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Modern Hot Water District Heating

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ABSTRACT

In the United States, steam district heating has been used extensively in universities, military installations, hospital complexes, and cities. However, many of the city systems have been abandoned because of competition from relatively cheap oil and natural gas. Most of the steam systems were inefficient and could not use natural gas and oil and economically serve their customers. The history of district heating in Europe is drastically different from that in the United States. The development of district heating in northern and eastern Europe started in the early 1950s. Hot water, rather than steam, was used as the transport medium and the systems have proved to be more economical.

Recently, the northern European concept has been introduced into two U.S. cities - St. Paul and Willmar, Minnesota. The hot water project in St. Paul started construction and operation in the summer and fall of 1983, respectively. The entire first phase of the St. Paul project will take two summers to construct and will connect approximately 80 buildings for a total of 150 MW(t). The system spans the entire St. Paul business district and includes privately owned offices and retail buildings, city and county government buildings, hospitals, the state capitol complex, and several industrial customers. The City of Willmar, Minnesota, replaced an old steam system with a modern hot water system in the summer of 1982. The first phase of the hot water system was constructed in the central business district. The system serves a peak thermal load of about 10 MW(t) and includes about 12,000 ft (3,600 m) of network. The Willmar system completed the second stage of development in the fall of 1983. These two new systems demonstrate the benefits of the low-temperature hot water district heating technology. The systems are economical to build, have high reliability, and have low maintenance and operating cost.

INTRODUCTION

District heating is a technology that originated in the United States and, more recently, has been successfully implemented in many European countries. In the United States, the majority of the systems use steam as a transport medium. Steam is produced at the central power plant and distributed through an underground piping network to residential, industrial, and commercial buildings. Before proceeding into the general description of district heating, it is important to define two basic terms:

1. District heating is the distribution of thermal energy from one or more centralized energy sources to commercial, industrial, and residential customers for space conditioning, domestic water heating, and auxiliary processes.
2. Cogeneration is the sequential production of electricity and useful thermal energy from the same energy source.

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The history of district heating in Europe is somewhat different from that in the United States. Modern hot water district heating systems have been developed and successfully implemented in many European cities. Low-temperature hot water, rather than steam, has been used as the transport medium. Many advantages over the steam district heating technology have been demonstrated. Recently, the northern European concept of low-temperature hot water district heating has been introduced into two U.S. cities, St. Paul, Minnesota, and Willmar, Minnesota. This paper will discuss the advantages of modern hot water district heating using the examples of St. Paul and Willmar.

BACKGROUND/HISTORY

District heating is not a new technology. The concept was first introduced over 100 years ago, and 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. The systems used exhaust steam from small dual-purpose power plants to heat buildings in the nearby business districts. The concept was successful, and district heating, combined with cogeneration, was widely accepted. During the 1950s, the introduction of inexpensive oil and natural gas for space heating reduced the rapid growth of district heating. During the 1960s and 1970s, many of the commercial district heating businesses were abandoned due to the competition from cheap oil and gas and the inefficiencies of the steam distribution technology. Presently, about 100 commercial district heating systems exist in the United States.

However, in the United States there are a large number of central heating systems where the owners of the systems are also users of the thermal energy. There are many such systems on university campuses, military installations, government complexes, and industrial installations. Often, these systems have central plants that supply thermal energy and sometimes electric power. The majority of these systems utilize steam as the distribution medium. There are relatively few hot water district heating systems, and most of the hot water systems operate at high temperatures [defined here as greater than 300F (150C)]. There are approximately 1000 district heating systems on university campuses and several hundred on military installations and other institutional complexes. Therefore, it can be concluded that the vast majority of district heating systems in the United States are situations where the district heating system owners are also the users of the thermal energy. Currently, the urban contribution for district heating constitutes a very small percentage. Modern low-temperature hot water district heating, with its attractive economics, is an alternative for U.S. cities. Many cities could replicate the experience of Willmar and St. Paul.

The history of district heating in Europe is not as old as in the United States. While examples of district heating date back to 1893 when the first system was installed in Hamburg, Germany, significant system development did not occur until the early 1950s. Since that time, a large number of modern low-temperature systems have been successfully implemented. The history of these systems demonstrates that they are cheaper to build and generally have significantly lower energy losses. In addition, the low-temperature hot water systems have lower maintenance and operating costs.

Sweden, a country with 8.1 million people, has been one of the leaders in the development of modern district heating systems. Approximately 3 million Swedes live or work on premises served by hot water district heating. The country has installed systems with a total capacity of 16,000 MW and expects to have installed capacity of 30,000 MW by the year 2000. There are approximately 106 cities in Sweden with district heating, and all the larger systems have incorporated cogeneration. The standard design for modern hot water systems is as follows: the system pressure is 100-250 psig (790-1830 kPa), the hot water supply temperature varies between 175F (80C) and 250F (120C), and the return temperature varies between 140F (60C) and 160F (71C). The variation of supply and return water temperatures is in relationship to the outside temperatures (figure 1).

Recently, the northern European concept has been introduced into two U.S. cities, St. Paul and Willmar, Minnesota. The hot water project in St. Paul started construction in the summer of 1983, and the system began operation in the fall of 1983. The entire first phase of the St. Paul project will take two summers to construct and will connect approximately 80 buildings, for a total of 150 MW(t) peak load. The system spans the St. Paul business district (figure 2) and includes privately owned office and retail buildings, city and county government buildings, hospitals, the state capitol complex, and several industrial customers. The city of Willmar, Minnesota (population, 20,000), replaced an old steam system with a modern hot water system in the summer of 1982. The first phase of the hot water system was constructed in the central business district (figure 3). The system serves a thermal load of 10 MW and includes about 12,000 ft (3,600 m) of distribution network. Willmar's piping system, which mostly includes small-diameter pipe, was installed for approximately $125/ft ($410/m) of distribution system. The Willmar system started a second phase of expansion in the summer of 1983 and is planning continued expansion in the future. The system currently serves residences as well as commercial, institutional, and industrial customers.

COMPARISON OF STEAM AND LOW-TEMPERATURE HOT WATER SYSTEMS

The comparison between steam and hot water systems in this section will be limited to applications that serve a space heating load. There will be no discussion of process applications that favor steam distribution. The comparison between hot water and steam will be made in three areas: (1) capital cost, (2) efficiency of the systems, and (3) maintenance of the systems. The comparison will be between a typical 100 psig (790 kPa) city steam system and a low temperature [<250F (<120C)] hot water system.

The capital cost of a conventional 100 psig (790 kPa) steam system is generally at least double the cost of a modern low-temperature water system. There are several reasons for this cost differential. Steam systems generally use a schedule 40 pipe, as compared to something between a schedule 10 and schedule 20 for hot water. The material in the hot water design is about half the material of the schedule 40 steam design. One reason for requiring the thicker wall in the steam system is thermal expansion stresses due to higher temperatures. The lower temperatures in the hot water system result in less thermal stresses, thereby allowing thinner wall construction. The lower temperatures also allow for the use of inexpensive polyurethane foam insulation and a polyethylene outer jacket. The polyurethane foam will only withstand continuous temperatures up to about 266F (130C), and is, therefore, not useful in most steam systems. Moreover, due to the lower temperatures and lower thermal stresses, the hot water system can be designed with fewer expansion compensators. The design of the low-temperature hot water system also includes shallow pipe burial, and the systems have prefabricated fittings and joints. Both of these features are conducive to easy installation.

Some data are available on the installed cost of modern district heating piping in the United States. As mentioned previously, the hot water system in Willmar, Minnesota, was installed for approximately $125/ft ($410/m) of network length. The system in St. Paul, for comparable piping sizes, will be installed for approximately $200/ft ($660/m). The installed cost of a typical 100 psig (790 kPa) steam system of the equivalent capacity ranges in price from $300 to $600/ft ($980 to $1960/m). This indicates that a new steam system is significantly higher in cost than a new thin-wall hot water system.

A new steam system with condensate return will have an operating efficiency in the range of 85% to 90%. The losses include 10% conduction loss through the insulation, 1% to 2% loss from traps, and 3% to 4% loss from miscellaneous leaks. In comparison, a new hot water system will have efficiencies of 90% to 95%. Almost all the losses are conduction through the insulation, and these are less than the conductive losses in a steam system due to the lower operating temperatures. The hot water systems also have no losses due to malfunctioning traps since there are no traps. Leaks in a hot water system are much easier to detect and repair. The International District Heating Association (IDHA) has operating statistics on 50 U.S. steam systems. These systems range in efficiency from approximately 85% down to 40%. The majority of the systems are older and have operating efficiencies of about 60%. The European district heating organization, UNICHAL, has operating statistics on several hundred European hot water systems, and the vast majority of these have operating efficiencies of 90% to 95%. The low-temperature hot water systems tend to be more efficient than new steam systems and tend to maintain their efficiency for many years.

The maintenance comparison between the steam system and the hot water system is similar to the efficiency comparison. Scandanavian systems show a cost for maintenance of .4% to 1% per year of the capital investment. It is estimated that the average for a new steam system would range between 1% and 2% per year. The steam system is higher due to the addition of trap maintenance and costly failures in the steel jacketed steam piping technology.

DISTRICT HEATING THERMAL ENERGY PLANTS

One of the major advantages of district heating is its inherent ability to use a variety of different fuels to supply thermal energy. District heating systems have the capability of using more abundant domestic fuels, such as coal, refuse, and nuclear energy. Industrial waste heat and geothermal energy also offer potential as thermal energy sources for hot water district heating systems. Low-temperature hot water systems can utilize sources of thermal energy at relatively low temperatures. It should be noted that while peak send-out temperature is usually in the 240-260F (115-126C) range, this temperature is utilized for only 1-2% of the annual cycle. Design return temperatures are 140-160F (60-71C). Hence, any source of thermal energy at a temperature greater than 160F (71C) could supply at least a part of the energy requirements of a system. These include a variety of industrial processes, as well as heat from reciprocating engines, and the use of heat pumps to recover energy from lower temperature sources.

However, the most common types of energy sources are heat-only boilers and cogeneration plants. The St. Paul system uses a heat-only coal plant located in downtown St. Paul. The Willmar system uses a coal-fired cogeneration plant that supplies low-pressure steam to a specially built hot water conversion station. The larger district heating systems in northern Europe have their thermal base load provided from cogeneration power plants. The cogeneration process is used to produce relatively inexpensive thermal energy. The production of low-temperature hot water requires only small sacrifices in the production of electricity, thereby reducing the cost of the thermal energy. For each unit of electricity sacrificed, 5 to 10 units of thermal energy are available for hot water district heating. For steam district heating, the electricity sacrificed is generally much greater, except of lower pressure [<15 psig (<210 kPa)] steam district heating systems.

Cogeneration can greatly improve the fuel utilization efficiency. The overall conversion efficiency of an electric-only plant is about 33% (figure 4). The remaining two-thirds of the energy is rejected to the environment through stack gas losses and the cooling system. In contrast, a hot water district heating/cogeneration plant can operate at an overall efficiency as high as 80%. This conservation advantage, coupled with the use of coal or other plentiful domestic fuels, allows the dual-purpose power plant to supply relatively cheap thermal energy to a district heating system.

CONSTRUCTION OF A MODERN DISTRICT HEATING SYSTEM

Many of the European hot water district heating systems are based on the well-proved VVF (Varme Verks Foreningen) Standard. Because this standard is in common use and does not favor any proprietary piping design, competition is very strong with concomitant low prices, favorable warranty terms, and good customer service. Both St. Paul and the Willmar systems are based on this standard.

The foam insulation in the VVF piping design transfers expansion and contraction forces from the steel carrier pipe to the jacket and thence to the washed sand backfill. The foam insulation is of a higher density than conventional practice, and its quality and bonding to the steel and polyethylene must be carefully specified. The friction forces on the jacket act to limit expansion movement without the need for concrete anchors. The piping system can often be installed with no conventional anchors, as it was in Willmar.

The relatively thin pipe wall is an integral part of the friction anchoring system that is included in the standard. While thermal stresses are the same in any thickness steel pipe, the thermally induced forces are lower in thinner wall pipe of equivalent diameter. These lower forces reduce the shear stresses to acceptable levels in the insulation, jacketing, and their interfaces. Because the steel pipe is restrained, welds do carry axial stresses, and proper quality control is essential. While normally not required by domestic codes, a radiographic inspection program utilizing quite high standards is recommended.

Air vents at high points and drains at low points are normal practice. Often the valves for both types of facilities may be located within customers' basements, obviating the need for expensive vaults. Drains may not be necessary for smaller lines, depending on the size, length, and type of service. Drains are routed first to an appropriate flash chamber and then to a storm or sanitary sewer. Because the frequency of draining is usually extremely low, drains do not represent a significant load on waste water treatment facilities. Along with drain facilities, the choices of valving locations and types of valves are functions of the desired reliability of service, economics, desired drain/repair times, etc. It may be noted that shut-off valves for individual customers will be quite expensive if located in the public right-of-way instead of inside buildings.

A trench drain is often located in the gravel base of the trench when groundwater is a potential problem. While the polyethylene jacketing system is designed to be protection from outside water, high water levels are undesirable and also can make installation and repair difficult. Drains are usually routed to storm sewers when available.

Most pipe manufacturers recommend a minimum cover of about two feet above the top of the piping. When it is necessary to reduce this, e.g., a service entrance, a concrete cap may be poured above the piping to protect it from traffic loads. Because the backfill is an integral part of the piping restraint system, it must be selected and compacted with some care. A washed sand is used, free of large rocks and trash.

A leak detection and location system acts to notify operators of water in the insulation and to locate it in the network. This system can be most useful in dealing with both failures in the steel piping itself, usually weld failures, and in penetrations of the polyethylene jacket by ground water, often caused by other utility construction. However, the very sensitivity to water that is required for proper alarm operation also can make exposed pipe and fitting ends vulnerable to water absorption during construction. If pipe and fitting ends are not protected from rain and groundwater prior to joint completion, water may be entrained in the foam and yield a spurious alarm signal.

TECHNICAL AND ECONOMIC ASPECTS OF BUILDING CONVERSION

The replacement of an existing steam district heating system with a new hot water system not only means replacing the pipe but also converting the building heating systems to be compatible with the new hot water system. In most cities, there is a wide variety of building heating, ventilating, and air-conditioning (HVAC) systems. This diversity results basically from a wide range in the size and age of buildings - from essentially new buildings to buildings that are 100 years old. Over this time period, there has been an evolution from (1) one-pipe steam perimeter radiation to (2) modern HVAC systems using air and/or water as a distribution media. The connection of a building with a hydronic HVAC system to a hot water district heating system is relatively easy because the systems are compatible. There needs to be only an interface with the district heating system and some new controls. The conversion of the buildings with internal steam heating systems is more difficult. The connection of these buildings to hot water district heating involves conversion and upgrading of the building's heating system from steam to hot water. The modification requires converting the steam perimeter heating to hot water (hydronic) operation. The main philosophy for performing this conversion is to use as much of the existing building HVAC equipment as possible. In Willmar and St. Paul, every attempt was made to use old steam radiators and steam coils. Using this philosophy drastically reduced the cost of building conversion.

As noted above, steam perimeter heating systems were widely used in the past. Hot water perimeter heating became more popular than steam in the 1950s for the following reasons: (1) easier and more precise controls for heat distribution to satisfy variation in heat demand from different building zones; (2) lower operating temperatures and the absence of steam traps, which decreases heat loss; (3) lower maintenance cost; and (4) less noise from radiators and induction units. The hot water, or hydronic space heating systems, are, therefore, preferred over the steam heating for functional, aesthetic, and economic reasons. Hence, conversion of existing steam perimeter heating to hot water perimeter heating usually increases the comfort of the occupant while simultaneously providing significant reductions in thermal energy use.

A typical connection of a hot water distribution system to the district heating system is shown schematically in figure 5. In general, three modes of heating are supplied: perimeter heating by radiation or induction units, ventilation air handling circuits with preheat and reheat coils in the air-handling ducts, and domestic water heating. In the city of St. Paul, a predominant number of buildings had steam heating systems. The second largest group of systems was in the new buildings and was all hot water. Another category was where the buildings had both steam and hot water, with steam usually supplied to the air-handling ventilation coils and hot water to the perimeter heating units. The fourth category in St. Paul was the all-air units, and these were usually the smaller buildings with either a single zone or a small number of individual zones. In Willmar, the majority of buildings were the all-steam type.

Depending on the type of internal building heating system, the cost of the building conversion varies significantly. The buildings that have hot water supplied to perimeter heating systems, air-side systems, or both are the most economical to convert. The average unit cost for such systems is $40/kW of demand. In contrast, buildings with internal steam systems have the highest unit conversion cost. The range for the cost is from $50 to $400/kW. The high end of the range is caused by significant upgrading and modernization. It usually indicates total replacement of the HVAC system. In many cases, the same conversion can be completed for approximately one-third the cost. In order to achieve these lower costs, one must closely follow the philosophy of trying to use as much of the existing equipment as possible and must have an understanding of the performance and requirements of the district heating system.

In St. Paul and Willmar, the payback periods for the building conversion have been five years or less. One of the features that reduces this payback is that the conversion from a steam to hydronic building produces a 10% to 20% energy savings within the building. Additional savings of about 15% can also be realized when conservation features, such as night setback controls, are included in the building conversion. Finally, the primary emphasis in both St. Paul and Willmar, with regard to converting the building heating system, is to have a system that is energy efficient and operationally effective for a minimum capital cost.

THE COST OF THERMAL ENERGY FOR MODERN HOT WATER DISTRICT HEATING SYSTEMS

A large initial capital outlay is needed to develop a new district heating system. The largest single component of the capital cost is the distribution network. Approximately 60% of the delivered energy cost from a new district heating system is related to debt retirement, whereas 30% is fuel cost and only 10% is nonfuel operating and maintenance cost. Therefore, the piping installation cost is a significant factor in the total system economics. It is important that these costs be reduced to the lowest possible levels. The hot water technology has several cost-saving features, and these were utilized in both St. Paul and Willmar. The total cost for the St. Paul system was $45.8 million, of which $19.5 million was the direct cost of the piping distribution system (table 1). The Willmar system cost $2.09 million, including $1.3 million direct cost for the piping distribution system (table 2). These costs do not include the building conversion. The building conversion cost was financed by the building owners. The building conversion cost in Willmar was approximately $0.5 million.

Some of the factors used in both the St. Paul project and the Willmar project to reduce the installation costs of the piping are the following:

1. Shallow burial of the piping system minimizes shoring costs and results in less material to be excavated. The quantity of new fill material is also reduced. These factors are additive and result in reduced installation cost.

2. Reduced piping installation time resulting from the use of prefabricated piping. Field work is reduced due to the minimum concrete form work, the factory-applied insulation, and the outer protective conduit. These time savings are easily translated into cost savings during construction.

3. Pipe routing flexibility is increased due to the prefabricating piping design, especially in the smaller sizes. This permits resolution of utility interference problems with minimal utility relocation or district heating piping design. Use of water as the heat transfer media also permits greater routing flexibility due to less stringent requirements on piping slope. Generally, the pipe can be laid to grade with only minor sloping for drainage of lines for repair procedures. This also permits the line segment to be sloped in either direction of flow, as it does not affect the operability of the system.

The rates for thermal energy in St. Paul are $.032/kWh, and in Willmar are $.025/kWh. These rates are competitive with the actual effective rates for natural gas. The conversion efficiency for heat on a district heating system is 100% of the metered value. This is in contrast to a natural gas system, which must account for the combustion efficiency on the customer side of the meter.

CONCLUSIONS AND SUMMARY

Modern hot water heating technology is available and has been widely used in many European cities and recently introduced into two U.S. cities, St. Paul and Willmar, Minnesota. Modern hot water technology offers the consumers three major advantages: competitive space heating energy costs, lower maintenance costs, and higher reliability. These advantages are achieved through the fuel flexibility aspect of district heating and the conservation potential of cogeneration. Lower maintenance cost and higher reliability are achieved due to the simplicity of the technology and consumer equipment.

The experience of Willmar and St. Paul demonstrates that the European concept of modern hot water district heating can be economically applied in the United States. The rate of construction for both of these systems exceeded that achieved in Scandanavia. Both of these systems sell energy at competitive prices with natural gas. Their experience also demonstrates that the conversion of the existing building heating systems can be easier than anticipated.

The northern European design concept for modern hot water district heating offers a low-risk method of achieving a low-cost district heating system. The benefits that have been achieved in Willmar and St. Paul could also be achieved in other communities. Their experience with the modern hot water technology could easily be replicated in many U.S. cities.

TABLE 1

Table 1. Cost of St. Paul district heating system.

Piping construction contract	$19,560,000
Other distribution system costs	4,950,000
Heat source modification contract	5,650,000
Other heat source costs	990,000
Mobile boilers, meters, and service equipment	740,000
CONSTRUCTION SUBTOTAL	$31,890,000
Financing costs (including insurance premium)	$ 2,430,000
Repayment of design and development costs	1,200,000
Reserve funds	3,750,000
Net interest during construction	3,750,000
Fuel inventory, operating losses, and capital improvements during construction	2,780,000
TOTAL COST	$45,800,000
COST PER PEAK THERMAL LOAD ($/kw)	$ 300

TABLE 2

Table 2. Cost of Willmar district heating system.

Distribution system	
materials	$ 364,966
installation	962,232
Heat-conversion station	
materials	75,389
installation	325,813
Engineering	175,000
Contingency, capitalized interest, and financing	$ 186,600
TOTAL COST	$2,090,000
COST PER PEAK THERMAL LOAD ($/kW)	$ 200

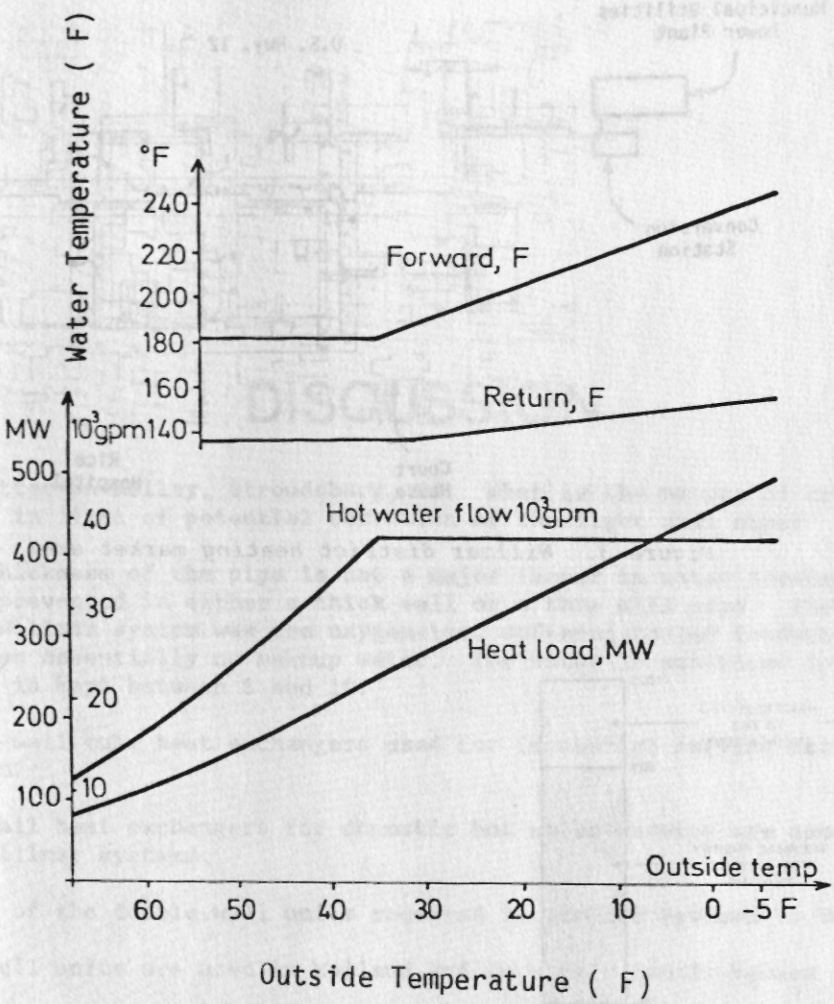

Figure 1. District heating system water temperatures and flow rate in relationship to outside temperatures

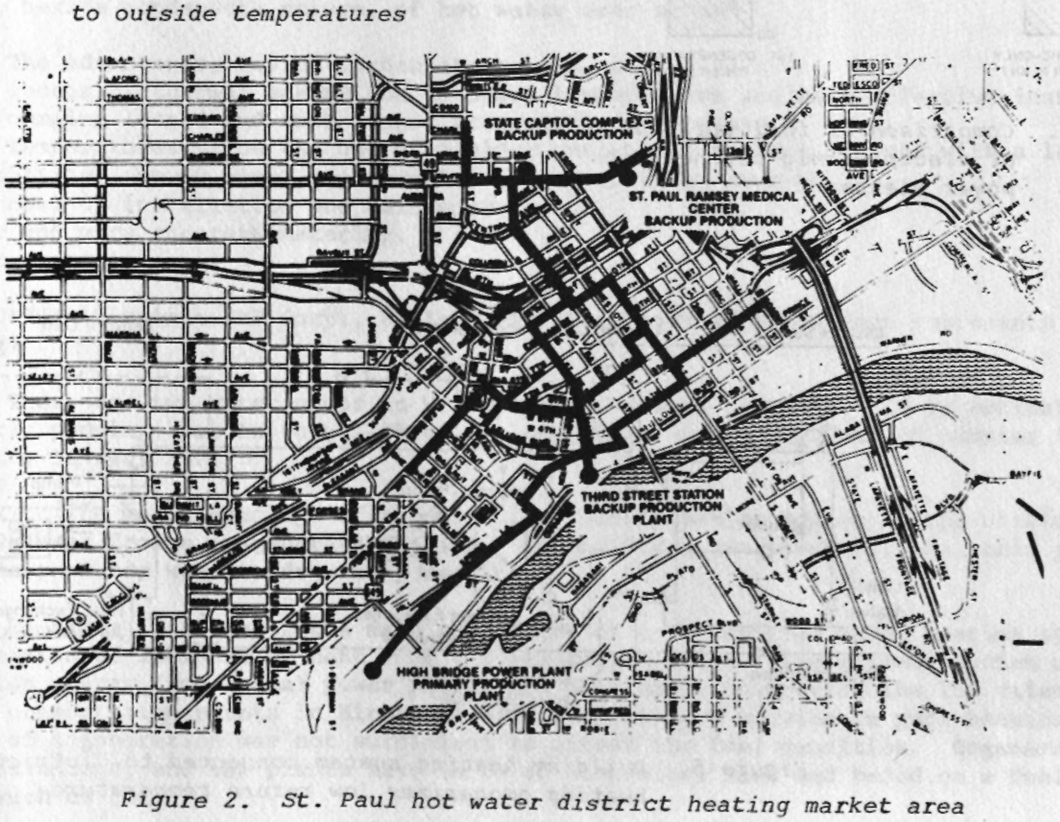

Figure 2. St. Paul hot water district heating market area

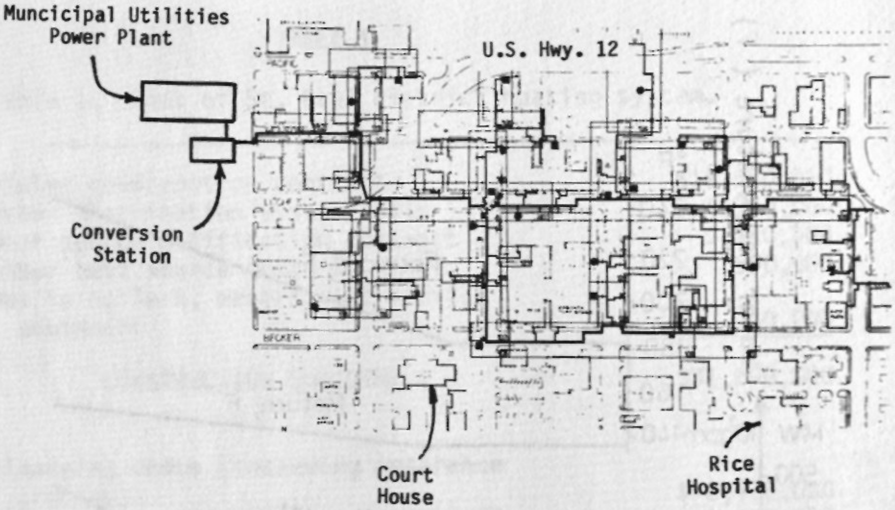

Figure 3. Willmar district heating market area

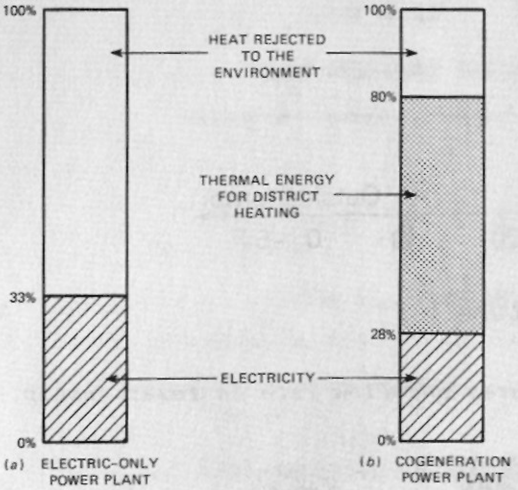

Figure 4. Comparison of fuel utilization of electric-only cogeneration power plants

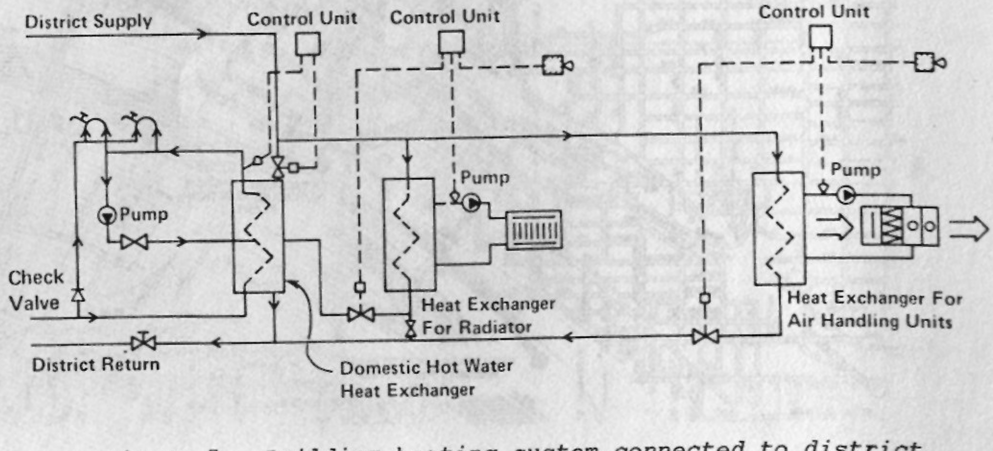

Figure 5. Building heating system connected to district heating emphasizes low return temperature

DISCUSSION

J.A. CLARK JR., Patterson-Kelley, Stroudsburg, PA: What is the nature of treatment of recirculated water in light of potential corrosion of the light wall pipe?

M. KARNITZ: The thickness of the pipe is not a major factor in water treatment. Internal corrosion must be prevented in either a thick wall or a thin wall pipe. The original waterfill for the Willmar system was the oxygenated, softened boiler feedwater. Since that time, there has been essentially no makeup water. The water is monitored for PH and oxygen. Normal PH is kept between 8 and 10.

CLARK: Are double-wall tube heat exchangers used for (domestic) service water heating in the St. Paul system?

KARNITZ: Double-wall heat exchangers for domestic hot water service are used in both the St. Paul and the Willmar systems.

CLARK: Is the use of the double-wall units required in similar systems in Europe?

KARNITZ: Double-wall units are used in Holland and in single-family houses in Scandanavian systems.

M.W. DIZENFELD, U.S. Dept. of Housing and Urban Development, Washington, DC: What is the advantage, beside condensate return, of hot water over steam?

KARNITZ: The advantages, beside condensate return, are:
- Lower losses of thermal energy due to lower temperatures and more effective insulation.
- Lower pumping lossed and much longer transmission distances.
- Lower temperatures allow the use of a wider variety of thermal sources with a lower availability. Power plant cogeneration is one of these sources.
- Lower cost of installation and maintenance.
- Easier and more accurate metering.
- Better control.

S. ZHUKOBORSKY, Virginia-KMP Corp., Dallas, TX: What part of total cost represents the cost of pumping?

KARNITZ: There are two water pumps in Willmar and three in St. Paul. It is estimated that the electric pumping cost is only 1-2% of the operating cost. The cost of pumping for a hot water system is very small.

ZHUKOBORSKY: The main advantage of a centralized water heating system is the utilization of inexpensive heat from a co-generating plant. In the first two presentations, this point was neither analyzed nor was it adequately mentioned.

KARNITZ: We agree that one of the main advantages of a centralized water heating system is the utilization of inexpensive heat from a cogeneration plant. The Willmar system utilizes cogeneration energy from a coal power plant, and this helps to provide the low rates. Some oil-fired cogeneration plants in Minnesota have discontinued service in part because the advantage of cogeneration was not sufficient to offset the fuel penalties. Cogeneration is only one advantage, and the plants have to be of economical size and based on a fuel resource such as coal.