ornl

OAK
RIDGE
NATIONAL
LABORATORY

UNION
CARBIDE

ORNL/TM-8927

Steam/Hot Water District Heating Evaluation at the Oak Ridge National Laboratory Site

M. A. Karnitz
H. A. McLain
M. H. Barnes
G. V. Murphy
L. N. McCold
M. C. Lindell

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A08 Microfiche A01

ORNL/TM-8927

ENERGY DIVISION

STEAM/HOT WATER DISTRICT HEATING EVALUATION AT THE OAK RIDGE NATIONAL LABORATORY SITE

M. A. Karnitz
H. A. McLain
M. H. Barnes*
G. V. Murphy
L. N. McCold
M. C. Lindell

---

*Consultant, Scantec, Inc.

Date Published: March 1984

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
under
Contract No. W-7405-eng-26

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The Oak Ridge National Laboratory site has a steam district heating system that was installed in the early 1940's. A large portion of the steam distribution system is buried, and recently there have been failures in the buried pipelines. This investigation compares the economics of renovating the existing east-end steam system with the economics of replacing this portion with a new hot water system. A decision must be made on the future of this portion of the system since it can no longer be considered reliable.

Renovation of the east-end portion of the steam system would include replacement of approximately 6,000 ft of pipe and is estimated to cost $4,160,000. It is anticipated that renovation to the east-end system would reduce the annual fuel bill by about 15% and cut maintenance costs. The new hot water system option would include installing 15,000 ft of buried piping at the east end of the plant. It would also include converting the buildings to be compatible with a new hot water system. This option would cost about $3,000,000 more than the steam renovation option; however, the hot water option has an annual savings in fuel and maintenance of about $665,000 over the steam renovation. The simple payback for the hot water option is 4.5 years. The hot water option is attractive, and it is recommended that the development of this system be pursued.

1. INTRODUCTION

1.1 Purpose and Scope of Study

The Oak Ridge National Laboratory (ORNL) steam district heating system was originally built in the early 1940s and was modified and expanded in the 1950s and 1960s. A large portion of the system is buried, and recently there have been a number of failures in the buried pipelines. The buried piping has been in service for more than 30 years and is approaching the end of its expected life. A UCC-ND Engineering Division report[1] states that most of the system's underground lines will need replacement to provide another 20 years of serviceable life.

The primary objective of this study is to compare the economics of major renovations to the portion of the existing steam system located at the east end of the plant, with the economics of a new hot water system that would totally replace this portion of the steam system. The economic comparison between the two options includes both the capital cost and the operating cost. It was necessary, therefore, to determine the cost of the proposed renovation of the present steam system and to make an estimate of the efficiency of the system after renovation. (Knowing the efficiency is an essential component in determining the steam system operating cost.) Also needed was a preliminary design for a hot water system on which the cost of such a system could be based. An estimate was also made of the efficiency of the hot water system to calculate its operating cost.

1.2 Background on the ORNL District Heating System

The ORNL district heating system was orignally built in 1943 and has been modified and expanded with the change or addition of facilities until it now includes approximately 3.8 miles of aboveground piping and 2.8 miles of underground piping. A large part of the steam distribution system located in the east end of the plant consists of buried piping (10,000 ft). However, the east-end system also has aboveground piping

(8,000 ft). The present steam plant was built in 1948 and was originally designed and operated on coal. The plant was converted to natural gas and oil in 1950 and reconverted back to coal in 1980. The plant produces 250-psig steam, of which about 10-15% is used to drive auxiliaries within the plant and the remaining 90% is exported from the plant to the piping network. Lower pressure steam, 125 psig, is also distributed to some areas of the Laboratory.

The steam is used primarily for building and water heating, and the largest single user is the 4500 building complex. However, the most critical area served by the steam system is the off-gas stacks in the 3000 area. These stacks have induction fans that are driven by electric motors, but they also have steam turbines on standby to provide backup for the electric fan drives. The underground portion of the distribution system services primarily the east end of the X-10 site including the 4500 area, 6000 area, and 7000 area. The aboveground portion of the system, which is part of the original system built in 1943, serves primarily the west end of the laboratory. The aboveground system shows only moderate signs of deterioration. The underground mains, which have been in service over 30 years, are showing evidence of extreme deterioration and need to be replaced in the near future to avoid extended forced outages. The east-end system serves approximately two-thirds of the load, and its availability is critical to both programmatic and service facilities.

The east-end system has significant losses resulting from deteriorating insulation, malfunctioning traps, general system leaks, and no condensate return. The thermal heat losses through the deteriorated insulation are a large portion of the energy losses. The failures of the old-style conduit-enclosed, thermally insulated pipe lines are primarily due to corrosion of conduit casing with subsequent soaking and deterioration of the thermal insulation. In addition, there has been failure of buried pipelines installed in loose-fill type insulation. The distribution system has approximately 300 steam traps, and there are approximately 2% (6 traps) that are in the failure mode at all times. Malfunctioning steam traps act as orifices and allow prime steam to escape. There are also miscellaneous leaks in the system at valves, underground bellows joints, and other steam pipe fittings. Generally, a well-maintained steam system has miscellaneous leaks that amount to about 4% of the total system load. The ORNL system has a much higher potential for leaks because the failed outer conduit exposes the bare pipe to groundwater. These leaks are often not easily detected and the mass loss (water) is dissipated into the surrounding soil. The ORNL steam system also has no condensate return. The condensate in each of the buildings is dumped into the sewer at approximately 150°F and this loss of heat energy amounts to about 10% of the steam energy consumed in the buildings. These four types of energy losses result in excess fuel consumption at the steam plant.

The aboveground steam distribution system shows only limited evidence of corrosion or deterioration and, with minor exceptions, could remain in service for another 10 to 20 years with conventional maintenance. The underground system has excessive deterioration and can be considered as approaching the end of its expected useful life. The system has had a number of failures and now has large energy losses. Some action must be pursued with regard to the underground system because the system can no longer be considered reliable.

1.3 History of District Heating

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 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. At the same time, utilities were introducing large, condensing electric power plants remotely located from urban areas. It was not economical to transport steam over the long distances from the power plants to urban areas. As the smaller, older cogeneration units were retired, sources for the steam district heating were eliminated and the cost of supplying steam from heat-only boilers escalated, making district heating even less attractive.

In the United States almost all of the commercial district heating systems utilize steam as the distribution media. The first systems were low-pressure systems of generally 5-10 psig. As the decades passed, steam pressures increased and most current city systems distribute steam in the range of 100-150 psig. This increase in pressure allows the systems to have larger steam capacities with smaller piping. Many of the U.S. city systems went out of business in the 1960s and 1970s due to (1) the competition from cheap oil and natural gas, (2) the cost increases during the transition from use of exhaust steam to prime steam, and (3) the inefficiencies of steam distribution technology.

The history of district heating in Europe was somewhat 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 a transport media and the systems have proven to be more economical. They are significantly cheaper to build and generally have significantly lower losses. In addition, the hot water systems have lower maintenance 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 in premises served by hot water district heating. The country has installed systems with a total capacity of 15,000 MW(t) and expects to have an installed capacity of 30,000 MW(t) by year 2000. There are approximately 100 cities in Sweden with district heating, and all of the larger systems have incorporated cogeneration. The standard design for modern hot water systems is as follows: the system pressure is 250 psig, the hot water supply temperature varies between 175°F and 250°F, and the return temperature varies between 130°F and 170°F. The variation of supply and return water temperatures in relationship to outside temperatures for a typical system is given in Fig. 1.1.

Recently the 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 the fall of 1983, respectively. The entire first phase of the St. Paul project will take two summers to construct and will connect approximately 100 buildings for a total of 150 MW(t) peak load. The system spans the St. Paul business district (Fig. 1.2) and includes privately owned office and retail buildings, city and county government buildings, hospitals, the State Capitol complex, and one industrial customer. 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 (Fig. 1.3). The system serves a thermal load of about 10 MW(t) and includes about 12,000 ft of distribution network. Figure 1.4 shows an example of the piping and service connections in Willmar. The installed cost including engineering and capitalization was slightly over $2,000,000. This sum also includes a heat conversion station which costs about $450,000. Willmar's piping system, which mostly includes small diameter pipe, was installed for approximately $125/ft of distribution system. The Willmar system started its second stage of development in the summer of 1983.

1.4 Comparison of Steam and Hot Water Systems

The comparison between steam and hot water systems in this section will be limited to applications that serve space heating loads. There will be no discussion of process application which strongly favors steam distribution. The comparison between hot water and steam will be made in three areas, (1) capital cost, (2) efficiencies of the systems, and (3) maintenance of the systems. The comparison will be between a typical 100-psig city steam system and a low-temperature (< 250°F) hot water

ORNL-DWG 82-15451

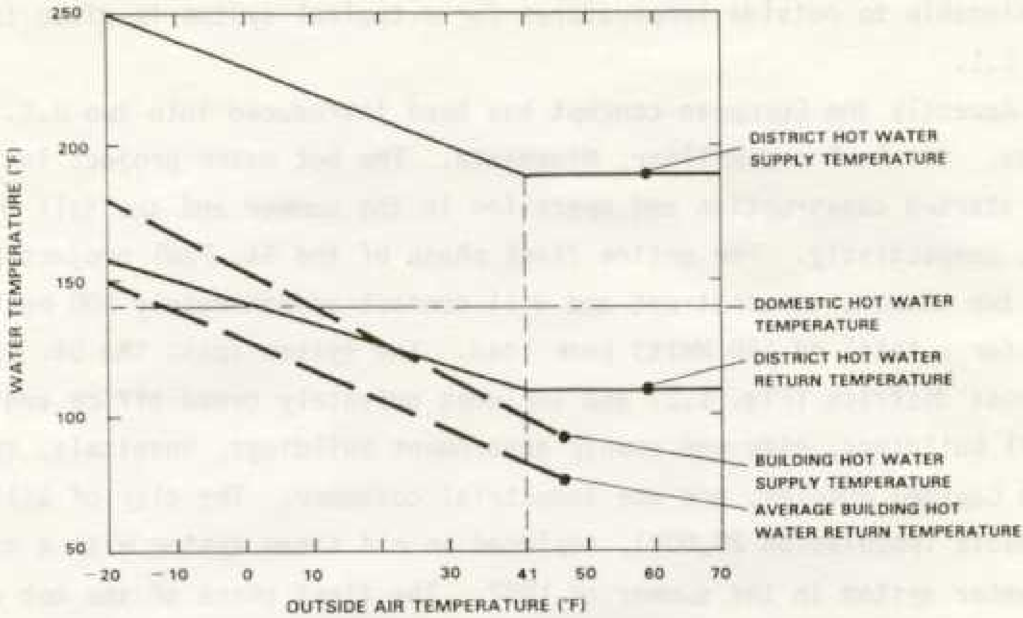


Fig. 1.1. Hot water temperatures for district heating system and hydronic building heating system as a function of outside air temperatures.

Fig. 1.2. St. Paul hot water district heating market area.

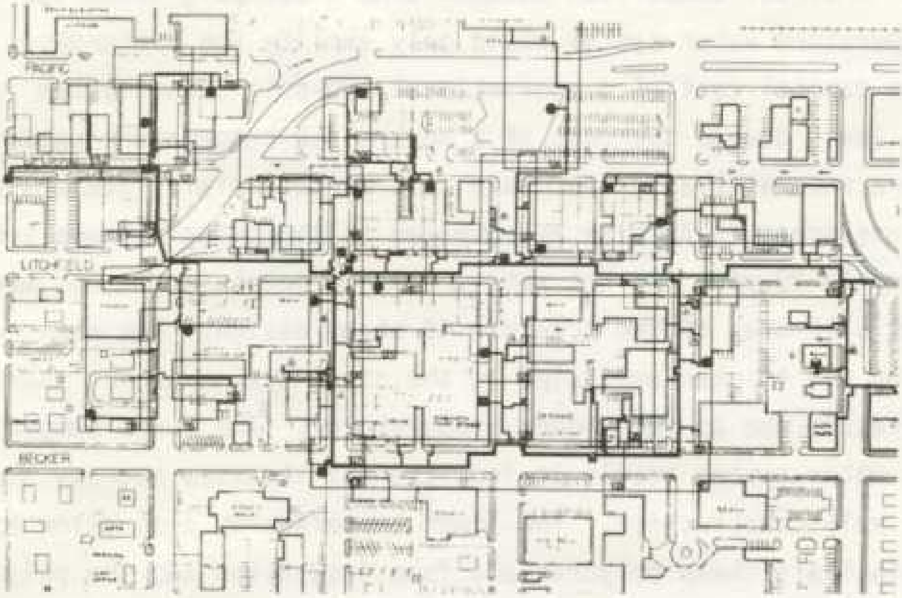


Fig. 1.3. Willmar district heating market area.

Fig. 1.4. Piping system in Willmar streets.

system. A direct comparison between ORNL's 250-psig steam system and a low-temperature water system would only amplify the differences.

The capital cost of a conventional 100-psig steam system is generally at least double the cost of a modern low-temperature water sytem. There are several reasons for this cost differential. Steam systems generally use schedule 40 pipe as compared to something between schedule 10 and schedule 20 pipe for hot water. The material in the hot water design is about half that of the schedule 40 steam design. The main reason for requiring the thicker wall pipe in the steam system is the thermal expansion stresses due to the higher temperatures. The lower temperatures in the hot water system result in less thermal stresses thereby allowing the thinner wall construction. The lower temperatures also allow for the use of a relatively cheap polyurethane foam insulation and the polyethylene jacket. Polyurethane foam will only withstand temperatures up to about 266°F and is therefore not useful in most steam systems. Moreover, due to the lower temperatures and lower thermal stresses, the hot water systems can be designed with fewer expansion loops. Some manufacturers are even trying to eliminate bellows and thermal expansion loops. These are so-called "No Comp" systems which can save an additional 5-10%. The design of the hot water systems also includes shallow pipe burial. The systems have prefabricated fittings and joints that 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 of network length. The system in St. Paul, for comparable size piping, will cost approximately $200/ft. The installed cost of a typical 100-psig steam system ranges in price from $300 to $500/ft. The data, therefore, indicate that a new steam system is significantly higher in cost than a new hot water system.

A new steam system with condensate return will have operating efficiencies in the range of 85-90%. The losses include about 10% conduction losses through the insulation, 1% losses from malfunctioning traps, and 4% from miscellaneous leaks. In comparison, a new hot water system will have an efficiency of 90-95%. Almost all of the losses are conduction through the insulation, and these are less than the conduction 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, and leaks in the water system are much easier to detect and repair. A new steam system with no condensate return can have operating efficiencies as high as 75-80%. The International District Heating Association (IDHA) has operating statistics on 50 U.S. city steam systems. These systems range in efficiency from approximately 85% down to 40%. The majority of the systems are older systems such as the one at ORNL, and most of them operate in the range of 50-60% efficiency. 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 90-95%.

The maintenance comparison between a steam system and a hot water system is similar to the efficiency comparison. The statistics from the Swedish district heating association show a cost for maintenance of 0.4-1% per year of the capital investment, and the majority of the systems average 0.5% per year. It is estimated that the average for a new steam system would range between 1-2% per year.

The advantages of the hot water systems are quite clear, and it makes sense to thoroughly investigate the use of this technology at ORNL.

2. STATUS OF THE ORNL STEAM SYSTEM

2.1 Description of the System

The ORNL steam system can be considered to consist of three parts: (1) the steam plant (building 2519), (2) the steam distribution system consisting of steam pipes, and (3) the internal building heating equipment which uses steam. These three elements of the steam system are described in this section. The steam plant consists of five boilers with a combined capacity of 300,000 lb/h of steam at 250 psig. Boilers 1 through 3 were installed in 1948 and burned coal until converted to burn natural gas in 1950. Boiler 4, which is nearly identical to boilers 1-3, was installed in 1956. In 1980 these four boilers were converted back to burning coal. Presently, these four boilers burn a washed and sized coal, and each boiler produces 50,000 lb/h of steam. These boilers are still capable of burning natural gas or #2 oil, but because of modifications they can produce only about 25,000 lb/h of steam on gas or oil. Boiler 5 is designed to burn natural gas or #2 oil. It has a capacity of 100,000 lb/h and is presently used as a backup boiler when either boilers 1-4 have insufficient capacity or one of them is out of service for repairs.

Steam leaves the plant through four lines (Fig. 2.1). Two 250-psig lines leave the south side of the plant. Another 250-psig line leaves the north side of the plant. The fourth line leaves the west side of the plant with 125-psig steam after passing through a pressure-reducing valve. Although there are four lines that leave the plant, the system is classified as having three networks. The simplest network is the 250-psig line which leaves the south side of the plant and goes to the 7500 area. The second network is defined by the 250-psig loop that serves the east end of the complex. From this loop there are branches to the 7000 area and to the 6000 area. This system will be termed the east-end system or the buried system (a large segment of the piping is underground). The third network is a 125-psig system that serves the area north and

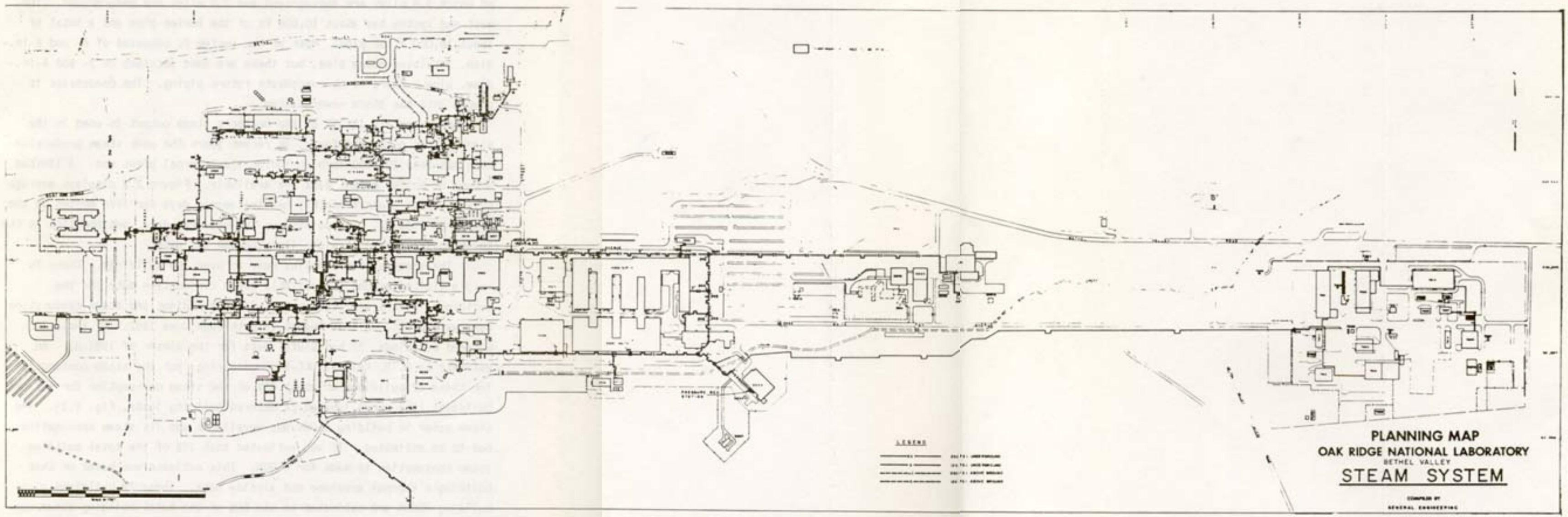


Fig. 2.1 Steam system distribution map.

west of the steam plant. This system serves the buildings in the 1500, 2000, 2500, and 3000 areas. This will be called the west-end system.

There are approximately 6.6 miles of pipe in the distribution system of which 3.8 miles are aboveground and 2.8 miles are underground. The east-end system has about 10,000 ft of the buried pipe and a total of about 18,000 ft of pipe. Most of the system is composed of 6- and 8-in.-diam. insulated steam pipe, but there are some sections of 3- and 4-in.-diam. pipe. There is no condensate return piping. The condensate is dumped into the storm sewer system.

Approximately 10-15% of the boiler's steam output is used in the plant to run pumps and fans. In recent years the peak steam production rate has been 208,000 lb/h including the internal plant use. A limited amount of boiler output data are available. Figure 2.2 displays average boiler output against monthly heating degree days for five months in the winter of 1981-82. The points are the measured data, and the line is the least-square-fitted straight line through the data.

The steam system supplies heat to over 100 buildings. There is only a limited amount of available steam consumption data for the buildings. There are steam meters in 30 buildings and steam consumption data were monitored from August 1976 through June 1982. Of those 30 metered buildings, 22 had useful data for the winter of 1981-82. An estimate by O. A. Kelley, UCC-ND Engineering, put the steam consumption for these 22 buildings at about 45% of the steam consumption for all the buildings (the curve labeled 22 metered building loads, Fig. 2.2). The steam meter in building 4500N was unreliable and its steam consumption had to be estimated. It was estimated that 15% of the total building steam consumption is made for 4500N. This estimate was based on that building's thermal envelope and airflow data. These 22 buildings plus building 4500N are estimated to use 60% of the total building steam consumption. The remaining buildings consumed the other 40%.

Using the data and the estimates, curves were developed for both the boiler output and the total building steam demand as a function of daily heating degree days (Fig. 2.3). The plant's sendout curve was developed

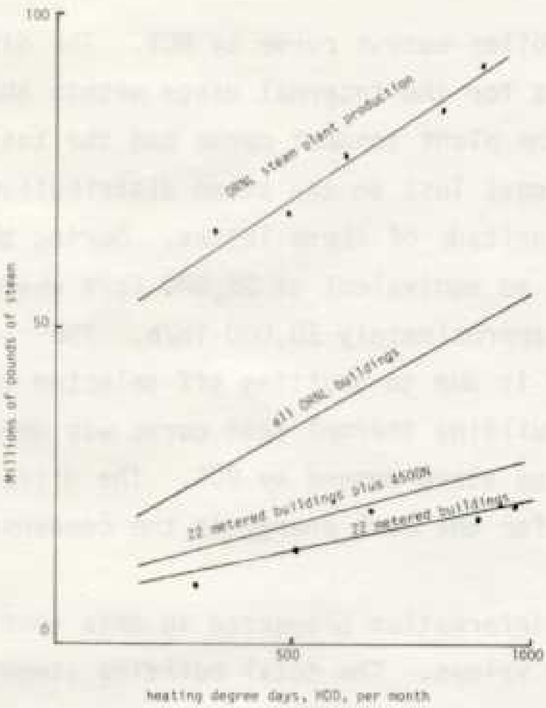


Fig. 2.2. Building loads and boiler steam production.

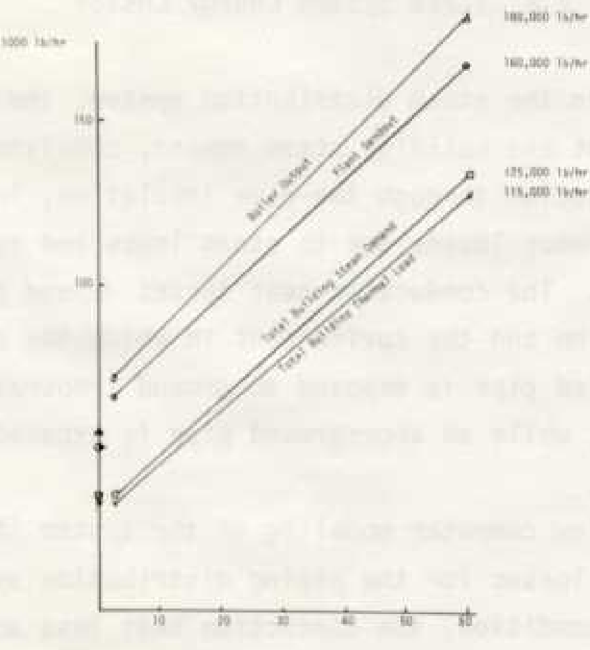


Fig. 2.3. Steam system output and consumption rate per heating degree day.

by multiplying the boiler output curve by 90%. The difference between these curves accounts for the internal usage within the steam plant. The difference between the plant sendout curve and the total building steam demand curve is the mass loss on the steam distribution system. In particular, note the magnitude of these losses. During the heating season the losses amount to an equivalent of 35,000 lb/h while in the summer they are reduced to approximately 20,000 lb/h. The reason for the lower levels in the summer is due to shutting off selected lines on the steam system. The total building thermal load curve was developed by multiplying the total building steam demand by 90%. The difference between these two curves accounts for the heat energy in the condensate that is dumped to the sewer.

The curves and information presented in this section are based largely on estimated values. The total building steam load estimates presented here easily could be 10-20% too large or too small, but at the present time this is the best estimate available. To obtain better values would require detailed building analysis or steam metering.

2.2 Steam System Energy Losses

The mass loss in the steam distribution system, the difference between plant sendout and building steam demand, consists of three components: heat conduction through the pipe insulation, losses from steam traps, and miscellaneous losses due to steam leaks and exposure of the pipe to groundwater. The conduction heat losses depend on the condition of the pipe insulation and the environment in which the pipe is located. For instance, a buried pipe is exposed to ground temperatures which vary between 40 and 70°F, while an aboveground pipe is exposed to temperatures between 5 and 100°F.

The pressure/flow computer modeling of the system (Appendix B) sums the conduction heat losses for the piping distribution system. For dry insulation in good condition, the conduction heat loss accounts for about 5,000 lb/h of condensate. From the temperature measurement study (Appendix A) the heat loss from the buried pipes in the 4500 area suggests that the insulation is damaged to the extent that the average heat loss is four times higher than the estimate for good insulation. Another study[2] also found that some of the aboveground pipe's insulation was missing or slightly damaged. Combining these two estimates, the pressure flow model predicted a conduction heat loss of 15,000 lb/h of condensate. The conduction losses are lower in the summer due to shutting off some steam mains. Therefore, for the analysis herein, the yearly average conduction heat loss is assumed to be 10,000 lb/h. The steam enthalpy is 1,200 Btu/lb and the steam system operates 8,760 hours during the year. Therefore, the annual conduction heat loss through insulation amounts to approximately 100×10^9 Btu/yr.

There are approximately 300 steam traps on the steam distribution system. There are also several hundred additional traps within the buildings. However, for this segment of the analysis the only concern is with those on the steam distribution system. Steam traps, unlike steam pipes, generally are not insulated. A properly functioning steam trap should be no more than about 30°F colder than the steam system.[4] It was assumed here that a typical trap is 10°F colder than the system. This means a trap on the 250-psig system is at 396°F and a trap on the 125-psig system is at 340°F. Most of the traps on the system are inverted bucket traps. A typical properly functioning trap will lose heat at a rate that is equivalent to 6 in. of uninsulated 4-in. pipe, about 1000 Btu/h. For all 300 traps, this amounts to 3×10^9 Btu/yr. In addition to this loss there are also traps in the failure mode. At any one time an estimated 6 traps (2%) are in the failure mode with the orifice open. A typical trap in this system has a 5/64-in.-diam. orifice. To be somewhat conservative it was assumed that the traps have 1/16-in.-diam. orifices, and, therefore, the 6 traps give an annual energy loss of 3×10^9 Btu/yr. This total trap loss for both conduction and the malfunctioning traps amounts to 6×10^9 Btu/yr.

Steam leaks and exposure of pipe insulation to groundwater, the third component of energy losses, are much more difficult to estimate. These two mechanisms are difficult to separate, and therefore are treated as one component. There is considerable evidence that portions of the underground pipe at ORNL are exposed to groundwater. Heat losses from the piping increase dramatically for this situation since the heat is advected from the pipe by the groundwater. It was beyond the scope of this study to determine the lengths of pipe exposed to groundwater. However, O. A. Kelley[3] of UCC-ND Engineering observed heat loss rates of 2,400-13,000 Btu/h per linear foot for buried pipe exposed to groundwater. This implies that 100 ft of this pipe would have heat losses of 2×10^9 to 11×10^9 Btu/yr.

Steam pipe leaks can increase the heat loss as much if not more than damaged insulation. For instance, a 1/8-in. hole (or four 1/16-in. holes) in a 250-psig line will lose about 2.3×10^9 Btu/yr. As identified in the infrared and temperature measurements study (Appendix A), there are three possible leaks in the buried system, and it can be assumed there are more that are yet unidentified. Just ten 1/8-in. holes in the buried system would lose 23×10^9 Btu/yr.

The losses discussed in this section are engineering estimates. The steam pipe conduction losses and the trap losses are probably the most reliable. The number of leaks is not based on any real count. For the buried system, detecting leaks is difficult and counting leaks is impractical. However, leaks and buried pipes exposed to groundwater are responsible for a significant part of the system energy loss.

2.3 Annual System Efficiency

The annual steam production from the boilers is about 700×10^6 lb/yr of steam. Approximately 10-15% is used within the plant, therefore, about 600×10^6 lbs (720×10^9 Btu) is put into the steam distribution system (Table 2.1). The steam distribution system mass losses (Fig. 2.3) amount to 35,000 lb/h during the winter heating season and 20,000 lb/h during the summer. A conservative estimate of the average is 25,000 lb/h for the whole year. This is equivalent to 220×10^6 lb/yr (264×10^9 Btu). The building yearly steam consumption is 456×10^9 Btu ($720 \times 10^9 - 264 \times 10^9$). As indicated in Sect. 2.1, about 10% of this energy is dumped to the sewer. Therefore, the annual building heat

Table 2.1 Annual steam system operating efficiency

Annual energy put into the steam distribution system, $600 \times 10^6 \times 1200$ Btu/lb	720×10^9 Btu
Annual mass losses of steam distribution system, 25,000 lb/h x 8760 h x 1200 Btu/h	264×10^9 Btu
Annual building steam consumption, $720 \times 10^9 - 264 \times 10^9$	456×10^9 Btu
Annual building heat energy consumption, $0.9 \times 456 \times 10^9$	410×10^9 Btu
Annual system energy losses, $720 \times 10^9 - 410 \times 10^9$	310×10^9 Btu
Annual operating efficiency, $410 \times 10^9 \div 720 \times 10^9$	57%

energy consumption is 90% of the buildings' steam consumption. The annual building heat consumption is 410×10^9 Btu which results in an overall system efficiency of approximately 57%.

For the winter of 1981-82, the annual fuel bill for coal, oil, and gas was approximately $2,100,000. Fuel cost for the winter of 1982-83 was lower due to lower coal prices caused by a depressed coal market. The $2,100,000 fuel bill is assumed in this study to be a reasonable estimate for future fuel bills. The overall system efficiency of 57% implies that the losses amount to $900,000 in wasted fuel.

As estimated in the previous section, the mass losses due to conduction were about 100×10^9 Btu and the losses due to traps were about 6 $\times 10^9$ Btu. Therefore, the difference between the total mass losses of 264×10^9 Btu and 106×10^9 Btu is assumed to be due to leaks and exposure to groundwater. These losses amount to 158×10^9 Btu and indicate that exposure to groundwater and leaks are the dominate losses.

It will be necessary in later sections to know the losses on the different parts of the system. This is especially true for the east-end system where comparison will be made with a new hot water system. The loads on the east-end system are assumed to be two-thirds of the total building heat load or 275×10^9 Btu/yr ($0.67 \times 410 \times 10^9$). This implies that the buildings on the west-end system and the system that serves the 7500 area use 135 x 10^9 Btu/year. Knowing these loads allows one to write the following equation in terms of the efficiency of the east-end system and the efficiency of the west-end system.

east-end system		west-end and 7500 area system		
$\frac{275 \times 10^9}{Eff_{east}}$	+	$\frac{135 \times 10^9}{Eff_{west}}$	=	720×10^9 .

This equation has two unknowns and can only be solved if there is another equation relating the two unknown parameters. However, since there is a known overall system efficiency and some known characteristics on each of the subsystems, an engineering estimate was made. The east-end system was assumed to have a lower efficiency than the overall system. Therefore an assumed efficiency of 53% for the east-end system results in a 67% efficiency of the west-end system. This appears to be a reasonable estimate and is used in the following chapters.

2.4 Steam System Capacity

Pressure/flow modeling of the steam distribution system (Appendix B) was done to analyze the losses and the capacity of the system. This section will be limited to a summary about the system capacity. The modeling was performed with a computer program that determines the balanced steady-state pressure flow relationship for a steam system. Two cases were analyzed; both were for a peak-hour building load of 123,000 lb/h. The first case modeled the system as it presently exists with a 250-psig sendout pressure. The second case modeled the system with a reduced sendout pressure of 200 psig.

The first case was an attempt to match the system as it is presently operated on a peak day. The pressures are given for various locations in Fig. 2.4. The lowest pressures on the high-pressure system are 226 psig

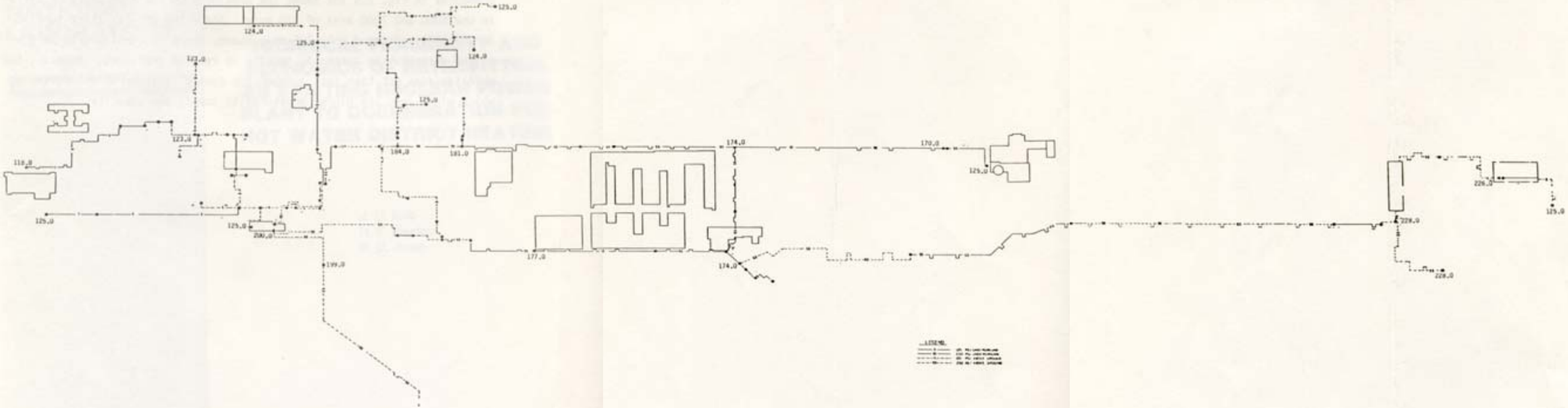


Fig. 2.4. Pressure map for 250 psig sendout.

in the 6000 area and 226 psig in the 7000 area. This 24-psig pressure drop indicates that the system has excess capacity and could serve a peak-hour building load of perhaps 175,000 lb/h.

A second case was modeled to determine the pressure drop at a reduced sendout pressure of 200 psig. The pressure map for this case is presented in Fig. 2.5 and shows low pressures on the high-pressure system in the 6000 and 7000 area of 170 psig. Since the off-gas stack turbines in the 3000 area need only 125-psig steam, there is considerable margin in the distribution system to operate at reduced pressures. However, the modeling does not take into account the control systems in the buildings which might need the higher pressures to supply the capacity.

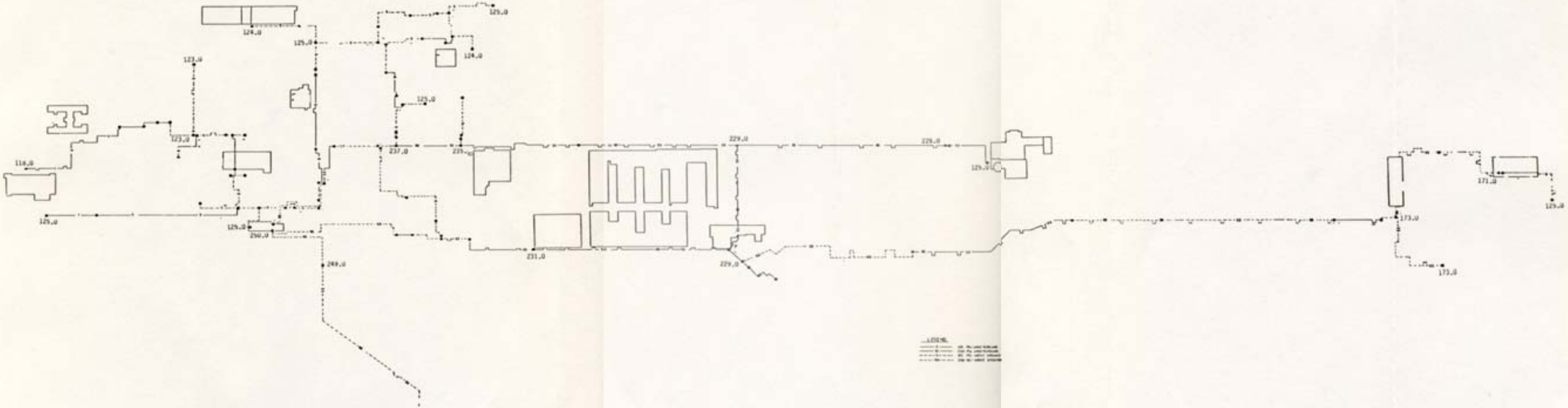


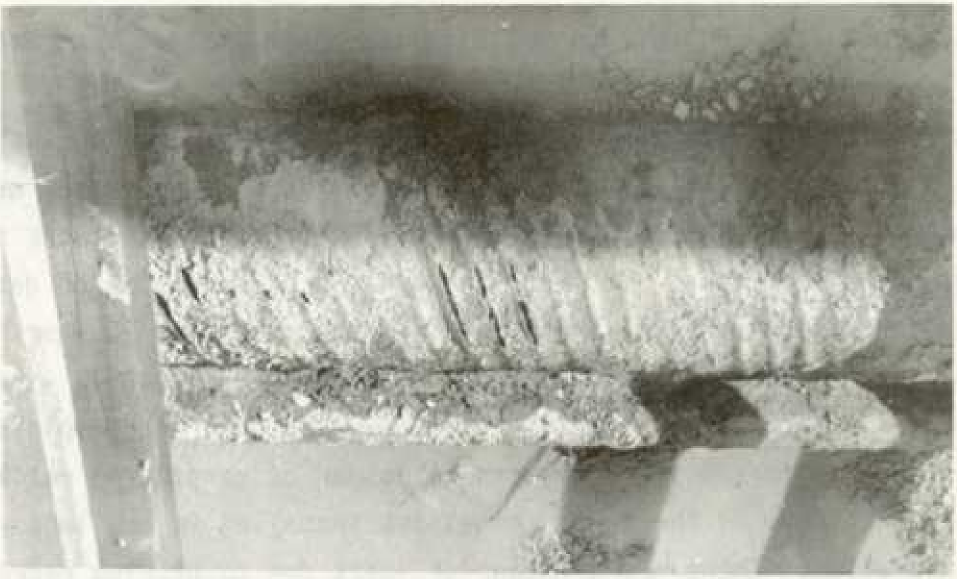
Fig. 2.5. Pressure map for 200 psig sendout.

3. RENOVATION OPTIONS FOR THE EXISTING STEAM DISTRIBUTION SYSTEM

A report evaluating the existing ORNL steam distribution was published in April 1983 by UCC-ND Engineering.[1] This chapter uses much of the material from the Engineering report. That report concludes that the aboveground piping shows little or no evidence of corrosion or deterioration and should be able to remain in service for another 20 years with conventional maintenance and repairs. However, the situation with the underground piping is completely different. The underground piping has been in service for 30 years and can no longer be considered reliable. There are failures in the buried pipelines installed in the loose-fill type insulation. There are a number of leaks due to pitting corrosion resulting from the insulation being wet. There is also the potential for additional ruptures in the remaining underground bellows type expansion joints that will result in the release of raw steam. However, the most costly failures are in the old-style steel conduit enclosed pipelines; primarily due to corrosion of the conduit casing with subsequential soaking of the thermal insulation and resulting excessive energy losses (Fig. 3.1). All of this is reported by UCC-ND Engineering and is further verified by the infrared and temperature measurements conducted in this investigation.

3.1 Renovation Needs to Upgrade the System

Several categories of changes are needed for upgrading the steam distribution system to provide another 20 years of service. The list of changes given in Table 3.1 includes improvements in operating efficiency, replacement of loose-fill insulation in underground mains, replacement of underfloor mains with mains around buildings, adding loop mains, refurbishment of system parts, and replacement of old-style steel conduit mains. There are six categories of renovations of which the first five are classified as high priority or urgent. The last category, replacement of old-style steel conduit, is classified as priority 2, which means it must be done in the near future. The refurbishment list provided in the Engineering Division evaluation report is much more extensive than



Corrosion damage of conduit casing.

Deteriorated insulation resulting from failures in the outer conduit.

Fig. 3.1. Failures in the old-style steel conduit enclosed pipelines.

Table 3.1 Steam system renovations

Description of equipment or system	Remaining estimated life (years)	Physical condition	Technology status	Estimated cost to replace/refurbish ($000)	Funding priority	Comments
1. Improvement in Operating Efficiency						
Aboveground replacement of underground main 5500 to 7000 areas, Phase 2	0-2	Poor	Inadequate	200	1	1200 ft of pipe
2. Replace Underground Mains						
8-in., 250-psig main along Central Ave. between Fourth and Fifth Streets	0-2	Poor	Unreliable	345*	1	Committed 440 ft of pipe
8-in., 250-psig along Third Street	0-2	Poor	Unreliable	100*	1	200 ft of pipe
3. Replace Underfloor Mains with Outside Mains Around Buildings						
8-in. at building 5500	0-2	Poor	Unreliable	302	1	
4. Add Loop Mains Between:						
Main supplies to bldg. 6000 and 7000 area, underground	New	New	Current	457	1	
Above 3-in. bldgs. 7012 and 7018	New	New	Current	148	1	
Aboveground 4-in. from Item 1 to 7000 area	New	New	Current	132*	2	
5. Refurbishment of System Parts						
Add gear operators and extension stems to pit isolating valves	New	New	Current	54	1	
Modify piping in Pits 29 and 40 and upgrade piping from 125 psig to 250 psig	New	New	Current	55	1	
			Subtotal	1216		
6. Replace Insulated Mains in Old Style Steel Conduit						
8-in., 250-psig underground main along Central Ave. in 4500 area and east of bldg. 4500N	5-10	Fair	Unreliable	792	2	1860 ft of pipe
8-in., 250-psig underground along Southside Drive from bldg 3502 to bldg. 5500	3-10	Fair	Unreliable	664	2	1200 ft of pipe
4-in., 250-psig underground between bldgs. 4500 and 6010	3-10	Fair	Unreliable	397	2	1200 ft of pipe
			Subtotal	1853		
			Grand total	3069		

*These items not included in cost comparison.

this limited list. The list provided in this report only focuses on the buried piping system that would be replaced by the proposed hot water system. This was done to allow a direct comparison between the investment that would be made in the renovation of the east-end steam system versus the new hot water system.

3.2 High Priority Renovation of the Underground System

There were five basic categories that were classified as high priority. The first of these is improvement in operating efficiency and the main item under this category is the replacement of the underground mains to the 7000 area with aboveground low-profile pipelines. The existing underground line is in contact with the groundwater and thereby has excessive heat loss. The estimated cost for the replacement is $200,000. This project is already under construction, and therefore is not included in the cost simulation in Table 3.1. The second category is the replacement of underground mains. One of the segments that needs replacing is an 8-in. underground line along Central Avenue between Fourth Street and building 3500. The failure of the insulation on this line resulted in an accident that caused an individual to be burned. The line was uncovered and a determination was made that there was a need for immediate replacement. The direct cost for replacement is $345,000. This line is an example of what could happen to other sections of the underground system, specifically the piping replacements listed under category 6. This project was not included in the cost savings due to the fact that a steam line will be needed to service the off-gas stack. The second segment that needs replacement under this category is an 8-in. underground line along Third Street. This is a 200-ft section of pipe that is believed to be in the loose-fill type insulation. There are indications that the insulation is saturated and that there is pitting of the pipe due to corrosion. It is estimated that this section can be replaced for $100,000. This project was also not included in the cost savings due to the fact that a steam line will be needed to service the off-gas stack.

The third category for renovation is replacement of underfloor mains with mains around buildings. The line to be replaced is the steam line that passes under building 5500, the high voltage accelerator laboratory. These underground lines have been in service for 25 years or more and there is some speculation of wet insulation. The cost of re-routing this line is estimated to be $302,000. The fourth category is the adding of loops to interconnect the system so that steam can be supplied from two directions. This was proposed because certain mains on the system are not reliable, and extended and costly outages could occur. The added looping is required because of the steam system's age and condition. Even after the other renovations are made, about two-thirds of the old system piping will remain in service, and the looping is necessary to insure decent reliabiity. The fifth category for renovation is the refurbishment of system parts. This includes added gear operators and extension steam to pit isolating valves. These are now necessary due to safety rules which require shutting off of the steam before entering a pit. Also under category five is the modification of the piping in Pits 29 and 40, and an upgrade of the piping from 125 psig to 250 psig. Both of these pits are in the 6000 area. The renovations in category five are estimated to cost $109,000.

The cost for renovation for all of these projects would be about $1,016,000. If a decision is made to proceed with a hot water system, all attempts should be made to avoid making this investment. If portions of the investment cannot be avoided, then all attempts should be made to minimize the investment. That means making only those repairs that are absolutely necessary.

3.3 Renovations Needed for Upgrading the System to Provide Another Twenty Years of Service

The sixth category listed in Table 3.1 is replacement of old-style steel conduit mains. Replacement of the 8-in. line in front of 4500N, and the 8-in. line east of 4500N, is recommended. Also recommended is replacement of a long section of 8-in. line along Southside Drive from building 3502 to building 5500. The third renovation listed under this category is the replacement of the 4-in. line from building 4500N to building 6010. The replacement of all these lines is a major investment, estimated to be $1,853,000.

The Engineering report indicates that the replacement of these lines will be necessary over the next 3 to 10 years. These are listed as priority 2 investments. From the new information from the ground temperature measurements (Appendix A), these lines will have to be replaced soon. The temperature measurements at several points indicate that there are either leaks or groundwater is in direct contact with the steam pipe. This situation is not stable and it is speculated that the leaks will tend to grow and cause a safety hazard similar to the situation in front of building 3525 as described under category 2. It is therefore anticipated that these replacements will have to be made in the same time frame as the other five categories of renovations.

3.4 Summary of the Cost of Renovation

The buried system (primarily in the east end of the plant) will need renovation in the near future. If a decision is made to renovate the existing steam system, it is recommended that the projects proposed in Table 3.1 all be implemented at the same time. The priority 2 renovations of replacement of old-style steel conduit mains should be changed to a priority 1 investment. Recent temperature measurements indicate potential serious problems that could affect both reliability and safety. The total cost for all of the renovations is $2,869,000. This investment will be directly compared with the new hot water system that is described in Sect. 4.

The operating efficiency improvements resulting from these renovations are difficult to estimate because of the losses in the present system. As presented in Sect. 2, the existing plant produces about 700 x 10^6 lb/yr of steam and exports to the distribution system about 600 x 10^6 lb (720 x 10^9 Btu). Presently the east-end system is about 53% efficient and requires 432 x 10^6 lb (519 x 10^9 Btu). The east-end system consists of about 18,000 ft of pipe of which 6,000 ft would be replaced under the proposed renovations. Therefore, it is estimated that the losses would only be reduced by an average of 8,000 lb/h. This amounts to 70 x 10^6 lb/yr (84 x 10^9 Btu). The east-end system would then have an annual operating efficiency of 63%. With an assumed sendout steam fuel cost of \$3.00/10^6 Btu (\$2.1 x 10^6/720 x 10^9 Btu), the annual savings in the fuel bill will amount to \$252,000.

In addition to the fuel savings, the renovations would also lower the maintenance costs. In calendar year 1983 the maintenance costs were about \$500,000; this includes conventional maintenance plus emergency repairs. The emergency repairs were considerable since major sections of lines were replaced. After the system is completely renovated, the maintenance cost should be considerably lower. However, there is still about two-thirds of the system that consists of older piping, which implies that the maintenance could be on the order of \$200,000 per year.

4. DEVELOPMENT OF A NEW HOT WATER DISTRICT HEATING SYSTEM AT THE ORNL SITE

The United States and Canada are virtually the only northern industrialized countries with any significant steam district heating. The northern Europeans, since the early 1950s, have developed and refined a hot water district heating technology. In the European systems, steam is generally limited to serving process loads. There are several hybrid hot water-steam systems where the hot water serves the large space heating load, and the steam serves a much smaller industrial process load. The hot water technology based on the European philosophy of design clearly supersedes steam for space heating applications. Therefore, one of the main objectives of this study was to determine the economic viability of replacing most of the buried steam system at ORNL with a new hot water system. This not only means replacing the pipe, but also converting the building systems to be compatible with the new hot water system.

4.1 Modern Hot Water District Heating Piping Technology

The piping design is assumed to be based on the well-proven VVF (Varme Verks Foreningen) standards used throughout Europe. The piping generally used in the modern hot water systems consists of two buried steel carrier pipes insulated with a high-density polyurethane foam and jacketed with a high-density polyethylene (Fig. 4.1). The pipe has thin walls, something between a schedule 10 and a schedule 20, which is sufficient to handle the thermal stresses induced by the 250°F temperatures. The high-density polyurethane foam insulation is stable at temperatures only up to 266°F. The foam insulation acts to transfer thermal stresses to the surrounding backfill which is normally a washed sand. Pipe insulation is also equipped with a double-wire alarm system which alerts operators to leaks or damage. The alarm system can be used to determine the location of the faults within three feet. The specifics of this technology are not limited to buried piping systems. There are analogous modifications to the design for aboveground piping. As in the case with steam systems, aboveground piping is cheaper than buried installations

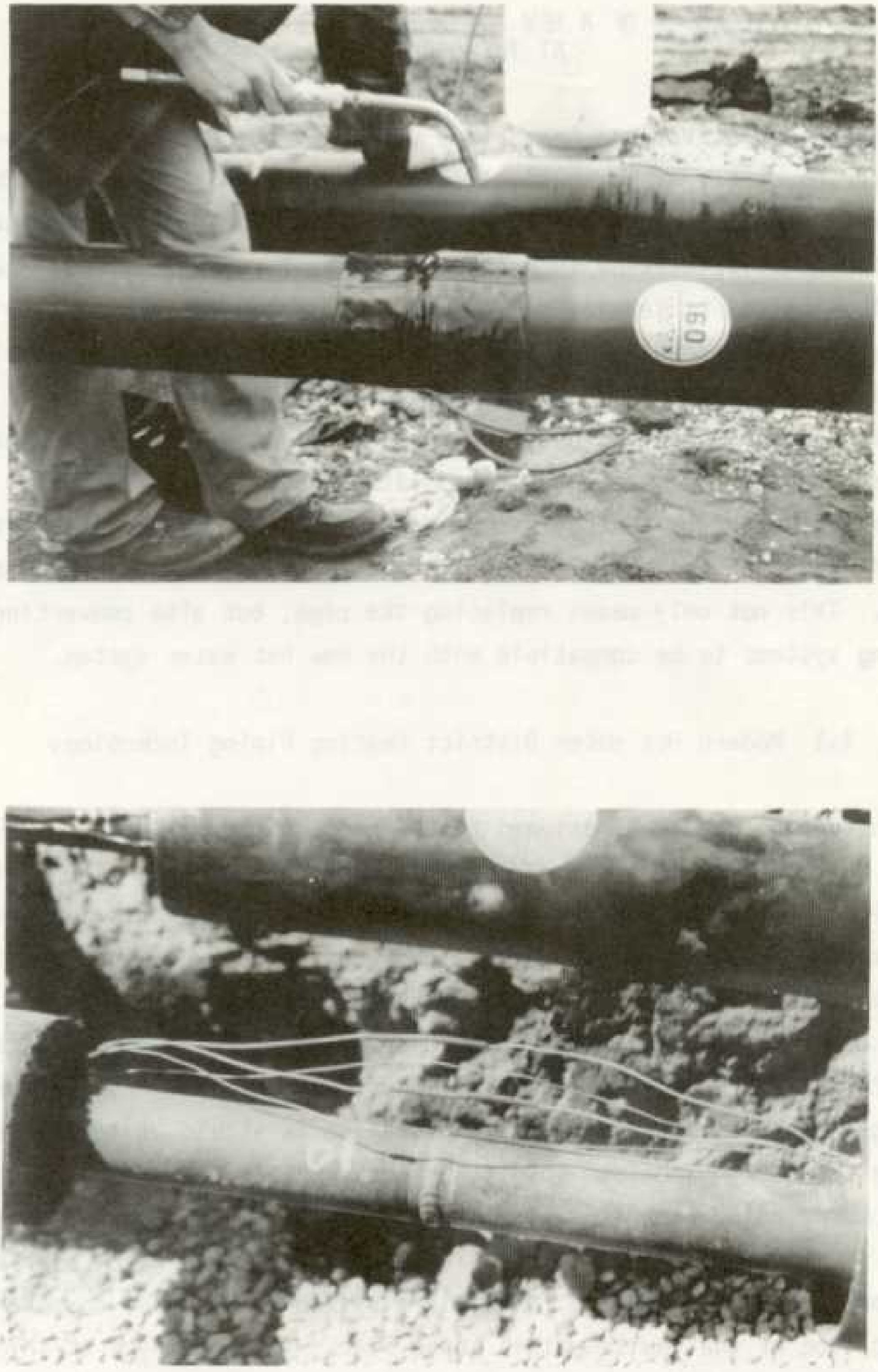


Fig. 4.1. Modern hot water piping technology.

and should be considered for some parts of the new hot water system at ORNL.

The hot water system requires a minimum number of vaults. One of the main reasons for vaults in steam systems is traps and hot water systems have no traps. Vaults are used only for bellows and valves in hot water systems. However, many times even the valves are buried directly. Generally, expansion is allowed by either bends or bellows type compensators. However, it should be noted that modifications to this approach are available. One new design is classified as a "No Comp" system. This involves thermal prestressing of the pipe prior to backfill and compaction. In principle, if no compensation devices or U-bends are required, a 5-10% cost savings is possible. Drawbacks include complicated and somewhat delicate construction techniques and the necessity to keep trenches open for relatively long periods of time. In some instances prolonged outage may damage the pipe if the "No Comp" technique is used.

4.2 Building Thermal Loads

The building heating loads are the foundation of a proper investigation of district heating. Thus, care must be taken to obtain accurate estimates of these loads as well as forecasting future additions. Loads on the existing buildings at ORNL were determined from (1) metered steam flow data and (2) estimates based on building thermal envelope and exhaust air flow data. Considerable judgment was required to interpret these data. The building steam meters were installed for information purposes only, and there was little incentive to maintain them. Thus, the historical meter data had to be examined carefully for each building to determine if they were reasonable. Estimating the loads from the building thermal envelope and air flow data is difficult at ORNL because of the wide spectrum of activities at the Laboratory. Many buildings contain large heat sources, such as laboratory equipment or main frame computers. Exhaust air requirements in the laboratories located in different buildings often are large and varying.

To compensate for the weakness of the building loads data, conservative estimates of the loads were used in all cases. Appendix C gives a tabulation of these loads. Conservative estimates of the building loads will tend to cause piping sizes to be higher with concurrently higher costs. Experience has shown that this error usually will be relatively small. Nevertheless, more accurate energy load estimates must be performed before construction. It is also important that future energy conservation measures be considered in these estimates.

4.3 Civil and Basic Piping Layout

The soils at the X-10 site had been reported as lean clays which are generally a simple environment for trenching. The only unusually high groundwater was in the area of the steam line running between building 5505 and the 7000 area. Other than this area, because of the relatively shallow trenches (3-4 ft) it is anticipated that only conventional trench drains will be required. The hot water district heating pipe is designed to withstand reasonable groundwater pressures. A potential significant factor that has been reported is the existence of soils having a low level of radioactivity. Such areas could affect the route of the pipe as well as increase the cost of construction. This must be carefully considered before construction.

Two basic piping networks (Figs. 4.2 and 4.3) are presented as possible options representing different approaches to "looping". These layouts do not take into account the existing underground utilities, unusual soil conditions that may exist in the area, or specific locations for compensation bends or vaults. An attempt was made to keep within the ORNL streets where possible. There are no major advantages for locating the piping in the street and other options should be investigated before construction. More detailed information on soils and utilities is needed before a decision on the locations of piping can be made. Routing changes resulting from this information may be important, but they are not likely to materially affect the cost.

The pipes were sized by conventional load/pressure/flow relations. A diversity of 90% was used on most branches with 100% used on individual service connections. This is a conservative simplified assumption and should be improved upon as details of the loads are obtained. In both

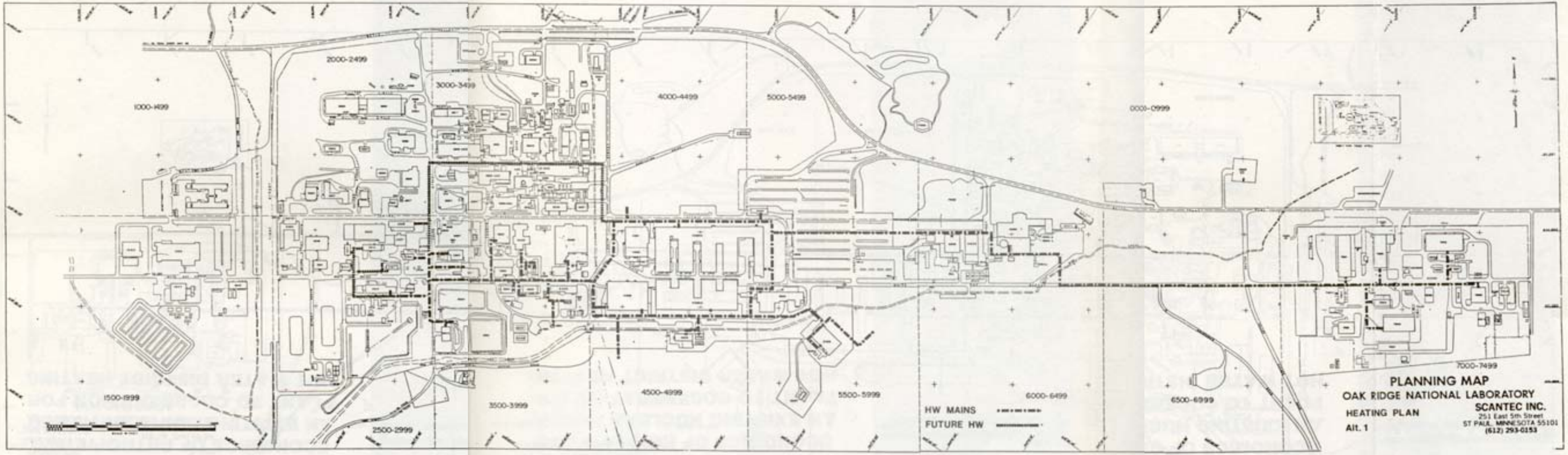


Fig. 4.2 Hot water district heating piping network - Alternative #1.

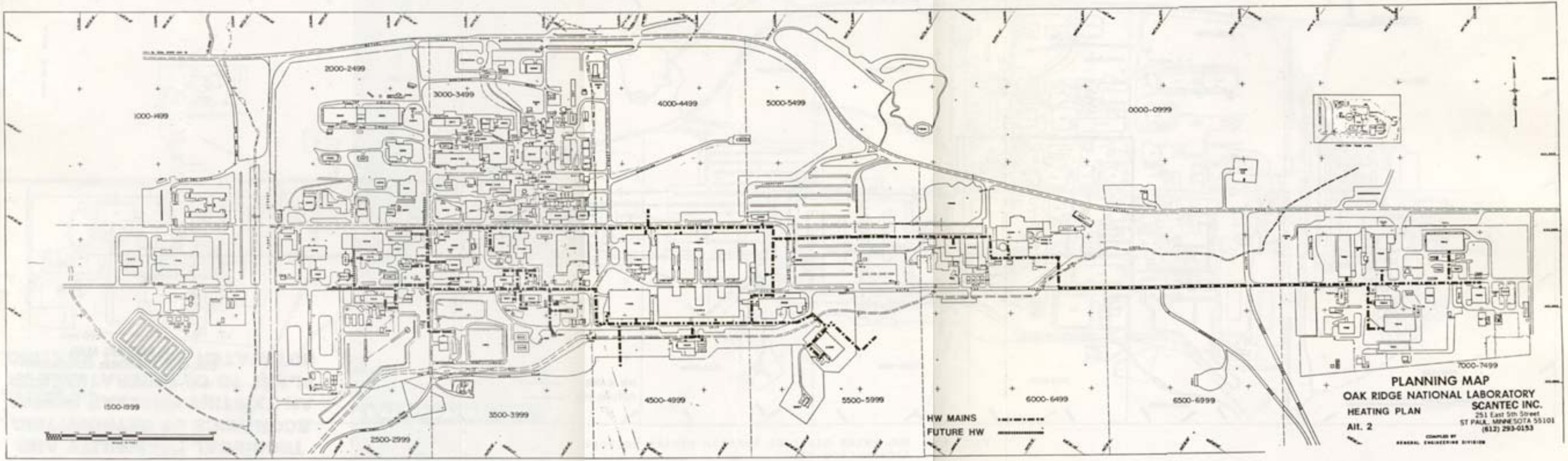


Fig. 4.3 Hot water district heating piping network - Alternative #2.

alternatives the pipes are sized to supply the 6000 and 7000 buildings through either of the main lines. Beyond that capability, no extra looping capacity has been included. Naturally, since all sizes are related to peak loads there will be excess capacity available during periods of less than peak demand. Capacity has been included for service to the 2000 area.

The largest size pipe needed in either alternative is 12-in.-diam that will serve as the main trunk line out of the plant. Alternative 1 has approximately 30,000 ft of various diameter pipes (Table 4.1) which means about 15,000 ft of trench for the piping system. One option that should be considered in the detailed design is to use the existing steam line to the 7000 area as part of the hot water system. Since it is relatively new, it could be used as a return water line and a new supply line could be constructed parallel to the existing line. This could reduce costs, however for this study it was assumed that both a new supply and return line would be run to the 7000 area.

Table 4.1 ORNL piping summary

Piping diameter (in.)	Length of trench* (ft)
Alternate 1	
12	1320
10	1000
8	1140
6	560
5	2490
4	2830
3	960
2.5	2110
Alternate 2	
12	410
10	2400
8	1640
6	570
5	2310
4	2730
3	820
2.5	2050

*Distances represent the estimated trench length. A dual piping length will be twice the trench length (the smaller service connections are not included).

4.4 Basic Design for a Hot Water Conversion Plant

The hot water system will require a source of hot water which is assumed to be the existing coal plant facility. It is assumed that a suitable site can be found adjacent to the existing steam plant for the conversion plant. Steam would be transmitted from the steam plant to the conversion plant. It is recommended that the steam be transmitted at the lowest possible pressures (30 psig) to allow for future flexibility. It is also assumed that a condensate return line would be installed from the conversion plant back to the steam plant. The equipment in the conversion plant includes heat exchangers, water expansion compensators, water pressurization equipment, and circulating pumps.

The proper design for the conversion plant is critical to a reliable operation, but its construction should be relatively straightforward. Figure 4.4 is a picture of a recently constructed hot water conversion plant for the municipal utility in Willmar, Minnesota. This plant cost approximately $450,000 which includes a brick exterior and contemporary architecture. Figure 4.5 is the detailed layout for the Willmar conversion plant. This conversion plant was sized for about 25 MW(t) capacity. It is estimated that the ORNL plant would be slightly larger at approximately 35 MW(t).

4.5 Technical and Economic Aspects of Building Conversion

One of the more critical aspects of this evaluation is the cost of converting the building systems to be compatible with a 250°F (120°C) hot water district heating system. One of the main concerns in cities is the diversity of the building heating systems in the central business districts. This diversity results basically from a wide range in the age of buildings and the age of the HVAC systems. This concern is not valid at the ORNL site since the HVAC systems in the larger buildings are all quite similar.

For this feasibility study the buildings were categorized into large buildings and small buildings (Table 4.2). In the area of the proposed

Fig. 4.4. Steam to hot water conversion plant in Willmar, Minnesota.

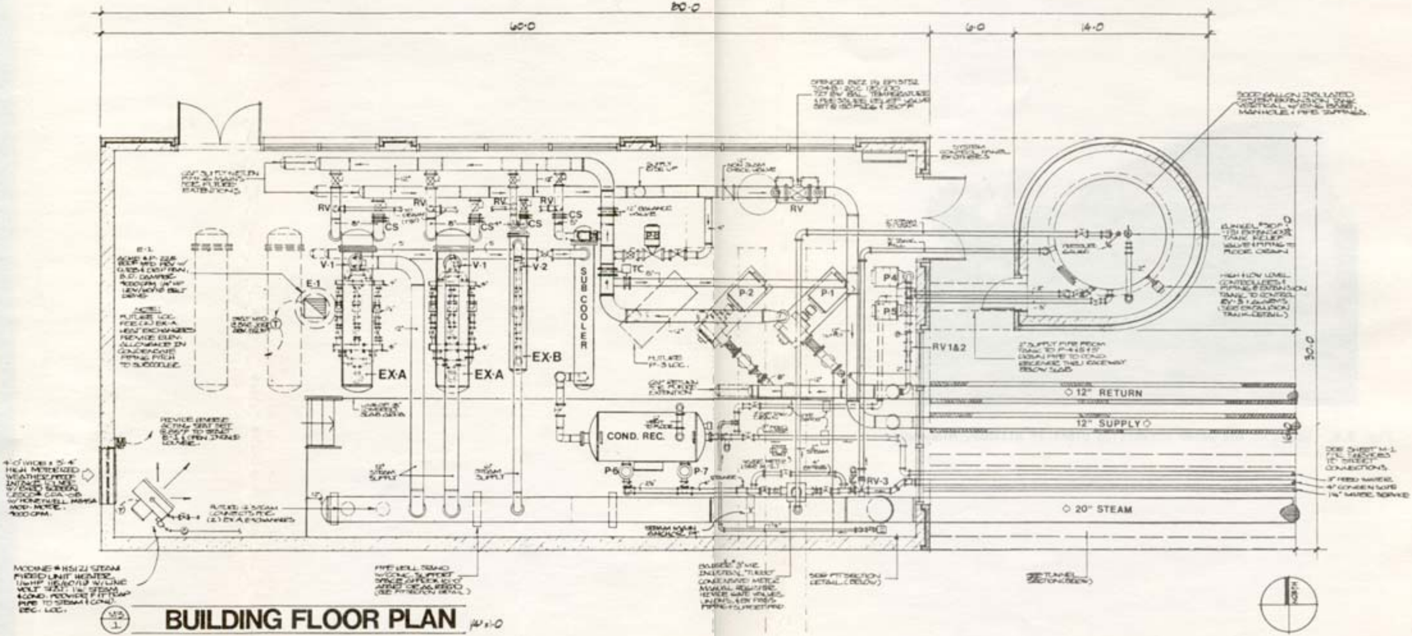


Fig. 4.5 Building floor plan for the hot water conversion plant in Willmar, Minnesota.

Table 4.2 Potential buildings connected to the new hot water system

Large buildings	Smaller buildings
4500N	3525
4500S	3550
4501, 4505 and 4507	3505
4508	3517
5500	3508
5505	3504
3500	3503
6000	3502
6010	4509
6025	7000 area

new system, the east end of the ORNL site, there are 10 larger buildings and approximately 15 smaller ones. The large buildings make up the majority of the loads and the HVAC systems for these large buildings are relatively uniform. Each building generally has several large air handlers with steam preheat and hot water reheat. The retrofitting of this type of heating system will be relatively simple because the only modification is to the steam preheaters. They either have to be replaced with hot water coils or possibly retrofitted for hot water use.

In some buildings there is also process steam that is used for stills and other laboratory experiments. The piping to serve this system is sized for relatively large loads even though the use of process steam is limited. It was assumed in this study that these loads would be met by small electric steam generators and the cost would be included in the building conversion cost. The cost estimates for the conversion of the existing building heating systems to use the hot water district heating were based on a study performed by Scantec, Inc.[5] Their study analyzed the conversion of three buildings, 4500N, 3500, and 6010, and extrapolated the results to seven other buildings. The ten buildings account for over 80% of the load to be served by the new hot water system. The average cost for the conversion is $72/kW. In comparison the City of St. Paul has had some recent bids on converting large buildings for their hot water district heating system (Table 4.3). These bids range in cost from approximately $30/kW to over $500/kW. The higher costs were for buildings that have one-pipe steam systems that require total renovations and modernization of the heating systems. The low-cost buildings (under $30/kW) already had modern hydronic systems and the conversion only consisted of installing a hot water-to-hot water heat exchanger and the control system. The conversion at ORNL is much simpler than most of the conversion for the buildings in St. Paul and therefore the cost of $72/kW is at the low end of the range of cost.

Table 4.3. Cost of building conversion for 1983 connections in St. Paul, Minnesota

Building	Actual cost	$/kW
City Hall Annex	$ 85,596.00	146.00
St. Paul Public Library	128,394.00	232.60
Landmark Center	222,700.00	287.00
U.S. Courthouse	123,700.00	119.63
Civic Center	139,900.00	42.40
Kellogg Square Apts.	279,866.00	48.50
Ramsey County Adult Center	93,500.00	90.45
Ramsey County CH/CH	674,000.00	266.60
YWCA	164,700.00	176.60
St. Paul Companies	330,000.00	112.63
Degree of Honor	195,140.00	356.70
Dayton's	59,785.00	29.50
Minnesota Museum of Art	112,000.00	569.47

4.6 Cost of a New Hot Water System

The cost estimates assumed here are based on construction cost experience in St. Paul and Willmar, Minnesota. As previously mentioned the piping design is assumed to be based on the well-proven VVF standards used throughout Europe as well as in the new systems in St. Paul and Willmar. The cost estimates are presented for two basic piping networks in Table 4.4. These two networks represent different approaches to looping. However, there is very little difference in the costs between the two options - only \$120,000. The costs presented are direct cost and do not include engineering, contingencies, and escalation to the time of construction. Alternative 1 is the lowest cost option with a cost of \$4,940,000. This includes the cost of building conversion and a metering system.

Table 4.4 Cost of new hot water system

	Alternate 1	Alternate 2
Piping and Insulation	\$1,740,000	\$1,861,000
Conversion Plant - 35 MW(t)	850,000	850,000
Building Conversion (\$50/kW)	2,300,000	2,300,000
Metering System	50,000	50,000
Total	\$4,940,000	\$5,051,000

4.7 Energy and Operating Improvements Resulting from the Hot Water System

The existing plant presently produces 700 x 10^6 lb/yr of steam and exports to the distribution system about 600 x 10^6 lb (720 x 10^9 Btu). The estimates made in Sect. 2 for the east-end piping system put the building thermal load at 275 x 10^9 Btu. Presently the east-end system is about 53% efficient, and thereby requires 519 x 10^9 Btu/yr.

The hot water system would have an efficiency of 90% and therefore save approximately 214 x 10^9 Btu/yr. With an assumed sendout steam fuel cost of \$3.00 per million Btu (\$2.1 x 10^6 ÷ 720 x 10^9 Btu) the annual savings of the fuel bill would amount to \$642,000. There are also secondary effects such as more efficient internal building systems due to better control and night setback. These efficiency improvements in the buildings could amount to additional savings of about 5%. To be conservative this small benefit was ignored.

In addition to the fuel savings the hot water system will also have lower maintenance costs. The Swedish District Heating Association has compiled long-term maintenance statistics and on a small system, such as the one at ORNL, the cost should be about 0.5% annually of the capital investment. This would amount to annual maintenance costs of \$25,000 to \$50,000. For the economic analysis performed in this study the higher amount of \$50,000 was used. This should cover any early problems with defective welds and joints. As mentioned previously, the hot water system would have a leak detection system and one of its important functions is to determine faults made during construction. This would have a small impact on higher maintenance during the first two or three years of service. However, there would be considerable cost savings in future years. The leak detection system can be used to determine the location of a fault within three feet. Therefore, excavation can be limited to a small area. The alarm system can significantly reduce maintenance costs while extending the life of the system.

The hot water system would allow additional cost savings due to reduced water consumption, reduced maintenance inside the buildings and reduced operation of the chillers during the winter months. The renovated steam system would still require a 100% boiler make-up water. The cost for make-up water includes water cost, water softener chemical cost, and softener maintenance cost. The estimated savings due to reduced water consumption for the proposed hot water system would be about \$50,000/yr. The new hot water system would also eliminate steam coils and steam traps inside the buildings. There is extensive maintenance on these items which would not be incurred with a hot water system. It is estimated that the hot water system would reduce the maintenance inside the buildings by about $50,000/yr. While converting the buildings to be compatible with the new hot water system there would also be the potential to obtain free cooling energy during the winter months. The new hot water coils in the big air handlers could be placed downstream of the present chilled water coils. The incoming fresh air could be used to make chilled water prior to being heated in the new hot water coil. There would be no additional capital cost to install the heating coils downstream of the chiller coils and it would allow significantly reduced operation of the chillers during the winter months. The cost of operating the chillers in the winter months is about $35,000/month. It is assumed that about half of this could be saved and over a three-month winter period this would amount to about $50,000. The total savings due to reduced water consumption, reduced maintenance inside the buildings, and reduced operation of the chillers amount to $150,000 annually.

The hot water system would require pumping power to move the water in the system. It is estimated that the hot water system at ORNL would require about 600,000 kWh. At an assumed cost of $0.04/kWh, the cost of pumping energy is $25,000 annually.

4.8 Other Options for Initiating a New Hot Water System

Total replacement of the buried piping system with a new hot water system is only one option. It is highly desirable because it would mean obtaining all the benefits of the hot water system in one step. There is the possibility of using portable conversion plants and installing the hot water system in a stepwise fashion. For example, a portable conversion plant could be placed south of 6000 and could be used to serve a new hot water system connecting the 7000 area. The steam system presently connecting those buildings would be abandoned. This stepwise construction process could be used to initiate the hot water system. However, there is the additional cost of a skid-mounted conversion plant (estimated to cost $100,000).

5. ECONOMIC COMPARISON BETWEEN RENOVATING THE STEAM SYSTEM VS A NEW HOT WATER SYSTEM

The main objective of this investigation is to compare the economics of renovating the existing buried steam system with the economics of a new hot water system that would totally replace the buried steam system. The economic comparison between the two options includes the capital cost, the annual fuel cost, and the annual maintenance cost. The comparison is limited to the area that is served by the steam system at the east end of the plant. This investigation did not evaluate the renovation of the west-end system or consider a hot water system for that area.

5.1 Capital Expenditure Comparison

As concluded in Sect. 3, the east-end steam system will need renovation in the near future. If a decision is made to pursue renovation, then it is recommended that the six categories listed in Table 3.1 be implemented at the same time. This investment should produce a relatively reliable and safe system. The direct construction cost for all six categories of renovation is \$2,869,000. The direct construction cost for a new hot water system as described in Sect. 4 is \$4,940,000. The two options are not completely comparable. For example, the hot water system includes the cost of a relatively accurate metering system that would allow for better heat energy management.

To derive the total capital cost of either the steam renovation or the hot water system, engineering and contingencies must be added to the direct construction cost. For the analysis, the engineering cost was assumed to be 20% of the direct construction cost. It was also assumed that contingencies were 25% of the direct construction cost. The total capital cost for the steam renovation is \$4,160,000, and \$7,160,000 for the hot water system (Table 5.1).

Table 5.1. Capital cost comparison

	Steam renovation	New hot water system
Direct construction cost	$2,869,000	4,940,000
Engineering cost (20% of direct cost)	574,000	988,000
Contingency (25% of direct cost)	717,000	1,232,000
Total capital cost	$4,160,000	$7,160,000

5.2 Operating and Maintenance Cost Comparison

The east-end steam system as it exists today has excessively high maintenance cost, and if no capital investment is made, the emergency maintenance cost can be expected to escalate. This method of doing business would be more costly because the emergency maintenance cost would carry a 30-40% surcharge over the planned steam renovation.

After the steam system renovations are made, it is estimated that the yearly distribution system maintenance will average $200,000 per year. This is relatively high because the renovations are only replacing about one-third of the pipe in the steam system. Therefore, the renovated system still has a lot of older steam piping. The maintenance on the hot water system is estimated to be $50,000 per year. The difference in the annual distribution system maintenance savings between the two options is $150,000 per year (Fig. 5.1).

As outlined in Sect. 4.7, the hot water system also allows for cost savings because of reduced make-up water consumption, reduced maintenance inside the buildings, and reduced operation of the chillers during the winter months. Each of these is estimated to be about $50,000; therefore, an additional $150,000 is added to the operation and maintenance (O&M) cost for the steam renovation option. The total O&M cost for this option including distribution system maintenance is $350,000 annually

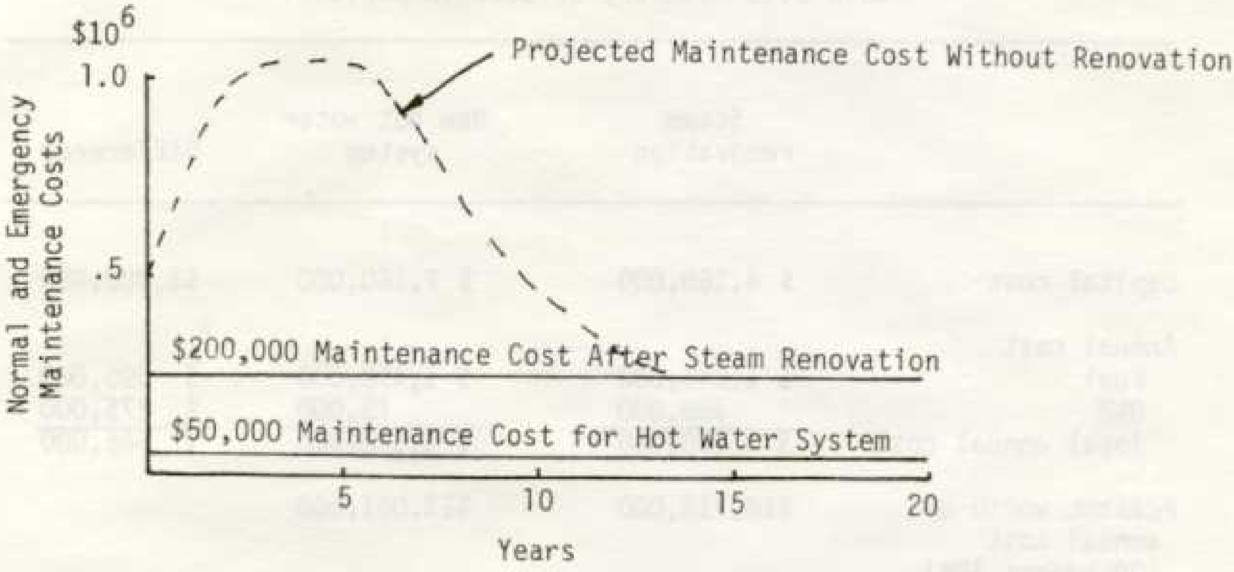


Fig. 5.1. Annual distribution system maintenance cost comparison.

(Table 5.2). Also as outlined in Sect. 4.7, the hot water system requires pumping power. Cost of the electricity used to provide this power is estimated to be $25,000/yr. This, added to the hot water system maintenance cost, gives a total O&M cost of $75,000/yr. The total O&M cost difference between the two options is $275,000/yr (Table 5.2).

5.3 Coal Energy Usage Comparison

Presently, the annual fuel cost for the steam system for a normal winter is $2,100,000* for the 720 x 10^9 Btu of energy put into the steam distribution system. The assumed sendout steam fuel cost is $3.00/$10^6$ Btu (2.1 x 10^6 ÷ 720 x 10^9 Btu). This amount does not include any labor or maintenance cost of the steam plant. The east-end system now uses 519 x 10^9 Btu of steam energy and has an annual fuel cost of $1,557,000 (Fig. 5.2). The east-end steam system after

---

*The $2,100,000 is the approximate fuel cost for the winter of 1981-82. The fuel cost for the winter of 1982-83 was lower due to lower coal prices caused by a depressed coal market. The annual cost for 1981-82 is assumed to be a reasonable estimate for future year cost projections.

Table 5.2. Summary of cost comparison

	Steam renovation	New hot water system	Difference
Capital cost	$ 4,160,000	$ 7,160,000	$3,000,000
Annual cost			
Fuel	$ 1,848,000	$ 1,458,000	$ 390,000
O&M	350,000	75,000	$ 275,000
Total annual cost	$ 2,198,000	$ 1,533,000	$ 665,000
Present worth of annual cost (20 years; 10%)	$18,712,000	$13,051,000	
Total present worth (20 years; 10%)	$22,872,000	$20,211,000	
Simple payback			4.5 years

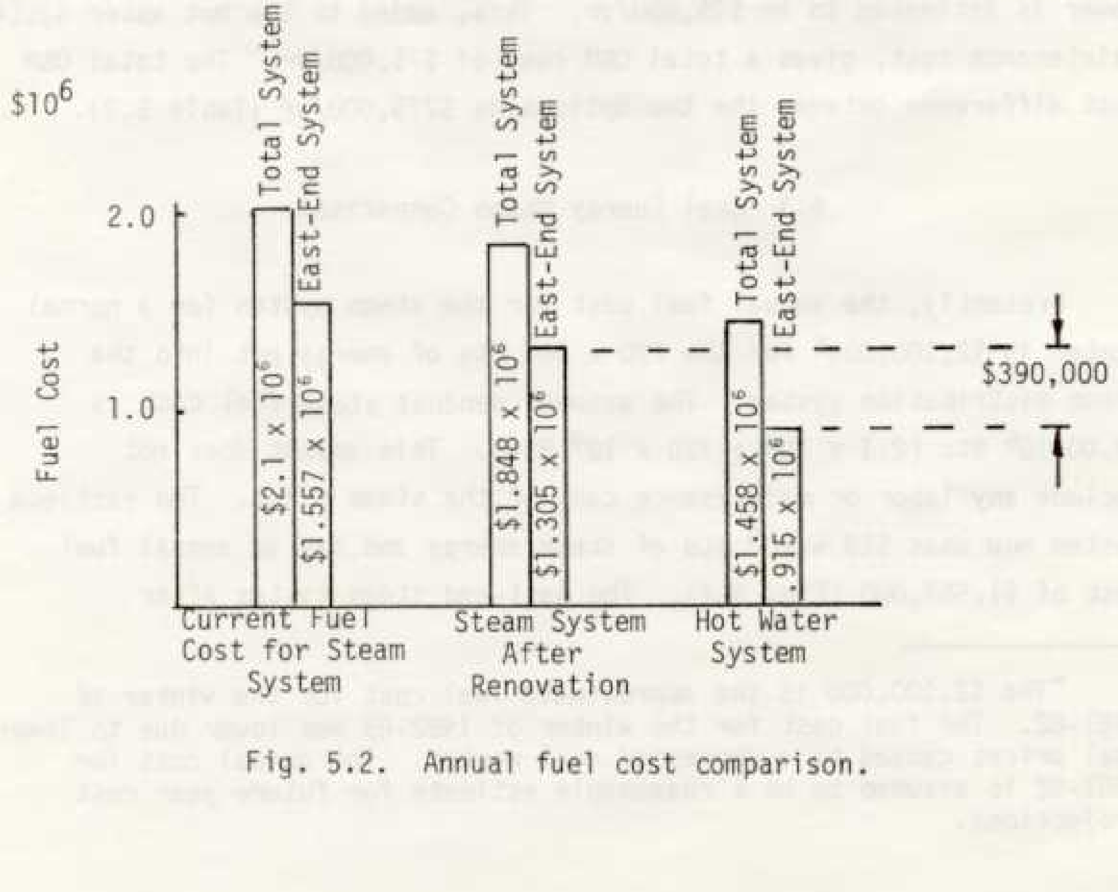


Fig. 5.2. Annual fuel cost comparison.

renovation would require 435 x 10^9 Btu and would have a fuel cost of $1,305,000. The hot water system would require 305 x 10^9 Btu and have a fuel cost of $915,000. The annual fuel cost savings of the hot water system over the steam system after renovation is $390,000.

5.4 Summary of the Cost Comparison

The hot water district heating option has a capital cost of $3,000,000 more than the steam renovations (Table 5.2). However, the total annual cost, which includes fuel, operation, and maintenance, has a $665,000 yearly savings in favor of the hot water option. The simple payback for the hot water option is 4.5 years. A present worth analysis also favors the hot water option. The steam system has a total present worth of $22,872,000 compared to the hot water of $20,211,000. The hot water system has a $2,600,000 present worth saving over the steam renovations.

6. CONCLUSIONS AND RECOMMENDATION

This investigation analyzed the status of the existing steam system, the proposed renovations to the steam system, and the option for a new hot water system. The conclusions are therefore categorized along the three areas of analysis.

The Status of the Existing Steam District Heating System

1. Because of recent failures and anticipated failures, the east-end or buried steam system can no longer be considered reliable. There are corrosion problems in the loose-fill buried pipelines and failures of the old-style steel conduit enclosed pipelines. These conclusions are based on an evaluation report by UCC-ND Engineering and further verified by measurements conducted in this investigation.

2. The east-end or buried system has an annual operating efficiency of about 53%. This system has significant losses resulting from deteriorated insulation, malfunctioning traps, general system leaks, and no condensate return. These losses account for $730,000 of annual fuel cost on a total of $1,557,000 for the east-end system.

Renovations to the Steam System and Efficiencies after Renovation

1. The proposed renovations for the east-end steam system would cost $4,160,000. All six categories of projects listed in Table 3.1 should be implemented to achieve a reliable and safe steam system.

2. The operating efficiency improvements resulting from the renovations is estimated to be 84×10^9 Btu which amounts to an annual savings in the fuel bill of $252,000.

New Hot Water System That Would Totally Replace the East-End Steam System

1. Hot water district heating is a proven technology that has been installed in hundreds of European cities and recently introduced into two U.S. cities, St. Paul and Willmar, Minnesota. The hot water systems are significantly cheaper to build than a steam system and have generally lower losses. In addition, the hot water systems have lower maintenance costs.

2. The hot water system described in this study would cost $7,160,000. The total annual savings in fuel and maintenance is about $665,000. Simple payback for the hot water option is 4.5 years.

A new hot water district heating system for the east part of the ORNL site has many advantages over renovation of the existing steam system. The advantages include good economics, higher reliability, better control, more accurate metering and a somewhat safer system. Because of these benefits, it is recommended that the development of a new hot water district heating system be pursued.

REFERENCES

1. G. J. Dixon, S. C. Harris, O. A. Kelly, Evaluation of Steam Distribution System - ORNL, Report No. X-OE-209, April 29, 1983.

2. Lockwood Greene Engineers, Inc., Drawing and Specification Transmittal, Job no. 82902.02, dated September 30, 1982.

3. O. A. Kelly, Steam Loss Test No. 1, and Repair Cost Justification, memo to file dated February 24, 1981.

4. E. S. Monroe, How to Test Steam Traps, Chemical Engineering, September 1, 1975.

5. M. H. Barnes, Building Conversion to Hot Water District Heating - Conceptual Design, Scantec, Inc., under Subcontract 37X-73915V, November, 1983.

APPENDIX A

DETERMINATION OF HEAT LOSSES FROM UNDERGROUND STEAM PIPELINES IN THE 4500 AREA OF ORNL

M. C. Lindell
H. A. McLain
P. W. Childs

DETERMINATION OF HEAT LOSS FROM UNDERGROUND STEAM PIPELINES IN THE 4500 AREA OF ORNL

INTRODUCTION

To gain some indication of the extent of heat losses from underground steam lines due to deteriorating insulation and steam leaks, part of the ORNL steam system was surveyed using two heat loss detection techniques. One technique, infrared thermography, uses an infrared scanning system to provide a visual display of ground temperature differences. Greater temperature differences between the ground over the steam lines and the undisturbed surrounding ground cause more intense visual displays. This technique was used to examine relative heat loss along the pipeline and to identify hot spots. Although infrared thermography can identify areas of significant heat loss, it cannot quantify that heat loss, hence, another technique must be used.

The second technique used in this survey involves the use of a subsurface ground temperature probe. This probe, which was simply a sheathed thermocouple, was used to measure ground temperatures about 6 to 8 in. below the surface in the area over the buried steam lines. By combining these temperatures with other parameters such as pipe depth, soil thermal conductivity and undisturbed earth temperature, an equation expressing pipe heat loss can be formed.

The approach used in this survey was to first scan the buried steam lines using an infrared scanning system in order to identify relatively high heat loss areas, and then obtain ground temperature profiles in those areas. The heat loss rates were determined from these profiles using the relation for buried pipe heat transfer. Using these heat loss rates in other heat transfer relations, the effective thermal conductivities of the buried pipe insulation were then estimated. These values give some indication of the condition of the insulation.

METHOD

Infrared Thermography

The underground steam line examined in this survey consists of the loop around the 4500 complex from the northwest corner of 4500N, east along Central Avenue, then south to 5500, and west along 4500S to the southwest corner of 4508 (Fig. 1). The loop was examined with an infrared movie camera from the roofs of those buildings, and the infrared images were recorded on a video cassette tape. The survey was conducted late at night so that ground temperatures would be stable, and influences from the sun and reflection effects would be minimized. Prior to the survey, conventional black and white pictures were taken (from the roofs during the daytime) so as to give reference pictures for the infrared views.

Subsurface Ground Temperatures

Ground surface temperatures can change quickly due to varying sun and weather conditions. For this reason, ground temperatures in the area of a steam pipe should be measured below the surface. In this study, temperature measurements were taken at a depth of about 6 to 8 in. The measuring device was a stainless steel sheathed thermocouple attached to a digital temperature indicator. Once the hot regions were identified by the infrared scan, temperature readings were taken in those areas. For comparison, readings were also taken in relatively cool areas. At each location readings were taken directly over the steam pipe, 2 ft to the side of the pipe, and 4 ft to the side of the pipe.

Heat Loss Rates

Heat loss per unit length of pipe can be estimated from the potential flow relation:[1]

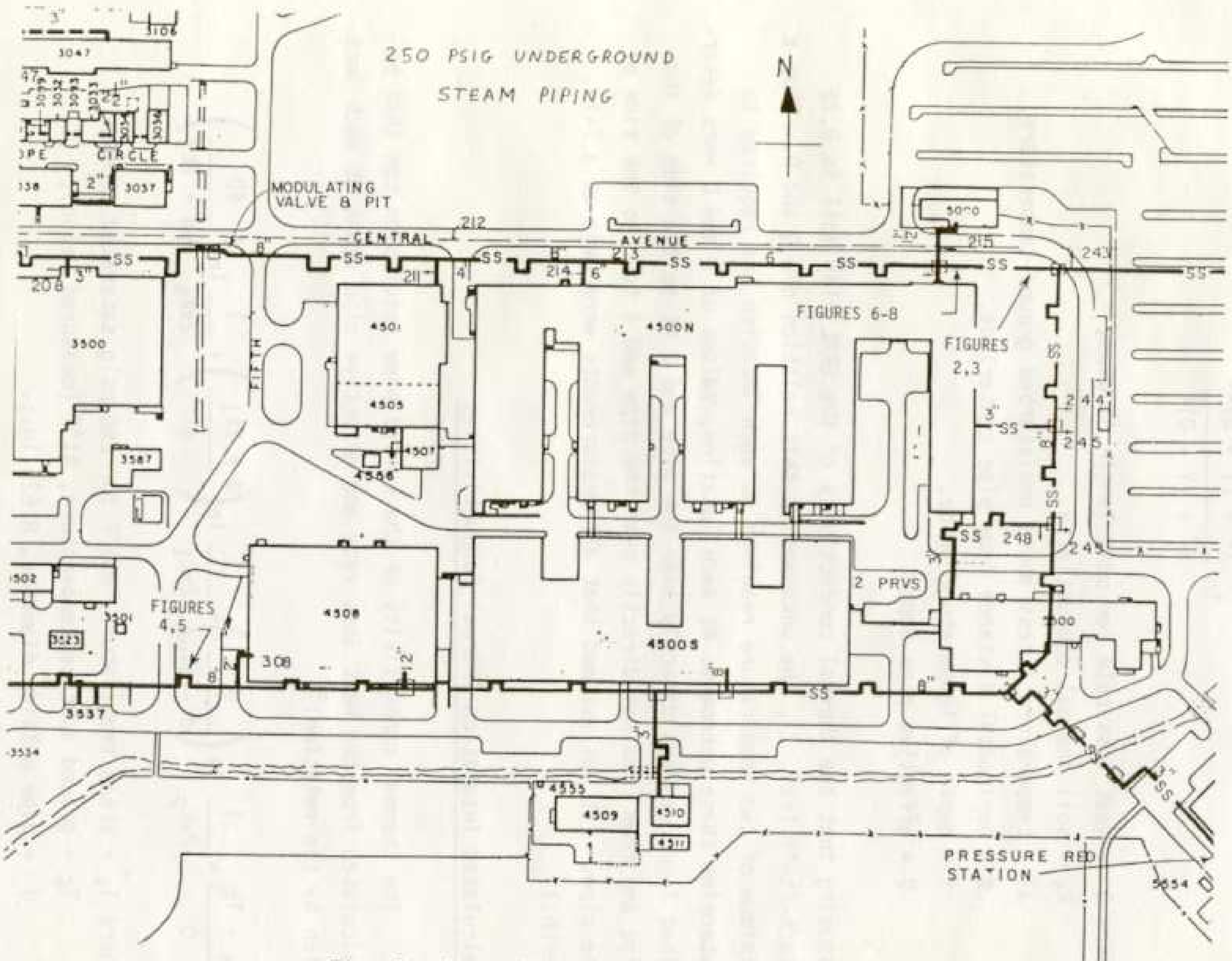


Fig. 1. Locations for picture survey of underground steam lines.

$$Q = \frac{4\pi k_s \Delta T}{\ln \dfrac{X^2 + (Y + D)^2}{X^2 + (Y - D)^2}}$$

where Q = heat loss rate per unit length of pipe,

k_s = soil thermal conductivity,

ΔT = temperature excess above undisturbed ground temperature,

X = horizontal distance from pipe centerline,

Y = depth of temperature probe,

D = effective pipe depth.

Assuming that the thermal conductivity of the ORNL clay soil is 0.75 Btu/h-ft-°F (ref. 2), the unknowns in this relation are Q and D. Thus a minimum of two temperature readings at each location are required to determine these unknowns. At each location, values of Q and D were determined from readings directly over the pipe and 2 ft to the side of the pipe and from readings directly over the pipe and 4 feet to the side of the pipe. (It was assumed that all measurements were made at a 7-in. depth.)

Calculated Insulation Thermal Conductivities

The thermal conductivity of the buried pipe insulation can then be calculated from the heat loss rate and effective pipe depth at each location by the relation:[3]

$$\frac{T_S - T_G}{Q} = \frac{1}{2\pi k_p} \ln\left(\frac{d}{d - 2t_p}\right) + \frac{1}{2\pi k_I} \ln\left(\frac{d + 2t_I}{d}\right) + \frac{1}{2\pi k_s} \ln\left(\frac{4D}{d + 2t_I}\right)$$

where T_S = steam temperature, 406°F for 250 psig saturated steam;

T_G = ground surface temperature, 81°F (measured value);

d = pipe outside diameter, 8.625 in.;

t_p = pipe wall thickness, 0.322 in.;

t_I = insulation thickness, 2.5 in.;

k_p = pipe wall thermal conductivity, 26 Btu/h-ft-°F;

k_I = effective insulation thermal conductivity;

k_s = soil thermal conductivity, 0.75 Btu/h-ft-°F.

This relation assumes that 2D/d is much greater than 1, which is reasonable here. Values of k_I were calculated from Q and D at each location determined from subsurface temperature readings directly over the pipe and 2 ft to the side of the pipe.

RESULTS

Infrared Thermography

The results of the infrared survey identified many regions of relatively high heat loss. In particular, significant heat loss was always evident in the vicinity of expansion loops. One possible explanation for this involves pipe movement. The movement of pipe in expansion loops, year after year, may eventually cause a premature breakdown of the outer pipe casing. This would permit moisture seepage which would damage the insulation and allow greater heat loss. In addition to the expansion loops, several other local hot areas were identified along straight runs of pipe, probably indicating deteriorating insulation. Only a few areas were noticed that were relatively cool.

As stated earlier, the infrared images were recorded on video cassette tape. From this tape, color slides and prints were developed. A few of these prints are included herein accompanied by the corresponding black and white image for reference. In the color infrared images, the color-temperature correspondence from hottest to coolest is: white, yellow, green, blue and black.

Figures 2 and 3

Figure 2 is the conventional black and white image of the area at the northeast corner of building 4500N looking east (see Fig. 1). Just

ORNL-PHOTO 3466-83

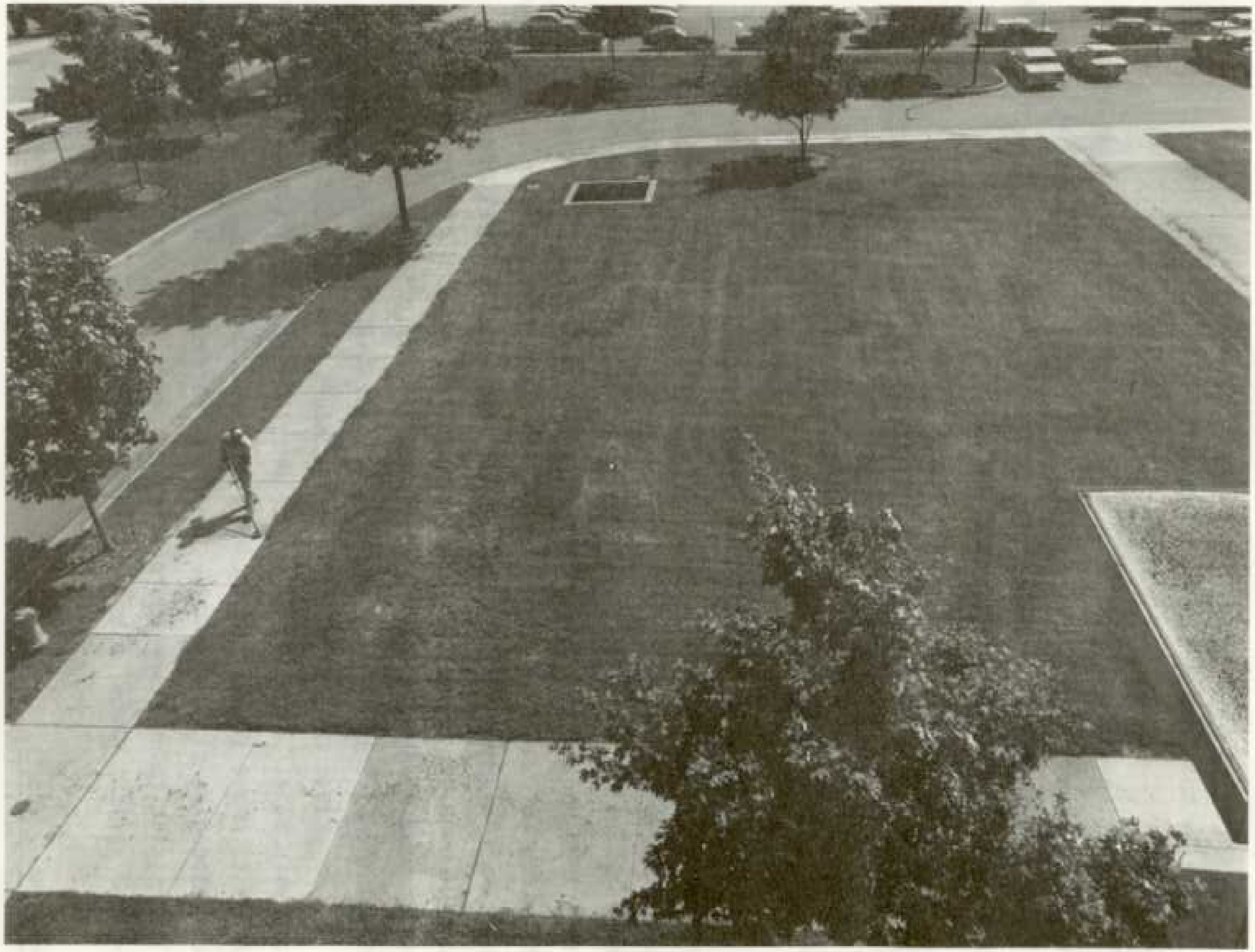


Fig. 2. Area east of northwest corner of 4500N.

ORNL-PHOTO 3883-83

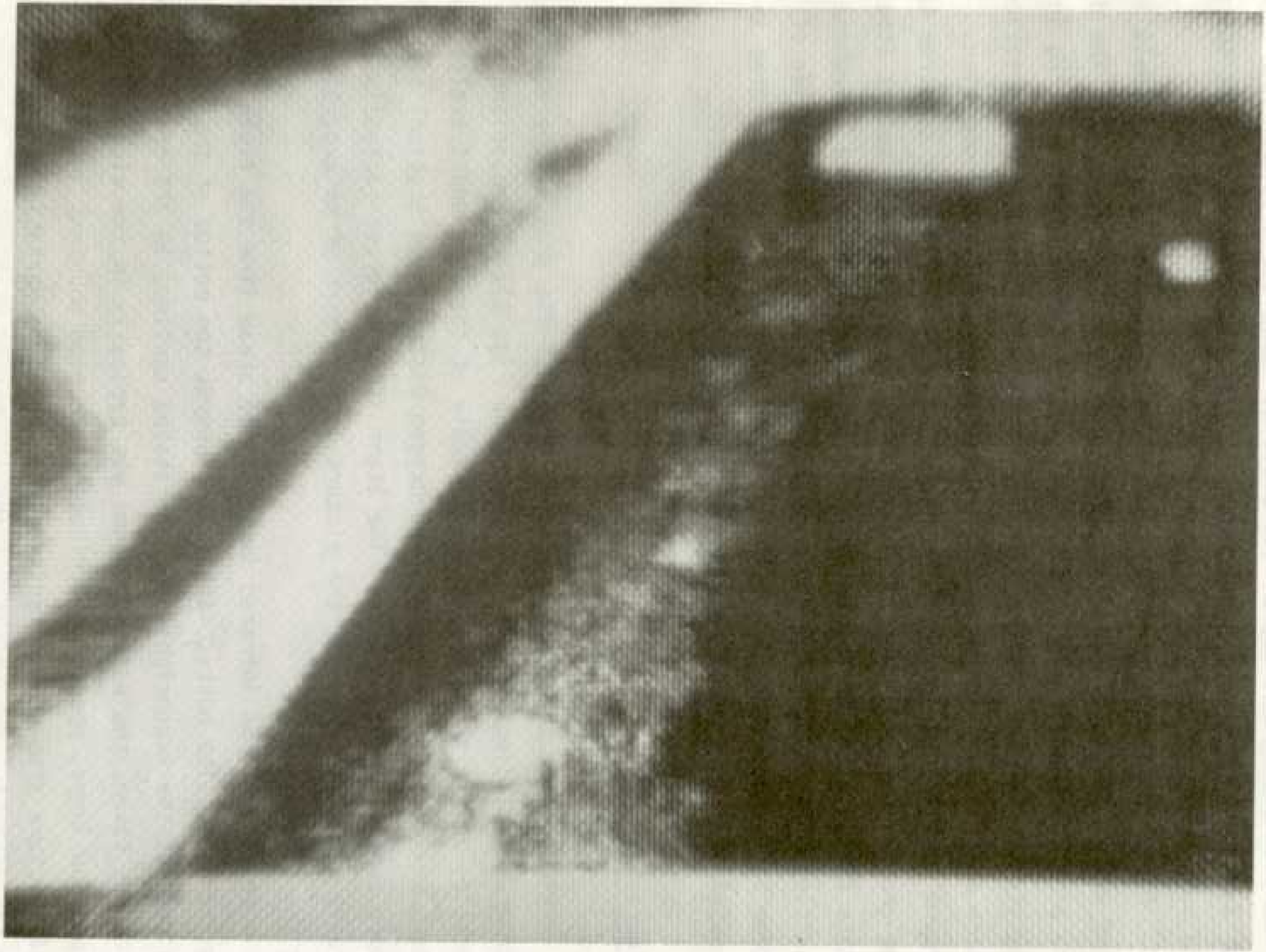


Fig. 3. Infrared image of area east of northwest corner of 4500N.

to the left, out of the picture, is the Main Portal. The pipeline runs parallel and to the right of the sidewalk at the left and enters the steam pit towards the top of the picture. From the pit, one line continues east under the road and another line exits the right side of the pit and runs south to the 5500 area.

Figure 3 is the infrared image of the same area. The sidewalk and road are white (i.e., relatively hot) due to heat retained from the day. The pipeline can clearly be seen next to the sidewalk and entering into the steam pit. The picture displays significant temperature variations, which most likely indicates wide variation in insulation condition. The ground in the lower part of the picture is relatively warm compared to the ground near the steam pit, as evident by the brighter colors (the white circle near the bottom of the picture is a subsurface telephone manhole). Note also that the pipeline which exits the right side of the steam pit is not even discernible in this picture. This indicates an area of relatively good insulation and little heat loss.

Figures 4 and 5

Figure 4 is the black and white image of the area at the southwest corner of building 4508 looking west (see Fig. 1). The pipeline runs parallel and to the right of the sidewalk at the left and travels underneath building 3537 (Hydrogen and Oxygen Distribution Station) near the upper center of the picture. The light strip of grass (actually dead grass) near the center of the picture is over part of an expansion loop in the steam line.

In Fig. 5, the infrared image of the steam line and expansion loop can be seen. The hottest areas are towards the bottom of the picture and on part of the expansion loop. As stated earlier, in all of the infrared pictures taken, the warmest ground was typically in the vicinity of expansion loops, possibly attributable to pipe movement in those areas. This picture also shows significant temperature variations, as is evident by the cool blue ground between the two hot regions.

ORNL-PHOTO 3463-83

Fig. 4. Area west of southwest corner of 4508.

ORNL-PHOTO 3882-83

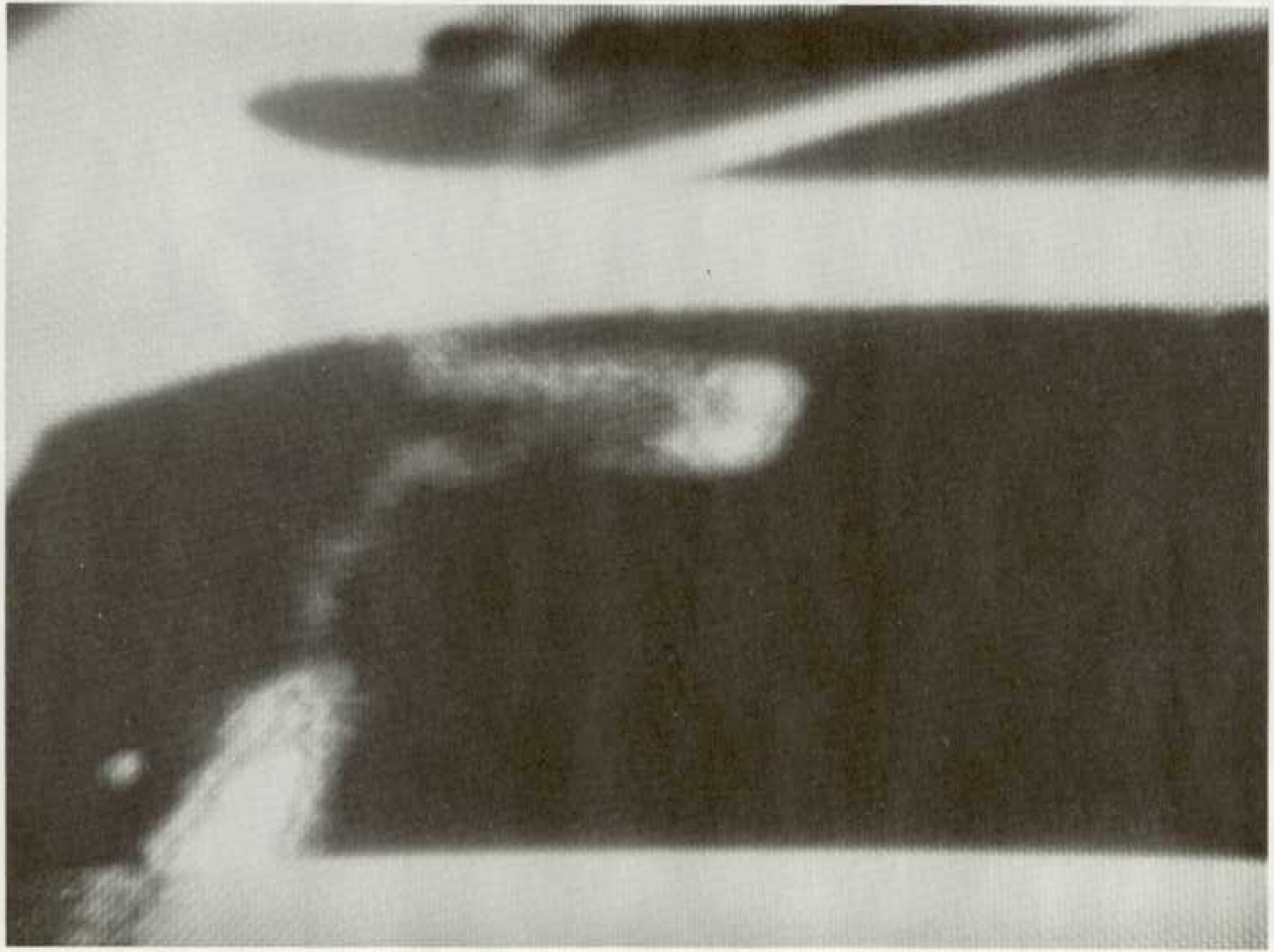


Fig. 5. Infrared image of area west of southwest corner of 4508.

Figures 6, 7, and 8

The intent of these pictures is to give an example of the magnitude of ground surface temperature differences in the vicinity of a hot spot. Figure 6 is a black and white image of the area in front of 4500N just across the street from the Main Portal (See Fig. 1). The pipeline runs parallel to the sidewalk from the steam pit through the center of the light area of grass and dirt. The manhole is for a sewer line.

Figure 7 is the infrared image of this same area. Note the intensity contrast between the sidewalk and the hot spot. In Figs. 3 and 5, the intensity of the sidewalk had to be tuned to a bright white in order to make the pipeline visible. In this picture, however, the hot spot itself was the greatest heat source, even hotter than the nearby sidewalk. The fact that this spot is much hotter than its surroundings accounts for the nearby pipe not being visible. That pipe is simply not within the same temperature scale.

In order to get an idea of the surface temperature differences that the infrared camera senses near a hot spot, a so called "line scan" was produced for the hot spot area shown in Fig. 7. Line scans give graphic displays of relative surface temperatures across any desired area in the camera view. Figure 8 is one of these line scans. Reading the graph from left to right, it represents the temperatures being sensed in a straight line from the cool grass on the right of the manhole, through the center of the hot spot (highest peak), and up to the sidewalk (lower peak). Each vertical division is 1.8°F. Hence, compared with surrounding ground the hot spot is about 17°F warmer, and compared with the sidewalk, about 6°F warmer.

Subsurface Ground Temperatures

As stated earlier in this report, infrared thermography can only display relative heat loss, it cannot quantify the loss. Hence, as a first step towards producing actual heat loss data, subsurface ground temperatures were measured at several locations along the steam line. Table 1 lists the various subsurface ground temperature recorded on a dry

ORNL-PHOTO 3456-83

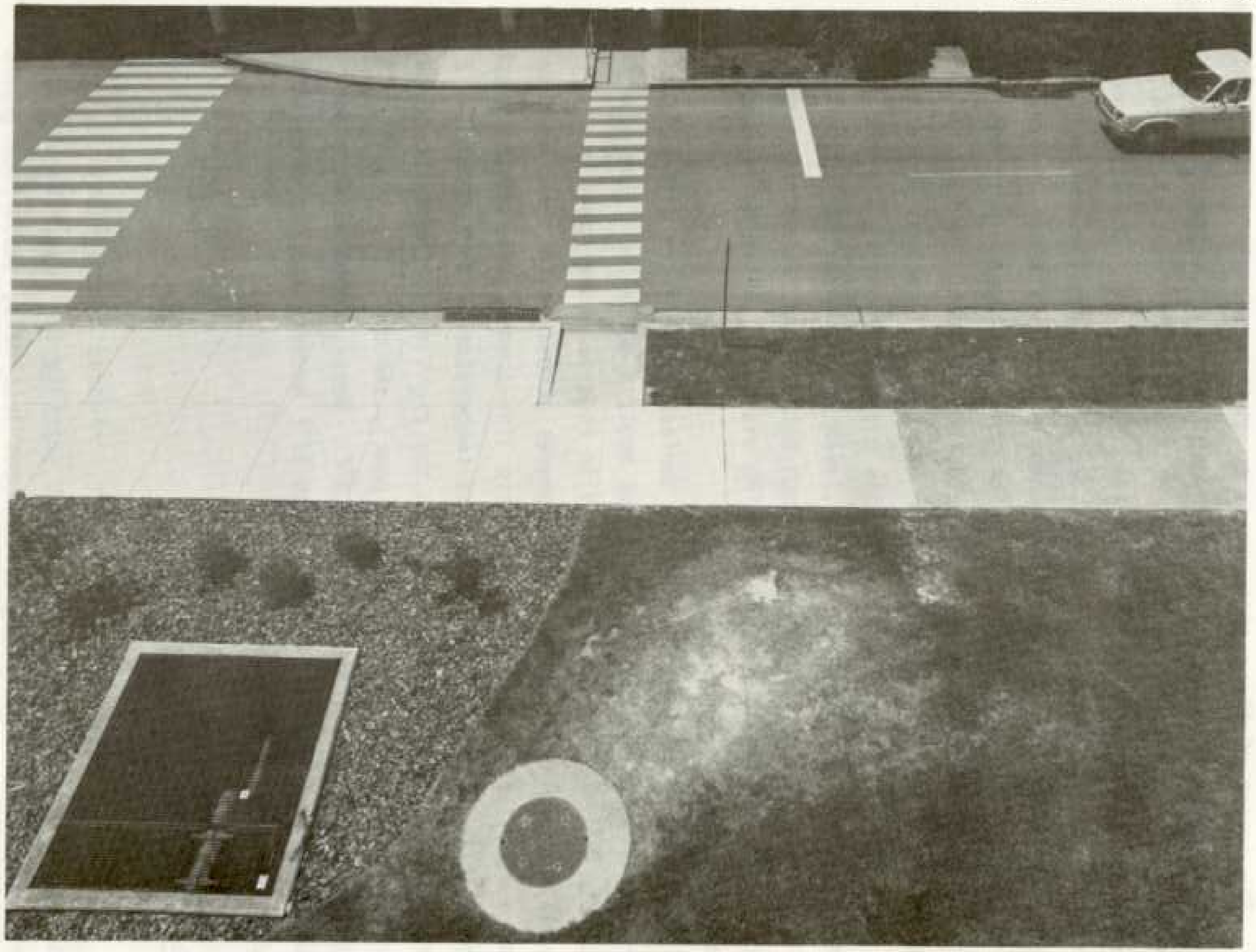


Fig. 6. Area north of northeast corner of 4500N.

ORNL-PHOTO 4194-83

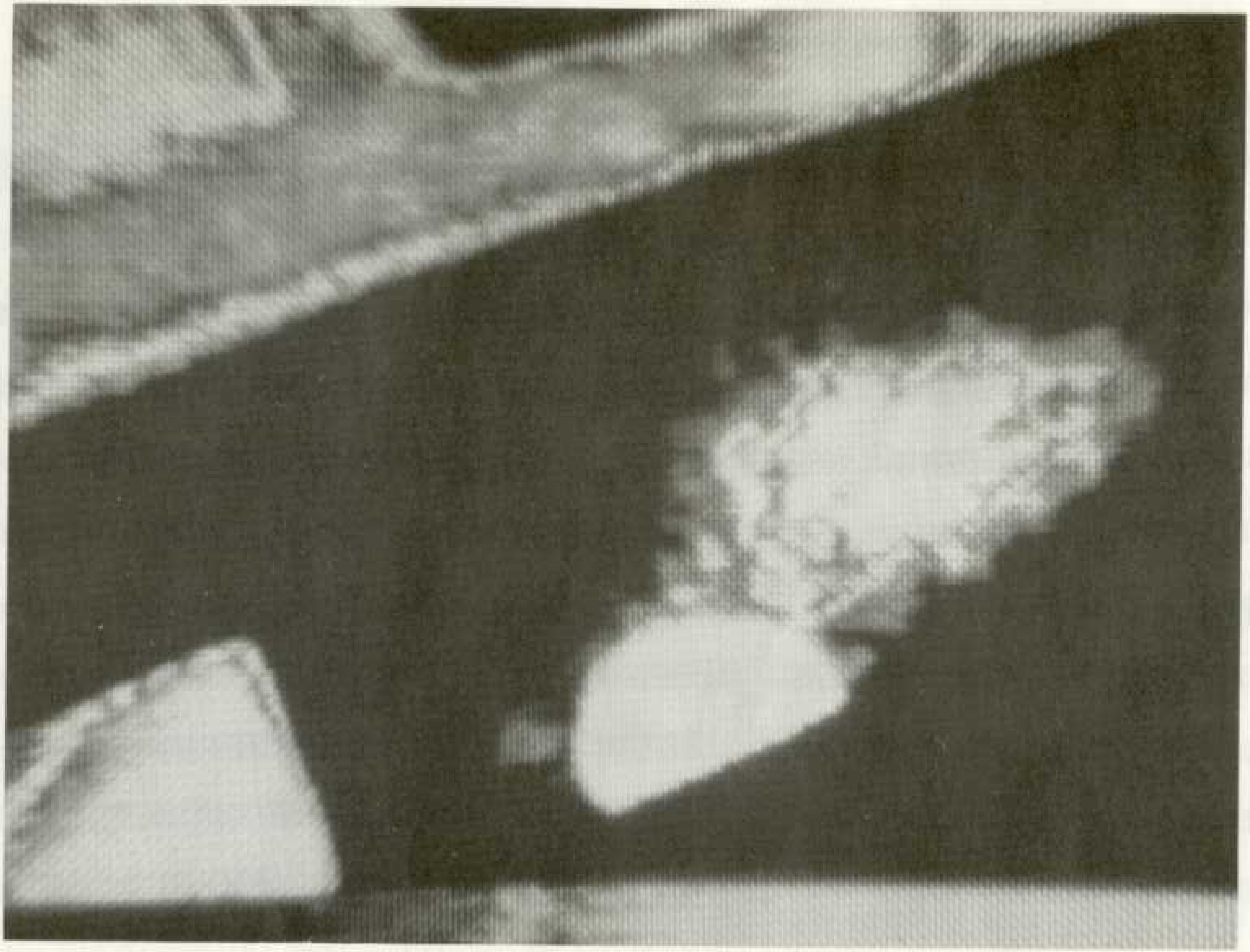


Fig. 7. Infrared image of area north of northeast corner of 4500N

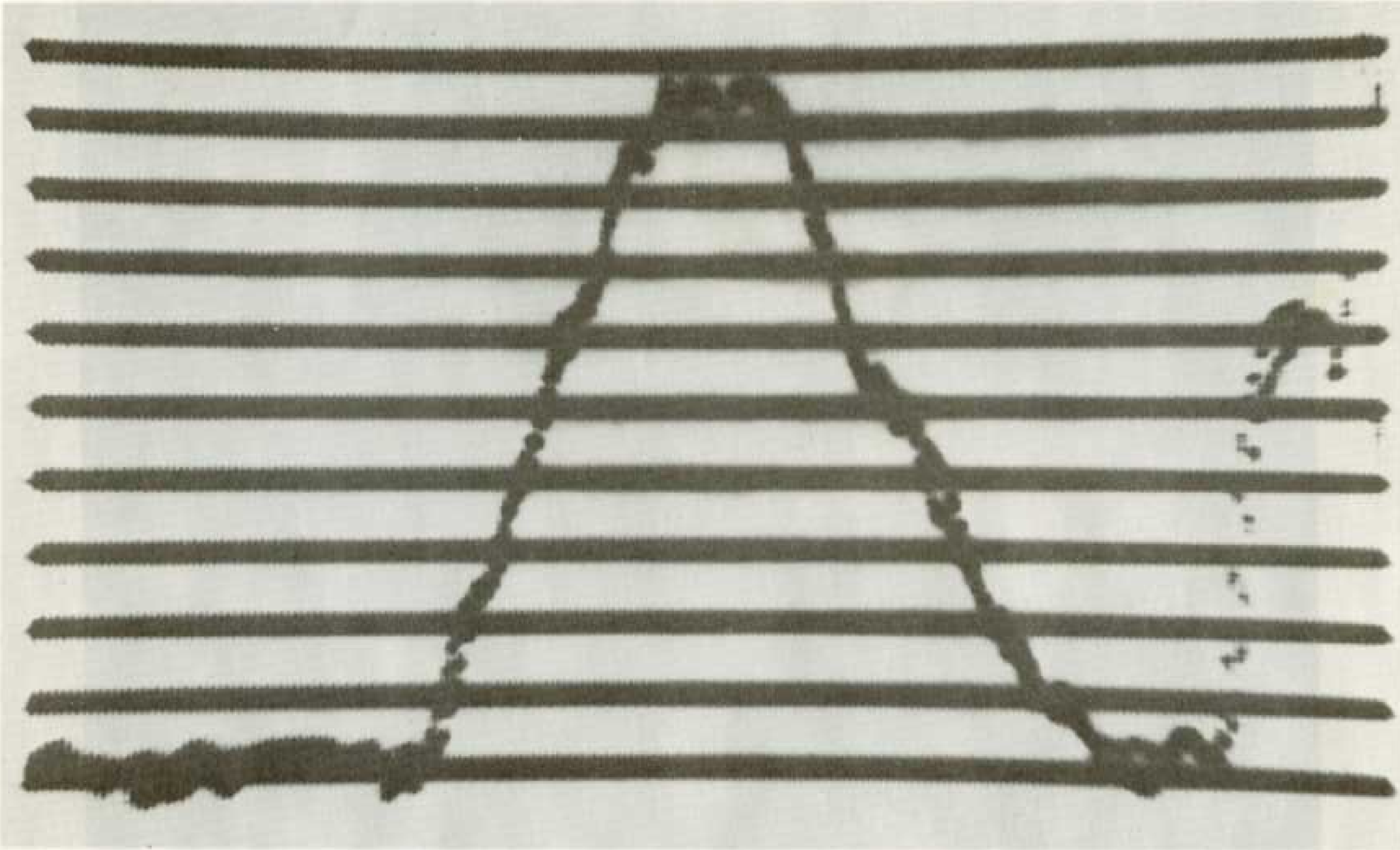


Fig. 8. Infrared "Line Scan" of high ground temperature area at northeast corner of 4500N.

Table A.1. Subsurface ground temperatures*

Location†	Directly over pipe	2 ft to the side	4 ft to the side	Ground appearance
1	124°F	110°F	99°F	Dead, little or no grass
2	(Normal ground temperature reading: 81°F)			
3	106°F	100°F	91°F	Light brown or yellow grass
4	112°F	108°F	99°F	Brown grass, partly bare
5	109°F	102°F	94°F	Brown grass
6	113°F	104°F	93°F	Brown grass, partly bare
7	92°F	88°F	81°F	Green or normal grass
8	(Normal ground temperature reading: 81°F)			
9	105°F	104°F	99°F	Light brown or yellow grass
10	110°F	107°F	97°F	Brown grass

*Conditions

Soil: Relatively dry

Probe depth: 7 inches

Normal ground temperature: 81°F

All readings taken on a hot summer morning, July 12, 1983.

†See Figure 9.

summer morning (July 12, 1983). Figure 9 shows where the readings were taken. The temperatures given should not be considered invariant because they can change with changes in ground moisture, time of day, and weather conditions. They do, however, give an idea of temperature comparisons between areas of varying insulation conditions. In the table, note the readings at Location 7. That area showed no signs of excessive temperature and within 4 ft of the first reading the temperature fell to the normal ground temperature of 81°F. This indicates an area of relatively good insulation and can be used as a base for judging other areas.

Heat Loss Rates

Rates of heat loss and the effective depths of the underground steam lines were determined using the buried pipe heat transfer relation and the measured subsurface temperatures. The results presented in Table 2 are for the locations that have significant temperature excesses. The linear heat loss rate at Location 7, the area having a minimum temperature excess, is estimated to be about 120 Btu/h-ft. Heat loss rates at the other locations are estimated to be about 400 Btu/h-ft or greater. The peak loss rates of about 700 Btu/h-ft are at Locations 9 and 10, the northeast corner of 4500N.

The temperature difference between 250-psig saturated steam and the normal ground surface is 325°F.

Calculated Insulation Thermal Conductivities

Values of the buried pipe insulation thermal conductivities calculated from the heat loss rates and effective pipe depths are presented in Table 3. At Location 7, the conductivity is calculated to be 0.03 Btu/h-ft-°F, which is about that for normal dry pipe insulation. At Locations 1, 3, 5, and 6, it is calculated to be about 0.3-0.5, which indicates that the insulation has deteriorated or is wet. Where the highest heat loss rates occur, Locations 4, 9 and 10, all of the heat loss could not be accounted for by the heat conduction relation. At

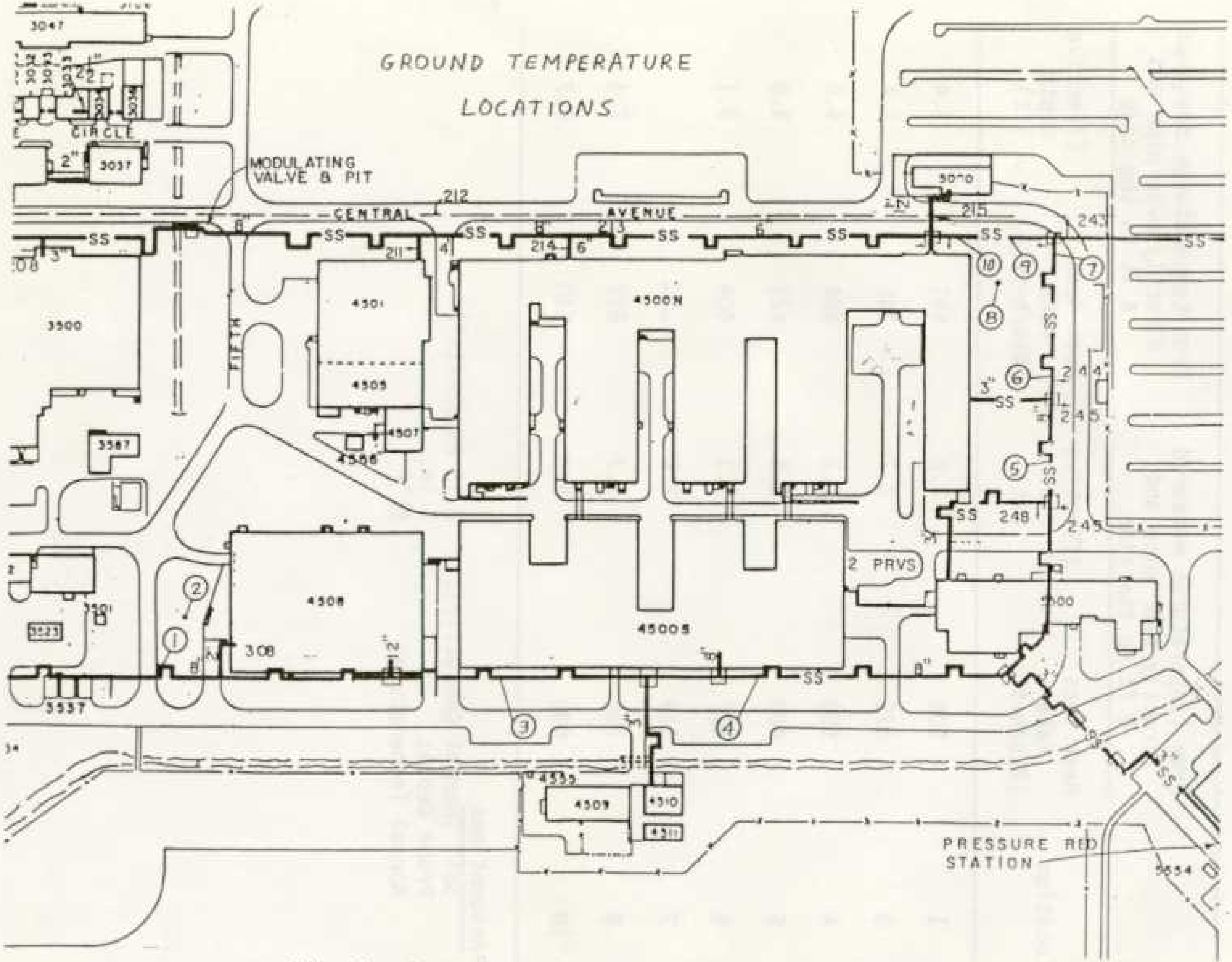


Fig. 9. Locations of measured subsurface ground temperatures.

Table A.2. Estimated underground pipe heat loss rates and effective depths*

	From temperatures measured directly over pipe and 2 ft to the side		From temperatures measured directly over pipe and 4 ft to the side	
Location	Heat loss rate (Btu/h-ft)	Effective depth (ft)	Heat loss rate (Btu/h-ft)	Effective depth (ft)
1	506	3.0	591	3.4
3	375	3.7	345	3.4
4	650	5.2	594	4.8
5	400	3.6	422	3.8
6	417	3.1	404	3.1
7	119	2.6	—	
9	758	7.7	699	7.1
10	698	6.0	540	4.7

*Assumptions

Soil Thermal Conductivity: 0.75 Btu/h-ft-°F
Probe Depth: 7 in.
Normal Temperature: 81°F

Table A.3. Calculated buried pipe insulation thermal conductivities, Btu/h-ft-°F

Location	Thermal conductivity	Interpretation
1	0.52	Wet or deteriorated insulation
3	0.23	Wet or deteriorated insulation
4		Water or steam leak
5	0.27	Wet or deteriorated insulation
6	0.27	Wet or deteriorated insulation
7	0.03	Dry insulation
9		Water or steam leak
10		Water or steam leak

these locations there appears to be water adjacent to bare pipe or pipe leakage.

REFERENCES

1. T. Kusuda, S. Aso, and W. Ellis, A Method for Estimating Heat Loss from Underground Heat Distribution Systems, National Bureau of Standards Draft Report, February 1, 1983.

2. ASHRAE Handbook, 1981 Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Chapter 23, 1981.

3. J. C. King, F. W. Hermann, and J. L. Squier, Determination of Heat Loss from Underground Steam Pipelines at NAF Atsugi, Japan, TM No. M-64-78-06, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California, September 1978.

APPENDIX B

PRESSURE/FLOW MODELING OF THE ORNL STEAM DISTRIBUTION SYSTEM

G. V. Murphy
H. A. McLain

Appendix B

PRESSURE/FLOW MODELING OF THE ORNL STEAM DISTRIBUTION SYSTEM

G. V. Murphy
H. A. McLain

ABSTRACT

The pressure-flow distribution in the ORNL steam distribution system was calculated using an existing steady-state network flow modeling program. The calculated results indicate that the pressure drops in the system are small and that the steam plant could be operated at lower pressure than the present pressure of 250 psig. Steam losses due to condensation in the system were calculated to be much lower than the losses determined by a mass balance of the system. This indicates that there are leaks in the system or some of the pipe in the system is exposed directly to groundwater.

1. INTRODUCTION

The purpose of this study is (1) to establish a pressure flow model of the existing steam distribution system, (2) examine thermal energy balance of the steam system to analyze the steam system energy losses, and (3) determine potential efficiency improvements that could be made by changing the operating strategy of the steam system.

2. DESCRIPTION OF THE OAK RIDGE NATIONAL LABORATORY STEAM DISTRIBUTION SYSTEM

2.1 CONFIGURATION OF THE STEAM DISTRIBUTION SYSTEM

The Oak Ridge National Laboratory steam distribution system consists of one main 250-psig steam service loop, two 250-psig branch steam service lines, a second main 250-psig steam line, and one 125-psig distribution system. See Fig. B.1 for the general layout of the steam distribution system.

The main 250-psig steam loop originates at the north side of the steam plant (Bldg. 2519), then extends east along White Oak Avenue, and continues north on Third Street. From Third Street, the steam line continues east on Central Avenue, then south on Sixth Street, and then west on Southside. From Southside, this steam line goes west on White Oak Avenue, then re-enters the steam plant on the south wall. This main service loop consists of a combination of 6- and 8-in. pipes. Two modulating valves exist in this service loop; one located on Central Avenue east of Building 3500 and the other on White Oak Avenue east of the steam plant.

The two 250-psig branch steam lines are extensions of this main steam service loop. One of these branches is a 4-in. diameter pipe and originates at the corner of Central Avenue and Sixth Street. This branch extends underground beneath the east parking lot to the 6000 area. The other branch is an 8-in. diameter pipe and originates south of Building 5500 and north of White Oak Creek. This branch extends west along White Oak Avenue to the 7000 area.

The second main 250-psig, 6-in. diameter steam pipeline originates on the south side of the steam plant. This steam line continues south along Third Street across the hill to the 7503 and 7900 areas. This steam line has one modulating valve.

The ORNL steam system also has a 125-psig distribution system which originates on the west side of the steam plant. This distribution system consists of a combination of various size pipes such as 4 in., 6 in., and 8 in. Combinations of these size pipes serve to create loops and branches in the distribution system. The 125-psig distribution system interconnects to the 250-psig main steam loop through two pressure regulating valves located on Central Avenue. This connection between the two systems serves to ensure that the 125-psig distribution system has sufficient capability to maintain steam to the emergency steam turbine and caustic sump pump in the 3039 Stack area.

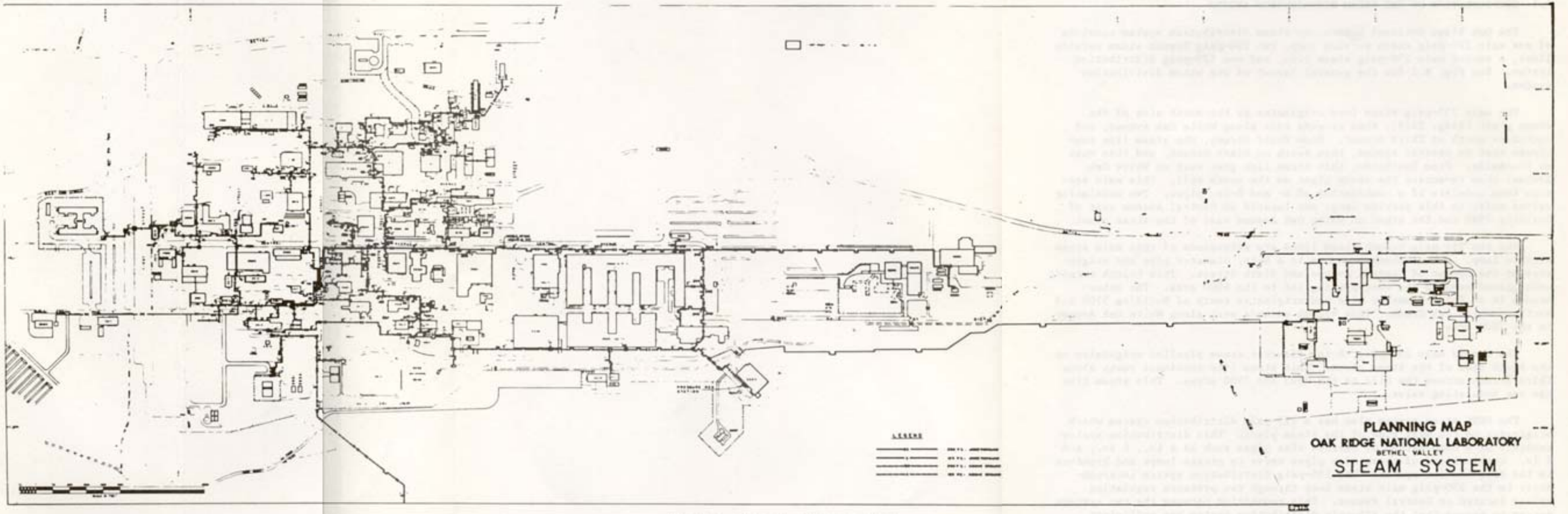


Fig. B.1. General layout of steam distribution system.

2.2 CRITICAL STEAM DEMANDS AND PRESSURE REGULATING VALVES

The steam distribution system has six major pressure regulating valve stations. These locations are as indicated on the node map in Fig. B.2 and denoted by the prefix PRV. The modulating valves mentioned above are all set to close when the downstream pressure reaches approximately 190 psig. The activation of these valves serves to drop the less critical loads downstream of the valves when a line breaks which may reduce steam supply to a critical customer. In this plant, there are two critical steam demands. They are the auxiliary steam turbines at the steam plant (Bldg. 2519) and the emergency steam turbine and caustic sump pump at the 3039 Stack area.

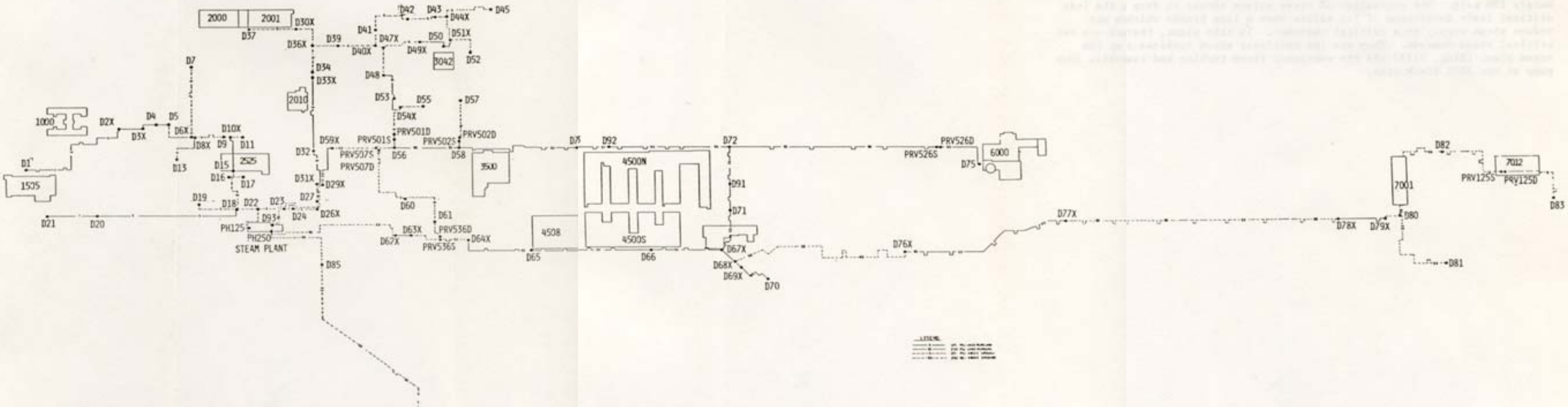


Fig. B.2. Node map of steam distribution system.

3. BUILDING STEAM DEMANDS AND STEAM PLANT PRODUCTION RATE FOR THE OAK RIDGE NATIONAL LABORATORY

3.1 BUILDING STEAM DEMANDS

The building load relationships used in the simulation of the ORNL steam distribution system were based on certain assumptions, using metered steam data, building load estimates by R. E. Peden,[1] and a past study entitled "ORNL Steam Allocation by Building" by O. A. Kelly.[2] Since only 23 out of 102 buildings have metered steam data in which we have confidence, these assumptions and the past study were very essential in establishing the steam system loads. The use of these data and assumptions in obtaining a valid base of data for building loads is discussed below.

In order to provide the simulation of the steam system for maximum load conditions, data obtained during the time period between November 1981 and March 1982 were selected for the analysis. During any other months of the year, summer shutdown occurs for a large portion of the steam distribution system including the line to the 7000 area.

The first step in obtaining the load equations is to derive the base and weather sensitive load components of the steam demand for the buildings having metered data. These components are obtained by using a linear regression program to plot the monthly steam demand versus the total monthly heating degree day for each building for the time period between November 1981 and March 1982. The intercept and slope of the linear regression relation are respectively the base and weather sensitive load components of the load equation for that particular building. An example of the load equation obtained for Building 6010 is as follows:

$$\text{Load} = 203.0 \, \frac{\text{M lb}}{\text{month}} + 0.544 \, \frac{\text{M lb}}{°\text{F} \cdot \text{day}} \, (\text{HDD})$$

$$\text{Load} = 20 \times 3.0 \, \frac{\text{M lb}}{24 \cdot 30 \text{ hr}} + 0.544 \, \frac{\text{M lb } (65-T)}{°\text{F} \cdot (24 \text{ hr})}$$

$$\text{Load} = \left[0.28 + \frac{0.02}{°\text{F}} \, (65°\text{F} - T)\right] \frac{\text{M lb}}{\text{hr}}$$

where 203.0 M lb/month is the base load, 0.544 M lb/°F · day is the weather sensitive component, $\sum_{n=1}^{30} (65°\text{F} - T_n)$ · day/month is the total monthly heating degree day (HDD) for $T_n \leq 65°\text{F}$, T is the ambient air temperature in °F, and 65°F is the temperature for a zero heating degree day. M lb denotes 1000 lb in the above and preceding equations. The value of the weather sensitive component is zero for any value of T above 65°F.

Since no measured data exist on the remaining 79 buildings, a simple derivation is applied to obtain a load equation for each unmetered building. First, the monthly building loads for each metered building during the period between November 1981 and March 1982 are summed for each month. The resulting sum for each month is plotted versus the corresponding monthly heating degree day using a linear regression program. This linear relation for the summation of the measured building loads is then

$$\text{Load} = [4638.9 + 26.71\ (\text{HDD})]\ \frac{\text{M lb}}{\text{month}}\ .$$

It was estimated by O. A. Kelley (based on floor area and exhaust air considerations) that the 23 buildings have metered data representing 59.6% of the building steam demand. Assuming that the measured loads are 59.6% of the total plant building load, the equation for the total monthly steam load is

$$\text{Total Steam Load} = \left(\frac{4638.9}{0.596} + \frac{26.71}{0.596}\ (\text{HDD})\right)\frac{\text{M lb}}{\text{month}} = [7783 + 44.82\ (\text{HDD})]\frac{\text{M lb}}{\text{month}}\ .$$

Converting this to M lb/hr, the load equation becomes

$$\text{Total Steam Load} = \left(\frac{7783}{24 \cdot 30\ \text{hr}} + \frac{44.82}{24\ \text{hr}}\ (\text{HDD})\right)\ \frac{\text{M lb}}{\text{hr}}$$

or

$$\text{Total Steam Load} = \left(10.81 + \frac{1.868}{°\text{F}}\ (65°\text{F} - \text{T})\right)\ \frac{\text{M lb}}{\text{hr}}$$

where 65°F is the zero heating degree day and T is the ambient temperature in °F. Note that for any value of T above 65°F, the value of the weather sensitive component is zero. The load equation for an unmetered building load is then assumed to be

$$\text{Load} = \left(0.1081 \cdot \text{X} + \frac{0.01868 \cdot \text{X}}{°\text{F}}\ (65°\text{F} - \text{T})\right)\ \frac{\text{M lb}}{\text{hr}}$$

where X is the percent steam used by the building relative to the total plant building steam load. Values of X were assumed to be those estimated by O. A. Kelley.[2]

This relation was used to obtain the unmetered building loads in the analysis of the steam distribution system.

It should be noted that originally the 23 measured building loads were used to obtain the corresponding building loads equation. It was later discovered that R. A. Peden had calculated load values for 4500N believed to be more representative than what was shown in the measured building steam data. A correction was then made to the load equations to obtain the final results as shown above.

3.2 STEAM PLANT PRODUCTION RATE

Using the monthly "Production and Usage Data" report on the steam plant, data are obtained on the steam production and monthly heating degree day (HDD) for the months November 1981 through March 1982.[3] Using this data and a linear regression program on curve fitting, the steam plant production rate equation is as follows:

$$\text{Steam Plant Production Rate} = [45133.08 + 48.996\ (\text{HDD})]\ \frac{\text{M lb}}{\text{month}}$$

where 45133.08 is the base steam plant output, 48.996 is the temperature dependent component, and HDD is the monthly heating degree days.

The steam plant utilizes 10% of the produced steam internally for steam turbines and deaerators. Correcting the above equation to reflect the steam plant sendout and converting to units of M lb/hr results in the following equation.

$$\text{Steam Plant Sendout} = \left[56.41 + \frac{1.837}{°\text{F}}\ (65°\text{F} - \text{T})\right]\ \frac{\text{M lb}}{\text{hr}}$$

where 56.41 is base steam plant sendout, 1.837 is the temperature dependent component and T is the ambient temperature in °F. Note for ambient temperatures above 65°F, the temperature dependent component is zero.

4. PIPE CONDUCTION AND CONVECTION HEAT LOSS COEFFICIENTS

4.1 ACCOUNTING FOR STEAM DISTRIBUTION SYSTEM HEAT LOSSES

The heat losses in a steam distribution system originate from valve pit leaks, pipe leaks, pipe and insulation conduction and convection heat losses, and steam trap losses. In this study, the steam distribution system was analyzed as (1) a well insulated system with no leaks or steam trap losses and (2) the existing steam system with somewhat degraded insulation and steam leaks. The following sections will provide the derivation of conduction and convection heat loss coefficients for the ORNL steam distribution system as a well insulated system and as it exists today.

4.2 HEAT LOSS COEFFICIENTS FOR A WELL INSULATED STEAM DISTRIBUTION SYSTEM

The linear heat loss coefficients for a well insulated steam system were assumed to be those derived from the monthly heat loss rates calculated by Milligan.[4] In a report to ORNL, Milligan calculated the monthly linear heat loss rates from the buried and aboveground pipeline in the steam distribution system assuming no degradation in the insulation. From these heat loss rates, the linear heat loss coefficients were calculated using the relation

$$K_{lin} = \frac{q/L}{\Delta T}$$

where K_{lin} = linear heat transfer coefficient;
q/L = energy loss rate per unit length;
q = energy loss in the form of heat;
L = length of line;
$\Delta T = T_s - T_g$ for underground pipeline;
$= T_s - T_a$ for aboveground pipeline;
T_s = saturated steam temperature;
T_g = ground temperature; and
T_a = ambient air temperature.

Milligan calculated the linear heat loss rates for the buried pipe using the relation

$$q/L = \frac{T_s - T_g}{R_p + R_i + R_g}$$

R_p = resistance through the pipe wall;

$$= \frac{\ln(r_2/r_1)}{2\pi\, k_p} ;$$

r_1, r_2 = inside and outside radius of the pipe, respectively;
k_p = thermal conductivity of the pipe wall;
R_i = resistance through the insulation;

$$= \frac{\ln(r_3/r_2)}{2\pi\ k_i}\ ;$$

r_2, r_3 = inside and outside radius of the insulation, respectively;
k_i = thermal conductivity of the insulation;
R_g = resistance through the ground;

$$= \frac{\cosh^{-1}(D/r_3)}{2\pi\ k_e}\ ;$$

D = depth of buried pipe;
r_3 = outside radius of insulation; and
k_e = thermal conductivity of the soil.

The linear heat loss rate relation for the aboveground pipeline was calculated by Milligan using the relation

$$K = \frac{q}{L} = \frac{T_s - T_a}{R_p + R_i + R_o} - S_r r_s \alpha + 2\pi r_e \varepsilon\sigma(T_o{}^4 - T_a{}^4)$$

where R_p, R_i = same as for buried pipeline relation,
R_o = outside film convection resistance,

$$= \frac{1}{2\pi r_3 h_o}\ ,$$

r_3 = outside radius of insulation, and
h_o = outside connection heat transfer coefficient.

h_o was calculated by the relation

$$\frac{2\ h_o r_3}{k_a} = C\ \frac{2r_3 u}{\gamma_a}{}^n$$

where C = 0.174, n = 0.618 for Reynold's Number $4000 \le \frac{2r_3\ u}{\gamma_a} \le 40{,}000$,

C = 0.0239, n = 0.805 for Reynold's Number $40{,}000 < \frac{2r_3\ u}{\gamma_a} \le 250{,}000$,

k_a = thermal conductivity of air,
γ_a = kinematic viscosity of air,
u = air velocity,
S_r = solar insulation heat flux,[6]
α = surface absorptivity, assumed by Milligan to be 0.15,
ε = surface emissivity, assumed by Milligan to be 0.04, and
σ = Stefan-Boltzmann constant.

Milligan assumed the following values of the various parameters in his study:

k_p = 25 btu/hr·ft·°F,
k_e = 0.4 btu/hr·ft·°F,
D = 4 ft,
u = 8 mph,
α = 0.5,
ε = 0.04, and
T_s = 406°F (for 250 psig steam).

Milligan used these values together with monthly average values of T_g, T_a, and S_r to calculate q/L for different size pipes with different insulations.

For this study, Milligan's q/L values for January were used to determine K_{lin}. Milligan's values of T_a = 37°F and T_g = 58°F for January were used in these calculations. Values of K_{lin} are in the next-to-last column in the NCES input data file for the well-insulated steam distribution system (Appendix I).

4.3 HEAT LOSS COEFFICIENTS FOR THE EXISTING STEAM DISTRIBUTION SYSTEM

For the ORNL steam distribution system as it exists at the present time (1983), a somewhat heuristic approach was used to estimate the heat loss coefficients. For the buried lines, the measurements and analysis by Lindell and McLain together (Appendix A) with the results of a study done by Lockwood-Greene Engineers, Inc.[8] were used to estimate the coefficients. For the aboveground lines, the Lockwood-Greene study results together with Milligan calculated heat loss rates were used to estimate the coefficients.

The buried steam line heat loss coefficient is based on information gathered from ground temperature measurements in the 4500N area. From these measurements, Lindell and McLain estimated that the heat loss coefficient for the 8-in. line in the 4500N area is

$$K_{lin} = \frac{1.5 \text{ Btu}}{\text{hr}\cdot\text{ft}\cdot{}^{\circ}\text{F}} \quad .$$

Assuming that the pipe is 4 ft deep and the soil thermal conductivity is 0.75 btu/hr·ft·°F,* this is the coefficient for a bare buried pipe, implying that the insulation has deteriorated. Neglecting the resistance of the pipe wall (it is small) for buried pipe, the heat loss coefficient is

$$K_{lin} = \frac{2\pi K_s}{\left[\ln \frac{D}{r_3} + \sqrt{\frac{D}{r_3}^{\,2} - 1}\right]}$$

If $\frac{D}{r_3} >> 1$

$$K_{1in} = \frac{2\pi K_s}{\ln\left(\frac{2D}{r_3}\right)}$$

For 8-in. pipe, this becomes

$$K_{1in} = \frac{2\pi(0.75)}{\ln\left(\frac{4 \times 48}{8.625}\right)} = \frac{1.5 \text{ Btu}}{\text{hr·ft·°F}}$$

This agrees with the measured value. It is assumed that this relation is applicable to other pipe diameters.

A correction factor of 10% is added to the calculated buried K_{1in} value to account for the heat losses from bare pipe, valves, and other sources in the valve pits. The 10% correction factor is based on the following assumptions:

- Each valve pit has 5 ft of bare pipe.
- Linear heat loss coefficients, K_{1in}, for bare pipe was determined by Lockwood-Greene Engineers, Inc.[8] Using the relation

  $$K_{1in} = \frac{1}{R_p + R_g}$$

  Lockwood-Greene assumed k_p = 26 Btu/hr·ft·°F and h_o = 6 Btu/hr·ft^2·°F. The h_o value includes both convection and radiation heat transfer, and is slightly conservative. Rain could increase h_o, but this is ignored in our calculations.
- The pipe length and the number of valve pits associated with each size of buried pipe.

Values of K_{1in} for the buried lines were thus assumed to be as shown in Table B.1.

---

*This is the thermal conductivity of clay soil given in the 1981 ASHRAE Fundamentals Handbook. This higher than 0.4 btu/hr·ft·°F value assumed by Milligan. The ASHRAE value is probably more representative of the ORNL site soils.

Table B.1. Heat loss coefficients for underground pipe of the existing steam distribution system

Pipe nominal diameter (in.)	Pipe outside diameter (in.)	Heat loss coefficient K_{1in} (Btu/hr·ft·°F)	Corrected heat loss coefficient K_{1in} (Btu/hr·ft·°F)
3	3.5	1.18	1.3
4	4.5	1.26	1.4
6	6.625	1.40	1.5
8	8.625	1.52	1.7
10	10.75	1.63	1.8

The heat loss coefficients for the existing aboveground pipeline were derived using data from the Lockwood-Greene study. The assumptions in obtaining the heat loss coefficients for this study are as follows:

- 3.8 miles or about 20,000 ft of aboveground lines of which 4338 ft has been damaged such that the effective thermal conductivity of the insulation has been increased 50%. Essentially 681 ft is bare pipe; 210 ft of this bare pipe has an outside diameter greater than 8 in.

- The Lockwood-Greene study assumes that the outside combined convection and radiation heat transfer coefficient for the bare pipe is 6 Btu/hr·ft·°F. This is slightly conservative as indicated on the previous page.

- Therefore, on the basis of the heat loss rates calculated in the Lockwood-Greene study, ratios of abnormal pipe to normal pipe losses are assumed to be as follows:

$$\frac{\text{Partially Damaged Pipe Heat Loss}}{\text{Normal Pipe Heat Loss}} = 1.5,$$

$$\frac{\text{Bare Pipe Heat Loss}}{\text{Normal Pipe Heat Loss}} = 20, \text{ Pipe} \leq 6\text{-in. outside diameter,}$$

$$\frac{\text{Bare Pipe Heat Loss}}{\text{Normal Pipe Heat Loss}} = 25, \text{ Pipe} \geq 8\text{-in. outside diameter,}$$

It should be noted in the Lockwood-Greene study, the solar insulation on the pipe is neglected because it is a relatively small effect. Therefore, the ratio of the overall heat loss coefficient for the existing system to that for the well insulated system for the overhead line in the steam system is

$$K_{1in} = \frac{\text{LWIP + ELDP + Length Bare Pipe <8-in. O.D. + Length Bare Pipe} \geq \text{8-in. O.D.}}{\text{Length of Overhead Line}}$$

$$= \frac{(20{,}000-4338-681) + (4338)(1.5) + (681-210)(20) + (210)(25)}{20{,}000} = 1.8 \ ,$$

where LWIP = Length of Well Insulated Pipe
ELDP = Effective Length of Damaged Pipe

Thus, linear heat loss coefficient derived from Milligan's data were increased by 80% to account for the damaged and exposed steam pipes.

Values of K_{1in} for the existing steam distribution system are listed in the next-to-last column in the NCES input data file for that system (Appendix I).

4.4 DIRECT STEAM LOSSES

Direct steam losses due to pipeline leaks and steam traps were assumed to be 4% of the total plant load on a 5°F day. It was assumed that these losses are distributed equally to nodes D65, D70, D72, and D73 where the base load at each node is increased 1.3 M lb/hr.

5. MODELING OF A STEAM DISTRIBUTION NETWORK

5.1 CONCEPTS OF THE MODEL

Although the basic relation for flow of steam through a pipe is simple, solution of a large number of these equations to describe the flow of steam in a pipe network must be done by an iterative procedure. For large networks, the only practical way of doing this is with the aid of the computer. The computer program chosen for this analysis is one that has been used successfully to describe the flow and pressure of steam in district heating systems in Akron, Baltimore, and New York. The program, designated as GASSS (Gas at Steady State Pipe System),[9,10] is a steady state program and does not account for transients in the system.

The basic concept of GASSS is the simulation of the steam network by lines representing the pipes and valves and by nodes representing the junctions of these lines. The model is constructed by use of the continuity equation (mass balance) at the nodes and the mechanical energy balance (pressure drop relations) in the lines. This results in a system of N equations and N unknowns. This system is solved by the Newton Raphson successive approximation method, and for efficiency it relies on sparse matrix programming.

Condensation of steam in the pipelines is accounted for by solving a heat-balance relationship to determine the rate of condensate formation for each section of pipe. Removal of condensate from the system is accounted for in the continuity equation at each node.

5.2 PRESSURE FLOW EQUATIONS

The basic one-dimensional mechanical energy balance equation describing the flow of a fluid in a pipe is

$$dP + \frac{\rho f\ V^2}{2g_c\ D}\,dx + \frac{\rho V dV}{g_c} = 0, \tag{B.1}$$

where

P = pressure,
V = velocity,
ρ = density,
f = Moody friction factor,
D = pipe diamter,
x = length, and
g_c = conversion factor, 32.2 $(lb_m \cdot ft)/lb_f \cdot s^2)$.

The mass flow rate of the pipe is

$$Q = \rho \frac{\pi D^2}{4} V \; , \tag{B.2}$$

where Q = mass flow rate. Combining

$$\rho dP + \frac{8Q^2}{\pi^2 g_c D^4} \left[\frac{fDx}{D} - 2\frac{d\rho}{\rho} \right] = 0 \quad . \tag{B.3}$$

Steam table data for dry saturated steam between 10 and 300 psia is correlated with the following equation of state:[9,10]

$$\rho = \frac{P^{0.946}}{K} \tag{B.4}$$

where K is a constant having a value of 343.4 when ρ is lb_m/ft^3 and P is psia. Substituting into Equation (B.3)

$$P^{0.946}\, dP + \frac{8kQ^2}{\pi^2 g_c D^4} \left[\frac{fdx}{D} - 1.892\frac{dP}{P} \right] = 0 \quad . \tag{B.5}$$

For steam flowing in pipes at velocities less than the sonic velocity, it can be shown numerically that the term 1.892 dP/P is insignificant compared to f(dx/D). It is interesting to note then that for a given mass flow rate, Q, Equation (B.5) shows that the pressure drop is nearly inversely proportional to absolute pressure of the steam.

Neglecting the last term and integrating, Equation (B.5) becomes

$$P_1^{1.946} - P_2^{1.946} = \frac{(1.946)(8)}{\pi^2} \; \frac{kfL(Q^2)}{g_c(D^5)} \tag{B.6}$$

or

$$Q = 0.7962\, D^{2.5} \sqrt{\frac{g_c}{kfL} \quad (P_1^{1.946} - P_2^{1.946})} \quad . \tag{B.6a}$$

The Moody friction factor f is a function of the Reynold's number and the relative pipe roughness. The Reynold's number is defined as

$$Re = \frac{DV\rho}{\mu} = \frac{4Q}{\pi D \mu} \quad , \tag{B.7}$$

where μ is the viscosity. In the 100- to 300-psia range, the viscosity of dry saturated steam is $1.37 \times 10^{-5} lb_m/(ft \cdot s)$.

In GASSS, the value of f can be specified for each length of pipe or can be calculated by the Colebrook-White relation. This relation correlates the values of f in the transition and fully turbulent flow regimen:

$$\frac{1}{\sqrt{f}} = 1.14 + 2 \log_{10} \frac{D}{\epsilon} - 2 \log_{10} \left[1 + \frac{9.28}{Re \frac{\epsilon}{D} \sqrt{f}} \right] \qquad (B.8)$$

where ϵ is the pipe roughness.

5.3 HEAT AND CONDENSATION LOSSES

As a pipe loses a small amount of heat to its surroundings, steam condenses inside the pipe and is not available for heating purposes. The losses depend upon the ambient conditions outside of the pipe, the temperature of the steam, the insulation on the pipe, and the length of the pipe.

Using the following definitions:

m_i = mass flow rate into pipe,
m_o = mass flow rate out of pipe,
m_c = mass flow rate of condensate, and
H = heat flow through the pipe wall.

there must be conservation of matter,

$$m_i = m_o + m_c \text{ and}$$

conservation of energy,

$$m_i h_i = m_o h_o + m_c h_c + H \qquad (B.9)$$

where h_i, h_o, and h_c are specific enthalphies of inlet steam, outlet steam, and condensate, respectively. Let $x = m_c/m_i$ be the fraction of steam condensed, then $h_i = (1 - x)\, h_o + xh_c + H/m_i$ is obtained by dividing Equation (B.9) by m_i and substituting x for m_c/m_i and $(1 - x)$ for m_o/m_i. Solving for x gives:

$$x = \frac{h_o - h_i + H/m_i}{h_o - h_c} \quad . \qquad (B.10)$$

The specific enthalphies h_o, h_i, and h_c are state functions. Assuming the steam is saturated, they can be determined from the steam tables if the inlet and outlet pressures are known. Heat loss from the pipe H is determined by the relation

$$H = U_i DL\, \Delta T_m = K_{lin}\, \Delta T_m \qquad (B.11)$$

where U_i = overall heat transfer coefficient,
D = inside pipe diameter,
L = pipe length,
ΔT_m = mean temperature difference, and
K_{lin} = heat loss coefficient.

Estimation of the heat loss coefficients K_{lin} in this study is discussed in Section 4 of this appendix.

The mean temperature difference in Equation (B.11) is the difference between the average temperature of the steam in the pipeline and the ambient temperature. For steam in a pipe having an inlet pressure of P_i and an outlet pressure of P_o, the average pressure can be found by first noting that the steam pressure drop relation, Equation (B.5) is approximately

$$PdP = -\alpha dx \tag{B.12}$$

where α is a constant. This implies that the pressure distribution in the pipe is

$$P = \left[\left(\frac{P_o{}^2 - P_i{}^2}{L}\right)x + P_i{}^2\right]^{\frac{1}{2}} \quad . \tag{B.13}$$

Integrating over the length of pipe and dividing by the length of pipe,

$$P_a = \frac{2}{3}\left[P_i + P_o - \frac{P_iP_o}{P_i + P_o}\right] \quad . \tag{B.14}$$

5.4 VALVE REGULATOR EQUATION

Control valves are usually rated in terms of a valve flow coefficient C_v, defined as the flow of 60°F water in gpm through the valve under a pressure difference of 1 psi. Thus, the quantity of liquid flow through the valve for a given pressure drop is

$$Q = C_v\sqrt{\Delta P\left(\frac{62.4}{\rho}\right)} \tag{B.15}$$

where Q = flow rate in gpm,
ΔP = pressure drop in psi, and
ρ = liquid density in lb/ft^3.

For gases flowing below the critical (sonic) velocity in the valve, Equation (B.15) is usually modified to be

$$Q_g = C_g\ P_1 \sqrt{\frac{\Delta P}{P_1}} \quad . \tag{B.16}$$

where Q_g = gas flow rate in standard ft^3/hr,
C_g = gas valve flow coefficient, and
P_1 = inlet gas pressure, psia.

The Fisher Company has modified this relation further for predicting flow of gas or steam through that company's regulators. For steam the relation is:

$$Q_s = C_s\ P_1 \sin \left[\frac{59.64}{C_1} \sqrt{\frac{\Delta P}{P_1}}\right]_{rad} , \tag{B.17}$$

where Q_s = steam flow rate in lb/hr,
C_s = steam valve coefficient, and
$C_1 = C_g/C_v$.

The constant 59.64 in Equation (B.17) results from the use of different units for C_g and C_v and assuming that the density in Equation (B.15) is that for air at standard conditions.

This relation can be used as a regulator equation in GASSS by allowing the C_s value to be an unknown. Then this equation simply allows for the difference in pressure on either side of the regulator. If the simulation situation demands a gate valve operation, then the C_s and C_1 value can be chosen for the particular valve or valve setting and the appropriate pressure drop will be computed across the valve depending on the flow rate that passes through the valve.[9,10]

6. MODELING OF THE OAK RIDGE NATIONAL LABORATORY STEAM DISTRIBUTION SYSTEM

The purpose of this analysis is to simulate the pressure-flow distribution in the ORNL steam distribution system as (1) a well insulated system with no leaks or steam trap losses and (2) the existing system with somewhat degraded insulation and direct steam losses through leaks and steam traps.

6.1 THE NODE MAP

The system is described in terms of nodes and node connecting elements. This analysis first requires the generation of a node map, shown in Fig. B.2. The map consists of nodes and node connecting elements. A node connecting element can be a pressure regulator or a length of pipe. On the node map, the node connecting elements are indicated by dotted or solid lines and nodes are indicated by dark dots. A node indicates a change in pipe size, transition from above- to below-ground, or the presence of a load. Each node is given a name consisting of a combination of letters and numbers. For example, the node D25X indicates this node is either a point where a transition in pipe size or transition from above-to below-ground or vice-versa occurs. Therefore, all node names terminating with an X can have any of these characteristics. A node represented, for example, as D25 is a load node and can appear anywhere in the system. In designating the nodes for a pressure regulator, there is a source and load side of the pressure regulating valve. Even though a load side is indicated in the node name, it does not mean a load really exists at that point. Only by examining the node file, can it really be known if a load exists at the load side of the pressure regulator. An example of a node name for a pressure regulating valve is PRV507S and PRV507D where S and D, respectively, represents the source and load side of a regulator.

6.2 PRESSURE-FLOW MODELING INPUT DATA

The GASSS simulation program requires the creation of three types of input data files to efficiently define the steam distribution system for computer simulation. The first file type is the node connecting element (NCE) data file which identifies and describes in detail the geometric and physical characteristics of the NCEs. The second type of data file is the nodes data file which describes what are the known and unknown loads at each node. The third data file is the loads data file which contains all the load nodes and the associated base and temperature or weather sensitive components of the load.

Input data files for the existing ORNL steam distribution system and the hypothetical well-insulated distribution system are presented in Appendix I.

6.3 NODE CONNECTING ELEMENT INPUT DATA

The node connecting elements (NCEs) represent the various pipelines and pressure regulators in the system. The NCE is specified as a type MS (Municipal Steam Pipe) or FI (Fisher Regulator). The NCE can have either unknown or fixed parameters which are used to characterize the parameters of the NCE.

The following information must be supplied for the pipeline element: the two nodes which the pipe element connects, NCE type, internal pipe diameter, and pipe length. Parameters such as friction factor, roughness, efficiency, heat loss coefficient, and ground or air temperature for each pipeline element can be provided or default values can be used for certain parameters. The ORNL system simulation utilized default values for roughness and efficiency of 0.0025 and 1.0, respectively. The friction factor is calculated for each NCE based on Reynold's Number and roughness for the ORNL system simulation. The following is an example of the input data for the pipeline connecting nodes D1 and D2X which have a 4.026 internal pipe diameter and a length of 677.0 ft.

D1 D2X MS 4.026 677.0 0.0 0.0 0.0 1.40 50.0

Note that the 0.0s indicated represent that default values or calculated values are to be used for this system simulation respectively for friction factor, roughness, and efficiency. 1.40 and 50.0 are, respectively, the heat loss coefficient and the ambient temperature difference.

The input data required for a pressure regulator are the nodes on each side of the regulator, NCE type, sizing coefficient C_g, maximum sizing coefficient C_{gmax}, ratio of gas-to-liquid sizing coefficient C_1, and minimum desired pressure drop ΔP. An example of the input line data for a regulator connected between nodes PRV501D and PRV501S is as follows:

PRV501D PRV501S FI S 25.00 50.00 32.00 10.00

The S in the input data line indicates that the steam sizing coefficient is an unknown parameter. The 25.00 is used as an intial estimate of the actual sizing coefficient. 50.00 is the maximum gas sizing coefficient. 32.00 is the gas-to-liquid sizing coefficient ratio. The number 10.00 is the minimum pressure drop across the regulator.

6.4 NODES

The nodes data file indicates the condition of each node in the system. The condition of a node is specified by three parameters which are pressure, node status word, and the elevation of each node. This system simulation assumes that all nodes have a zero elevation. The pressure at all nodes except the steam plant (Bldg. 2519) and regulators were unknown. Therefore, the pressures supplied in the remaining nodes in the data file for this system were initial estimates. The pressure and flow for the regulators were known values in this simulation. The following are letters used to indicate a node status word:

Q = flow known, pressure unknown;
P = pressure known, flow unknown; and
B = pressure known, flow known.

Several examples of the node data for various node types are as follows:

Node name	Elevation	Pressure	Load	Node Status
D3X	0.0	120.0	0.0	Q (transition or intermediate node)
PH250	0.0	250.0	0.0	P (supply node)
PRV125D	0.0	125.0	-0.011	B (regulator load node)

It should be noted that no load data are entered when initally creating the nodes file. The load data are generated for required nodes by a separate loads file just prior to implementing the first system simulation. The means by which the load data are entered into the nodes file are discussed in the next section.

6.5 LOADS

The loads file is a separate file from the data file which contains all the load nodes of the steam distribution system and their associated base and weather sensitive load components. In GASSS, the loads file is used to generate the loads for each load node and insert them into the nodes file. This is accomplished by creating a column vector using the GASED5.1 program.[10] This column vector is created by summing the base load in column one and the weather sensitive load component of column two evaluated at a desired ΔT. This is done for each load node. The resulting sum is placed in column three of the load file. The results in column three represent the column vector which is loaded into the corresponding load nodes of the nodes data file. The loading of a column vector into the data file need occur only once unless modifications to the loads occur in order to obtain a system analysis for alternative load conditions.

7. RESULTS

7.1 SUMMARY OF BACKGROUND ON ANALYSIS

This analysis investigates two different scenarios of the ORNL steam distribution system. The first scenario is a well insulated steam system with no direct steam losses. The second scenario is the steam system with present estimated conduction and convection heat losses and direct steam losses. For each of these, a simulation was made for operating the steam plant with an output pressure of 250 psig and 200 psig. The pressures in the low pressure portion of the distribution system were not varied since 125 psig can be realized downstream of the pressure regulating value whether the upstream pressure supply is 250 psig or 200 psig. The loads, due to the intermittent starting of the backup steam turbine and caustic sump pump, are relatively insignificant and therefore, were ignored. Let it again be noted that the building load demand correlations were developed from data obtained during the months of November 1981 and March 1982. The loads for the system simulations were based on an ambient air temperature of 5°F. The ambient ground temperature was assumed to be 50°F in these simulations.

The predicted pressures for the well insulated and existing steam system is shown in Table B.2. A more detailed description of the results is discussed below.

7.2 ANALYSIS OF WELL INSULATED STEAM SYSTEM

The analysis of a well insulated system for a steam plant output pressure of 250 psig results in a flow of -5.054, -123.988, and 129.042 M lb/hr, respectively, for steam condensate, system loads and system supplies, or plant output. Note that loads with a minus (-) prefix represent steam being removed from the system. The minimum pressure for the high- and low-pressure distribution systems at a plant output of 250 psig are 230.70 psig and 118.15 psig occurring, respectively, at nodes PRV125S and D1. See the node map in Fig. B.2 for the location of these nodes. The results of a system simulation with the steam plant output pressure reduced to 200 psig is a flow of -4.695, -123.988, and 128.683 M lb/hr, respectively, for the steam condensate, system loads and system supplies, or plant output. The minimum pressures in the steam system are 176.12 psig and 118.15 psig, respectively, for the 200-psig and 125-psig distribution system occurring concurrently, at nodes PRV125S and D1. See Fig. B.3 and Fig. B.4, respectively, for the pressure maps of the steam system with plant output pressures of 250 psig and 200 psig.

7.3 ANALYSIS OF CURRENT STEAM SYSTEM

The pressure-flow simulation analysis of the current steam system is approximated by having somewhat deteriorated insulation and direct steam losses. The first simulation of this sytem with a steam plant pressure

Table B.2. Comparison of pressures for well insulated and existing steam system

Node number	Well insulated steam system plant output pressure node pressure		Existing steam system plant output pressure node pressure	
	200 lb	250 lb	200 lb	250 lb
D1	118.0	118.0	118.0	118.0
D21	125.0	125.0	125.0	125.0
D6X	123.0	123.0	123.0	123.0
D7	123.0	123.0	123.0	123.0
D37	124.0	124.0	124.0	124.0
D36X	125.0	125.0	125.0	125.0
PH125	125.0	125.0	125.0	125.0
PH250	200.0	250.0	200.0	250.0
D45	125.0	125.0	125.0	125.0
D52	124.0	124.0	124.0	124.0
D55	125.0	125.0	125.0	125.0
D56	187.0	240.0	184.0	237.0
D58	185.0	238.0	181.0	235.0
D85	199.0	249.0	199.0	249.0
D65	182.0	235.0	177.0	231.0
D68X	179.0	233.0	174.0	229.9
D72	179.0	231.0	174.0	229.0
PRV526S	176.0	231.0	170.0	226.0
D75	125.0	125.0	125.0	125.0
D80	178.0	233.0	173.0	228.0
D81	178.0	233.0	173.0	228.0
PRV125S	176.0	231.0	171.0	226.0
D83	125.0	125.0	125.0	125.0

*Locations of nodes are shown in Fig. B.2.

output of 250 psig and a system load of -129.188 M lb/hr results in the formation of condensate at the rate of -14.009 M lb/hr. The low pressures for the 250-psig and 125-psig distribution system are, respectively, 225.89 psig at node PRV526S and 117.61 psig at node D1. The second simulation of this system with a steam plant pressure output of 200 psig and a system load of -123.188 M lb/hr results in the formation of -13.085 M lb/hr of steam condensate requiring a plant sendout of -129.188 M lb/hr. The low pressure of the 200-psig and 125-psig distribution system are, respectively, 170.27 psig at node PRV526S and 117.61 psig at node D1. See Figs. B. 5 and B.6, respectively, for pressure maps of the steam plant with output pressure of 250 psig and 200 psig.

The conclusion of these pressure-flow simulations indicate that the pressure drop in the well insulated and the current steam system is minimal. Also both systems behave essentially as a large pressure header regardless of the steam plant output pressure. Note that at the High Flux Isotope Reactor (7900) area, the pressures are higher than the minimum pressure in the system despite the great distance from the steam plant. This is due to the relatively low loads in the 7900 area.

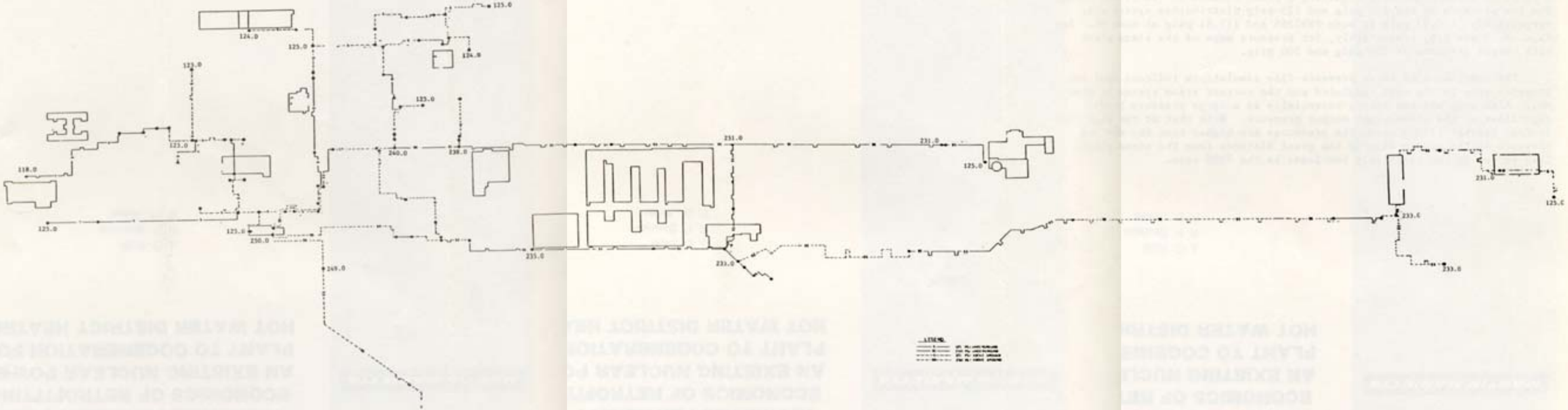


Fig. B.3. Pressure map of a well-insulated steam distribution system for a plant output of 250 psig.

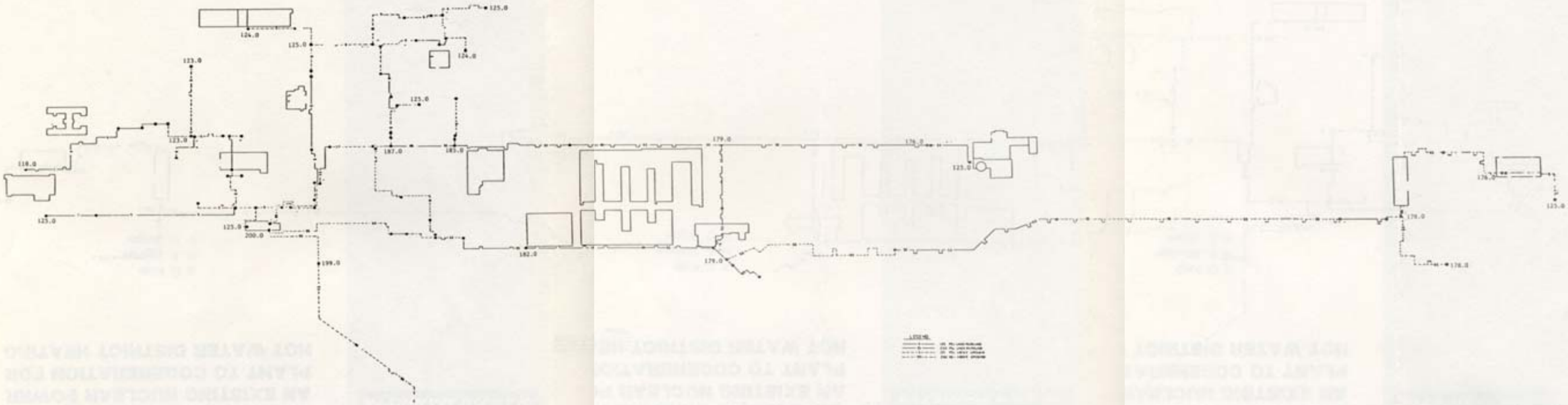


Fig. B.4. Pressure map of a well-insulated steam distribution system for a plant output of 200 psig.

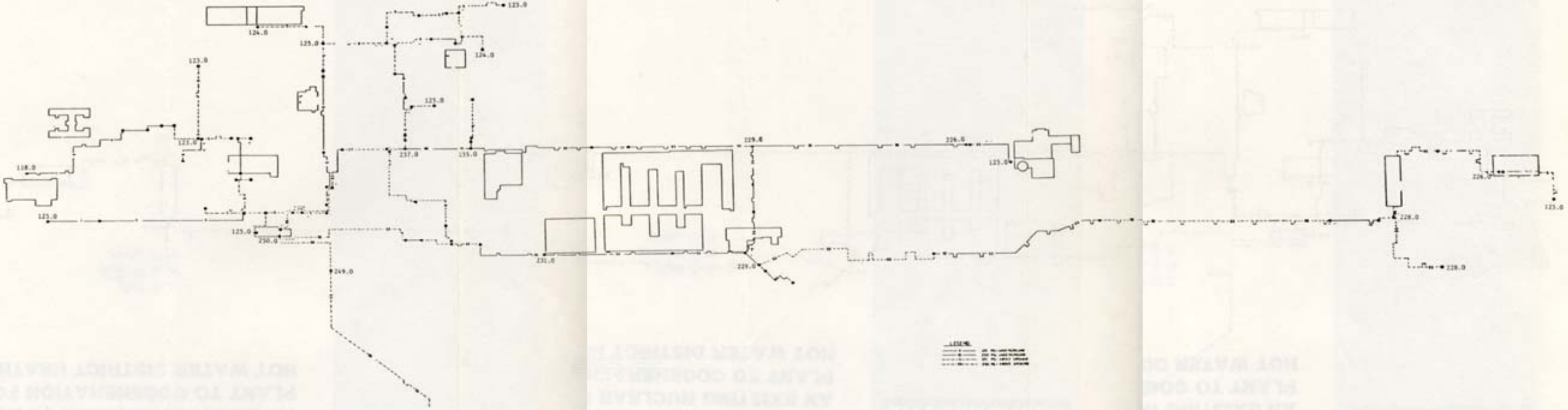


Fig. B.5. Pressure map of the existing steam distribtuion system for a plant output of 250 psig.

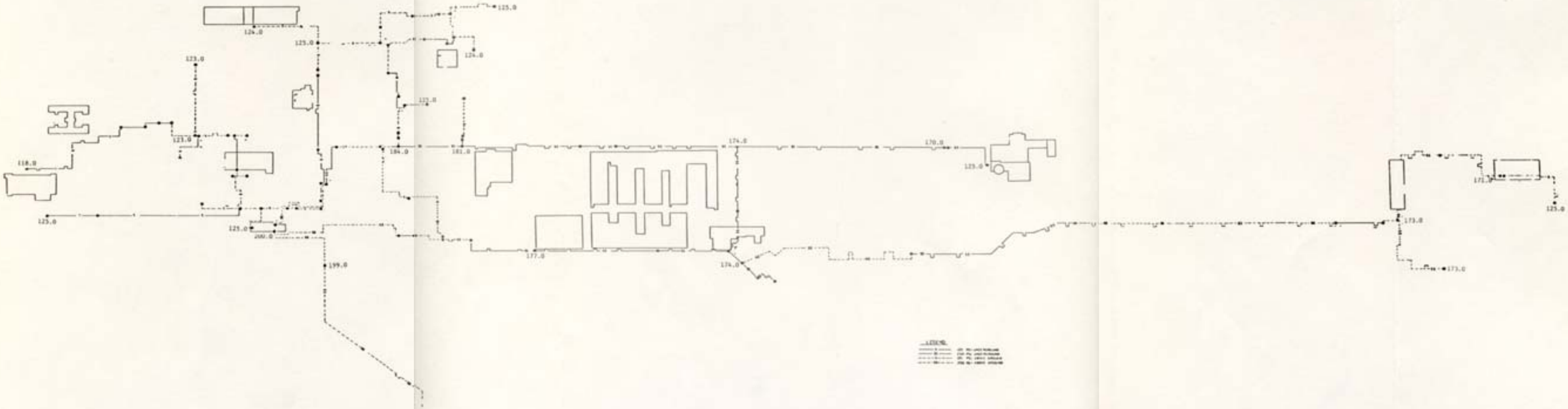


Fig. B.6. Pressure map of the existing steam distribution system for a plant output of 200 psig.

8. CONCLUSION

- The steam plant can be operated at a reduced plant sendout pressure of 200 psig with minimal effect on the steam users.
- Operating the well insulated or existing steam system at a plant sendout of 200 psig or 250 psig results in minimal reduction or increase in the formation of condensate. The amount of condensate formed will not vary more than 1 M lb/hr.
- The steam distribution system behaves essentially as a large pressure header with minimum pressure losses.
- The steam losses for the existing steam distribution system are much greater than predicted by this analysis. This is readily seen by comparing the mass balance in the analysis of the existing system versus the steam plant sendout of the equation obtained from the linear regression relation for a 5°F ambient day (Section 2.1 of the main report).

9. REFERENCES

1. R. E. Peden, Personal Communication, July 1983.

2. O. A. Kelly, ORNL Steam Allocation by Building, June 15, 1981.

3. G. D. Dixon, Personal Communication, May 1983.

4. M. W. Milligan, Steam Distribution Energy Loss Study, September 1975.

5. M. W. McAdams, Heat Transmission, 3rd Ed., McGraw-Hill, New York, 1954.

6. P. R. Ryan, D. R. Harleman, Analytical and Experimental Study of Transient Cooling Pond Behavior, Ralph M. Parson Laboratory No. 161, Massachusetts Institute of Technology, January, 1973.

7. ASHRAE Handbook, 1981 Fundamentals, page 23.22, "Thermal Conductivity for Clay Soil."

8. Lockwood-Greene Engineers, Inc., "Steam Pipe Survey," Preliminary Report for ORNL, September 1982.

9. Michael A. Stoner, "Modeling of Steady State Pressure-Flow Response of Steam and Water Systems," Proceedings of the International District Heating Association, Held in Cooperstown, New York, June 24-26, 1974, Vol. LXV, pp. 53-59.

10. GASSS Service User's Guide, Stoner Associates, Inc., Document GASSS.1U, May 1982.

Appendix I

DATA INPUT FILES

1. ORNL Steam Distribution System Modeled as a Well-Insulated System
2. Existing ORNL Steam Distribution System

1. ORNL Steam Distribution System Modeled as a Well-Insulated System

```
TITLE
THE OAK RIDGE NATIONAL LABORATORY STEAM DISTRIBUTION SYSTEM MODELED AS A WELL
INSULATED SYSTEM WITH A PLANT OUTPUT PRESSURE OF 250 PSIG
ZZZZ
CONVERT
FLOW         1.             'MLB/HR  '
LENGTH      1.             FEET
ZZZZ
SYSTEM
VISCOS      0.000000425
OPTIONS     NCES       CONTCHK   NODES
MAXITER       25
SUPER       NO
DISPLAY
ZZZZ
NCES
 D1         D2X        MS        4.026      677.000 .00000 0.000 .000000 0.254   50.
 D2X        D3X        MS        6.065       47.000 .00000 0.000 .000000 0.315   50.
 D3X        D4         MS        6.065      188.000 .00000 0.000 .000000 0.315   50.
 D4         D5         MS        6.065       66.000 .00000 0.000 .000000 0.315   50.
 D6X        D7         MS        3.068      489.000 .00000 0.000 .000000 0.285    5.
 D5         D6X        MS        6.065      192.000 .00000 0.000 .000000 0.353    5.
 D6X        D8X        MS        3.068       20.000 .00000 0.000 .000000 0.353    5.
 D8X        D9         MS        6.065      174.000 .00000 0.000 .000000 0.353    5.
 D9         D10X       MS        6.065       33.000 .00000 0.000 .000000 0.353    5.
 D10X       D11        MS        6.065       65.000 .00000 0.000 .000000 0.353    5.
 D8X        D13        MS        3.068      201.000 .00000 0.000 .000000 0.224   50.
 D10X       D15        MS        6.065      199.000 .00000 0.000 .000000 0.315   50.
 D15        D16        MS        6.065       80.000 .00000 0.000 .000000 0.315    5.
 D16        D17        MS        3.068       80.000 .00000 0.000 .000000 0.231   50.
 D16        D18        MS        6.065      216.000 .00000 0.000 .000000 0.353    5.
 D18        D19        MS        2.067      220.000 .00000 0.000 .000000 0.222    5.
 D18        D20        MS        4.026      867.000 .00000 0.000 .000000 0.244   50.
 D20        D21        MS        4.026      266.000 .00000 0.000 .000000 0.244   50.
 D18        D22        MS       10.020       88.000 .00000 0.000 .000000 0.560    5.
 D22        PH125      MS       11.938      155.600 .00000 0.000 .000000 0.608    5.
 D22        D23        MS       11.938      175.000 .00000 0.000 .000000 0.608    5.
 D23        D24        MS       11.938       70.000 .00000 0.000 .000000 0.608    5.
 D24        D26X       MS       11.938      130.000 .00000 0.000 .000000 0.608    5.
 D26X       D27        MS       10.020       35.000 .00000 0.000 .000000 0.560    5.
 D27        D31X       MS       10.020       29.000 .00000 0.000 .000000 0.560    5.
 D31X       D32        MS       10.020      163.000 .00000 0.000 .000000 0.336   50.
 D32        D33X       MS        7.981      344.000 .00000 0.000 .000000 0.241   50.
 D33X       D34        MS        7.981       33.000 .00000 0.000 .000000 0.288    5.
 D34        D36X       MS        7.981      143.000 .00000 0.000 .000000 0.241    5.
 D36X       D30X       MS        6.065      105.000 .00000 0.000 .000000 0.310    5.
 D30X       D37        MS        4.026      357.000 .00000 0.000 .000000 0.209    5.
 D36X       D39        MS        7.981      130.000 .00000 0.000 .000000 0.348    5.
 D39        D40X       MS        7.981      241.000 .00000 0.000 .000000 0.348    5.
 D40X       D41        MS        6.065      105.000 .00000 0.000 .000000 0.310    5.
 D41        D42        MS        6.065      277.000 .00000 0.000 .000000 0.348    5.
 D42        D43        MS        6.065      174.000 .00000 0.000 .000000 0.348    5.
 D43        D44X       MS        6.065       87.000 .00000 0.000 .000000 0.348    5.
 D44X       D45        MS        3.068      280.000 .00000 0.000 .000000 0.285    5.
 D40X       D47X       MS        6.065       63.000 .00000 0.000 .000000 0.310    5.
 D47X       D48        MS        6.065      153.000 .00000 0.000 .000000 0.310    5.
 D47X       D49X       MS        4.026      266.000 .00000 0.000 .000000 0.341    5.
 D49X       D50        MS        4.026      139.000 .00000 0.000 .000000 0.264   50.
 D50        D51X       MS        4.026       88.000 .00000 0.000 .000000 0.264   50.
 D51X       D44X       MS        4.026      185.000 .00000 0.000 .000000 0.342    5.
 D51X       D52        MS        3.068      213.000 .00000 0.000 .000000 0.285    5.
 D48        D53        MS        6.065      194.000 .00000 0.000 .000000 0.227   50.
 D53        D54X       MS        6.065      102.000 .00000 0.000 .000000 0.227   50.
 D54X       D55        MS        4.026      126.000 .00000 0.000 .000000 0.209    5.
 D54X       PRV501D    MS        6.065      184.000 .00000 0.000 .000000 0.310    5.
PRV501D     PRV501S    FI  S           25.000         50.000 32.000  10.00
PRV501S     D56        MS        5.761       56.000 .00000 0.000 .000000 0.322   50.
D58         D56        MS        7.625      368.000 .00000 0.000 .000000 0.339   50.
D57         PRV502D    MS        4.026      196.000 .00000 0.000 .000000 0.342    5.
PRV502D     PRV502S    FI  S           50.000        100.000 32.000  10.00
PRV502S     D58        MS        3.826       85.000 .00000 0.000 .000000 0.259   50.
D93         D29X       MS        7.625      600.000 .00000 0.000 .000000 0.526    5.
D29X        D59X       MS        7.625      171.000 .00000 0.000 .000000 0.305   50.
D59X        PRV507S    MS        7.625      342.000 .00000 0.000 .000000 0.358    5.
PRV507S     PRV507D    FI  S           20.000         40.000 32.000  10.00
PRV507S     D56        MS        7.625       50.000 .00000 0.000 .000000 0.339   50.
PRV507D     D60        MS        4.026      491.000 .00000 0.000 .000000 0.342    5.
D60         D61        MS        4.026      287.000 .00000 0.000 .000000 0.342    5.
D61         PRV536D    MS        3.068       85.000 .00000 0.000 .000000 0.285    5.
PRV536D     PRV536S    FI  S           20.000         40.000 32.000  10.00
```

```
PH250    D62X     MS      7.625    822.000 .00000 0.000 .000000 0.455    5.
D62X     D63X     MS      7.625     73.000 .00000 0.000 .000000 0.310   50.
D63X     PRV536S  MS      7.625    179.000 .00000 0.000 .000000 0.455    5.
PRV536S  D64X     MS      7.625    176.000 .00000 0.000 .000000 0.455    5.
D64X     D65      MS      7.625    787.000 .00000 0.000 .000000 0.310   50.
D65      D66      MS      7.625    525.000 .00000 0.000 .000000 0.310   50.
D66      D67X     MS      7.625    466.000 .00000 0.000 .000000 0.310   50.
D67X     D68X     MS      7.625     95.000 .00000 0.000 .000000 0.310   50.
D68X     D69X     MS      3.826     75.000 .00000 0.000 .000000 0.350    5.
D69X     D70      MS      3.826    130.000 .00000 0.000 .000000 0.259   50.
D67X     D71      MS      7.625    309.000 .00000 0.000 .000000 0.310   50.
D71      D91      MS      7.625    175.000 .00000 0.000 .000000 0.310   50.
D91      D72      MS      7.625    262.000 .00000 0.000 .000000 0.310   50.
D72      D92      MS      7.625    225.000 .00000 0.000 .000000 0.339   50.
D92      D73      MS      7.625    790.000 .00000 0.000 .000000 0.339   50.
D73      D58      MS      7.625    769.000 .00000 0.000 .000000 0.339   50.
D72      PRV526S  MS      3.826   1170.000 .00000 0.000 .000000 0.247   50.
PRV526S  PRV526D  FI  S        20.000          40.000 32.000  10.00
PRV526D  D75      MS      4.026    488.000 .00000 0.000 .000000 0.244   50.
D68X     D76X     MS      7.625   1442.000 .00000 0.000 .000000 0.320    5.
D76X     D77X     MS      7.625    851.000 .00000 0.000 .000000 0.330   50.
D77X     D78X     MS      7.625   1630.000 .00000 0.000 .000000 0.320    5.
D78X     D79X     MS      7.625    304.000 .00000 0.000 .000000 0.330   50.
D79X     D80      MS      7.625     83.000 .00000 0.000 .000000 0.320    5.
D80      D81      MS      2.900    581.000 .00000 0.000 .000000 0.240    5.
D80      D82      MS      3.826    597.000 .00000 0.000 .000000 0.210    5.
D82      PRV125S  MS      2.900    483.000 .00000 0.000 .000000 0.240    5.
PRV125S  PRV125D  FI  S        15.000          30.000 32.000  10.00
PRV125D  D83      MS      3.068    257.000 .00000 0.000 .000000 0.240    5.
PH250    D85      MS      5.761    532.000 .00000 0.000 .000000 0.428    5.
D85      D86      MS      5.761   3133.000 .00000 0.000 .000000 0.488    5.
D86      D87      MS      5.671   1484.000 .00000 0.000 .000000 0.488    5.
D87      D88      MS      5.761   1468.000 .00000 0.000 .000000 0.510    5.
D88      D89      MS      5.761    497.000 .00000 0.000 .000000 0.510    5.
D89      D90      MS      3.826    563.000 .00000 0.000 .000000 0.247    5.
PH250    D93      MS      7.625     17.000 .00000 0.000 .000000 0.247    5.
ZZZZ
NODE
 D1          0.00      120.00000       -5.824   G
 D4          0.00      120.00000       -0.123   G
 D5          0.00      120.00000       -0.368   G
 D7          0.00      120.00000       -0.144   G
 D9          0.00      120.00000       -0.491   G
 D11         0.00      120.00000       -0.492   G
 D13         0.00      120.00000       -0.534   G
 D15         0.00      120.00000       -1.046   G
 D16         0.00      120.00000       -0.246   G
 D17         0.00      120.00000       -0.246   G
 D18         0.00      120.00000       -0.246   G
 D19         0.00      120.00000       -0.246   G
 D20         0.00      120.00000       -0.358   G
 D21         0.00      120.00000       -0.358   G
 PH125       0.00      125.00000        0.000   P
 D23         0.00      120.00000       -0.123   G
 D24         0.00      120.00000       -0.246   G
 D27         0.00      120.00000       -1.229   G
 D32         0.00      120.00000       -0.368   G
 D34         0.00      120.00000       -1.966   G
 D37         0.00      120.00000       -2.703   G
 D39         0.00      120.00000       -0.293   G
 D42         0.00      120.00000       -0.368   G
 D50         0.00      120.00000       -1.720   G
 D51X        0.00      120.00000       -0.983   G
 D52         0.00      120.00000       -0.614   G
 PRV507S     0.00      240.00000       -0.614   G
 PRV501D     0.00      125.00000       -1.106   B
 PRV502D     0.00      125.00000       -0.736   B
 D53         0.00      120.00000       -1.046   G
 D56         0.00      120.00000       -1.475   G
 D57         0.00      120.00000       -3.285   G
 D58         0.00      120.00000       -4.151   G
 D60         0.00      120.00000       -1.144   G
 D61         0.00      120.00000       -1.229   G
 PRV536D     0.00      125.00000       -0.614   B
 D65         0.00      120.00000      -12.996   G
 D66         0.00      240.00000      -20.474   G
 D70         0.00      240.00000       -0.932   G
 D71         0.00      240.00000       -4.216   G
 D73         0.00      240.00000       -7.005   G
 PRV526D     0.00      125.00000       -1.768   B
```

D75	0.00	120.00000	-1.666	G
D80	0.00	240.00000	-2.203	G
D81	0.00	240.00000	-0.246	G
D82	0.00	240.00000	-0.011	G
PRV125D	0.00	125.00000	-1.352	B
D83	0.00	120.00000	-0.737	G
PH250	0.00	250.0000	0.000	P
D85	0.00	240.00000	-0.123	G
D86	0.00	240.00000	-0.861	G
D87	0.00	240.00000	-0.615	G
D88	0.00	240.00000	-1.351	G
D90	0.00	240.00000	-6.059	G
D91	0.00	240.00000	-0.845	G
D2X	0.00	120.00000	0.000	G
D3X	0.00	120.00000	0.000	G
D6X	0.00	120.00000	0.000	G
D8X	0.00	120.00000	0.000	G
D10X	0.00	120.00000	0.000	G
D22	0.00	120.00000	0.000	G
D26X	0.00	120.00000	0.000	G
D30X	0.00	120.00000	0.000	G
D31X	0.00	120.00000	0.000	G
D33X	0.00	120.00000	0.000	G
D36X	0.00	120.00000	0.000	G
D40X	0.00	120.00000	0.000	G
D41	0.00	120.00000	0.000	G
D43	0.00	120.00000	0.000	G
D44X	0.00	120.00000	0.000	G
D45	0.00	120.00000	0.000	G
D47X	0.00	120.00000	0.000	G
D48	0.00	120.00000	-4.301	G
D49X	0.00	120.00000	0.000	G
D54X	0.00	120.00000	0.000	G
D55	0.00	120.00000	0.000	G
PRV502S	0.00	240.00000	0.000	G
D29X	0.00	240.00000	0.000	G
D59X	0.00	240.00000	0.000	G
PRV507D	0.00	125.00000	0.000	B
PRV536S	0.00	240.00000	0.000	G
D62X	0.00	240.00000	0.000	G
D63X	0.00	240.00000	0.000	G
D64X	0.00	240.00000	0.000	G
D67X	0.00	240.00000	0.000	G
D68X	0.00	240.00000	0.000	G
D69X	0.00	240.00000	0.000	G
D72	0.00	240.00000	-2.264	G
D92	0.00	240.00000	-16.122	G
PRV526S	0.00	240.00000	0.000	G
D76X	0.00	240.00000	0.000	G
D77X	0.00	240.00000	0.000	G
D78X	0.00	240.00000	0.000	G
D79X	0.00	240.00000	0.000	G
PRV125S	0.00	240.00000	0.000	G
D89	0.00	240.00000	0.000	G
D93	0.00	240.00000	-1.106	G
ZZZZ				

LOADS FILE FOR THE OAK RIDGE NATIONAL LABORATORY STEAM DISTRIBUTION SYSTEM
MODELED AS A WELL INSULATED SYSTEM

COLUMN 1 IS THE BASE LOAD
COLUMN 2 IS THE WEATHER SENSITIVE COMPONENT OF THE LOAD

THESE LOADS REPRESENT A 24 HOUR DEMAND PER DAY

D1	.709	.085248
D4	.011	.001868
D5	.032	.005604
D7	.03	.0019
D9	.043	.007472
D11	.044	.007472
D13	.03	.008404
D15	.32	.0121
D16	.022	.003736
D17	.022	.003736
D18	.022	.003736
D19	.022	.003736
D20	.38	-.000369
D21	.38	-.000369
PH125	0.0	0.0
D23	.011	.001868
D24	.022	.003736
D27	.108	.01868
D32	.032	.005604
D34	.173	.02989
D37	.237	.041096
D39	.031	.004368
D42	.032	.005604
D48	.378	.065384
D50	.151	.026152
D51X	.086	.014944
D52	.054	.00934
PRV507S	.054	.00934
PRV501D	.097	.016812
PRV502D	.064	.011208
D53	-.07	.0186
D56	.130	.022416
D57	.052	.053884
D58	.425	.062108
D60	.13	.0169
D61	.108	.01868
PRV536D	.054	.00934
D65	.45	.2091
D66	-1.248	.362036
D70	.59	.0057
D71	.94	.0546
D72	.022	.03736
D73	.616	.106476
PRV526D	.28	.0248
D75	.43	.0206
D80	.185	.033626
D81	.022	.003736
D82	.003	.00014
PRV125D	.119	.020548
D83	.065	.011208
PH250	0.0	0.0
D85	.011	.001868
D86	.076	.013076
D87	.055	.00934
D88	.3541	.016616
D90	1.625	.073908
D91	.0648	.013
D92	1.242	.248
D93	.097	.016812

2. Existing ORNL Steam Distribution System

```
TITLE
MODEL OF THE EXISTING OAK RIDGE NATIONAL LABORATORY STEAM
DISTRIBUTION SYSTEM WITH A PLANT OUTPUT PRESSURE OF 250 PSIG
ZZZZ
CONVERT
FLOW        1.          'MLB/HR    '
LENGTH      1.          FEET
ZZZZ
SYSTEM
VISCOS      0.000000425
OPTIONS     NCES      CONTCHK   NODES
MAXITER       25
SUPER       NO
DISPLAY
ZZZZ
NCES
 D1       D2X       MS      4.026     677.000 .00000 0.000 .000000 1.400   50.
 D2X      D3X       MS      6.065      47.000 .00000 0.000 .000000 1.500   50.
 D3X      D4        MS      6.065     188.000 .00000 0.000 .000000 1.500   50.
 D4       D5        MS      6.065      66.000 .00000 0.000 .000000 1.500   50.
 D6X      D7        MS      3.068     489.000 .00000 0.000 .000000 0.513    5.
 D5       D6X       MS      6.065     192.000 .00000 0.000 .000000 0.635    5.
 D6X      D8X       MS      3.068      20.000 .00000 0.000 .000000 0.635    5.
 D8X      D9        MS      6.065     174.000 .00000 0.000 .000000 0.635    5.
 D9       D10X      MS      6.065      33.000 .00000 0.000 .000000 0.635    5.
 D10X     D11       MS      6.065      65.000 .00000 0.000 .000000 0.635    5.
 D8X      D13       MS      3.068     201.000 .00000 0.000 .000000 1.300   50.
 D10X     D15       MS      6.065     199.000 .00000 0.000 .000000 1.500   50.
 D15      D16       MS      6.065      80.000 .00000 0.000 .000000 0.472    5.
 D16      D17       MS      3.068      80.000 .00000 0.000 .000000 1.300   50.
 D16      D18       MS      6.065     216.000 .00000 0.000 .000000 0.635    5.
 D18      D19       MS      2.067     220.000 .00000 0.000 .000000 0.4   5.
 D18      D20       MS      4.026     867.000 .00000 0.000 .000000 1.400   50.
 D20      D21       MS      4.026     266.000 .00000 0.000 .000000 1.400   50.
 D18      D22       MS     10.020      88.000 .00000 0.000 .000000 1.008    5.
 D22      PH125     MS     11.938     155.600 .00000 0.000 .000000 1.094    5.
 D22      D23       MS     11.938     175.000 .00000 0.000 .000000 1.094    5.
 D23      D24       MS     11.938      70.000 .00000 0.000 .000000 1.094    5.
 D24      D26X      MS     11.938     130.000 .00000 0.000 .000000 1.094    5.
 D26X     D27       MS     10.020      35.000 .00000 0.000 .000000 1.008    5.
 D27      D31X      MS     10.020      29.000 .00000 0.000 .000000 1.008    5.
 D31X     D32       MS     10.020     163.000 .00000 0.000 .000000 1.800   50.
 D32      D33X      MS      7.981     344.000 .00000 0.000 .000000 1.700   50.
 D33X     D34       MS      7.981      33.000 .00000 0.000 .000000 0.518    5.
 D34      D36X      MS      7.981     143.000 .00000 0.000 .000000 0.434    5.
 D36X     D30X      MS      6.065     105.000 .00000 0.000 .000000 0.558    5.
 D30X     D37       MS      4.026     357.000 .00000 0.000 .000000 0.376    5.
 D36X     D39       MS      7.981     130.000 .00000 0.000 .000000 0.626    5.
 D39      D40X      MS      7.981     241.000 .00000 0.000 .000000 0.626    5.
 D40X     D41       MS      6.065     105.000 .00000 0.000 .000000 0.558    5.
 D41      D42       MS      6.065     277.000 .00000 0.000 .000000 0.626    5.
 D42      D43       MS      6.065     174.000 .00000 0.000 .000000 0.626    5.
 D43      D44X      MS      6.065      87.000 .00000 0.000 .000000 0.626    5.
 D44X     D45       MS      3.068     280.000 .00000 0.000 .000000 0.513    5.
 D40X     D47X      MS      6.065      63.000 .00000 0.000 .000000 0.558    5.
 D47X     D48       MS      6.065     153.000 .00000 0.000 .000000 0.558    5.
 D47X     D49X      MS      4.026     266.000 .00000 0.000 .000000 0.614    5.
 D49X     D50       MS      4.026     139.000 .00000 0.000 .000000 1.400   50.
 D50      D51X      MS      4.026      88.000 .00000 0.000 .000000 1.400   50.
 D51X     D44X      MS      4.026     185.000 .00000 0.000 .000000 0.479    5.
 D51X     D52       MS      3.068     213.000 .00000 0.000 .000000 0.513    5.
 D48      D53       MS      6.065     194.000 .00000 0.000 .000000 1.500   50.
 D53      D54X      MS      6.065     102.000 .00000 0.000 .000000 1.500   50.
 D54X     D55       MS      4.026     126.000 .00000 0.000 .000000 0.376    5.
 D54X     PRV501D   MS      6.065     184.000 .00000 0.000 .000000 0.558    5.
 PRV501D  PRV501S   FI  S          25.000          50.000 32.000  10.00
 PRV501S  D56       MS      5.761      56.000 .00000 0.000 .000000 1.500   50.
 D58      D56       MS      7.625     368.000 .00000 0.000 .000000 1.700   50.
 D57      PRV502D   MS      4.026     196.000 .00000 0.000 .000000 0.616    5.
 PRV502D  PRV502S   FI  S          50.000         100.000 32.000  10.00
 PRV502S  D58       MS      3.826      85.000 .00000 0.000 .000000 1.400   50.
 D93      D29X      MS      7.625     600.000 .00000 0.000 .000000 0.947    5.
 D29X     D59X      MS      7.625     171.000 .00000 0.000 .000000 1.700   50.
 D59X     PRV507S   MS      7.625     342.000 .00000 0.000 .000000 0.644    5.
 PRV507S  PRV507D   FI  S          20.000          40.000 32.000  10.00
 PRV507S  D56       MS      7.625      50.000 .00000 0.000 .000000 1.700   50.
 PRV507D  D60       MS      4.026     491.000 .00000 0.000 .000000 0.616    5.
 D60      D61       MS      4.026     287.000 .00000 0.000 .000000 0.616    5.
 D61      PRV536D   MS      3.068      85.000 .00000 0.000 .000000 0.513    5.
 PRV536D  PRV536S   FI  S          20.000          40.000 32.000  10.00
```

```
PH250    D62X     MS      7.625     822.000 .00000 0.000 .000000 0.819    5.
D62X     D63X     MS      7.625      73.000 .00000 0.000 .000000 1.700   50.
D63X     PRV536S  MS      7.625     179.000 .00000 0.000 .000000 0.819    5.
PRV536S  D64X     MS      7.625     176.000 .00000 0.000 .000000 0.819    5.
D64X     D65      MS      7.625     787.000 .00000 0.000 .000000 1.700   50.
D65      D66      MS      7.625     525.000 .00000 0.000 .000000 1.700   50.
D66      D67X     MS      7.625     466.000 .00000 0.000 .000000 1.700   50.
D67X     D68X     MS      7.625      95.000 .00000 0.000 .000000 1.700   50.
D68X     D69X     MS      3.826      75.000 .00000 0.000 .000000 0.630    5.
D69X     D70      MS      3.826     130.000 .00000 0.000 .000000 1.400   50.
D67X     D71      MS      7.625     309.000 .00000 0.000 .000000 1.700   50.
D71      D91      MS      7.625     175.000 .00000 0.000 .000000 1.700   50.
D91      D72      MS      7.625     262.000 .00000 0.000 .000000 1.700   50.
D72      D92      MS      7.625     225.000 .00000 0.000 .000000 1.700   50.
D92      D73      MS      7.625     790.000 .00000 0.000 .000000 1.700   50.
D73      D58      MS      7.625     769.000 .00000 0.000 .000000 1.700   50.
D72      PRV526S  MS      3.826    1170.000 .00000 0.000 .000000 1.4  50.
PRV526S  PRV526D  FI  S         20.000          40.000 32.000  10.00
PRV526D  D75      MS      4.026     488.000 .00000 0.000 .000000 1.400   50.
D68X     D76X     MS      7.625    1442.000 .00000 0.000 .000000 0.576    5.
D76X     D77X     MS      7.625     851.000 .00000 0.000 .000000 1.700   50.
D77X     D78X     MS      7.625    1630.000 .00000 0.000 .000000 0.576    5.
D78X     D79X     MS      7.625     304.000 .00000 0.000 .000000 1.700   50.
D79X     D80      MS      7.625      83.000 .00000 0.000 .000000 0.576    5.
D80      D81      MS      2.900     581.000 .00000 0.000 .000000 0.432    5.
D80      D82      MS      3.826     597.000 .00000 0.000 .000000 0.378    5.
D82      PRV125S  MS      2.900     483.000 .00000 0.000 .000000 0.432    5.
PRV125S  PRV125D  FI  S         15.000          30.000 32.000  10.00
PRV125D  D83      MS      3.068     257.000 .00000 0.000 .000000 0.432    5.
PH250    D85      MS      5.761     532.000 .00000 0.000 .000000 0.770    5.
D85      D86      MS      5.761    3133.000 .00000 0.000 .000000 0.878    5.
D86      D87      MS      5.671    1484.000 .00000 0.000 .000000 0.878    5.
D87      D88      MS      5.761    1468.000 .00000 0.000 .000000 0.918    5.
D88      D89      MS      5.761     497.000 .00000 0.000 .000000 0.918    5.
D89      D90      MS      3.826     563.000 .00000 0.000 .000000 0.445    5.
PH250    D93      MS      7.625      17.000 .00000 0.000 .000000 0.445    5.
ZZZZ
NODE
D1            0.00        120.00000         -5.824   Q
D4            0.00        120.00000         -0.123   Q
D5            0.00        120.00000         -0.368   Q
D7            0.00        120.00000         -0.144   Q
D9            0.00        120.00000         -0.491   Q
D11           0.00        120.00000         -0.492   Q
D13           0.00        120.00000         -0.534   Q
D15           0.00        120.00000         -1.046   Q
D16           0.00        120.00000         -0.246   Q
D17           0.00        120.00000         -0.246   Q
D18           0.00        120.00000         -0.246   Q
D19           0.00        120.00000         -0.246   Q
D20           0.00        120.00000         -0.358   Q
D21           0.00        120.00000         -0.358   Q
PH125         0.00        125.00000          0.000   P
D23           0.00        120.00000         -0.123   Q
D24           0.00        120.00000         -0.246   Q
D27           0.00        120.00000         -1.229   Q
D32           0.00        120.00000         -0.368   Q
D34           0.00        120.00000         -1.966   Q
D37           0.00        120.00000         -2.703   Q
D39           0.00        120.00000         -0.293   Q
D42           0.00        120.00000         -0.368   Q
D50           0.00        120.00000         -1.720   Q
D51X          0.00        120.00000         -0.983   Q
D52           0.00        120.00000         -0.614   Q
PRV507S       0.00        240.00000         -0.614   Q
PRV501D       0.00        125.00000         -1.106   B
PRV502D       0.00        125.00000         -0.736   B
D53           0.00        120.00000         -1.046   Q
D56           0.00        120.00000         -1.475   Q
D57           0.00        120.00000         -3.285   Q
D58           0.00        120.00000         -4.151   Q
D60           0.00        120.00000         -1.144   Q
D61           0.00        120.00000         -1.229   Q
PRV536D       0.00        125.00000         -0.614   B
D65           0.00        120.00000        -14.296   Q
D66           0.00        240.00000        -20.474   Q
D70           0.00        240.00000         -2.232   Q
D71           0.00        240.00000         -4.216   Q
D73           0.00        240.00000         -8.305   Q
PRV526D       0.00        125.00000         -1.768   B
```

D75	0.00	120.00000	-1.666	G
D80	0.00	240.00000	-2.203	G
D81	0.00	240.00000	-0.246	G
D82	0.00	240.00000	-0.011	G
PRV125D	0.00	125.00000	-1.352	B
D83	0.00	120.00000	-0.737	G
PH250	0.00	250.00000	0.000	P
D85	0.00	240.00000	-0.123	G
D86	0.00	240.00000	-0.861	G
D87	0.00	240.00000	-0.615	G
D88	0.00	240.00000	-1.351	G
D90	0.00	240.00000	-6.059	G
D91	0.00	240.00000	-0.845	G
D2X	0.00	120.00000	0.000	G
D3X	0.00	120.00000	0.000	G
D6X	0.00	120.00000	0.000	G
D8X	0.00	120.00000	0.000	G
D10X	0.00	120.00000	0.000	G
D22	0.00	120.00000	0.000	G
D26X	0.00	120.00000	0.000	G
D30X	0.00	120.00000	0.000	G
D31X	0.00	120.00000	0.000	G
D33X	0.00	120.00000	0.000	G
D36X	0.00	120.00000	0.000	G
D40X	0.00	120.00000	0.000	G
D41	0.00	120.00000	0.000	G
D43	0.00	120.00000	0.000	G
D44X	0.00	120.00000	0.000	G
D45	0.00	120.00000	0.000	G
D47X	0.00	120.00000	0.000	G
D48	0.00	120.00000	-4.301	G
D49X	0.00	120.00000	0.000	G
D54X	0.00	120.00000	0.000	G
D55	0.00	120.00000	0.000	G
PRV502S	0.00	240.00000	0.000	G
D29X	0.00	240.00000	0.000	G
D59X	0.00	240.00000	0.000	G
PRV507D	0.00	125.00000	0.000	B
PRV536S	0.00	240.00000	0.000	G
D62X	0.00	240.00000	0.000	G
D63X	0.00	240.00000	0.000	G
D64X	0.00	240.00000	0.000	G
D67X	0.00	240.00000	0.000	G
D68X	0.00	240.00000	0.000	G
D69X	0.00	240.00000	0.000	G
D72	0.00	240.00000	-3.564	G
D92	0.00	240.00000	-16.122	G
PRV526S	0.00	240.00000	0.000	G
D76X	0.00	240.00000	0.000	G
D77X	0.00	240.00000	0.000	G
D78X	0.00	240.00000	0.000	G
D79X	0.00	240.00000	0.000	G
PRV125S	0.00	240.00000	0.000	G
D89	0.00	240.00000	0.000	G
D93	0.00	240.00000	-1.106	G
ZZZZ				

LOADS FILE FOR THE OAK RIDGE NATIONAL LABORATORY STEAM DISTRIBUTION SYSTEM MODELED AS IT EXISTS TODAY

COLUMN 1 IS THE BASE LOAD
COLUMN 2 IS THE WEATHER SENSITIVE COMPONENT OF THE LOAD

THESE LOADS REPRESENT A 24 HOUR DEMAND PER DAY

D1	.709	.085248
D4	.011	.001868
D5	.032	.005604
D7	.03	.0019
D9	.043	.007472
D11	.044	.007472
D13	.03	.008404
D15	.32	.0121
D16	.022	.003736
D17	.022	.003736
D18	.022	.003736
D19	.022	.003736
D20	.38	-.000369
D21	.38	-.000369
PH125	0.0	0.0
D23	.011	.001868
D24	.022	.003736
D27	.108	.01868
D32	.032	.005604
D34	.173	.02989
D37	.237	.041096
D39	.031	.004368
D42	.032	.005604
D48	.378	.065384
D50	.151	.026152
D51X	.086	.014944
D52	.054	.00934
PRV507S	.054	.00934
PRV501D	.097	.016812
PRV502D	.064	.011208
D53	-.07	.0186
D56	.130	.022416
D57	.052	.053884
D58	.425	.062108
D60	.13	.0169
D61	.108	.01868
PRV536D	.054	.00934
D65	1.75	.2091
D66	-1.248	.362036
D70	1.89	.0057
D71	.94	.0546
D72	1.322	.03736
D73	1.916	.106476
PRV526D	.28	.0248
D75	.43	.0206
D80	.185	.033626
D81	.022	.003736
D82	.003	.00014
PRV125D	.119	.020548
D83	.065	.011208
PH250	0.0	0.0
D85	.011	.001868
D86	.076	.013076
D87	.055	.00934
D88	.3541	.016616
D90	1.625	.073908
D91	.0648	.013
D92	1.242	.248
D93	.097	.016812

APPENDIX C - BUILDINGS LOAD DATA

bldg.	Metered Load Lbs/hr	Floor Area sq ft	Make-up air CFM	Jan.Consumpt M Lbs	Steam kw	Area kw	Airflow kw	Max. kw
1503	706	6000	460	1191	207	60	9	207
1505	3681	91712	30854		1079	917	574	1079
1506	1400	16780	10414		410	168	194	410
2000	920	22680	4100		270	227	76	270
2001	920	25863			270	259	0	270
2007	102	1965	300		30	20	6	30
2008	144	4851	4800	80	42	49	89	89
2010	511	11770	5000		150	118	93	150
2011	204	5804	2200		60	58	41	60
2013	409	11488		13	120	115	0	120
2016	102	2360			30	24	0	30
2018	204	6362			60	64	0	64
2019	0	820			0	8	0	8
2024	409	10300			120	103	0	120
2026	1022	23390	20000		299	234	372	372
2069	307	7013			90	70	0	90
2500	307	8650			90	87	0	90
2506	307	8744	500		90	87	9	90
2511	0	380			0	4	0	4
2516	204	5741			60	57	0	60
2517	204	4743			60	47	0	60
2518	148	10125		70	43	101	0	101
2519	920	23614			270	236	0	270
2523	3593	4000			1053	40	0	1053
2525	1046	27622	33000	751	306	276	614	614
2528	204	2987	4300		60	30	80	80
2531	409	9004	4500		120	90	84	120
2567	102	3340	4500		30	33	84	84

bldg.	Metered Load Lbs/hr	Floor Area sq ft	Make-up air CFM	Jan.Consumpt M Lbs	Steam kw	Area kw	Airflow kw	Max. kw
2621	204	5469			60	55	0	60
3001	204	43114			60	431	0	431
3003	307	7605	1800		90	76	34	90
3010	409	8427	4000		120	84	74	120
3017	170	10244	2000	145	50	102	37	102
3019A	1636	38537	20000		479	385	372	479
3019B	307	3787	20000		90	38	372	372
3024	511	12400			150	124	0	150
3025	1046	59085	21800		306	591	406	591
3026C	307	8376	2000		90	84	37	90
3026D	613	16110	4500		180	161	84	180
3028	716	17054	8000		210	171	149	210
3029	102	2273	4100		30	23	76	76
3030	102	720	5000	330	30	7	93	93
3031	102	720	5000		30	7	93	93
3032	102	720	5000		30	7	93	93
3033	102	720	5000		30	7	93	93
3033A	0	882			0	9	0	9
3034	0	1200			0	12	0	12
3036	102	1449			30	14	0	30
3037	307	8185			90	82	0	90
3038	307	7548	4060		90	75	76	90
3042	1431	37369	9000	733	419	374	168	419
3044	204	3059	8000		60	31	149	149
3047	1686	25630	17700	752	494	256	329	494
3074	102	3513	2000		30	35	37	37
3080	409	11027			120	110	0	120
3082	0	225			0	2	0	2
3104	307	7330	1000		90	73	19	90

Bldg.	Metered Load Lbs/hr	Floor Area sq ft	Make-up air CFM	Jan.Consumpt M Lbs	Steam kw	Area kw	Airflow kw	Max. kw
3118	0	900			0	6	0	6
3500	3067	79491	16000		899	556	298	899
3502	511	12136			150	85	0	150
3503	511	12206	2000		150	85	37	150
3504	307	7316	3500		90	51	65	90
3505								
3508	1144	13680	12500		335	96	233	335
3517	613	16708	2000		180	117	37	180
3518	102	1680			30	12	0	30
3523	0	1200			0	8	0	8
3525	1227	26723	19500		360	187	363	363
3531	0	364			0	3	0	3
3534	0	450			0	3	0	3
3541	102	800	8000		30	6	149	149
3543	0	600			0	4	0	4
3544	0	2837	1000		0	20	19	20
3550	342	12327	1000		100	86	19	100
3587	102	3402			30	24	0	30
3592	102	1200	8000		30	8	149	149
4500N	3300	341692	242700		967	2392	4518	4518
4500S	20228	274451	442000		5927	1921	8227	8227
4501	2045	36426	73000		599	255	1359	1359
4505	3578	78445	63000		1048	549	1173	1173
4507	204	3812	5200		60	27	97	97
4508	12996	99030	198200		3808	693	3689	3808
4509	204	5950			60	42	0	60
5000	204	6300			60	44	0	60
5500	4216	51965	92000		1235	364	1712	1712

INTERNAL DISTRIBUTION

1. F. D. Boercker
2. M. A. Broders
3. R. S. Carlsmith
4. V. Carmony
5. F. C. Chen
6. J. E. Christian
7. T. L. Dahl
8. G. A. Dailey
9. R. C. Devault
10. G. J. Dixon
11. D. J. Eiler
12. J. C. Elrod
13. Carl Fox
14. E. C. Fox
15. W. Fulkerson
16. K. E. Gant
17. S. E. Hamblen
18. S. C. Harris
19. M. T. Huie
20. F. R. Kalhammer
21. S. I. Kaplan
22-31. M. A. Karnitz
32. S. V. Kaye
33. H. F. Keesee
34. O. A. Kelly
35. Les Klien
36. J. O. Kolb
37. E. H. Krieg
38. T. R. LaPorte
39. D. W. Lee
40. D. L. Lennon
41. M. A. Lindell
42. J. F. Martin
43. L. N. McCold
44. L. A. McDonald
45. H. A. McLain
46. J. W. Michel
47. W. R. Mixon
48. L. I. Moss
49. G. W. Oliphant
50. M. Olszewski
51. R. E. Peden
52. R. W. Peelle
53. H. Perez-Blanco
54. C. H. Petrich
55. G. D. Pine
56. W. R. Ragland
57. M. W. Rosenthal
58. W. Simon
59. K. W. Sommerfeld
60. J. H. Sorensen
61-80. S. W. Southards
81. I. Spiewak
82. T. K. Stovall
83. J. H. Swanks
84. J. W. Van Dyke
85. A. H. Voelker
86. R. L. Wendt
87. T. J. Wilbanks
88. W. H. Williams
89. Central Research Library
90. Document Reference Section
91-92. Energy Information Library
93. Laboratory Records (RC)
94-95. Laboratory Records
96. ORNL Patent Office

EXTERNAL DISTRIBUTION

97. B. Abrahamson, FVB District Heating Engineering, Inc., Vasteras, Sweden
98. Conrad Aas, Northern States Power Company, 414 Nicollet Mall, Minneapolis, MN 55401
99. M. Todd Anuskiewicz, Michigan Energy and Resource Research Association, 1200 Sixth Street, Room 328, Detroit, MI 48226
100. Lars Astrand, Uppsalla Kraftvarme AB, Sweden
101-105. M. H. Barnes, Scantec, Inc., 251 East 5th Street, St. Paul, MN 55101
106. Lt. Commander Thomas M. Boothe, United States Navy, Headquarters Naval Material Command, Navy Department, Washington, DC 20360
107. T. R. Butzbach, Lockwood Greene Engineers, Inc., P.O. Box 3561, Oak Ridge, TN 37830

108. Wyndham Clarke, Department of Housing and Urban Development, 451 Seventh Street SW, Room 5146, Washington, DC 20410
109. W. Dolan, USA-CERL, P. O. Box 4005, Champaign, IL 61821
110. C. W. Easton, 3515 Rainier Bank Tower, Seattle, WA 98101
111. R. M. Gerzetich, Consumer Power Company, 212 West Michigan Avenue, Jackson, MI 49201
112. J. L. Gillie, Consumers Power Company, 4000 Clay Avenue, SW Grand Rapids, MI 49508
113. Neal Goldenberg, Department of Energy, Bldg-GTN, Washington, DC 20545
114. Robert P. Groberg, HUD, 451 7th Street, SW, Washington, DC 20410
115. E. S. Helms, Lockwood Greene Engineers, Inc., P. O. Box 3561, Oak Ridge, TN 37830
116. Herbert Jaehne, St. Paul District Heating Development Co., Inc., 138 Bremer Bldg., 417 North Robert Street, St. Paul, MN 55101
117. Algernon H. Johnson, Johnson Bros. Corporation, 1500 South Lilac Drive, Tyrol West Building, Minneapolis, MN 55416
118. Clarence Kadrmas, P. O. Box 937, 704 Litchfield Ave., Willmar, MN 56201
119. Jake Kaminsky, Department of Energy, 1000 Independence Ave., SW, Washington, DC 20585
120. Ted Kapus, Department of Energy, Office of Building Energy Research and Development, 1000 Independence Ave., SW, Washington, DC 20585
121. Allen Kennedy, Argonne National Laboratory, EES Division, 9700 South Cass Avenue, Building 362, Argonne, IL 60439
122. John King, Code L63, Naval Civil Engineering Laboratory, Port Hueneme, CA 93043
123. Kjell Larsson, Plogvagen 1 B, S-18351 TABY, Sweden
124. R. Eric Leber, American Public Power Association, 2301 M Street, NW, Washington, DC 20037
125. Jens Madsen, Brown Boveri Corporation, 1460 Livingston Avenue, North Brunswick, NJ 08902
126. Peter Margen, Studsvik Energiteknik AB, S-611 82, Nykoping, Sweden
127. John Millhone, Department of Energy, 1000 Independence Avenue, SW, Washington, DC 20585
128. Hans Nyman, District Heating Development Company, 417 N. Robert Street, 138 Bremer Building, St. Paul, MN 55101
129. Merle Potter, Michigan State University, Department of Mechanical Engineering, E. Lansing, MI 48823
130. Alan Rubin, Nuclear Regulatory Commission, 7920 Norfolk Avenue, Room 266, Bethesda, MD 20555
131. E. G. Segan, USA-CERL, P. O. Box 4005, Champaign, IL 61821
132. William Savage, Department of Energy, NE-550, Washington, DC 20545
133. K. L. Stierhoff, 1735 Eye Street, NW, Suite 611, Washington, DC 20006
134. Ronald E. Sundberg, Minnesota Energy Agency, American Center Building, 150 East Kellogg Boulevard, St. Paul, MN 55101

135. Norman Taylor, International District Heating Assoc., 1735 Eye Street NW, Suite 611, Washington, DC 20006

136. Office of the Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN 37831

137-163. Technical Information Center, Department of Energy, P. O. Box 62, Oak Ridge, TN 37831