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New District Heating System Economic Factors Vary with Different Supply Temperatures

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ABSTRACT

District heating has been in use for many years and offers economic, environmental, and energy conservation benefits. A new district heating system may be based on either a steam or hot water distribution system. The supply media choice is based upon the composition of the load and other factors. This report discusses the relative advantages of steam vs hot water systems and between hot water systems of varying temperatures. Points of comparison include: capital costs, cogeneration efficiencies, building conversion costs, operating and maintenance costs, energy losses, maximum transport distances, and cooling applications. The major conclusion is that a thorough analysis of the market, including building equipment and consumer requirements, is essential in designing a district heating system and is of primary importance in determining the optimum supply temperature.

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1. INTRODUCTION

Many district heating sources were consulted during the preparation of this document. These sources are listed in the appendix, A District Heating Bibliography. These sources contain detailed historical, cost, and design information that is very useful and beyond the scope of this report.

1.1 <u>Definition</u>

Before proceeding into the general description of district heating, it is important to define two basic terms:

- District heating is the distribution of thermal energy from one or more centralized energy sources to commercial, industrial, and residential consumers for space conditioning, potable water heating, and auxiliary processes.
- Cogeneration is the process of producing both electricity and useful thermal energy from a single energy source.

1.2 U.S. District Heating Highlights

District heating is not a new technology. The concept was first used in Lockport, New York, over 100 years ago. The first systems were designed around heat-only boilers that supplied steam for space heating. During the early part of the 20th century, the first small cogeneration district heating plants came into existence. These systems used the exhaust steam from small dual-purpose power plants to heat buildings in nearby business districts. As a result, district heating combined with cogeneration was widely accepted. During the later 1940s, however, the introduction of inexpensive oil and natural gas for space heating reduced the rapid growth of district heating. At about the same time, utilities were introducing large condensing electric power plants located remote from the urban areas. It was not economical to transport steam over such long distances. As the smaller, older cogeneration units were retired, sources for the district heating system steam were eliminated and the costs of supplying steam escalated, making district heating even less attractive.

Many U.S. steam district heating businesses were not profitable because of such factors as inadequate rates or the lack of proper metering devices. For example, as the costs increased during the transition from the use of exhaust steam to prime steam, rates were kept low by regulation. As a result, utilities shut down many small district heating systems because they were not profitable. Current statistics from the International District Heating Association show total annual utility steam sales of 8.44×10^7 GJ (80×10^{12} Btu). It is estimated that nonutility district heating systems (government institutions and college campuses) use a total quantity of steam about equal to that of utilities. District heating thus satisfies less than 1% of the demand for heating in the United States.

1.3 European District Heating Highlights

The history of district heating in Europe is somewhat different from that in the United States. The development of district heating networks in northern and eastern Europe started in the late 1940s. Hot water, rather than steam, was used as a transport medium, and for large systems hot water has proved to be the more economical of the two. European systems tend to have larger service areas than those in the United States. They serve lower heat-load density regions and use remotely located cogeneration power plants. The aggregated annual growth rate of district heating in these countries is presently about 20%/year.

1.4 Benefits of District Heating

A district heating system has the potential to offer consumers many major advantages over operating their own building boilers. The advantages include (1) competitive space-heating energy costs, (2) lower maintenance costs and higher reliability, (3) improved air quality in the community, (4) improved safety (compared with fuel-fired systems), (5) smaller space requirements, and (6) lower initial capital costs for new buildings. The most important advantage to the consumer is clearly the economic advantage. This advantage is usually achieved through the fuel flexibility aspect of district heating and the conservation potential of cogeneration. The economy of fuel flexibility is seen at large central boiler plants capable of firing the lowest price fuel, be it coal, natural gas, or refuse. Cogenerating thermal energy for district heating and electricity makes economical use of the boiler steam. The steam district heating system in Milwaukee successfully competes with the natural gas space-heating fuel by using both the fuel flexibility and the cogeneration conservation features. A system in Uppsala, Sweden, competes with oil space heating and is successful only because of the cogeneration conservation aspects. District heating systems can compete through the fuel flexibility feature by using a relatively inexpensive fuel such as coal.

Another consumer advantage is the lower maintenance cost and high reliability. This advantage is a result of the simplicity of the consumer's equipment. The main component of this equipment is a series of heat exchangers that are similar to car radiators. The heat exchangers seldom need maintenance and in addition, no boiler operator is needed. Therefore, the simplicity of the building equipment results in higher reliability and lower consumer maintenance costs.

The district heating system also has the potential for improving ground level air quality in a community. Emissions from one stack at a central power plant replace emissions from many low-level space-heating stacks, and more effective controls can be put on the central stack than on the many low-level stacks. However, the overall effect of district heating on air quality depends to a large extent on the type of fuels being replaced in the individual units.

1.5 Steam vs Hot-Water District Heating

A hot-water district heating system has many advantages over a steam system, although some industrial uses or hospital loads may require steam service. A hot water district heating system has lower energy transport costs that result in more economical distribution over larger distances than is typical for steam systems. Thermal energy transported by steam is limited to a maximum distance of about 8 km (5 miles), whereas a hot-water system can transport energy with low energy losses for up to 80 km (50 miles). Another significant advantage is that in a cogeneration system hot water can be produced more cheaply than steam of district heating quality [~0.7 MPa (100 psig)]. A modified or new cogeneration plant does not sacrifice as much electricity when producing hot water as when producing steam for a district heating system. The hot-water temperatures range from 82 to 150°C (180 to 300°F). The lower electricity sacrifice means lower thermal energy costs. Hot water is also compatible with thermal storage systems that may allow a district heating system to follow its thermal load while being supplied by a cogeneration turbine that may be operated to follow an electrical system demand. Also, a hot-water distribution system is more flexible than a steam system. Hot water from various sources can be used, and new pumping stations can be added to extend the system (large steam compressors are not commercially available). As a result, a hot-water system is more adaptable to meeting the changing needs of a community.

The majority of modern buildings are constructed with internal hot-water or hydronic distribution systems. These systems allow for more effective control of the heating system and do so with considerably less noise. The most modern heating and ventilation systems are compatible with the hot-water district heating system. Of course these buildings could also be heated with a steam district heating system, but energy losses are incurred in the use of pressure-reducing equipment.

For these reasons a hot-water district heating system should be considered whenever an existing steam system is due for replacement or when an existing steam district heating system is being expanded beyond the current system boundaries.

There are several disadvantages which tend to impede hot water district heating efforts in the United States. The primary impediment is that U.S. engineering and construction firms are not as familiar with state-of-the-art hot water technology as with steam technology. Therefore, they prefer to design steam systems instead of water district heating systems.

Hot water district heating systems have limited cooling applications. Unless the supply temperature is higher than 270°F, absorption cooling is not economically viable. Steam turbine-driven chillers are also not adaptable to hot-water district heating systems.

1.6 Components of the Cost of District Heating Energy

Approximately 60% of the delivered energy cost from new district heating systems is incurred as capital cost and interest charges, whereas 30% is fuel cost, and only 10% is nonfuel operating and maintenance cost (Fig. 1). This estimate is based on a coal cogeneration hot-water district heating system supplying buildings having primarily hot-water heating systems. The 60% of the delivered thermal energy cost that is capital cost can be further subdivided into transmission and distribution, consumer equipment and energy plant costs. Figure 2 shows the approximate distribution of these capital costs. The transmission and distribution cost encompasses the cost of the major transmission system from the power plant to the neighborhood and the distribution piping to individual buildings. The building heating system adaptation and necessary metering equipment comprise the consumer equipment costs. The energy plant is a coal cogeneration facility.

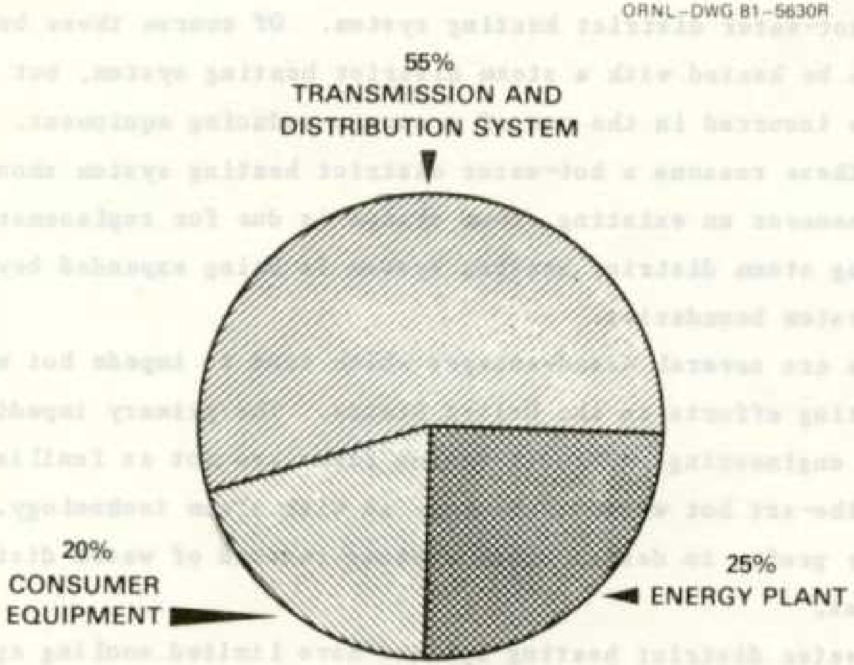

Fig. 1. Capital investment is the largest cost component of district heating.

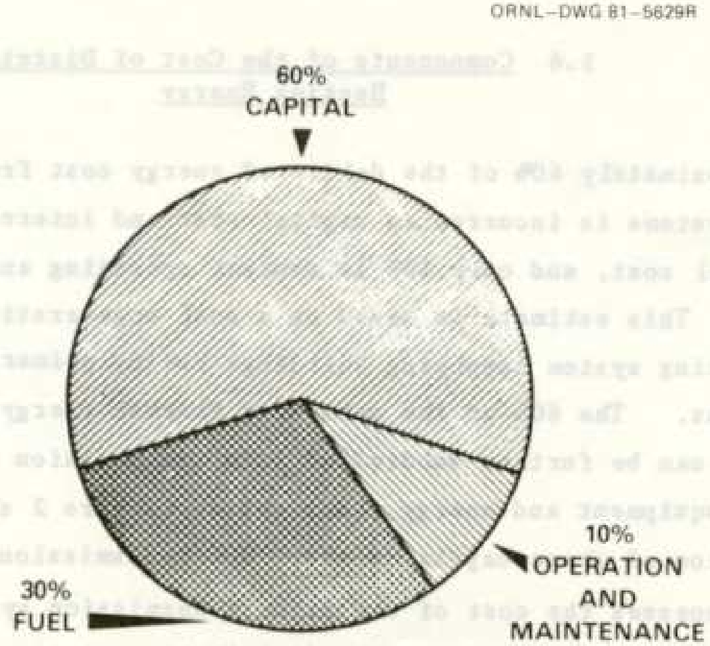

Fig. 2. Distribution piping is the largest district heating capital cost.

A large initial capital outlay is needed to develop a new DH system including the installation of the distribution network, conversion of building heating systems and the modification of existing power plants with new cogeneration equipment. Although this type of cost is typical of most utility projects, it is a deterrent to initiating a new district heating system in the United States.

Cost estimates for modern hot-water U.S. district heating systems are based on assumptions and comparisons with similar projects in the United States. Actual data in the United States are practically non-existent since only a small number of new U.S. district heating systems exist and none of them are hot water systems. A good example of using similar systems to get reasonable estimation of district heating costs is demonstrated by the district heating cost estimates originating from sewer construction cost information. Sewer construction costs have a large historical data base, both for construction and nonconstruction costs including piping, manholes, pumps, trenches, shoring, dewatering, and pavement removal and replacement, which are similar to district heating distribution systems. But there are obvious differences between sewer and district heating piping. For example, sewer costs are for a single-pipe system, rather than the two-way supply and return district heating piping. District heating piping would incur additional costs for items such as insulation, expansion joints, and thicker walled steel pipes. Trenching and shoring costs for district heating would tend to be lower since shallower burial is possible. These types of discrepancies in comparing similar systems can result in significant cost estimating errors.

Site specific conditions add another level of imprecision to this cost estimation approach. Costs depend upon whether the construction is done in a fully developed urban area (with existing pavement, underground utilities, and a high labor rate) or in a developing rural area without these costly features that will make a considerable difference in the piping system installation costs. Other site specific conditions such as the type of terrain and local construction codes also affect the installed piping cost.

In this report, a conceptual approach is used to discern the relationships between the district heating system supply temperature and various cost components. The general trend of system costs, rather than their precise magnitude, is discussed to focus attention on the cost components of major significance.

2. SYSTEM ECONOMIC PARAMETERS

High-temperature water district heating systems (HTS) are defined as systems having a distribution supply temperature of around 177°C (350°F). HTS will be compared to low-temperature water systems (LTS), systems having supply temperatures around 93°C (200°F) or less and moderate-temperature systems (MTS) with temperatures in the range of 93 to 121°C (200 to 250°F). Each system has design characteristics that favor it over the others in particular site-specific situations.

2.1 High-Temperature Water Systems (HTS)

High-temperature systems are favored over the lower temperature alternates in most cases where the heat load is predominantly steam-heated buildings or industrial processes requiring the higher temperature. The HTS can serve hot water and steam building heating systems as well as higher temperature industrial loads and absorption air conditioning units.

Large industrial customers and commercial customers such as hospitals, steam cleaners, and canneries and the summer air conditioning loads tend to increase the base load over the summer months and may improve the overall district heating system economics. The main cost components of a district heating system, including the power plant, building retrofit, and distribution piping system are affected differently by the supply temperature. For the distribution system, costs increase with increasing supply temperatures. Thicker gauge pipes, sturdier valves, and better insulation are necessary with higher supply temperatures and pressures. Accompanying these more costly materials are higher installation costs, again increasing the overall cost of the distribution system.

The fuel costs also tend to increase with increasing supply temperature. With an extraction turbine cogeneration system, it has been shown that as the extraction temperature (i.e., the district heating supply temperature) increases, the electricity production decreases. Figure 3 shows the trade-off and was generated using a turbine-cycle computer model. This decrease in electrical output decreases the overall efficiency of the

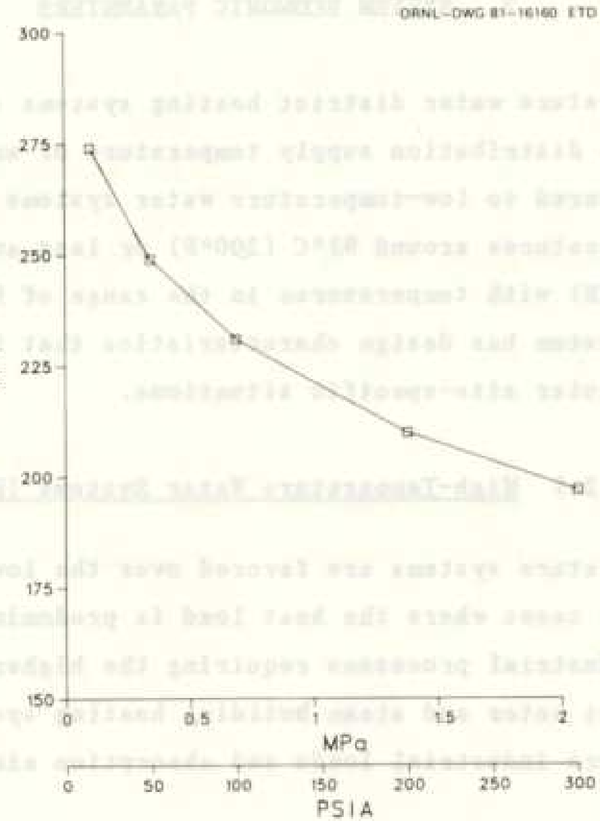

Fig. 3. Electrical output vs extraction steam pressure for a 358-MVA generator with a 125-kg/s (1 x 10^6 lb/h) steam extraction. The throttle pressure was 24.2 MPa (3515 psia).

system. A decreased efficiency means more fuel must be consumed to provide the same energy services, and fuel costs are therefore higher.

Thermal and fluid losses could also be counted against fuel costs since the greater these losses are, the more fuel is needed to deliver the same amount of energy to the customer. These types of losses are most serious with HTS. Steam traps can represent significant losses for steam systems.

The building retrofit subsystem is the only component cost exhibiting a relatively lower cost for HTS; in contrast, the fuel and piping components show a higher cost. This occurs because of the simplicity of retrofitting most customers to an HTS. Steam and hot water (hydronic) building heating systems require only the addition of a heat exchanger (with monitors and controls) to the existing heating system. No extensive reworking of the building heating system is required. With a high supply temperature, the difference between the supply and the return temperature is high when serving hydronic buildings; therefore, the same amount of heat can be transferred using a smaller heat exchanger and pipe size. (The temperature difference is not as great for steam-heated buildings; however, a significant amount of energy remains in the return water.) High-temperature water can also be used to produce low-pressure steam [55 kPa (8 psig)], and most absorption air conditioning retrofits and industrial loads are therefore economical.

In order to determine the effect a particular component cost has on the total system cost, it is necessary to know what fraction of the total cost that component represents. The transmission and piping system is responsible for ~55% of the total capital costs. Therefore, any fractional change in piping system cost would have a significant impact on the total capital cost. Since the building retrofit cost and energy plant cost each contribute less than one-half as much to the total capital cost as does the piping system, a percentage change in these system costs would have less than half the impact on total capital costs.

The focus is on capital costs because the other portions of total costs (operation and maintenance and fuel costs) are not significantly affected by the choice of supply temperatures. Fuel costs are somewhat more sensitive than operation and maintenance costs to variations in the supply temperatures, and fuel costs are a larger portion (30%) of total costs.

2.2 Low-Temperature Systems (LTS)

The low-temperature hot water district heating systems are capable of having the lowest overall system costs — a consequence of numerous cost-saving aspects. In the distribution and transmission piping system, the use of low cost materials (plastic pipe) with relatively inexpensive insulation (polyurethane) decreases costs substantially. These materials facilitate easier and cheaper installation. Thermal energy losses are minimal because of the relatively small temperature difference between the water and the earth and the excellent insulating ability of polyurethane.

The building conversion costs can also be appreciably lowered if the building heating system is connected directly to the district heating system. This eliminates the need for an expensive heat exchanger. This method is also more energy efficient thus lowering fuel costs. Thermal energy costs are less when cogenerating as shown in Fig. 4. Since lower temperature thermal energy is extracted, less electrical energy is sacrificed, thus, increasing the overall energy efficiency of the power plant. It is also possible to use back-pressure cogeneration with LTS, giving the highest cogeneration yield.

LTS also have their drawbacks. It is difficult to serve steam-heated buildings, industrial loads, and air conditioning with this system. It is frequently limited (by economics) to hydronic building heating systems.

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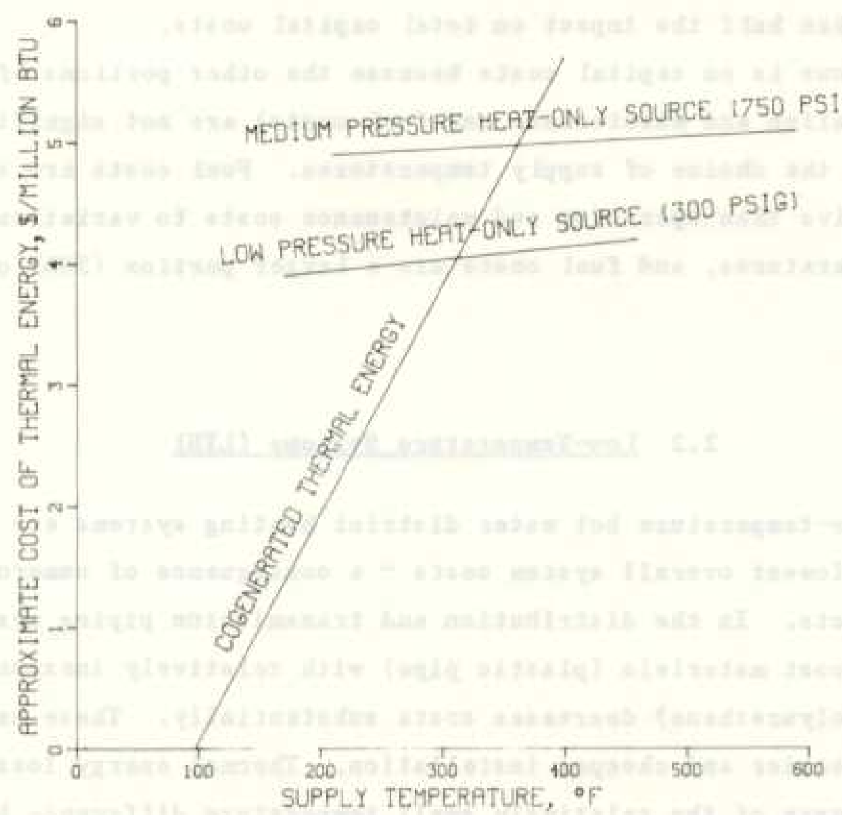

Fig. 4. The approximate cost of thermal energy varies with the supply temperature level.

Seasonal loads are uneven because of the small summer load which is essentially domestic water heating. The plant capacity factor is diminished and that increases the plant cost per unit of energy delivered.

Pumping costs are high relative to higher temperature systems. For example, consider a supply temperature of 93°C (200°F) and a return temperature not lower than 60°C (140°F) (a reasonable scenario) which leaves a temperature difference of 33°C (60°F). By increasing the supply temperature to that of an HTS, the temperature difference would increase accordingly. With a smaller temperature difference, less heat is transferred to a building per quantity of district heating water circulated. Thus, with a lower temperature difference more pumping is necessary to supply a given amount of heat. Heat exchanger costs also increase with decreasing supply temperatures.

The design temperature differences between the supply and return district heating water also affect the pipe size and therefore the pipe cost. As an example, a 50°C (90°F) temperature difference for a 200-MW_t system requires a pipe diameter of 66 cm (26 in.). Decreasing the temperature difference to 39°C (70°F) results in a 15% increase in required pipe diameter to 76 cm (30 in.).

2.3 Moderate-Temperature Systems (MTS)

Moderate-temperature water district heating distribution systems contain many aspects of the LTS and HTS. MTS are defined as systems having supply temperatures in the range of 93 to 121°C (200 to 250°F). At the lower end of this temperature scale, MTS operates much like the LTS with similar characteristics, such as low piping system material and installation costs, relatively low cogenerated thermal energy cost, and low thermal energy losses. Building retrofit costs are very similar to the LTS system although the heat exchangers may be smaller and less expensive.

For a given temperature difference, the distribution piping becomes more expensive as the supply temperature increases as shown in Fig. 5. This is a result of the pipe material changing from plastic to thin wall steel to thicker wall steel and the insulation changing from polyurethane

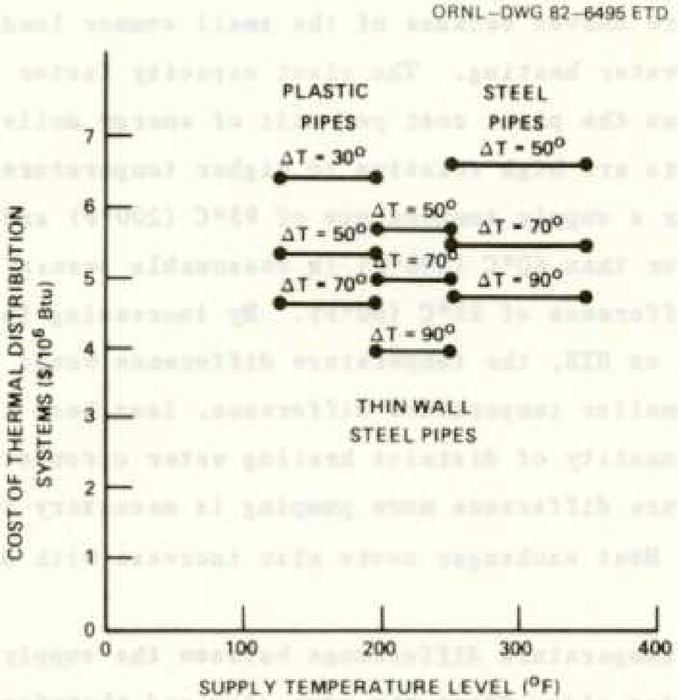

Fig. 5. With higher supply temperature systems, the distribution system requires more expensive construction materials and methods.

to more expensive mineral wool. Additional expansion joints are also required resulting in higher material and installation costs.

Cogeneration in the power plant is less efficient for higher supply water temperature. Figure 3 shows the typical relationships of extraction temperature/pressure to the reduction in electrical production. Economical use of cogeneration requires that the reduction be as low as possible. The cost of reduced power production is incorporated into the district heating thermal energy costs.

2.4 Variable-Temperature Systems (VTS)

District heating systems with variable supply temperatures show promise as the most efficient systems for specific situations. The hot water district heating system being planned for St. Paul will supply thermal energy at a maximum temperature of 121°C (250°F) with the supply temperature decreasing to 88°C (190°F) with increasing outdoor air temperature, as shown in Fig. 6. This type of variable temperature supply schedule is used in many European hot water district heating systems to provide

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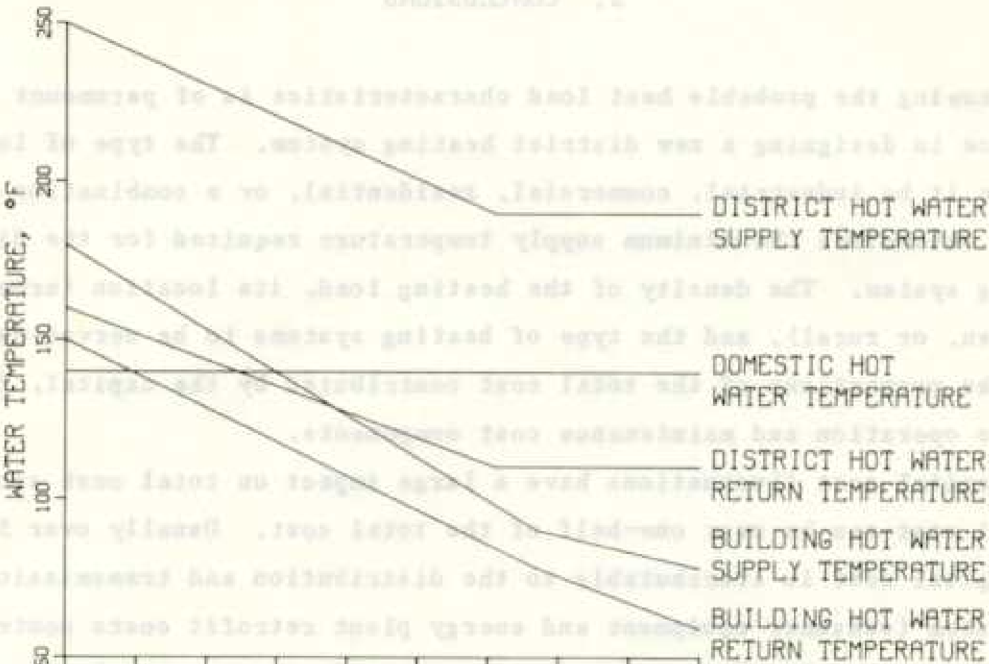

Fig. 6. Hot water temperatures for district heating system and hydronic building heating system as a function of outside air temperature.

for predominantly building heating and domestic hot water heating demands. Reducing the supply temperature as the outdoor air temperature increases (and the building heating demand decreases) and also holding the maximum supply temperature to 121°C (250°F) reduces the cost of the St. Paul piping distribution system, the cost of cogenerated thermal energy to the district heating utility, and hence the long-term cost of district heating to the consumers for the following reasons:

1. The overall efficiency of the cogeneration power plant is improved, and the electrical production losses are minimized.
2. Low-cost, prefabricated pipe and polyurethane foam insulation conduits can be utilized.
3. Heat losses and corrosion are minimized.
4. The piping system design, fabrication, and testing do not have to conform to the Minnesota Code for High Pressure Steam Piping and Appurtenances and are therefore less expensive.

3. CONCLUSIONS

Knowing the probable heat load characteristics is of paramount importance in designing a new district heating system. The type of load, whether it be industrial, commercial, residential, or a combination of these, determines the minimum supply temperature required for the district heating system. The density of the heating load, its location (urban, suburban, or rural), and the type of heating systems to be served determine the proportions of the total cost contributed by the capital, fuel, and the operation and maintenance cost components.

Capital cost fluctuations have a large impact on total cost since the capital cost can be over one-half of the total cost. Usually over 50% of the capital cost is attributable to the distribution and transmission piping system (consumer equipment and energy plant retrofit costs contribute the remainder). Realizing the significance and relative magnitudes of these cost components help in developing a perspective for evaluating new district heating systems.

Optimizing the supply temperature in relation to the total cost of the delivered energy is the major goal in designing a new district heating system. A knowledge of the relationships between supply temperature and piping system, consumer equipment, and energy plant costs is critical for this optimization. Understanding these capital cost trends for different supply temperatures ultimately reflects the total cost trends since capital costs are the most significant and temperature sensitive component of the total cost. The total system cost usually increases with higher supply temperature because of higher capital and fuel costs. The fuel cost rise is attributable to a decrease in cogeneration efficiency and an increase in thermal losses. The capital cost reflects the higher piping system costs.

Building heating system retrofit cost may become an important variable for distinguishing between low- and medium-temperature district heating system costs. For a heating load consisting primarily of steam heating systems, the building retrofit cost decreases above the supply temperature at which steam can be supplied to existing heating systems. This is in contrast to the expensive changes usually required to retrofit steam heating systems to low-temperature district heating systems. The disadvantage of lower temperature systems is that retrofitting steam-heated buildings may not be economical. In contrast, a heating load composed primarily of hydronic heating systems does not require high supply temperature. A lower total cost in this case results from a lower capital cost (less expensive piping system) and a lower fuel cost (higher cogenerating efficiency).

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