculates the total fuel cost, base fuel cost of producing electricity, and the cost of producing steam at a given pressure and flow rate.

Total fuel cost, TCOSTF, determines the amount, per hour, of the fuel cost as it is transformed from stored chemical energy into steam by the steam generator, and the total cost of energy added to the system that produces power. To find TCOSTF, the cost of fuel, the energy characteristics of the turbine, and the efficiency of the steam generator must be known. TCOSTF is found from the following equation:

$$TCOSTF = \frac{FCOST * (GF * (GFH-HRC) + GFR * (GFRH-GRH)}{SGE} \qquad 8.7.1$$

where, TCOSTF = total fuel cost in the heat cycle, \$ per hour

FCOST = cost of fuel, \$ per million BTU's

GF, GFH, GFR, GFRH, are the mass flow rates and steam enthalpies of the particular turbine-generator under consideration, see Figure 8.12.

SGE = steam generator efficiency, first law, percent

HRC = final feedwater enthalpy, BTU's per pound

Total fuel cost, it will be noticed from equation 8.7.1, includes all the energy added to the system much like the calculation of the gross heat rate. Therefore, even if steam is sold from the plant at enthalpies levels below those capable of producing electric power, the energy in the steam still has a value which can be determined from TCOSTF.

If we assume for the moment that the plant is single-purpose, and the obtainable condenser back-pressure is 1.75 in. Hg (853 kilo-newtons/m^2), then the exhaust enthalpy is about 1,050 BTU's/pound

(2.4 kilojoules/kilogram) and the non-extraction output is found from the following equation:

$$\text{ENERNON} = \frac{\text{GF} * (\text{GFH-GH}) + \text{GFR} * (\text{GFRH-GRH})}{3414} \qquad 8.7.2$$

where GF, GFH, GFR, GFRH and GRH are characteristics of the turbine, see Figure 8.12,and GH is the exhaust enthalpy assuming the plant is single-purpose.

The cost of producing electricity, BFCELE, is the total fuel cost, TCOSTF, divided by the non-extraction output ENERNON.

$$\text{BFCELE} = \frac{\text{TCOSTF}}{\text{ENERNON}} \qquad 8.7.3$$

where BFCELE = base fuel cost of producing electric energy, $ per kilowatt hour.

The actual output of electric power from the extraction turbine-generator is considerably less than ENERNON. Given high extraction flow rates and pressures the actual output of electricity can be as low as 10 percent of the total fuel energy input. These plants, with high rates of extraction generally used by industries, are quite economical for both utility companies and process steam users. The cases examined in this feasibility study are for moderate extraction flow rates and low pressures, resulting in smaller decreases in the output of electricity.

To calculate the actual output of electric power, the model determines the extracted steams' equivalent power in kilowatts from the demand flow rate DEMAN, the extraction enthalpy XENTH, and the obtainable exhaust enthalpy in the plant via equation 8.6.5. The equivalent kilowatts of the extracted steam, ENEXKW, is used to reduce the non-extraction output, resulting in the actual power output of the extraction turbine.

$$\text{ENERACT} = \text{ENERNON} - \frac{\text{DEMAN} * (\text{XENTH}-\text{GH})}{3414} \qquad 8.7.4$$

where ENERACT = actual output of the extraction turbine generator, kilowatts

ENERNON = non-extraction output of an equivalent single-purpose turbine-generator, kilowatts

DEMAN = mass flow rate of the demand for steam, pounds per hour

XENTH = extracted steam enthalpy, BTU's per pound

GH = exhaust enthalpy, BTU's per pound.

Base fuel cost of producing electricity was found from the cost of fuel and the efficiency of conversion from stored chemical energy to electricity. The cost of extracted steam can be found from the base fuel cost of electricity and the kilowatt equaivalence of the extracted steam as follows:

$$\text{BFCX} = \frac{\text{ENEXKW} * \text{BFCELE} * 1000}{\text{DEMAN}} \qquad 8.7.5$$

where BFCX = base fuel cost of extracted steam, $ per 1,000 pounds

ENEXKW = kilowatt equivalence of extracted steam, kilowatts

DEMAN = mass flow rate of steam demand, pounds per hour.

The energy costs associated with the feedwater cycle, deaerator and boiler feed pump are in the range of $0.0026 per kilowatt hour and $0.02 per 1,000 pounds of steam. Instead of figuring these costs hourly, as are other costs, they are treated as constants because the plant is assumed operating at base-load. The final cost of producing steam and electricity includes the above energy costs for auxiliary equipment.

The other method of cost separation for steam and electricity is based on an established cost of producing electricity. Unit cost of electricity is calculated from the heat rate for an equivalent single-purpose plant, fuel price, and steam generator efficiency.

$$\frac{\text{Fuel price X turbine heat rate}}{\text{Steam generator efficiency}} = \text{\$ per kilowatt-hour} \qquad 8.7.6$$

Total fuel cost is calculated as in equation 8.7.1 and reduced by the actual power output, ENERACT, equation 8.6.6, multiplied by the cost of electricity, equation 8.7.6.

The power equivalent of extracted steam is found as in equation 8.6.5 and used in a ratio of total equivalent power for extracted steam multiplied by the fuel cost attributed to steam (Leung, 1973).

These two methods arrive at similar costs for producing steam and electricity. The cost method based on an established cost of electricity generally results in lower costs for electricity and higher costs for steam. And the energy equivalence method generally predicts the opposite.

By separating the cost of producing electricity and steam for a dual-purpose plant, the model has the ability to predict changes in production costs as fuel prices increase, without interference from capital costs. Later the system's sensitivity to increasing fuel costs will be examined.

The total capital costs associated with equipment, interest on investment, taxes, insurance, depreciation allowances, etc. are calculated separately for each case under consideration and determined on a per unit output basis, adding to the cost of production. Each case requires different capital expenditures, therefore a general procedure is outlined from which each case follows more or less the same steps.

The costs of the steam system are divided into two catagories, direct costs and indirect costs, to which are added contingency and escalation costs. The sum total of all these costs represents the total capital cost of the steam function of the dual-purpose plant.

Direct costs are those costs directly involved in the production and distribution of steam. The direct costs associated with the production of steam include cost of water treatment, extra cost of extraction turbine generator and miscellaneous plant equipment, and in some cases an extra steam generator. The direct cost of distributing steam includes all parts of the steam distribution system, pipes, meters, labor, etc.. as outlined in Chapter VI.

All cases considered in this study return condensate from the community to the power plant. To insure the quality of this water, an additional water treatment system is included. This condensate polishing system is designed to perform two functions; filtering out iron oxides, and removal of dissolved minerals which may have infiltrated into the condensate.

The cost of the water treatment system is determined at various flow rates by the following set of equations:

At 400 gpm (200,000 pounds per hour), system price is approximately,

$$\text{Price} = \$150 * \text{GPM} \qquad 8.7.7$$

at less than 400 gpm, the price divider is

$$\text{Divider} = \left(\frac{400\ \text{GPM}}{\text{Actual GPM}}\right)^{.6} \qquad 8.7.8$$

at more than 400 gpm, the price multiplier is

$$\text{Multiplies} = \left(\frac{\text{Actual GPM}}{400\ \text{GPM}}\right)^{.6} \qquad 8.7.9$$

For example, at 400 gpm, the cost of the water treatment system is about $60,000 (Cochran, 1976). The model calculates water treatment cost based on maximum flow for the year.

For reliability of operation, an extra steam generator is added capable of supplying the steam requirements of the steam distribution system. These cases include those systems designed with only one extraction unit. Cost of the extra steam generator is found from the maximum flow and pressure requirements of the distribution system.

$$\text{Steam capital} = 4.0 * \left(\frac{\text{Flow}}{100{,}000}\right)^{0.846} * \left(\frac{\text{Pressure}}{900}\right)^{0.125} \qquad 8.7.10$$

where Flow = maximum demand for steam, pounds per hour

Pressure = pressure required by the steam distribution system, pounds per square inch.

The cost equation for the extra steam generator is from the Energy Industrial Center Study, (EICS, 1975). It is stated, as are all costs in the model, in current dollars based on operation in 1980. Results derived from the equations, from the Energy Industrial Center Study, tend to overestimate cost of equipment when compared with other estimates, but with the sky rocketing cost of equipment for power generation; probably not by much (Olds, 1974).

The estimated cost of the dual-purpose is in the range of 11 percent more per kilowatt installed than a single-purpose plant of the same size (EICS, 1975). This extra cost is added to the direct cost of the steam function of the dual-purpose plant. The model first calculates the cost of a single-purpose plant and then finds the extra cost, based on 11 percent, for the extra equipment needed for the extraction of steam. Direct cost to steam includes changes in the main power building, yard work, steam generating equipment, draft system, steam instruments and controls, sulfur dioxide removal, turbine-generator, feed water system, service systems, process steam system, and miscellaneous plant equipment to facilitate steam extraction capability. Other costs and interest during construction are the same as calculated in finding the cost of the electric part of the plant, shown shortly.

Indirect costs includes interest on investment, taxes, insurance, etc. based on a plant life expectancy of 30 years. Indirect cost is figured as 30 percent of direct with contingency costs 10 percent of indirect and direct costs, and an escalation factor of 10 percent. The sum total of all these costs is the total capital investment for the steam system (Miller et al, 1971).

Total Capital Cost = direct cost + indirect cost + contingency cost + escalation factor   8.7.11

where direct cost = all equipment directly or indirectly supporting the extraction of steam plus the cost of investment to distribute steam

indirect cost = 30 percent of direct cost

contingency cost = 10 percent of direct and indirect

escalation factor = 10 percent of all costs

Based on an annual fixed charge rate of 15 percent of total capital cost, and an operating and maintenance cost of 5 percent of total capital cost, the cost of steam due to capital is found from the following equations:

Total Capital Cost * .20 = Annual Cost of distributing steam, $ 8.7.12

$$\underset{\$ \text{ per } 1{,}000 \text{ pounds}}{\text{Cost of distributing steam}} = \frac{\text{Annual cost of distributing steam}}{\text{Annual output of steam}}$$

The model calculates these costs on a yearly basis. Together with the cost of producing steam,the final break-even cost of steam is determined.

Capital costs associated with the electric power producing part of the dual-purpose plant where developed with the following set of assumptions (EICS, 1975).

1) all monetary figures are stated in current dollars

2) assumed rate of inflation is 10 percent in 1975, 5 percent until 1980. The consumer price index was taken as indicator of inflation.

3) power plant investment per unit of generating capacity has escalated 2.75 percent per year in excess of the rate of inflation.

4) utility industry average fixed charge rate of 17 percent by 1980.

5) no costs are incurred for shortages of materials to construct the plant

6) plant operate at base-load with capacity factor of 85 percent, average utility is around 55 percent

7) power economics were based on coal as steam generator fuel. with investment for particulate and sulfur-dioxide removal

8) straight-line depreciation was used, with a plant life of 30 years.

9) property taxes and other miscellaneous capital related costs were assumed to be 2 percent of original investment per year.

The range of investment for electric-steam power plants is shown in Table 8.1.

The model calculates the capital cost of the electric part of the system based on the non-extraction rating of the dual-purpose plant, as if it were a single-purpose plant. Annual fixed charge rate of 17 percent and 2 percent of the total capital investment, determine the annual cost of capital and operation for the electric function of the plant. This cost is

TABLE 8.1

Investment in New Plants ($ per kilowatt)

year operational	coal	oil	gas	nuclear
1974	346	303	243	355
1975	373	325	262	378
1976	392	341	274	405
1977	419	363		432
1978	457	395		461
1979	498	429		498
1980	533			551

Reference: Energy Industrial Center Study. 1975. Dow Chemical Company, National Science Foundation. Report No. PB-243 823. National Technical Information Service, Springfield, VA.

divided by the actual yearly output of electricity to find the cost of producing electricity with respect to capital investment, and operation and maintenance costs.

$$\text{Capital investment} = \$ \text{ per kilowatt} * \text{rated size of plant} \qquad 8.7.13$$

$$\text{Annual operating cost and fixed charge} = \text{capital investment} * .19$$

$$\text{Cost of electricity} = \frac{\text{Annual cost}}{\text{Yearly output}} + \text{cost of producing electricity from fuel}$$

The economic feasibility model of the dual-purpose power plant system provides an ability to test the system under many different conditions. Also, this method separates all steam function costs from those of the electric function. Therefore, electric users are not subsidizing steam users, and vice versa.

VIII.8 Validation

Now that the major components of the model and the overall structure of the model have been presented, we now turn to the issue of validation. Primarily, the issue of validation is whether the model represents what it was set out to do. How much confidence can we have in the results derived from the model, and does the model correctly represent the real world system?

Many of the models, in fact most, developed in the last few years that attempted to understand the energy situation have not addressed the issue of validation directly. The large-scale modeling group, i.e., Meadows, Forrester, Mesarovic, usually considered special cases for each component of the model. After showing that the component model satisfactorily did what it was intended to do, they went on to find model results using all the components. It can only be assumed that this group feels that a model is valid if the components are valid.

The two general classes of models, predictive and normative, have different, but not separate, validation criteria, since few models are purely normative or predictive. Normative models usually deal with "what ought to be" and validation issues deal mainly with the representation of the model structure and the input parameters. For predictive models validation includes evaluation of both the model's logical structure and its predictive power. Three levels of predictive capability may be identified (Hoffman and Wood, 1976). First, there is the ability to predict the direction of a response to some perturbing factor. A second level of capability involves the ability to predict the relative magnitude of a response to perturbing factors, and the third level involves the prediction of the absolute magnitude of the response to a perturbing factor. Or more generally validation is the result of examining each aspect of the model for logical consistency with known facts, and the model's structure for proper representation of the interaction of its components.

Really, a model is never validated in the strict sense of the word. Rather degrees of confidence are established through a series of tests of the model. Usually, these tests include comparison with past data or directly with the real system, structural sensitivity studies, and input/out sensitivities.

Structural sensitivity asks the question, "Would an alternative description give better results?" Really, there is no good answer to this question because a model has been developed after a long iterative process, from which emerges a better model each time. Whether the choice of structure is finally correct is just difficult to say.

The present model can not be easily compared with real world systems, at least not in a meaningful way. There are dual-purpose plants in operation, but the unique designs considered in this study make comparison with these systems difficult. Many are old, in fact a representative from Westinghouse indicated that they have not built an extraction turbine in 15 years, and usually these older systems supply only industrial users. The newest dual-purpose plant is a large nuclear plant supplying Dow Chemical with process steam in Midland, Michigan. Also, the communities used to test the economic feasibility of the dual-purpose plant in this study are "idealized" and specilized to Michigan's climate.

One component, the power plant, is general enough that by changing some of the parameters, its predictive power can be tested. For example, a base-load electric generator plant had costs in 1975 as shown in Table 8.2 on the following page. The model predicts base-load electric generation costs at 9.29 mills per kWh for capital, 11.8 mills per kWh for fuel, and 2.5 mills per kWh for operation and maintenance under the same set of conditions.

TABLE 8.2

Base-load Electric Generation Costs, Mills per kWh, 1975 dollars

	Coal*
Capital	9.30
fuel	10.11
other	2.00
	21.41

* Assumes fuel price of $1.10 per million BTU's, low sulfur cost.

Capital cost of plant $380 per kilowatt, fixed charge rate of 15 percent, capacity factor of 70 percent.

Reference: National Energy Outlook. 1976. Federal Energy Administration, Report No. FEA-N-75/713. FPO, page 187.

Cost of generating electricity from coal at $.71 per million BTU's has been calculated by FEA in 1975 dollars, the results show capital at 11.74 mills per kWh, fuel 6.85 mills per kWh. and 3.50 mills per kWh for other (FEA, 1976). The model predicts 11.8 mills for capital, 7 mills for fuel, and 2.5 mills for operation and maintenance. In both cases, there is good agreement between model results and figures presented by the Federal Energy Administration . Over the range of $.40 to $1.80 per million BTU's the model shows linear growth in the cost of generating electricity from coal, which is what we would expect. Of course, the total cost of generating electricity does not, in general, go up linearly because projections into the 1980's must include increased fixed charges and operating costs. But, if the model is adjusted to include changes in fixed charges, and operating and maintenance costs, the predicted cost of electricity is quite close to the estimated costs shown by FEA. They estimate 1985 costs in the range of 21 to 22 mills per kWh, the model predicts these costs at 21.3 mills per kWh (FEA 1976).

VIII.9 Summary

In this chapter we have seen the methodology used to construct the model and components of the model. Validation issues have been addressed and the model's results appear to be valid.

Next the model is used to show the economics involved in using a dual-purpose plant to supply low pressure steam to urban communities. Using the reference areas developed earlier, the economic feasibility of this alternative energy producing system will be shown.

CHAPTER IX

CASES AND RESULTS

Technical and economical feasibility of a dual-purpose power plant providing steam to a small urban community has many dimensions. We seek information as to the type of community, i.e., which community life-style provides the best economic incentives to realize the system, and what constraints must be placed on the power plant itself to realize the system.

To find answers to these questions a series of test cases are presented to determine which community is best served by the dual-purpose plant, and under what constraints. After defining the community, we examine plant size, cost of producing steam and electricity, sensitivities to higher fuel and capital costs. And then we address the generalities. What is the minimum steam demand required to realize the system, and under what conditions? Which size unit is best able to supply steam and electricity at competitive prices? And what needs to be done to make these systems an attractive alternative to large electric power plants located far from load-centers?

There are many variables which an be varied in the simulation model, and initially the intent was to have the model general enough to include as many different situations as possible. But the shear number of different combinations possible necessarily forces a limited number of hopefully, representative cases. Therefore, the results included here are not exhaustive by any means and general relationships shown at the end of this chapter should help identify answers to questions not directly presented in the cases considered. Additionally, it should be emphasized that this study was done to determine if smaller communities and smaller power plants could be used alternatively to produce energy for society. Very large communities, with high population densities, do provide the economic incentives to realize the dual-purpose plant, and are not included in the results.

IX.1 Case 1 - Multi-family Dwellings

This community provides an opportunity to test what some students of the environmental, energy, and economic crises believe is the only way we can live in the future, while maintaining our current standard of living. They point to the fact that these communities use less energy, take less land, and provide all the services needed by the inhabitants. Since commercial services are integrated with the housing units, the distance between home, work, and play can be very short for many of the residents, and the amount of petroleum used by the population can be reduced. In addition, residents could cooperate in many services and lower their individual cost of living by using re-cycling systems, food co-ops, etc. But, initially, the community uses steam from the power plant until the community is established and alternative services are provided by energies derived from within the community. This is the case we consider first.

Approximately 16,000 people live in this community designed with elementary and secondary schools located equal distance from multi-family apartment buildings. Schools were sized to accommodate about 5,000 students, assuming primarily families choose to live in the area.

Commercial services were designed to include all types of shopping and speciality stores. All buildings are air conditioned by steam absorption air conditioning systems, space heating and water heating also use steam. The whole area complex covers an area of one square mile.

First test of economic feasibility with the dual-purpose plant assumes that the plant is located adjacent to the community. The plant is a single unit 200 MW electric power plant with an extra steam generator used to supply the steam system during maintenance or outages of the electric energy producing system. Assuming a capacity factor of 85 percent and a fuel cost of \$.75/MBTU (\$.71/G joules) for coal, the power plant produces annually 1.40×10^9 kilowatt-hours of electricity and 1.10×10^9 pounds of steam. The cost of electricity produced averages 18 mills/kWh for the year, with 8 mills/kWh of the cost directly a function of fuel cost. Average steam cost is 4.79/MBTU (\$4.54/G joules), of which 4.43/MBTU (4.20/G joule) represents capital, and operation and maintenance cost of the steam system. The cost of producing steam is only \$.36/MBTU (\$.34/G joule).

Now what does this mean to the average family in the community? Apartment residents would pay nearly \$143 in the coldest month for space heating and water heating. And about \$80 in the month of July for air conditioning and water heating. By contrast, if the apartments used natural gas, in January their bill would be \$70, and if they used electricity only in the apartment buildings their bill would be almost \$270 - at current average retail cost of electricity.

Table 9.1 lists the costs of energy for residential and commercial use in 1975 dollars. Without any restrictions on the use or supply of natural gas in the residential and commercial sectors, the price which makes steam competitive with other fuels, mainly natural gas, is \$3.00 to \$4.00/MBTU (\$2.85 to \$3.80/G joule). It should also be remembered that the cost of using steam can be a little higher than natural gas and still be competitive since using steam requires no investment in a furnace and maintenance costs. Currently steam is sold in the range of \$3 to \$5/MBTU (\$2.85 to \$4.74/G joule) by district heating companies and their number of customers is increasing.

TABLE 9.1

Energy Cost in 1975 Dollars, \$/MBTU (\$/G joule)

natural gas[1,2] (deregulated)	1.90(1.80) to 3.00(2.85)
synthetic gas[2] from coal	3.03(2.87) to 4.27(4.05)
electricity[2]	7.60(7.21) to 9.12(8.65)
fuel oil[2]	3.10(2.94) to 3.79(3.60)

Reference:[1] Morse, F. H., and M. K. Simmons. 1976. Solar Energy. Annual Review of Energy. Annual Reviews Inc. Palo Alto, California. page 146.

[2] Federal Energy Administration. 1976. National Energy Outlook. Report No. FEA-N-75/713. FEA. Washington, D.C. pages 160 and 244.

With increasing costs of the steam distribution system, the cost of steam increases radically. Since nearly 90 percent of the final cost of steam is directly a function of the total capital investment, and operation and maintenance costs, at \$6 million to install the steam distribution system the final cost of steam is \$4.40/MBTU (\$4.17/G joule). Whereas, at \$8 million to install the steam distribution system, the final cost of steam jumps to \$5.10/MBTU (\$4.84/G joule). Under the influence of higher costs for the tunnel steam distribution system, the cost of steam is nearly three times higher. Making the tunnels option too costly.

This first test of economic feasibility for the dual-purpose plant supplying the multi-family community considered a 200 MW unit. If a 60 MW unit is used instead, the steam system can be reduced in total cost from \$24.5 million to \$20.0 million. Assuming an increased cost of the electrical function of the plant from \$375/kw for the 200 MW unit to \$430/kw for the 60 MW unit, the total capital investment decreases from \$72.0 million to \$25.8 million, respectively. While the 200 MW unit produces steam at \$.36/MBTU (\$.34/G joule), the 60 MW unit produces it for \$.39/MBTU (\$.37/G joule) and final cost of steam is \$4.39/MBTU (\$4.17/G joule) for the 200 MW unit, \$4.02/MBTU (\$3.81/G joule) for the 60 MW unit.

It seems to make little difference which size plant is used to produce steam since 90 percent of the final cost is a direct function of the cost of distributing steam. By constrast, the final cost of electricity from these two plants is quite different. The 200 MW unit has an annual electricity output of nearly 1.40×10^9 kWhs at a final cost of 18 mills/kWh and the 60 MW unti has an annual output of 405×10^6 kWhs at 21 mills/kWh. Not much is gained by reducing the size of the unit as far as steam costs are concerned but, the cost of electricity is directly influenced. Which is a result of the fact that as the unit size is decreased, with the same steam demand, the total amount of electricity generated is reduced, since removing the same amount of steam from the smaller unit reduces more severely the amount of steam producing shaft work in the lower end of the turbine. The trade-off here is to gain a small advantage in reduced steam costs, but increase the cost of producing electricity.

Moving the power plant 1 mile (1.6 kilometers) from the community adds nearly $1.5 million to the installation cost of the steam transport system. The same capital cost is incurred for distributing the steam in the community, $7.0 million. Steam costs over $5/MBTU ($4.74/G joule) from the 200 MW unit and $4.36/MBTU ($4.14/G joule) from a 60 MW unit. Located 2 miles (3.2 kilometers) and 3 miles (4.8 kilometers) the 200 MW unit has final steam costs of $5.55/MBTU ($5.27/G joule) and $6.21/ MBTU ($5.89/G joule), respectively. And the 60 MW unit remains nearly competitive, at $4.70/MBTU ($4.46/G joule) at 2 miles (3.2 kilometers) and $5.36/MBTU (45.09/G joule) at 3 miles (4.8 kilometers). Assuming that the 60 MW unit cost $430/kw to install, the 200 MW unit $375/kw to install, and the cost of fuel $.75/MBTU ($.71/G joule) in all cases.

The smaller unit seems to have an advantage when the plant is located far from the steam load center. As a result of the fact that it adds less to the total capital investment in the steam system. But the 60 MW unit produces electricity for nearly 18 percent more than the 200 MW unit.

The multi-family dwellings community is economically feasible, if the 200 MW unit plant is located within a one-mile radius of the load center. Steam demand is maximum at 140,000 pounds/hour taken from a turbine with an input flow of 1.3×10^6 pounds/hour. Since less than 11 percent of the steam is diverted from the low-end power cycle, the plant still produces sufficient quantities of electricity to keep the cost of electricity competitive. A 60 MW unit, by contrast, has nearly

28 percent of its steam diverted from the low-end power cycle and produces steam at competitive prices with natural gas, but as a result averages 21 mills/kWh for electricity. And can be located within a 2 mile (3.2 kilometers) radius of the community.

IX.2 Case 2 - Single-family Dwellings

The one square mile of single-family houses is not a community per se, but rather an expansion of an existing city. In that sense, it is like suburbia without commercial services within the area.

Houses in the area are two stories on lots of 60 x 135 feet (18 x 41 meters) with 1,500 feet^2 (70m^2) of useful floor space. There are 2,560 houses in the square mile with a population of about 10,240 people. Steam supplies energy for space heating and water heating, and because absorption air conditioning is not available for small houses, air conditioning must be done with the use of other fuels.

The cost of installing the steam distribution system is very high, $13 million. Even though most pipe diameters are small, every street in the area has a main steam line because of the dense spatial organization of the houses. In other cases, main steam lines were placed on every other street, reducing the installation cost. But in the single-family dwellings area, this technique did not significantly reduce the cost of installation. In fact, in some arrangements this technique increased the cost because of the increased length of services required between houses and main steam lines.

Under the same conditions as Case 1, the 200 MW unit is located adjacent to the area and a coal price of $.75/MBTU ($.71/G joule) then the cost of producing the steam averages $.36/MBTU ($.34/G joule), and the cost of electricity averages 17.6 mills/kWh. Total yearly output of steam is 462 X 10^6 pounds at an average demand rate of only 53,000 pounds/hour. With a total capital investment in the steam system of nearly $32 million, it should not be surprising to find the cost of steam is $14.11/MBTU ($13.39/G joule). Since at this cost of investment and low demand rate, $13.75/MBTU ($13.05/G joule) of the final cost of steam is for distribution costs. The cost of steam for such a system is much too costly.

To the average home owner in the area, the cost of space heating and water heating would be $480 in the month of January. Even though home owners did not invest in a furnace, the cost of steam is still 5 times higher than using natural gas and almost twice as high as if they used electricity.

If the commercially-sized 200 MW unit is replaced by a small 60 MW unit, some reduction in the total capital investment can be realized. Whereas the 200 MW unit had a total steam system cost of nearly $32 million, a 60 MW system costs about $27 million. But the final cost of steam is still too high at $12.02/MBTU ($11.40/G joule) even though the plant can produce steam for $.39/MBTU ($.37/G joule). The trade-off cost in reducing the size of the plant is shown in the different costs of electricity. The 200 MW averaged 17.6 mills/kWh while the 60 MW averaged 20.3 mills/kWh, assuming an 85 percent capacity factor. Therefore, we gain a small decrease in the cost of steam but increase the cost of electricity if smaller plants are used as dual-purpose plants.

It is probably impractical to increase the steam demand by increasing population density in the single-family dwellings area. Since at nearly twice the demand for steam the area would be a crowded subdivision, with average homeowners still paying $7.20/MBTU ($6.83/G joule). Even if the cost of installing the steam distribution system is lowered to $2 million, average homeowners would still be spending $172 in the month of January. Which is still $5.05/MBTU ($4.79/G joule), the upper level at which steam is just competitive with natural gas.

The steam demand which finally brings the cost of steam down to competitive prices is nearly 150,000 pounds/hour. Implying a population density of almost 29,000 people per square mile. An intolerable 11 people per house or 7,250 houses per square mile with 4 people per house. Therefore, it appears that the case of the homogeneous community of only single-family dwellings is practically an impossible economic environment for the dual-purpose plant. And unless there can be drastic reductions in the cost of connecting steam users to the plant, there is little hope that at reasonable population densities areas comprised of only single-family houses can be supplied steam from a dual-purpose plant.

IX.3 Case 3 - Commercial Area

The commercial area was sized to provide services for a population of 15,000 to 20,000 people. Characteristics of which were developed from Michigan communities. The area includes a shopping mall, office buildings, parks, an amusement area, a hospital, and other commercial services separated from the mall. In the first test of economic feasibility, the commercial area covers one half of one square mile.

Again, the power plant is a single 200 MW unit with an extra steam generator for reliability purposes. The total capital cost of the steam system is nearly $14 million with a yearly demand of 537 X 10^6 pounds of steam. Steam costs \$5.55/MBTU (\$5.27/G joule) and electricity 17.7 mills/kWh. Yearly output of electricity is 1.4 X 10^9 kilowatt-hours, assuming a capacity factor of 85 percent. Since the system was designed to extract at lowest possible pressures, little power is lost from the turbine and the cost of electricity is very reasonable.

Moving the power plant to a location 1 mile (1.6 kilometers) from the steam load center increases the cost of steam to \$6.26/MBTU (\$5.94/G joule), \$5.90/MBTU (\$5.60/G joule) of which is for distribution costs alone. At 2 miles (3.2 kilometers) steam costs \$7.17/MBTU (\$6.80/G joule), and if the plant is modified to include two 200 MW units, both with extraction capabilities, the extra steam generator can be eliminated. But the cost of steam goes up to \$8.59/MBTU (\$8.15/G joule) because the additional extraction unit costs \$4.25 million more than the extra steam generator. Moving the two-unit plant 1 and 2 miles (1.6 and 3.2 kilometers) from the load center increases the cost of steam to \$9.30/MBTU and \$10.21/MBTU (\$8.82 and \$9.69/G joule), respectively.

Whether the plant is one or two units, the average cost of producing steam, a direct function of fuel cost, does not change appreciably. Steam extracted at 70 psia (482 K newtons/m^2) can be produced at \$.36 to \$.38/MBTU (\$.34 to \$.136/G joule), assuming a fuel price of \$.75/MBTU (\$.71/G joule). It is the cost of distributing steam and capital costs which limit the economic feasibility of the system. At larger steam demand, steam costs go down considerably. For example, enlarging the commercial area to one square mile increases the yearly total demand to nearly 1.07 X 10^9 pounds. And the cost of steam drops to \$3.98/MBTU (\$3.78/G joule) with a distribution cost of only \$3.63/MBTU (\$3.33/G joule).

TABLE 9.2

Higher Operation and Maintenance Costs
and the Cost of Steam

Operation and Maintenance Cost - Case 3 (percent of total capital investment)	Cost of steam \$/MBTU (\$/G joule)
5	5.55 (5.27)
10	6.49 (6.14)
15	7.79 (7.39)
20	9.09 (8.62)

At these higher demands for steam, one square mile of commercial area could be served by a plant located 3 miles (4.8 kilometers) from the steam load center and still be economically feasible. At one mile (1.6 kilometers) steam costs \$4.34/MBTU (\$3.99/G joule), and at two and three miles (3.2 and 4.8 kilometers) the cost is only \$4.79 and \$5.45/MBTU (\$4.40 and \$5.01/G joule), respectively.

With the tunnel steam distribution system in place of the buried steam pipe system, considered in all cases up to this point, steam costs are generally too high. If the plant is located next to the half of one square mile commercial area, the cost of steam is \$6.81/MBTU (\$6.26/G joule). And with tunnels used to distribute steam in one square mile of commercial services the cost of steam is \$5.50/MBTU (\$5.22/G joule). In general, tunnels may be attractive because of lower operation and maintenance costs but with no clear way to evaluate the reduced operating costs, tunnels are an expensive option.

Various charges for operation and maintenance costs are shown as they affect the final cost of steam in Table 9.2. The steam systems considered in this study have an annual fixed capital change of 15 percent of total capital investment. To which is added 5 percent of total captial investment for operation and maintenance costs. Usually district heating companies report operating and maintenance costs in the range of 5 to 15 percent of total capital investment (Miller et al, 1971). Since the systems in this study are new and take advantage of years of experience from district heating companies, the lower rate of 5 percent was used in all cases. But the final cost of steam can be very sensitive to the assumed cost of operation and maintenance and all steam costs quoted here can be 17 to 40 percent too low for systems with high operation and maintenance costs.

All of the cases considered so far have been small in comparison with other studies done on dual-purpose plants serving cities or industrial complexes, since they could be built within a reasonable amount of time. And because they match, in construction time, the period during which a power plant is planned and finally put on-steam. The commercial area case is a good example for considering start-up costs since areas like it are built next to existing cities more often than other cases considered so far. From the results of Case 3, the commercial area provides the highest steam demand covering the least amount of area. Therefore, the costs of installing the initial system are lowest, with the cost of steam competitive with other fuels. City planners knowing that a particular commercial area was in the planning stage could coordinate their efforts with utility engineers to make an assessment of the potential for using a dual-purpose plant to provide energy to the area. The benefits in energy efficiency and low cost reliable energy for consumers could, in time, develop a whole new city surrounding the commerical area utilizing steam from the plant.

IX.4 Case 4 - Small Urban Community

Next we should examine the possibilities of a small urban community served by a dual-purpose plant. To do this, the characteristics of the commercial area and the single-family dwellings area are combined.

The population of the small urban community is 10,240 people with a commercial sector located adjacent to the housing area. Total yearly steam demand is 997 X 10^6 pounds with a total capital investment in the steam system of \$35 million. The final cost of steam is \$7.44/MBTU (\$7.06/G joule), \$7.09/MBTU (\$6.64/G joule) of which is distribution costs. Electricity averages 17.8 mills/kWh based on fuel cost of \$.75/ MBTU (\$.71/G joule).

Distribution costs, again, restrict the feasibility of the system, but if the community was designed with integrated housing and commercial buildings, some reduction in the total capital cost could be realized. A target cost of \$5/MBTU (\$4.74/G joule) limits the installation cost of the steam distribution system to about \$7 million. However, it is unlikely that the cost of actual steam distribution system could be reduced by half as this figure requires.

The other alternative is to increase the steam demand and determine the point at which the small urban community is economically feasible. At nearly 1.4 X 10^9 pounds per year the cost of steam is lowered to \$5.05/MBTU (\$4.79/G joule). To reach this demand the community should have about 15,000 people per square mile. Moving the plant 1 mile (1.6 kilometers) from the community requires the population density to be at least 17,000 people per square mile. And at two miles the density should not be less than 21,000 people per square mile for economic operation of the plant. With the plant at three miles from the steam load center demand must average 190,000 pounds/hour or a yearly total of 1.67×10^9 pounds. Consequently, at these higher demand rates the plant itself could easily be a two-unit plant, both with extraction capabilities, reducing costs because the extra steam generator is more costly than the modification costs of the second unit.

To be economically feasible, the small urban community should have a heterogeneous mix of commercial buildings, multi-family dwellings, single-family homes, and industry, if possible. And not a homogeneous layout of single-family homes, as in Case 2. Although industrial demand for steam is specialized at particular pressures and time of day, and is not considered directly in this study, any possibility of supplying industrial users increases the economic prospects of the system. And communities with the above characteristics, with some industrial users available, are good candidates for the dual-purpose plant system.

The small urban community case has shown signs of economic feasibility because the commercial area provides a buffer when the steam demand falls in the single-family area. Steam demand from these two areas, commercial and single-family, almost compliment each other, particularly in the summer. When the demand for steam falls in the single-family areas where steam is not used for air conditioning, steam demand increases dramatically in the commercial sector as air conditioning energy requirements increase. Without this buffer, as seen in Case

2, single family areas do not provide enough steam demand to be economically feasible alone.

IX.5 Steam Displaces Other Fuels

As mentioned in Chapters IV and VII, steam used for space heating and cooling, and water heating reduces the inefficient use of other energy resources. To measure this impact we examine the residential sector of the small urban community of Case 4.

Since it is not generally known which fuels are used, an average, by commercial establishments we must confine our attention to single-family houses where information is available on fuel use. Taking Michigan as an example, the percentage use of energy resources is shown, by type in Table 9.3.

Assuming that the population of 10,240 people selects to use fuels in the same quantities as the averages shown in Table 9.3, we would expect approximately 1,843 homes using natural gas, 512 homes using fuel oil, and 128 homes using electricity for space heating. Water heating fuel use breaks down as 1,843 of the houses using natural gas, and 640 using electricity. Steam is not used for air conditioning and does not replace electricity used for air conditioning.

In Michigan these houses, 1,500 feet^2 (70 m^2), average 180 X 10^6 BTU's (190.04 X 10^9 joules) per year for space heating and water heating. Of which 83 percent is for space heating and 17 percent for water heating. With 2,560 houses in the small urban community, the use of steam replaces the yearly use of 332 X 10^6 cubic feet (9.40 X 10^6 cubic meters) of natural gas, 11 X 10^6 kilowatt-hours of electricity, and 13,209 barrels of oil. And all of these fuels are replaced by low-pressure steam, from coal our most abundant energy resource, <u>after</u> it has produced shaft-work and generated electricity.

TABLE 9.3

Percentage of Fuel Use
By Residential Sector

Heating Fuels	Percent
natural gas, LP or bottle	72
fuel oil	20
electricity	5
other, coal, wood	3
Water Heating	
natural gas, LP or bottle	72
electricity	25
other, fuel oil, wood, coal or coke	3

Source: Census Report for Michigan. 1976 U.S. Bureau of Census. Washington, D.C.

Thermodynamically this is very appealing. The first law efficiency of this system is nearly 70 percent, see Chapter IV. While within the second law, the effectiveness of this system is nearly twice that of a conventional power plant. This is accomplished because the available energy[1] of coal burned in the plant is consumed to produce shaft work

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[1] Available energy measures the potential of a system to do useful work. Energy is made unavailable, if in the system, energy is degraded to atmospheric conditions and no useful work is done. Useful work is work not done on the atmosphere. Effectiveness is a measure of availability of a system. In simplistic terms effectiveness can be defined as the ratio of the available energy of the output of the system divided by the available energy of the input. Therefore, using electricity, completely available energy to heat water, which has little available energy, the effectiveness is very low.

and generate electricity. The remaining energy in the steam is extracted in low-temperature heating tasks where the availability of energy is not important. For example, the home gas furnace has an effectiveness of only 13 percent because the output of the furnace, hot air, has little available energy. However, if steam is used instead, the effectiveness is nearly 70 percent since the input of low-pressure steam has nearly the same available energy as the output. The same situation holds for the gas water heater and the electric water heater which have effectiveness ratings of only 17 and 25 percent, respectively. And again, replacing these energy resources by steam increases their effectiveness to nearly 60 percent.

This system, extracting steam from a dual-purpose plant and using it to do low-temperature heating tasks, has accomplished two important energy results. Coal is used to produce steam from which the available energy is consumed to produce electricity and then the remaining heat energy of the steam is used for tasks that require little available energy. In addition, fuels which have high available energy are replaced by the indirect use of coal transformed into steam. Consequently, the system reduces the use of high quality, highly available, fuels in the community while at the same time increasing the use of our most abundant energy resource, coal.

IX.6 Generalizations

In this final section we address the questions of plant size, costs, and extraction characteristics as they affect the economic feasibility of the system. We have already learned that at higher steam demand rates, dual-purpose power plants can be quite economically attractive. What is important to this study is not how cheap can we make the price of steam and electricity. But rather, how smaller demand rates, higher costs, and size of unit affect the economic feasibility of these systems.

First we will examine two important parameters which are dependent upon the community and play a critical role in determining the economic feasibility of the system. Extraction pressure and flow depend upon the tasks for which steam is supplying energy and the demand for steam by the community. We have already learned that greater extraction flows have a positive affect on economic feasibility, from the examples considered in Cases 1 through 4. Now the general relationship between extraction pressure and flow, unit size, and the cost of energy produced will be presented.

Throughout this study, the strategy has been to extract steam at the lowest pressure possible while still satisfying the pressure requirements of the steam transport and distribution system. This was done because of the realization that as higher extraction pressures are required, the cost of steam and electricity increases. To understand this relationship Figure 9.1 shows the cost of steam at various extraction pressures. As the extraction pressure increases, the cost of producing steam increases from \$.36/MBTU (\$.34/G joule) at 70 psia (483 k newtons/m^2) to \$.58/MBTU (\$.55/G joule) at 150 psia (1,034 k newtons/m^2) for the 200 MW unit. An increase of over 60 percent.

At the same extraction flow the cost of producing steam varies according to extraction pressure because greater extraction pressures remove higher available energy from the power cycle. Therefore, the equivalent kilowatts of the extracted steam is greater, also the cost, because high pressure steam can generate more electricity (has more available energy). Moreover, higher extraction pressures increase the cost of electricity because the total power output of the turbine is reduced.

decreasing the generator output. For example, at the same flow and 70 psia (483 k newtons/m^2) the cost of electricity averages 19 to 21 mills/kWh and at 150 psia (1.034 k newtons/m^2) the cost ranges from 20 to 45 percent higher. Where the larger units, 200 MW, experience a 20 percent increase in the cost of electricity going from 70 to 150 psia (483 to 1,034 k newtons/m^2), smaller units, 70 MW, experience a 45 percent increase over the same pressure range.

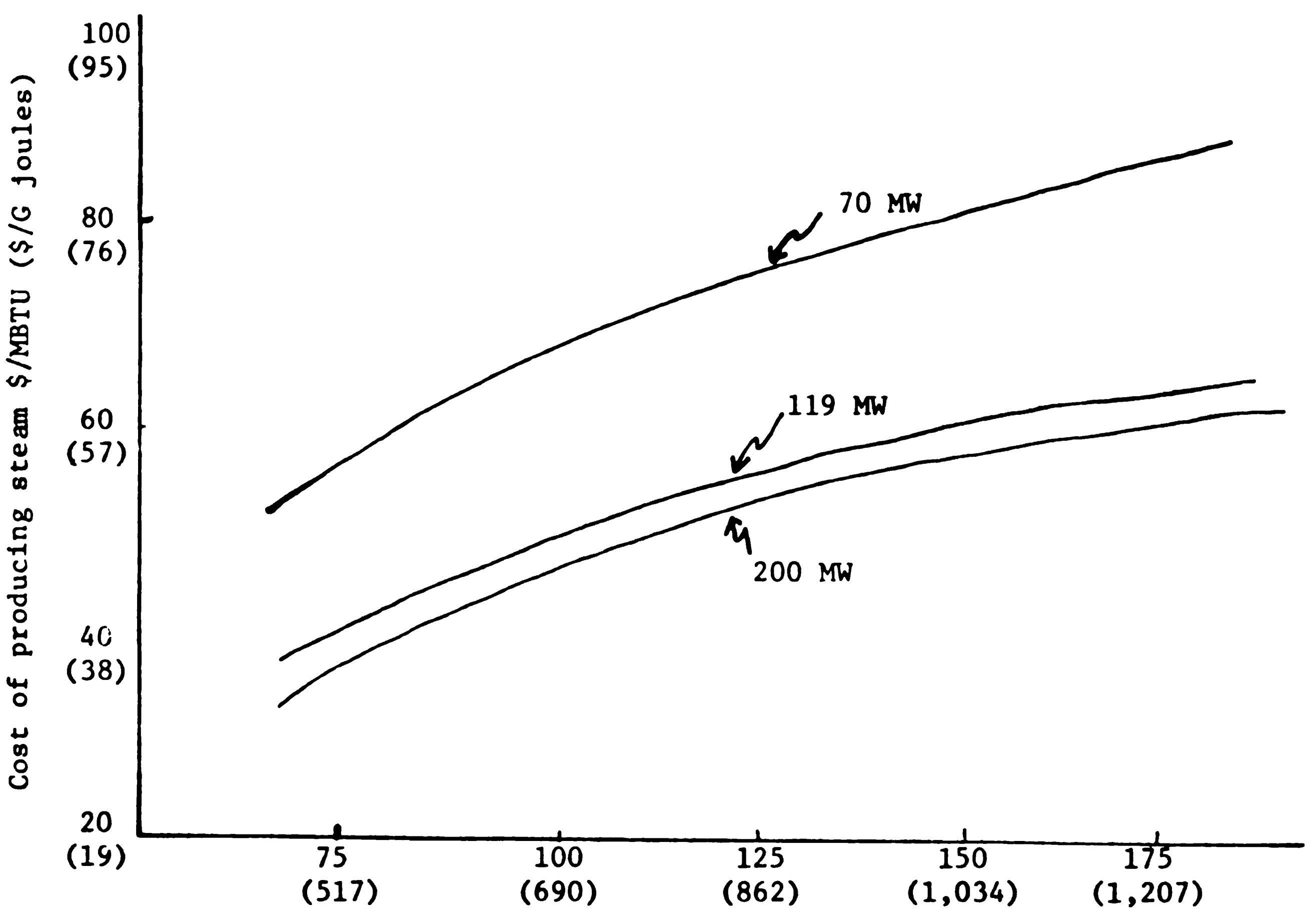

Figure 9.1 Cost of Producing Steam at Various Extraction Pressures*.

* assumes fuel cost of $.75/MBTU.

At the same extraction pressure the cost of steam decreases with increasing steam demand. From Figure 9.2 it is clear that it makes little difference which size unit is considered, under the same costs of installing the steam distribution system and fuel cost, the final cost of steam is about the same. While the cost of producing steam from various sized units indicates that larger units produce steam at lower costs, see Figure 9.1, the reverse situation holds when all costs are included. Figure 9.2 assumes that the installed cost of the steam distribution system is $13 million and a fuel cost of $.75/MBTU ($.71/G joule). Since smaller units add less to the total capital cost of the steam system, the final steam cost is less than from larger units.

Over 90 percent of the final cost of steam is dependent upon distribution costs i.e., exclusive of fuel, and since all units produce steam at about the same cost, for a given extraction pressure, the most critical cost is incurred as a result of installating the steam distribution system. Figure 9.2 assumes that the installation costs of the steam distribution system is $13 million. If the price of natural gas does not increase radically the minimum average steam demand would have to be at least 176,000 pounds/hour with a maximum flow of not more than 200,000 pounds/hour. Reducing the installation cost to $6 million changes the cost picture significantly. Whereas all units need at least 176,000 pounds/hour to be competitive with natural gas at $13 million, at $6 million all units are competitive with 80,000 pounds/hour average extraction flow. For example, if the installation cost of the steam distribution system is $6 million, the 70 MW unit has a final steam cost of $4.48/MBTU ($4.25/G joule) and the 200 MW unit $5.55/MBTU ($5.27/G joule) with an annual average extraction flow of 80,000 pounds/hour.

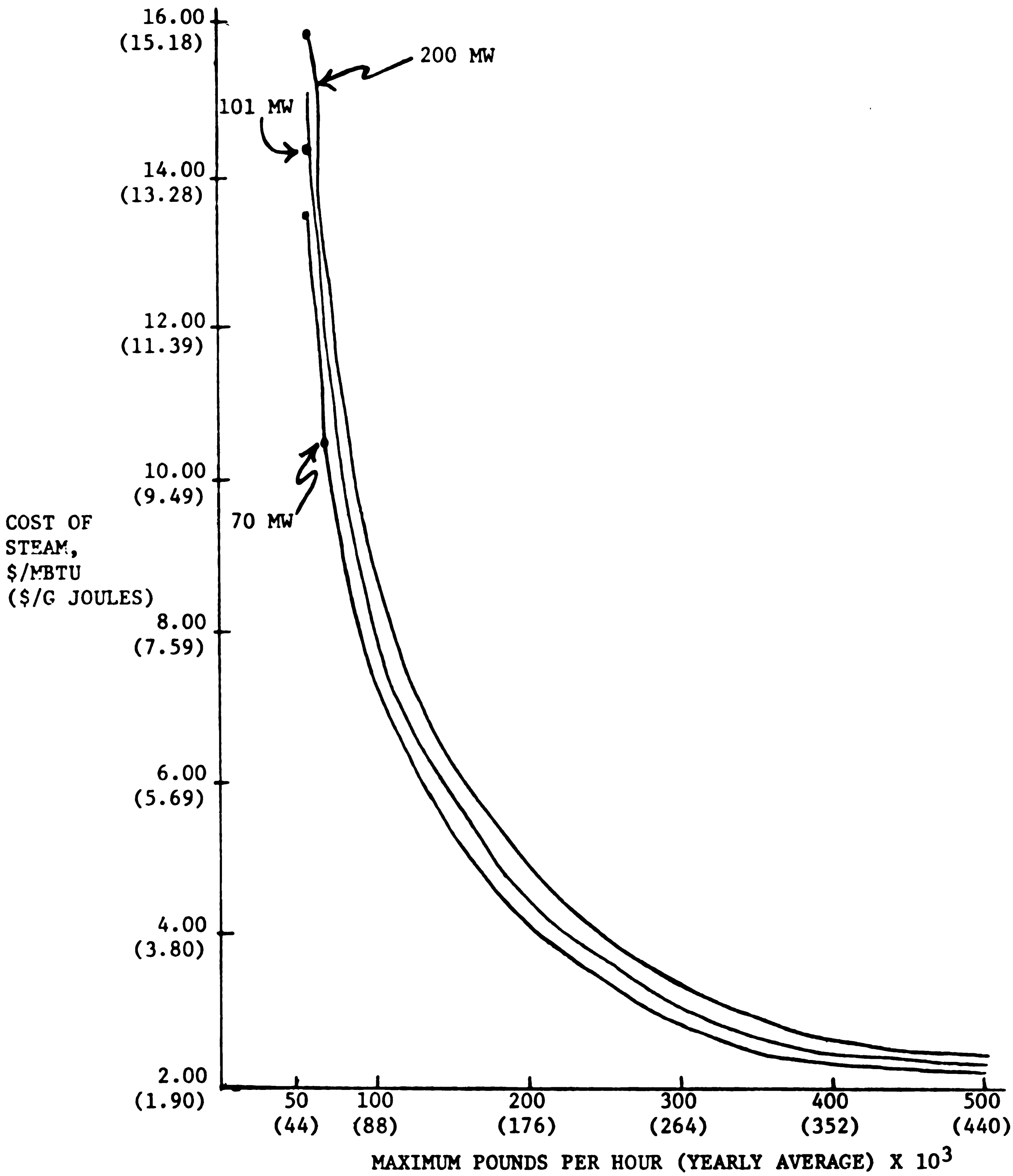

Figure 9.2 Cost of Steam at Various Extraction Flows

In general, we can conclude that for any size unit the cost of producing steam i.e., the cost of transforming chemical energy of the primary fuel into steam, is nearly the same and has little impact on the final cost of steam, see Figure 9.1. We can conclude this because the cost of producing steam from the plant is very small in comparison with the cost of distributing the steam. The critical factors are steam demand or extraction flow, and the cost of installing the steam distribution system.

Since the dual-purpose plant costs nearly 11 percent more than the cost of a single-purpose plant of the same size. Smaller units add less to the total capital cost of the steam system, even though they cost more per installed kilowatt than larger units. Therefore, smaller units, like the 70 MW unit in Figure 9.2, can provide steam at competitive prices before larger units at the same steam demand rate. But in doing so, smaller units lose their competitive advantage with large plants when it comes to the cost of electricity.

We now turn to sensitivity analysis to determine what happens to the cost of electricity and steam if the system is subjected to high costs for fuel and equipment.

Table 9.4 shows that larger units are affected most by higher costs for the electric function of the dual-purpose plant. As might be expected, if the cost of installing the electrical part of the plant is increased \$77/kW, the cost of steam increases by \$.21/MBTU (\$.20/G joule). Whereas, smaller units are affected least by increasing costs per kilowatt, we have already seen that the really important facts that overcomes this cost is the steam demand rate. And if the demand is high enough to

TABLE 9.4

Installed Cost of Unit and Cost of Steam

	average cost of steam, $/MBTU ($/G joule)			
	Size of Unit, MW			
$ per kilowatt	70	101	119	200
373	4.34(4.12)	4.26(4.04)	4.44(4.21)	4.82(4.57)
385	4.36(4.14)	4.27(4.05)	4.46(4.23)	4.85(4.60)
400	4.37(4.15)	4.29(4.07)	4.48(4.25)	4.89(4.64)
450	4.42(4.19)	4.36(4.14)	4.56(4.33)	5.03(4.77)

Assumes 200,000 pounds per hour extraction at about 70 psia, and $.75/ MBTU's fuel cost. Direct cost of steam distribution system $13,000,000.

provide an economically attractive environment for the dual-purpose plant, a 21 percent increase in the cost of installing the electrical part of the plant has a little affect in the cost of steam, increasing it by only 4 percent.

Table 9.5 presents these same increases for the cost of the electric power plant as they affect the cost of electricity from a dual-purpose plant. It does not seem to matter which cost is used, the final cost of electricity is quite reasonable. Although the capacity factor of these plants is high, 85 percent, it is not unrealistic to assume an 85 percent capacity factor since these plants must operate almost continuously to keep the cost of steam competitive, and thus the cost of electricity low. If the plant is a single-unit plant and not used continuously, then the extra steam generator must be used to insure steam supply to the community served. The cost of producing steam from the extra steam generator is in

TABLE 9.5

Installed Cost of Unit and Cost of Electricity

	average cost of electricity, mills per kWh			
	Size of Unit, MW			
$ per kilowatt	70	101	119	200
373	20.6	18.6	18.1	18.3
385	20.9	18.9	18.4	18.6
400	21.4	19.4	18.8	19.0
450	22.9	20.7	20.2	20.4

Assumes 85 percent capacity factor, 200,000 pounds per hour extraction at about 70 psia, and $.75/MBTU fuel cost. Direct cost of steam distribution system is $13,000,000.

range of $.85/MBTU ($.81/G joule). Increasing the cost of producing steam over the cost of extracting from the turbine by nearly 136 percent.

Sensitivity to higher fuel costs are shown in Table 9.6. Extracting at 70 psia (483 K newtons/m^2) and $.75/MBTU ($.71/G joule) fuel cost, steam costs $.36/MBTU ($.34/G joule) to produce from a 200 MW unit. Raising the cost of fuel to $1.50/MBTU ($1.42/G joule), the highest cost projected for 1985 for low-sulfur coal by FEA, increases the cost of producing steam by about 100 percent.

All units increase the cost of producing steam at about the same rate under the influence of higher fuel prices. Figure 9.3 indicates that the smaller unit increase a little faster than larger units. But the final cost of steam is affected only slightly by doubling fuel prices, increasing 13 percent for small units and only 7 percent for larger units.

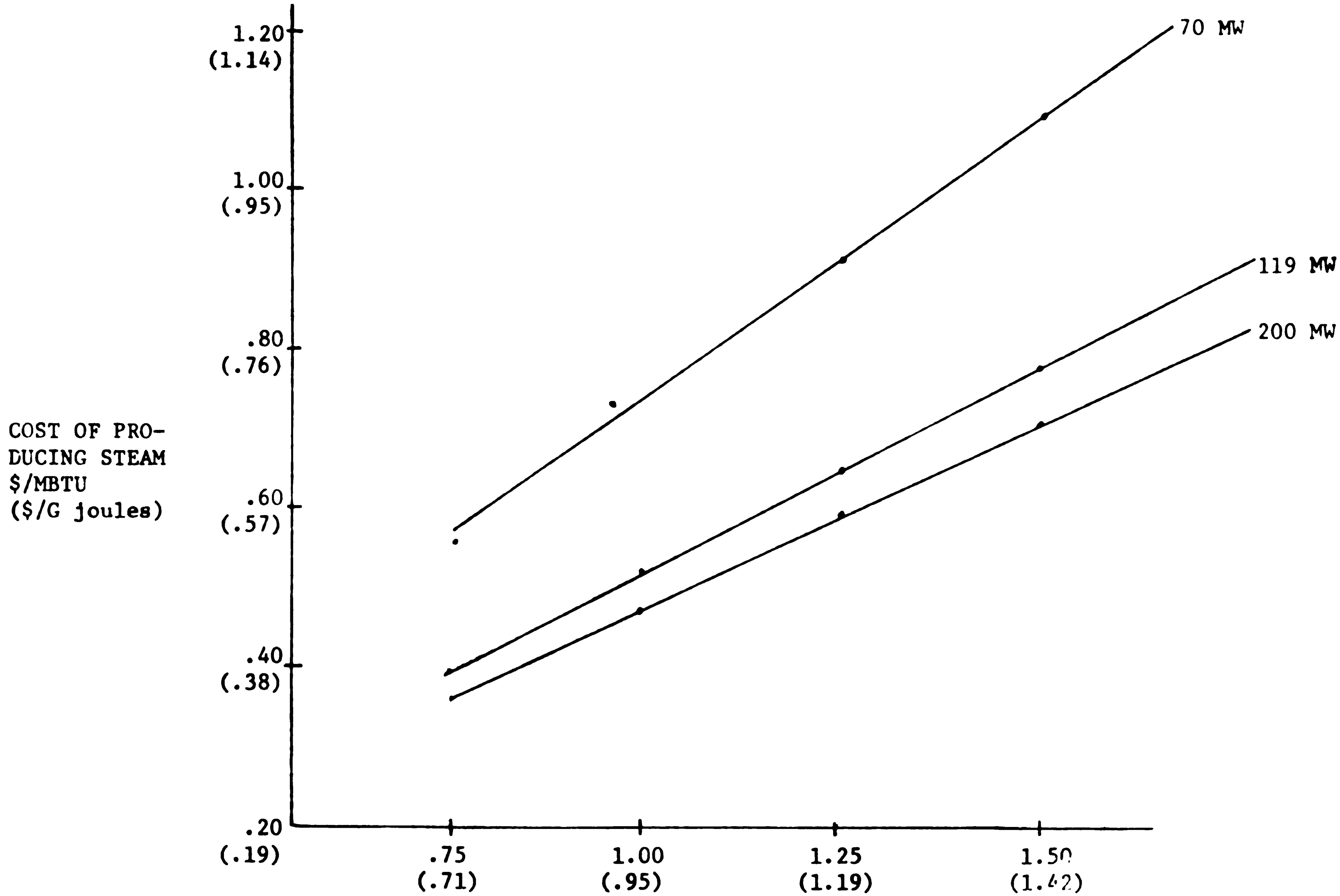

Figure 9.3 Cost of Producing Steam Cost of Fuel.

TABLE 9.6

Increased Fuel Costs and the Cost of Producing Steam and Electricity*

fuel cost $/MBTU ($/G joules)	cost of producing steam, $/MBTU ($/G joules)	cost of producing electricity, mills/kWh
.40 (.38)	.19 (.18)	4.3
.50 (.47)	.24 (.23)	5.3
.75 (.71)	.36 (.34)	8.0
.80 (.76)	.38 (.36)	8.5
1.00 (.95)	.47 (.45)	10.7
1.10 (1.04)	.52 (.49)	11.8
1.25 (1.19)	.59 (.56)	13.4
1.50 (1.42)	.71 (.67)	16.0

* Assumes extraction at 70 psia (483 K newtons/m^2) and 700,000 pounds per hour. Costs are fuel costs only. 200 MW unit.

The cost of producing electricity doubles with a doubling of fuel costs, see Table 9.6. All units are affected equally with respect to fuel costs, increasing the final cost of electricity from the plant by nearly 45 percent as a result of doubling fuel costs. Which makes electricity, a by product in these systems, the most sensitive to higher fuel costs.

In general, if there is sufficient demand for steam by a given community, all units can be expected to produce steam in the range of $.40 to $.60/MBTU ($.38 to $.57/G joule). The final cost of steam in the community decreases with increasing demand but as extraction flows increase from smaller units, 70 MW and smaller, the cost of electricity increases out of proportion to the benefits gained by lower steam costs. Although smaller plants add less to the total capital investment and thus need lower demand rates of steam as compared with larger plants, they can be expected to be more sensitive to higher fuel and equipment costs.

IX.7 Summary

This chapter has considered which community provides the best economic environment for dual-purpose plants, examined the costs of steam and electricity from these plants, and finally sensitivity to higher fuel costs and some important equipment.

To be competitive with other fuels, steam should not exceed \$4 to \$5/MBTU (\$3 to \$4/G joule), and even at these prices, steam may be too high, especially if the cost of natural gas is not completely deregulated. We found the minimum average annual demand for steam to be in the range 176,000 pounds/hour and if the capital costs to construct the system could be lowered, this minimum demand rate dropped considerably. At minimum demand rates, smaller units produce reasonably priced steam. But with increasing steam demand, the cost of electricity favors the larger plants.

The community best suited for a dual-purpose plant is a mixed, but well planned, grouping of commercial building, school, hospitals, multi-family dwelling units, and industry, if available. Single-family dwellings are too costly to be initially used as a start-up development for a dual-purpose plant or as the only user of steam. But a small commercial area is a good start-up development for a dual-purpose plant. In addition, the plant does not always have to be located right in the community since the commercial area had sufficient demand to allow the plant to be located quite a distance from the load center and still produce steam competitively.

APPENDIX

APPENDIX

Simulation Program Structure

The program is a modular or structured computer program incorporating eight subroutines, each designed to do a set of specific tasks, see Figure A1. The order in which subroutines are called is dependent upon the energy system under consideration, which is reflected in the structure of the driver or main program. Initial values and economic parameters needed by each subroutine are also stored in the driver program.

The steam demand subroutine uses either estimated monthly averages or hourly values as input to the remaining subroutines. More accurate data increases the validity of the results, and hourly estimates of steam demand based on temperature parameters should be used. Another alternative is to use a representative demand curve with random fluctuations to simulate real steam demand. Hourly steam demand by either method includes steam losses in transport and distribution, since this time-dependent steam demand is the demand as seen by the power plant.

In actual practice many dual-purpose power plants operate in two modes. During low-steam demand periods, late night to early morning, the plant operates at a level of output that will supply minimum steam demand for space and water heating. The plant then shifts to a higher level of output during peak demand periods for air conditioning and commercial steam demand, and regulates the output to keep the return condensate temperature near a predetermined level.

Hourly steam demand from the community, including steam losses, is input to the subroutine which determines the affects of extraction on

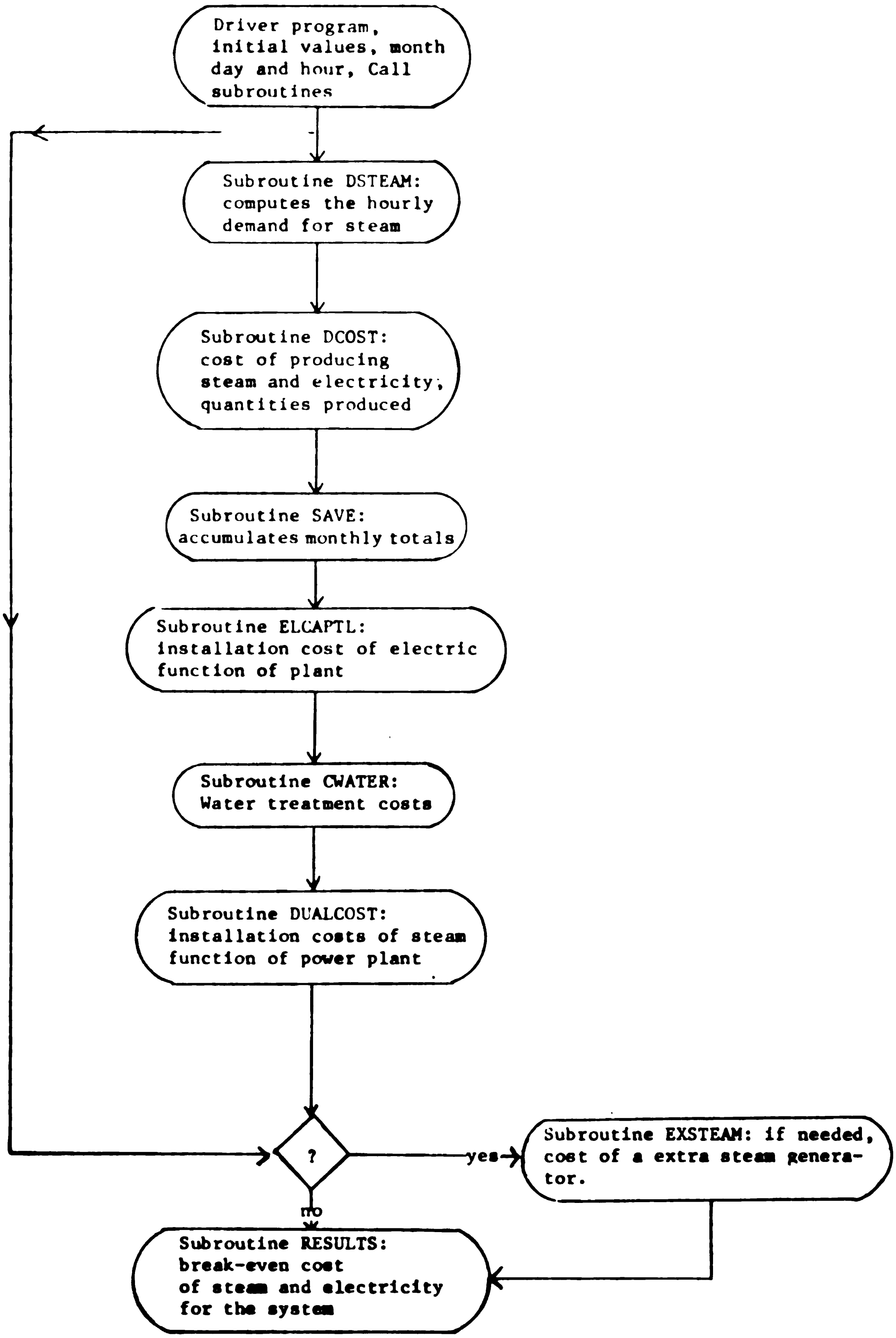

Figure A1. Program Structure

the production of electricity. Turbine characteristics, dependent upon rated unit size, are used with steam demand flow rate and extraction pressure to derive hourly output of electric power. This subroutine also derives the cost of producing steam and electricity using the same variables. Fuel cost and the enthalpy characteristics of the turbine are major constraints on the cost of production for both steam and electricity.

The hourly energy produced and costs of producing steam and electricity are accumulated in a subroutine from which monthly averages are determined. All inefficiencies of conversion and internal plant energy use are included in the energy and costs derived for this subroutine. Thus, the accumulated monthly averages reflect actual energy and cost dynamics for a given turbine, steam demand, and fuel cost.

The remaining subroutines calculate total capital investment for the system under consideration. All dual-purpose power plant systems must have additional water treatment capacity because they all receive condensate from the community. This cost is added to the steam function. In some configurations an extra steam generator is also added to the power plant to insure adequate steam supply during maintenance of the electric function of the plant. This cost is also added to the steam function.

A variety of methods are available to determine the total capital investment in the electric function of the plant. The method used in this study assumed that the power plant was a single purpose power plant and derived the capital cost based on a cost per installed kilowatt. This approach gives flexibility in the model because various installed costs can be considered.

Modifications to the turbine to facilitate steam extraction; steam controls, and steam headers, where charged to the steam function.

Generally, a percentage of the total capital cost of the electric part of the plant should give accurate estimates. Actual costs are difficult to determine since extraction turbines have not been built regularly. The basic capital cost method used in all cases considered was to separate the capital costs of the dual-prupose power plant and not have steam users subsidize electric users or vice versa.

The capital budgeting technique used to derive the break-even cost of steam and electricity to the community assumed a standard annual fixed charge rate for electricity and a capital recovery factor for steam. Adding to these per unit output costs, the cost of producing steam and electricity based on fuel cost, the resulting break-even cost was determined. The lifetime of both the plant, and the steam transport and distribution system was assumed to be 30 years.

Operation and maintenance costs for the steam system were added as a percent of the total capital investment. Final simulation runs included cost and energy variations to test the sensitivity of the break-even cost of steam and electricity to different economic parameters. This method allows the designer to final an optimum dual-purpose power plant for any given community under a variety of different economic conditions.

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