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HIGHWAY BRIDGE DEICING USING PASSIVE HEAT SOURCES

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16. Abstract

This report investigates controlling bridge icing with heat sources which are not generated by the consumption of fossil fuel. Heat derived from ground water, the earth, sanitary sewer or domestic water lines, and alternatives center around heat pipe technology to transfer heat into bridge deck to avoid the risk of circulating water in the bridge deck. Designs are based on controlling preferential icing rather than maintaining an ice free bridge. Costs range from $24 to $55 based on 1981 prices with heating from sanitary sewer being the lowest.

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I. INTRODUCTION

Ice on bridges presents a serious problem to motorists both in safety and in the ability to accelerate and climb grades. Elevated structures are particularly susceptible to icing because of the movement of air under the deck instead of thermally stable earth. Under certain weather conditions structures can ice up before the roadway does, creating a surprise hazard for the motorist. Solutions to this problem range from the usual maintenance procedures of plowing, salting, and sanding to the use of heat from various sources to melt the ice and snow. The usual maintenance practices are generally the most cost-effective but are not without problems. Heating of structures is generally very expensive, limiting its use to spots where deicing is very important. Heating structures generally requires the consumption of precious fossil fuels making it an unacceptable alternative. Some innovative heating systems which have been studied recently involve the use of earth heat or geothermally heated water. These systems are more attractive because they do not require the consumption of fossil fuels to operate. The capital cost of earth heat systems is high because numerous wells must be drilled, cased, and grouted in order to extract the earth heat. Geothermally heated structures are expected to be less costly but require geothermal activity in the area.

This study will explore systems for deicing roadway structures in Colorado which do not depend on the consumption of fossil fuels for a heat source. First, this will involve describing conceptual designs, life expectancy, performance, and cost estimates for potential systems. Second, it will involve describing a methodology for design and analysis for passive heating on a project-by-project basis.

Five methods of bridge deck heating will be covered in this report as follows:

1. Shallow ground water circulating through heat pipes in the bridge and returned back into the ground.

2. Deep aquifer ground water circulating through heat pipes in the bridge and returned back into the ground.

3. Sanitary or domestic water circulating through heat pipe headers.

4. Solar collectors and buried water tank storage.

5. Use of earth heat and heat pipes for deicing bridge deck.

This report is divided into a discussion of these five types of heating systems. After each type of system is described and design considerations discussed, a sample analysis will be provided. A railroad overpass in Littleton (which is currently under design) will have a steep grade entering downtown Littleton. Icing on this structure will create a very hazardous situation. This structure will be used as a sample of the methodology developed in this study. Finally, implementation of this report and its findings will be discussed.

II. BACKGROUND

Ground water, although cold (40 to 60 deg. F; 5 to 15 deg. C), contains enough heat to deice roadways. Heat can be extracted from the ground and ground water using ammonia-filled heat pipes with only a minimum temperature differential. Other sources of water such as sanitary sewer and domestic water could be used for a source of heat. If a sufficient volume of water is available, very little water temperature would be lost as it passes through the heat exchangers.

Other possibilities include solar energy to supplement earth heat stored in an underground water tank to be transferred to the structure as needed.

Colorado, along with many other agencies, has performed research on bridge deicing. The studies investigated the use of insulation, electricity, geothermal energy, and earth heat to reduce icing on bridges and roadways. Electrical and earth heat systems have been shown to be technically feasible (see Reference 1-6). However, cost of the systems is presently high($50/sq. ft., the electrical system being costly to operate and the earth heat system having a high initial cost). Heating with geothermal energy is also a feasible method ($10-20/sq. ft.) (see Reference 7) but is limited to areas where this resource is available. Although inexpensive, $1/sq. ft., thermal insulation comes with mixed blessings. Although the insulation helps the bridge deck retain heat and slightly delays icing at the onset of a storm, it can also increase a deck's propensity to frost up on clear nights. A deck can radiate its heat into a clear night sky; and without heat entering from the bottom of the deck, temperatures can drop below the dew point and frost can occur.

Ground water has been considered as a promising way to use earth energy for bridge deicing. This method is a potentially cheaper ($30 to 40/sq. ft.) way of using earth energy over using long heat pipes because it eliminates the need to drill and grout numerous 100-foot wells. Ground water heat was preliminarily investigated by Colorado for an underpass just west of Vail. Because of the shortage and low temperature of ground water in the area, emphasis of the study was shifted to solar heating.

Both of these systems were investivated to prevent runoff water from freezing inside the tunnel rather than to melt snow as it falls. In fact, the area to be heated is not exposed to falling snow. The more general problem of icy bridge decks exposed to all the elements was not addressed in this study. Ferrara and Yenetchi (Reference 5) performed a preliminary evaluation of using solar collectors and underground water tank storage. The indication is that the system has a definite cost advantage over earth heat/heat pipe systems. Both solar and ground water systems show potential of cost advantages over earth heat or electrical systems; however many questions as to the design and performance of these systems need to be answered.

III. HEAT PIPE HEAT EXCHANGERS

Water has a tremendous capacity to store heat and is relatively abundant. Even though a source of water feels cold, it may have enough heat to melt ice. The secret to using water to deice bridge decks is to construct a heat transfer system which is efficient enough to transfer the needed power (heat) without exceeding the temperature drop available; i.e., since ice melts at 32 deg. F (0 deg. C), a heat transfer system operating with water at 50 deg. F (10 deg. C) must be able to transfer the needed power to the surface of the roadway without losing more than 18 deg. F (10 deg. C). A heat transfer system which is both efficient and economical is a key factor in utilizing low temperature water sources for bridge deicing.

A. Alternate Systems

In order to transfer the heat of the water to the surface of the bridge deck, various systems were considered. The most direct approach would be to circulate the water directly through pipes embedded in the bridge deck. This method was rejected because of the possibility of corrosion, leakage, and freeze-up resulting in serious damage to the bridge deck. Also, corrosion of the pipes would reduce effectiveness and life of the heating system. A second method would be to use a non-corrosive, non-freezing fluid to circulate through pipes in the deck and a separate heat exchanger to transfer heat from the water to the fluid. This method would require an additional pump and heat exchanger to circulate the special fluid. The additional fluid and heat exchanger would also increase the temperature drop of the system.

A good way to avoid the problems of direct circulation and the inefficiency of a separate fluid system is to use heat pipe technology. Heat pipes use the phenomenon of the boiling and condensing of a working fluid such as ammonia to transfer heat. Since large amounts of heat are involved in these phase changes, heat transfer can be accomplished with good efficiency.

Two systems using heat pipe technology were evaluated by Nydall (Reference 10) in Glenwood Springs in conjunction with a study to determine feasibility of using geothermal hot water for bridge deicing. The first system is composed of 6-inch and 3-inch eccentric steel pipes with 1-inch steel pipe fingers which are buried in the roadway (see Figure 1). Warm water flows through the 3-inch pipe and boils liquid ammonia contained in the 6-inch pipe. The vapor ammonia rises into the fingers where it condenses, provided the walls of the fingers are at a lower temperature than the liquid ammonia (see Figure 2). Since the vapor ammonia gives up its heat of vaporization when it condenses, tremendous amounts of energy can be transferred with only a small circulation of ammonia. Once condensed, the liquid ammonia can drain back and be reboiled. This system was designed and manufactured by the Seta Corporation of Wyoming.

The second system evaluated was composed of a 6-inch steel pipe with 1/2" steel heat pipes extending through the wall of the 6-inch pipe. One end of each 1/2" steel heat pipe is embedded in the pavement while the other end runs longitudinally inside the 6-inch pipe (see Figure 3). Water is circulated through the 6-inch pipe and around the submersed 1/2-inch heat pipes. Heat from the water boils the liquid ammonia in the 1/2" pipes which in turn condenses in the fingers buried in the pavement. This submersed heat pipe heat exchanger system was designed and built by Energy Environment, Inc. of New Mexico.

The submersed heat pipe design is expected to have a higher initial efficiency (conductivity) than the eccentric manifold design. It has more contact surface area between the water and the heat pipes. In addition, the submersed pipes tend to redirect the flow of water and create more turbulence. This increased turbulence enhances the water's ability to transfer its heat to the pipes.

The eccentric manifold design is sensitive to tilt, while the submersed heat pipe design is not. For a typical 8-foot manifold, performance of the evaporator will start degrading when the tilt exceeds 2 1/2%. If grade of structure exceeds 2 1/2%, grade transverse manifolds would have to be used. This is due to the liquid's draining to one end of the evaporator. This is not the case with submersed heat pipes. This problem can be eliminated if film boiling rather than pool boiling is employed in the manifold. Liquid ammonia could drip out of the fingers and form a film on the inner pipe re-evaporating as it gains heat from the surface. This method generally produces less temperature drop in the vaporization process than pool boiling and will significantly improve the performance of the system.

Utilization of this film boiling process would require a significant amount of development work because of critical features of this phenomenon. Film boiling may be utilized in future heat pipe systems but is not at present considered state-of-the-art.

The submersed heat pipe design has its problems. The most serious problem is fabrication and corrosion protection. Because the pipes must protrude through the outer pipe, a substantial amount of welding has to be performed. Coating these welds on the interior of the pipe with all the heat pipes in the way is a difficult task. It may be impossible to accomplish complete coating coverage. Since corrosion will take place as fast or faster on even a small unprotected spot, a reasonable lifetime of the system could not be achieved. Periodic mechanical cleaning of this type of system is not possible. This is not a real problem when clean water sources are used, but for geothermal or sanitary sewer water it would present a problem.

Since the eccentric manifold is a viable system, despite some drawbacks, it was chosen as the basis for this study. The submersed heat pipe system was not considered for this study because of the problem of corrosion protection. This is not to say that with some development work this system should not be a viable system.

B. Materials and Fabrication

Use of ammonia as the working fluid for these systems is by far the best choice for the following reasons:

1. Ammonia has a very high heat of vaporation.
2. At 32 deg. F (0 deg. C) ammonia will boil and condense at a reasonable pressure.
3. The safety problem of ammonia is not significant on an outside installation.

The use of steel as the fabrication material is by far the best choice for the following reasons:

1. Steel pipe is readily available and relatively low in price.
2. Fabrication with steel is relatively easy and a well developed technology.

FIGURE 1

Eccentric Manifold Heat Pipe Heat Exchanger

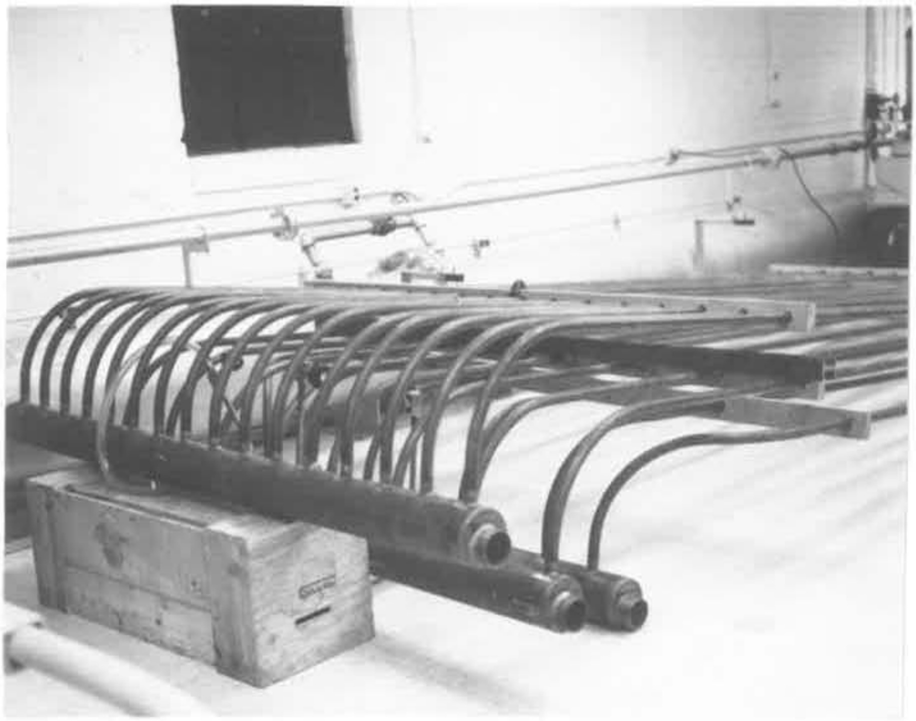


FIGURE 2

Crossection of Manifold
Heat Pipe Heat Exchanger

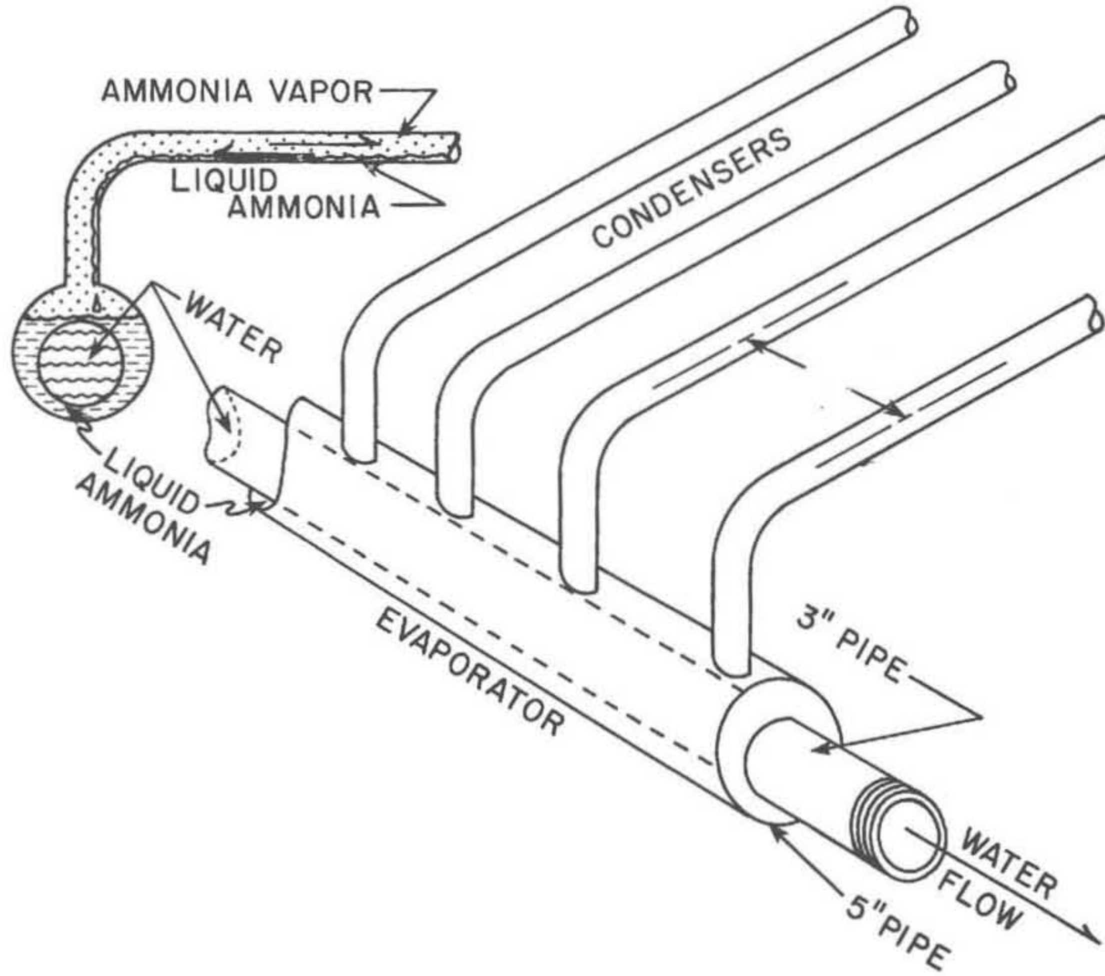
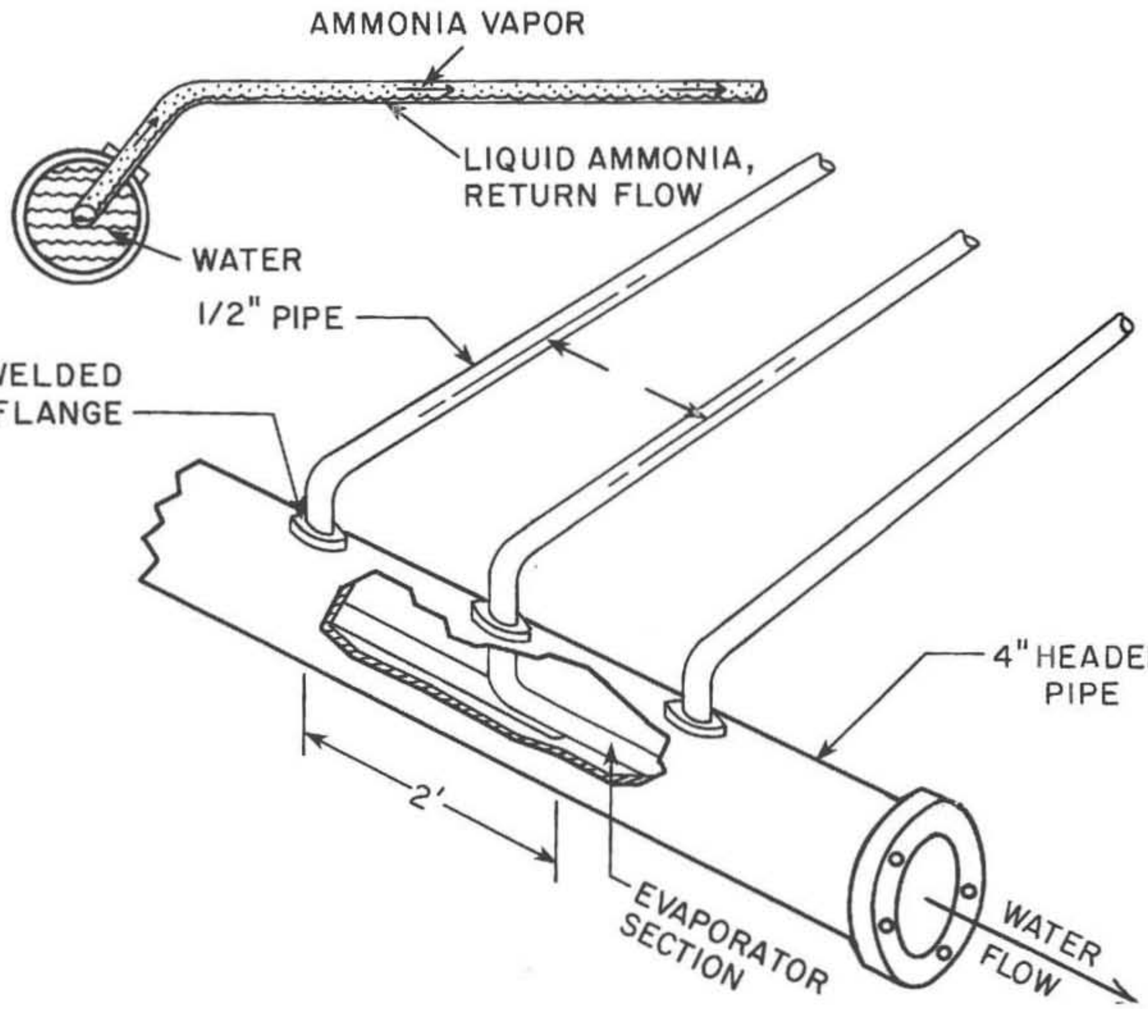


FIGURE 3

Submersed Heat Pipe Heat Exchanger



3. The coefficient of expansion of steel is very close to that of concrete reducing the problem of stress caused by heating and cooling of the concrete bridge deck.
4. Steel is unaffected by the presence of pure ammonia.
5. Although corrosion can take place where water contacts the steel, it can be reasonably controlled with a protective coating.
6. Steel pipes have the potential of substituting for some reinforcement of the concrete.

Fabrication of heat pipes is critical. First the system must be made leak free because loss of the working fluid will render the system useless. Even the smallest leak would deplete the working fluid in a few years of operation. This mandates the use of welded connections rather than threaded. Next cleaning of the inside is important because a dirty surface will inhibit condensation and vaporization which will reduce the effectiveness of the system. Some contaminates may even react with the ammonia and produce gases which can inhibit complete circulation of the working fluid. Finally, it is necessary that the system be completely evacuated of all other gases before the pure ammonia is introduced. Vacuum levels of less than 10^{-6} torr for 24 hours are necessary.

C. Exchanger Performance

The goal in design of the heat transfer system is to come up with a system that is efficient enough to provide the power required at the surface with the water temperature available. The temperature of the water source is a key factor in the cost and feasibility of this type of heating system. As the source water temperature approaches freezing, efficiency of the heat transfer system must get better and better. Near 40 deg. F (4 deg. C), costs of a sufficiently efficient heat transfer system skyrocket.

Several design parameters control the conductance (performance of these heat pipe heat exchangers). First, reducing the thickness of concrete over the condenser pipes in the bridge deck will significantly improve performance. Since this is a no-cost change, pipe coverage should be minimized. It was assumed for this analysis that the absolute minimum coverage is to be 1.1 inches. This corresponds to a depth of 2 inches from the center of 1/2" NPT pipe. Any less cover and cracking and subsequent corrosion and spalling would occur.

The primary design method of controlling performance of the heat exchangers is to vary the length and spacing of the condenser pipes. By reducing the spacing between condenser pipes, the temperature loss from the working fluid to the surface of the deck can be reduced. Similarly, by reducing the length of the condenser pipe, the area serviced by each unit length of evaporator section will be reduced. This will reduce the temperature drop between the working fluid and the water. Figure 4 is a graph of heat exchanger conductance for various lengths and spacing of the condenser pipes. Note that for short condenser pipes the temperature drop in the evaporator section is small, and the condenser pipe spacing controls the performance. For long condenser pipes the temperature drop in the evaporator section becomes important, and decreasing spacing becomes an ineffective way to improve performance.

In order to determine the power (heat flux) available at the surface near freezing, the conductance must be multiplied by the temperature drop between the water and the surface. It should be assumed that the surface of the deck must be kept at or above 34 deg. F (1 deg. C) to effectively melt snow. Additionally the water temperature should be that of the discharge. High flow rates should be employed to keep the discharge temperature close to the inlet temperature especially when the available temperature difference is small. Based on the water giving up 25% of its temperature difference as it passes through the system and on the criteria of delivering 9.5 w/sq.ft. (100 w/sq. m.*) at a surface at 34 deg. F (1 deg. C), the water temperature scale on the left of Figure 4 was created. (See Appendix B for heat flux available from a water source.) This is a scale of the water temperature required to provide 100 w/sq. m. of heat flux to the deck based on the corresponding system conductance. Note that 41 deg. F (5 deg. C) water is the limit of feasibility for this system. If significant melting of snow is desired, requiring 19 to 28 w/sq. ft. (200 to 300 w/sq. m.) the available temperature would have to be significantly higher.

D. Cost of Heat Exchangers

Cost of these heat exchanger systems is also an important part of design considerations. The following cost estimates are based on a September 28, 1981 letter from SETA Corporation. Although this letter only prices four configurations, costs for other configurations can be inferred from these four. This letter and the computations for other configurations are in Appendix A. Figure 5 is a graph of cost versus configuration of condenser pipes. These costs are based on material prices in September of 1981. These costs are very sensitive to steel prices and would change significantly if steel prices change. Also costs are expected to go down as the technology grows and fabrication techniques are improved such as cleaning, leak testing, and epoxy coating techniques. Recent conversations with SETA Corporation executives indicate some cost reductions have already been achieved.

*Note that 9.5 w/sq. ft. (100 w/sq. m.) is slightly more heat than 60 deg. F (15 deg. C) earth could provide to a freezing surface of a roadway. If 100 w/sq. m. is delivered, control of preferential icing is assured.

FIGURE 4

HEAT CONDUCTANCE VERSUS CONDENSER
PIPE CONFIGURATION

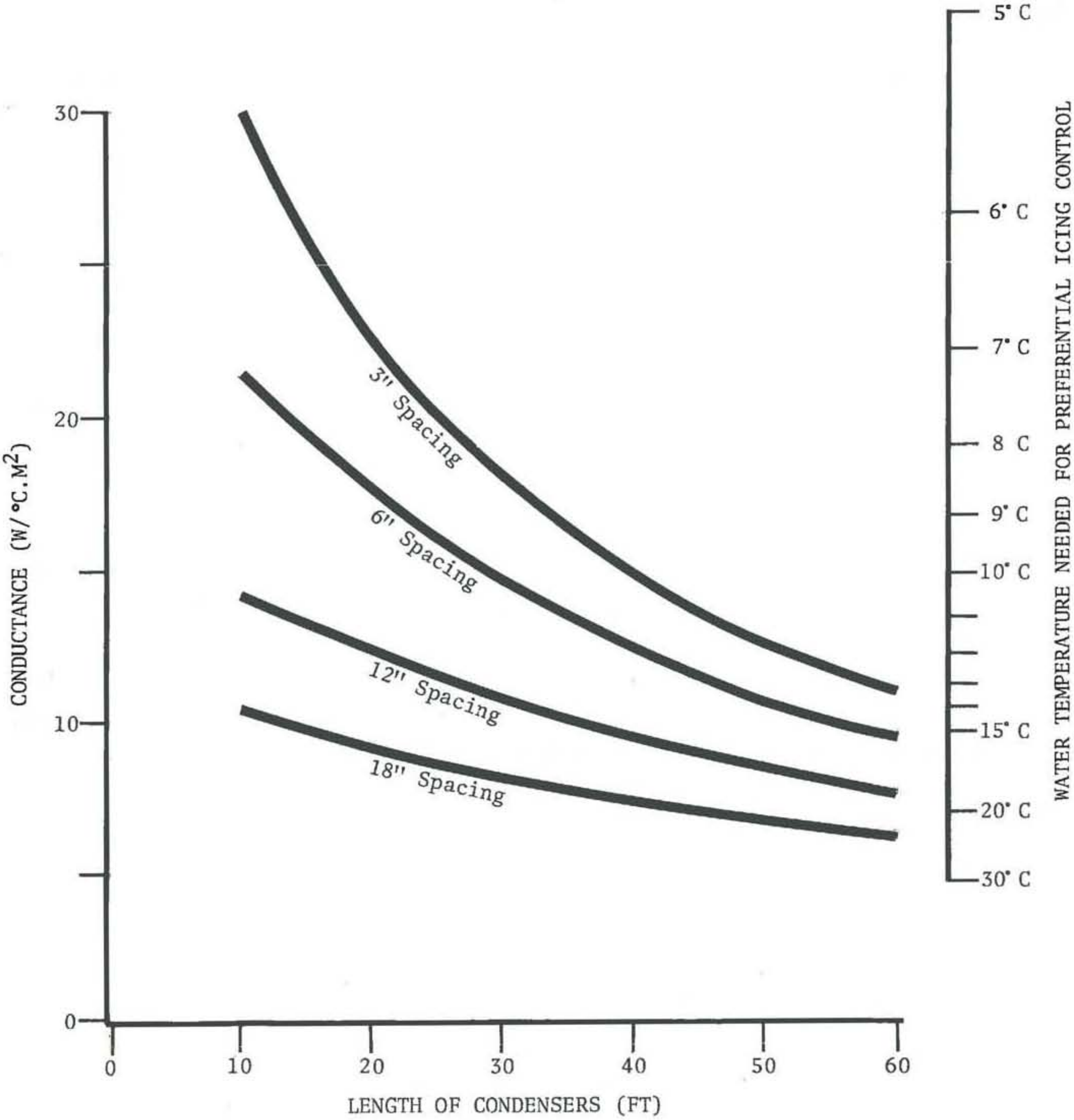
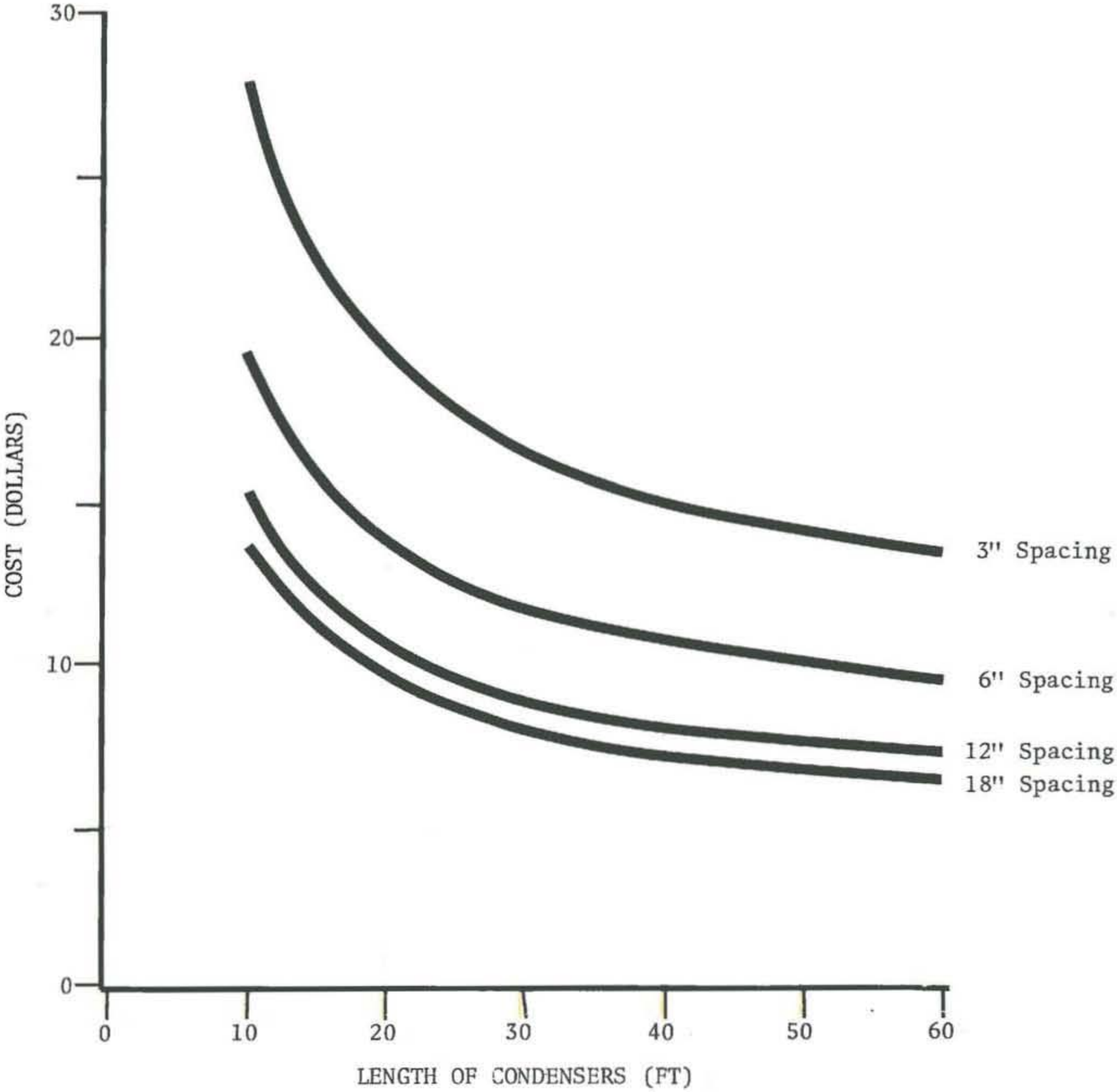


FIGURE 5

COST VERSUS CONDENSER
PIPE CONFIGURATION



IV. HEATING WITH GROUND WATER

Two types of ground water are available in many areas of Colorado. The first type will be referred to as shallow ground water. This shallow ground water is from a well less than 300 ft. (100 m.) deep, and its temperature is in the 50 deg. F (10 deg. C) range. The second type of ground water is from deep aquifers. A well of 1300 ft. (400 m.) or greater must be drilled in order to tap this source. Temperature of this water is much more impressive being around 75 to 85 deg. F (25-30 deg. C).

The amount of shallow ground water which can be extracted from a well is usually limited by the permeability of the surrounding soil and rock. Permeabilities and, therefore, volumes are usually too low to be useful for roadway deicing. In areas where both highly permeable materials and water are present such as deep gravel deposits of river beds, substantial volumes of water can be pumped from a single well. These volumes can be over 160 gal/min (10 l/s) out of a single well. Water volumes in this range can be sufficient to control icing of 6000 sq. ft. (560 sq. m.) of bridge. A typical deep well into an aquifer can also produce 160 gal/min (10 l/s) which, because of the higher temperatures, can control icing on 10,000 sq. ft. (930 sq. m.) of bridge.

A typical ground water heating system will be composed of the following:

- 2 wells
- 1 well pump
- Piping between well and structure
- Heat pipe heat exchangers

Water must be pumped out of one well, circulated through the heat pipe heat exchanger mounted on the structure, and returned to the second well (see Figure 6). By returning the water back to the ground, no water resources would be consumed and, therefore, no water rights would be required. Major cost items for such a system would be as follows:

1. Drilling and casing wells
2. Pumping system
3. Interconnecting piping system
4. Heat pipe heat exchangers
5. Maintenance (oiling pump, repair, turning system on and off at beginning and ending of season)
6. Electrical cost

A cost and feasibility analysis for heating the Alamo Street bridge in Littleton, Colorado with well water will be presented in Section VII of this report.

V. HEATING WITH DOMESTIC OR SANITARY SEWER WATER

Utility water lines are usually numerous in a populated area and tend to travel along existing streets. For a major pipe line servicing a large populated area, flow rates can be sufficient to heat a major bridge even during low demand periods. Domestic water supplies derived from surface water generally enter the pipe in the winter at very cold temperatures ~34 deg. F (1 deg. C), too cold to be used for deicing. However, heat from the earth raises this temperature as the water flows underground. If sufficient distance is present from the treatment plant, the water temperature can be raised to a point where it is usable.

A more promising source of heat is from sanitary sewer water. Sewer water enters the piping system at a much higher temperature, and the surrounding earth tends to maintain that temperature. Temperatures similar to earth temperatures can be expected (50 deg. F) (10 deg. C).

Both water sources are plagued by the problem of dramatic changes in flow rates from peak periods to low demand periods. Water flow rates during the minimum periods must be sufficient to supply desired heat to the bridge. Conversely, pipe capacity must be large enough to handle the peak demand flow. In addition, additional capacity is usually built into utility systems to allow for expected growth. For sanitary sewers the ratio between peak and minimum flow generally runs around 6 to 1 (see Reference 11). Typically the system is designed for twice the present peak period flow to allow for future growth. This translates into a capacity to minimum flow rate of 12 to 1. If a heating system requires 160 gal/min (10 l/s) as a minimum, a water line with a capacity of 1900 gal/min (120 l/s) must be tapped. This would usually require a 12 inch pipe (see Appendix C for calculations), i.e. a sewer pipe would have to be at least one foot diameter in order to expect it to carry sufficient volume during minimum periods to heat a bridge. The design concept would be to tap into this sewer line and pump sufficient volume of water out to provide the desired melting, typically 10 l/sec (160 gal/min). The water would be circulated along the bridge through heat exchangers and be returned to the sewer line down stream (see Figure 7). Any excess volume beyond that pumped would follow the normal pipe line. Assurances must be made that the volume in the sewer pipe does not drop below the pumping rate.

For sewer line sources which do not have sufficient minimum flows for adequate bridge heat, a storage tank can be provided (see Figure 8). If sufficient average flows are available, a storage tank would provide sufficient water during low flow periods. The tank would also have the added benefit of reducing peak demands on the sewage treatment facility.

For domestic water the ratio between design demand and minimum demand is much greater due to residential irrigation and the requirements for fire protection. In order to assure adequate flow during minimum demand periods supply pipe diameters of 2 - 3 feet must be tapped. The initial concept was to direct the entire water line through the heat pipe heat exchangers connected to the bridge. This would provide an effectively passive system because no pumping would be required. This concept was deemed unfeasible for the following three reasons:

1. Heat pipe heat exchanger manifolds would have to be over three feet in diameter.
2. Heat transfer efficiency between the water and the evaporator is substantially lower for larger pipes especially during periods of low flow (see Appendix D for analysis).
3. Because of the usually low temperature of domestic water sources, low efficiency in the heat transfer process cannot be tolerated.

In order to utilize the heat in the domestic water supplies a system similar to that for tapping sanitary sewers would be required (see Figure 8). The water must be pumped out of the pipe, line circulated through the heat pipe heat exchangers on the bridge, and returned to the water line down stream of where it is extracted.

In conclusion, domestic or sanitary sewer water can be used for controlling icing problems on bridge decks. Water can be pumped out of a pipe line circulated through heat pipe heat exchangers and returned. Sanitary sewer lines appear to be a better source because of higher temperatures available. Domestic water sources may not have sufficient temperatures for this purpose unless the bridge is a long distance from the water treatment plant, or the water is derived from wells.

FIGURE 6

Heating System Using Ground Water

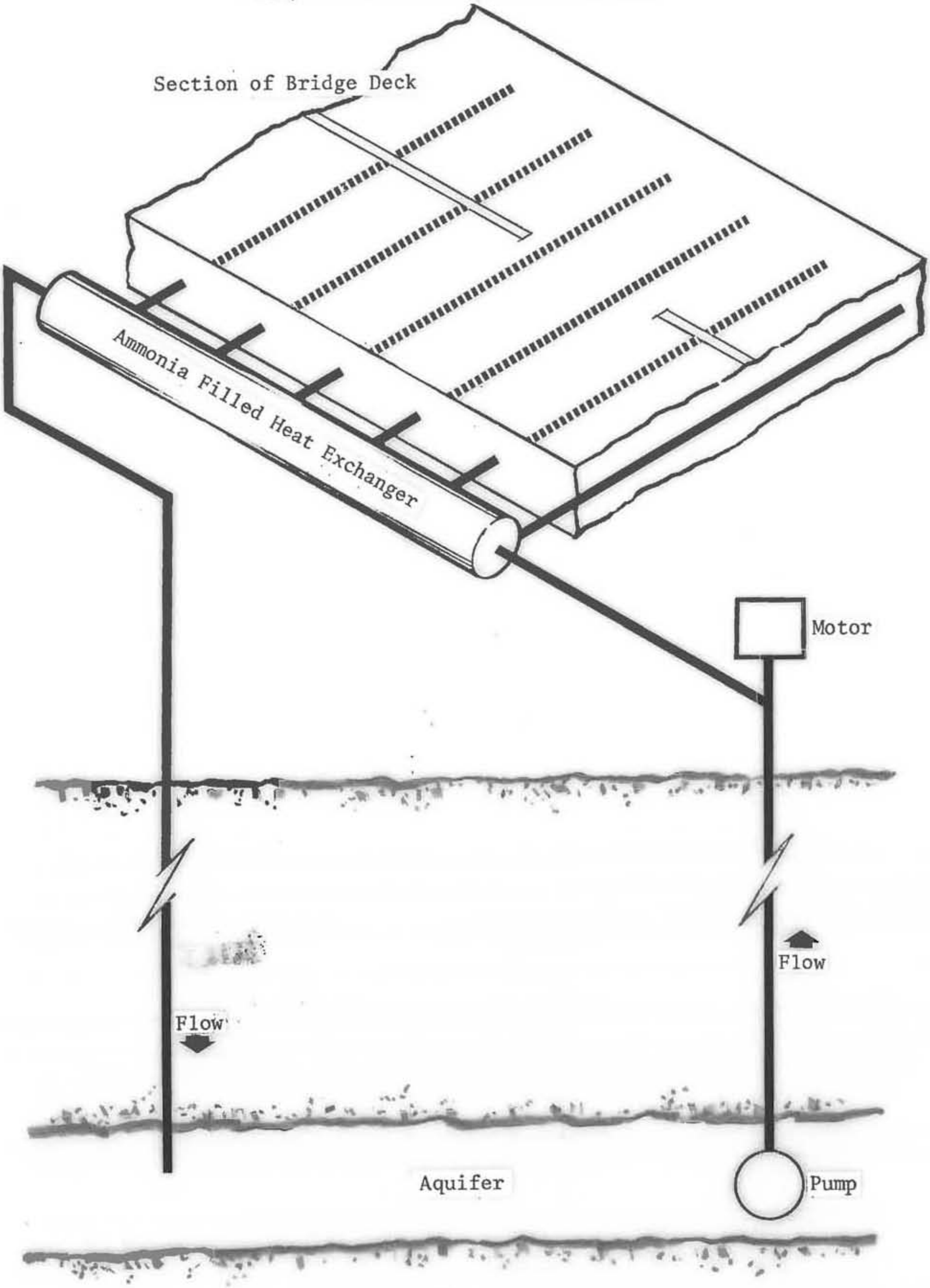


FIGURE 7

Heating System Using Sanitary Sewer Water

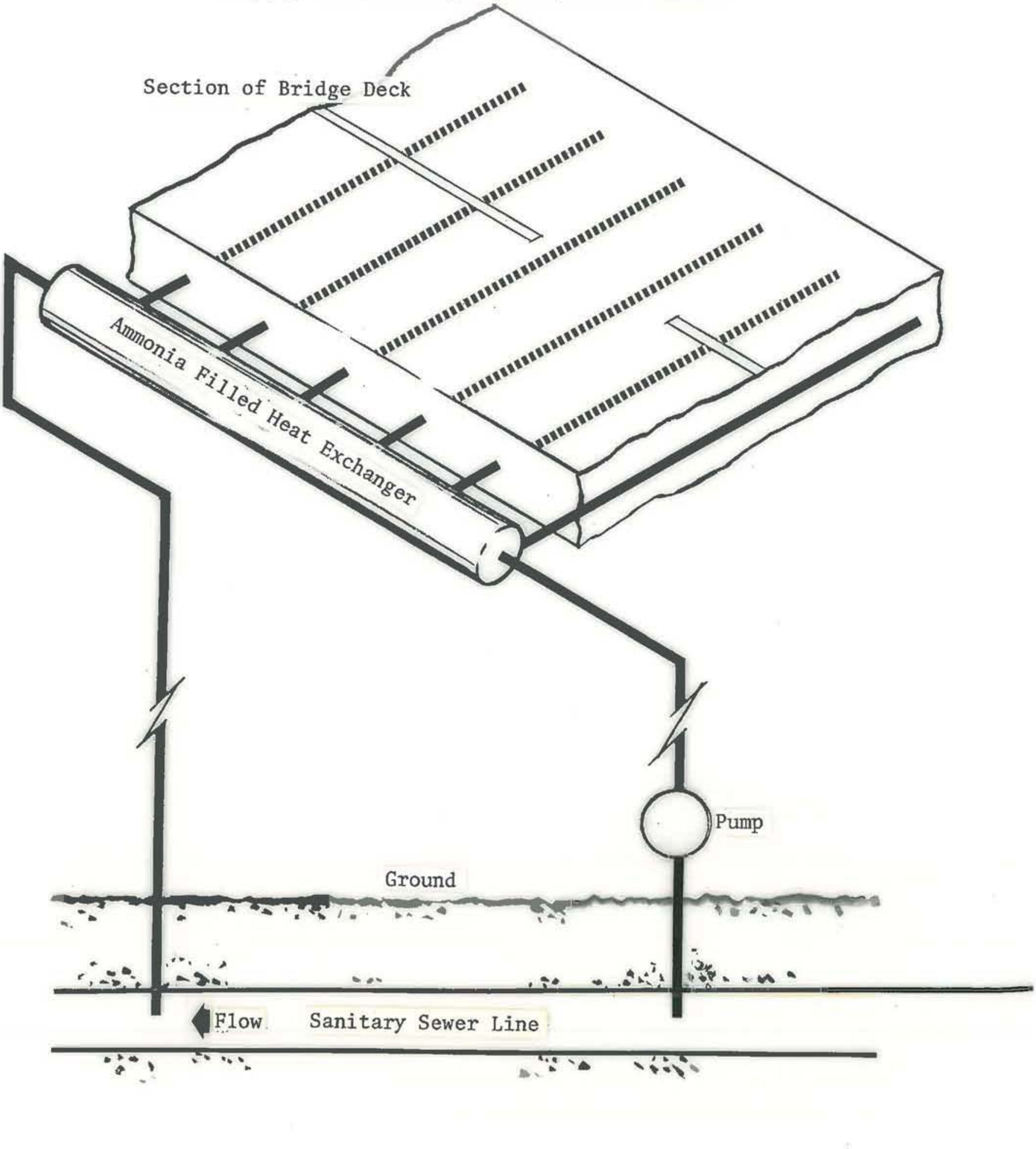
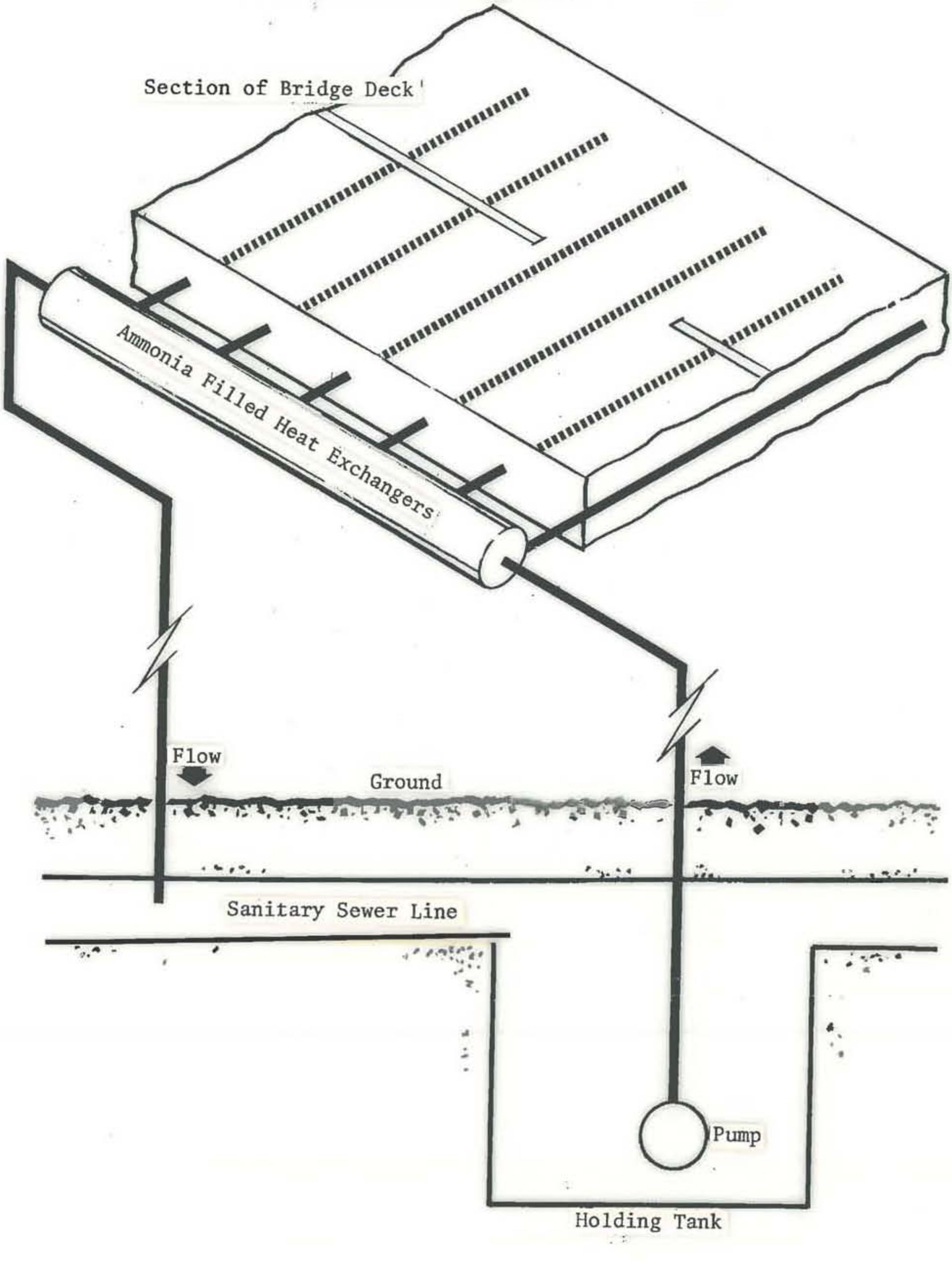


FIGURE 8

Heating System Using Sanitary Sewer Water with Holding Tank



VI. SOLAR HEATING

The use of sunlight to control icing on a bridge deck is a feasible method without consuming precious fossil fuels. Icing control is usually required when no sun is available; therefore, the sun's energy must be collected and stored until it is needed to heat the bridge deck. Two methods of using solar heat will be discussed. The first method will be based on collecting solar energy with commercial solar panels, and the second method will be based on using the bridge deck to collect solar energy.

A. Solar Heating Using Solar Panels

The first solar heating system to be considered will be composed of off-the-shelf solar collector panels, a large insulated water storage tank, and heat pipe heat exchangers (see Figure 9). The solar collectors will collect heat from the sun and transfer it to circulating water. The warm water will be exchanged for cooler water in a large insulated water tank. The water in the water tank will be circulated through the heat pipe heat exchangers on the structure as needed.

The system will require at least two electrical pumps, one to circulate water through the heat exchangers on the bridge and one to circulate the water through the solar collectors. The solar collectors will be designed to drain during the idle periods to avoid freeze-up of the water.

Several controls will be necessary to operate this system efficiently. One control should sense the temperature of the collector and the water storage and operate the solar collector circulating pump only when the collector temperature significantly exceeds the water storage temperature. This type of control is available off-the-shelf, and its operation is straightforward.

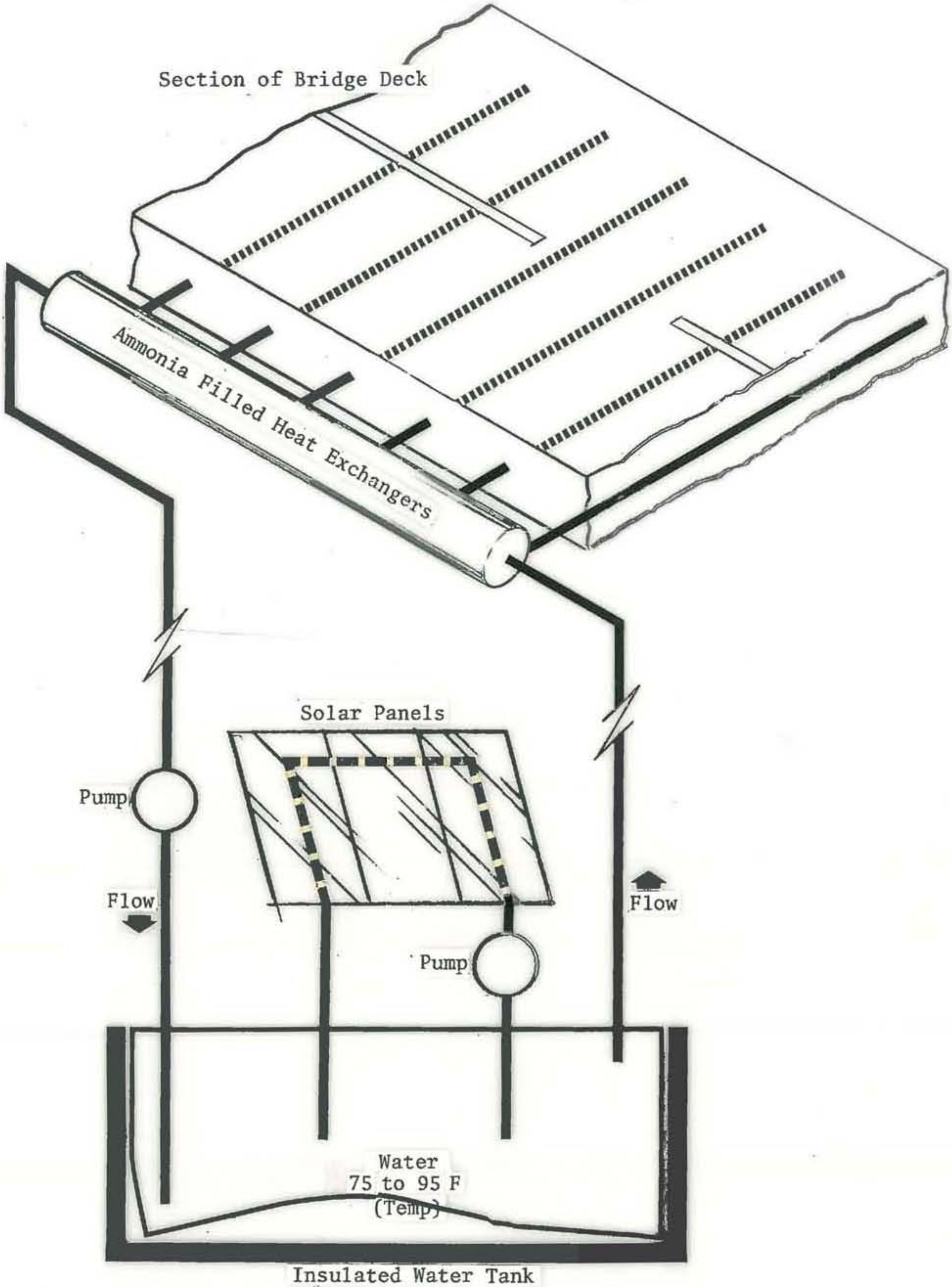
A second control is necessary to operate the pump which circulates the water through the bridge heat exchangers. The pump could be set to start whenever the deck is close to freezing and wet. However, turning the pump on at this time may be too late. If the deck drops below freezing in a dry state, ice will form as soon as snow or water falls on the deck. If the pump is turned on at this time, ice will remain on the surface for several hours until the system is able to bring the deck up above freezing again. To compound this problem, reliable detectors that detect all forms of water and ice are not available.

A second possibility is to turn the pump on whenever the deck approaches freezing. This will avoid the problem of anticipating a wet deck, but it means a lot of heat will be used to keep the deck warm when it is dry. These dry and cold conditions are typical along the Front Range in Colorado. It can be argued that during dry clear spells in the winter, ample heat will be collected and be lost through the walls of the tank even if it is not consumed to heat the deck. Also preferential icing usually occurs during the onset of the storm. If the system could not control icing during this part of the storm, the most hazardous bridge condition would still prevail. Based on this argument, the evaluation will be based on operating the heating system whenever the deck approaches freezing. This control can be accomplished with an off-the-shelf thermostat.

Computer program HEAT was developed to determine the heat required throughout the season to control icing (see Appendix E). The program uses NWS (National Weather Service) data (Reference 18) to compute heat losses

FIGURE 9

Heating System Using Solar Panels



and gains from a bridge deck surface. Based on this program, it would require 12600 BTU/sq. ft. (39.7 kwh/sq. m.) to keep the bridge deck up to 35 deg. F (1 deg. C) during all of December 1979 and January 1980. This analysis assumed that no more than 63 BTU/hr-sq. ft. (200 w/sq. m.) will be used in this attempt. During severe storms 63 BTU/hr-sq. ft. will not be enough power to maintain the surface above freezing, but during these times the adjacent roadways will also freeze up. The program does not consider the energy required to melt the snow. Based on average precipitation rates for December and January in Denver an additional 420 BTU/sq. ft. (1.3 kwh/sq. m.) will be required to melt the one inch of precipitation. This represents only 3% of the total requirement, and snow plows may remove part of the snow before it is melted. In order to be conservative, this additional 420 BTU/sq. ft. will, however, be considered in the design.

Systems for collecting solar energy have been researched extensively over the past ten years. Flat plate collectors are simple in design and can be used for systems requiring temperatures under 212 deg. F (100 deg. C). When delivery temperatures are below 100 deg. F (40 deg. C) a reasonably designed flat plate collector can be expected to convert approximately half of the solar radiation incident on it into heat.

For a horizontal surface in Denver, Colorado (Latitude 39 deg.) average solar radiation for December and January are 8822 and 10160 kj/sq. m.-day respectively (777 and 895 BTU/sq. ft.-day) (Reference 15). The amount of solar energy incident on a flat plate collector in the winter can be increased by a factor of 2.8 by tilting the panel to 55 deg. at a latitude of 40 deg. (see Appendix F for calculation). Based on this and a 50% efficiency of the collector, a collector tilted at 55 deg. should collect 12350 and 14230 kj/sq. m.-day (1088 and 1253 BTU/sq. ft.-day) in

December and January respectively. Based on Program HEAT computer output in Appendix E, 5084 BTU/sq. ft. would have been required in December. Therefore, a solar collector with 15% of the area of the bridge deck would be required. Similarly for January 7494 BTU/sq. ft. would be required. The heat could be delivered by a collector with 19% of the area of the bridge deck. Since January requires more collector area, sizing of the solar collectors should therefore be based on the losses and gains during January. An additional area of solar collector must be added to make up for loss from snow melting and from the circulating system and the storage tank.

Additional solar collector area may be added to allow for weather which is more severe than that modeled. If preferential icing control is the primary goal of bridge heating, additional capacity may not be necessary. More severe weather would reduce approach temperatures, and less performance of the heating system would be adequate to match the action of the approaches.

Based on the computer listing in Appendix E, a 5-day energy supply must be stored in order for the system to maintain icing control from January 27 through January 31 (longest time without significant solar input). This corresponds to 2367 BTU/sq. ft. (total losses from January 27-31). Based on Figures 4 and 5 a reasonably economical heat exchanger system can be provided if water temperature is above 59 deg. F (15 deg. C) while very little additional economy is achieved by using temperatures higher than 68 deg. F (20 deg. C). It follows that the water storage tank should be designed so minimum water temperature is between 59 to 68 deg. F (15 to 20 deg. C). Since flat plate solar collectors can efficiently heat water to 90 deg. F (32 deg. C), two alternatives are available. First, the cheapest heat exchanger design can be used in conjunction with a water tank sized to drop 20 deg. F when it gives up its design heat storage. Second, a slightly more expensive heat exchanger design can be used in conjunction with a water tank sized to drop 30 deg. F when it gives up its design heat storage. It is expected the savings realized by using the lowest efficiency heat exchanger would more than compensate for the extra cost of a 50% larger water tank; therefore, the design will be based on the larger tank.

The 2367 BTU/sq. ft. of storage can be achieved by dropping 14.3 gal/sq. ft. of water 20 deg. F, i.e. 14.3 gal. of water storage is required for every square foot of bridge deck (582 l/sq. m.). For a nominal 10,000 sq. ft. (930 sq. m.) bridge deck a 143,000 gal. (541,000 l) storage tank is required. This translated into a 36x36x15 ft. deep water tank with 4750 sq. ft. of insulated sides, based on an internal water temperature of 85 deg. F, a 4-inch thick layer of urathane insulation with a .025 BTU/hr-ft-deg. F thermal conductivity and an earth temperature of 50 deg. F. 300,000 BTU/day will be lost through the walls of the tank.* This represents 930 BTU loss for every square foot of bridge deck for a typical size bridge deck during January. Total January losses will be composed of this loss plus the heat to melt the precipitation plus the heat loss due to the exposure (Program HEAT). This will be 8630 BTU/sq. ft. With a solar panel collecting 1253 BTU/sq. ft.-day in January, panels amounting to 22% of the area of the bridge deck are required.

$$* \quad H = \frac{(4750 \text{ sq.ft.})\,(85\text{–}50 \text{ deg.F})\,(.025 \text{ BTU/hr-sq.ft.F})}{(.333 \text{ ft})} \quad X \quad 24 \text{ hr/day}$$

<u>In summary</u> -- for climates similar to Denver's, a solar collector surface area tilted at 55 deg. with the equivalent of 22% of the surface area of a bridge deck would be required to control preferential icing.

Additionally 14.3 gallons of thermal water storage would be required for every square foot of bridge deck (582 l/sq. m.).

B. Heating with solar energy collected by the bridge deck.

A system has been conceived which collects heat from the bridge deck during warm sunny days in winter and stores it for later use when needed to control icing. The feasibility of such a system will be examined here.

Program HEAT was primarily developed to examine the feasibility of using a bridge deck as a solar collector (see Appendix E). This program determines the amount of energy that can be collected by a surface and the amount of energy lost by a surface based on weather data and an assumed surface temperature. The program was first executed based on a surface temperature of 34 deg. F (1 deg. C). This corresponds to the amount of energy required to prevent the surface of the deck from freezing. For December 1979 and January 1980, it is 12576 BTU/sq. ft. In order for this type of system to be feasible, the deck must be able to collect at least this amount (12576 BTU/sq. ft.) when it is at a somewhat higher temperature. This higher temperature is necessary because of the thermal resistance of the heat transfer system. Based on Figure 4, the lowest feasible water temperature which can be used for icing control is 5.5 deg. C. The deck would have to be 4.5 deg. C higher than this in order for heat to flow into water storage. If we assume a 1 deg. C change in water temperature as it stores heat, the deck would have to collect the energy to store in the thermal storage when the surface was 11 deg. C (52 deg. F) or higher. Based on this 52 deg. F, Program HEAT was executed to find out how much energy could be collected. The energy only amounted to 4802 BTU/sq. ft., far short of the 12567 BTU/sq. ft. required. Based on this rough analysis it can be confidently concluded that a system based on the bridge deck being the solar collector is infeasible.

VII. HEATING WITH EARTH HEAT

Earth heat is actually a form of solar heating where the ground itself is the heat reservoir. Heat enters the earth during the summer when solar radiation and ambient temperatures are high and is stored in the thermal mass of the ground. Because the ground temperatures never get very high (50-60 deg. F), an efficient method is required to transfer this heat from the earth to the freezing bridge deck. Heat pipes can provide this thermal link between the earth and the bridge. By evaporating the working fluid in the earth and condensing it in the pipes in the bridge, high heat transfer rates over long distances can be accomplished with little temperature drop.

The most recent use of earth heat and heat pipes is in Laramie, Wyoming where a small bridge over Spring Creek is heated to prevent preferential icing (see Figure 10). One-hundred-foot long sections of 3-inch pipes act as the evaporator section of the system. Each pipe is placed in a hole drilled in the ground and grouted into place. Each evaporator pipe is manifolded to four condenser pipes cast into the bridge deck to form a continuous heat pipe. Others have used circulating liquid or contact conduction to transfer the heat from heat pipes in the ground to the heat pipes in the bridge. Wyoming's continuous heat pipe system has the advantage of less temperature drop but requires partial fabrication of heat pipes in the field. The dual heat pipe system as tested by Ferrara and Yenetchi (Reference 3) encounters the extra temperature drop between the two heat pipes but allows total fabrication in the factory. Because of the extreme cleaning requirements and the sensitivity of heat pipe performance to contamination and leaks, even partial fabrication of heat pipes in the field was considered infeasible by earlier researchers.

FIGURE 10

Earth Heat System at Larimie, WY.

Wyoming DOT and its contractors have shown that partial heat pipe fabrication in the field is possible. Monitoring of the performance of the system over the next few years will determine if undetected contamination or leaks deteriorate system performance. No problems are expected because the fabrication process went well and testing was thorough. Since feasibility of field fabrication of heat pipes has been demonstrated, a continuous heat pipe should be considered because of the improved performance over a dual system.

The major cost of such a system is the drilling and grouting of numerous holes in which to place the evaporators. Each square foot of bridge deck requires one to two feet of evaporator section in the ground (3 - 6 m/sq. m. Combined with the cost of the heat pipes, cost can be 40 to 50 $/sq. ft. The Wyoming bridge Heating cost and estimates made by Ferrara and Yenetchi (Reference 3) when adjusted for inflation are both in this range. Cost may become less as the technology develops.

Land adjacent to the bridge deck equivalent to one to two times the area of the bridge is required for the heat pipe field. Although no structure should be built on top of the heat pipe field, other uses are possible, such as a park or parking lot.

Heat delivered from the earth tends to be less uniform over time than the other systems discussed. Upon initial onset of a storm early in the season, power delivered to the roadway surface is maximum. As the storm continues, power delivery drops due to depression of the earth temperature near the heat pipes. Upon completion of the storm and natural warming of the roadway surface, earth temperatures near the heat pipes begin to recover. If sufficient time and warm weather persist before the next storm, almost maximum power will be available again. As the winter progresses, temperatures in the heat pipe field drop, and toward the end of the season power delivery is a minimum. Summer radiation and warm air will then rejuvenate the earth for the next winter.

When preferential icing control is the main goal, this type of performance is not necessarily bad. Preferential icing is most serious early in the winter and early during the onset of a storm. This is because approach temperatures tend to be highest at those times. This is precisely the time the most power is delivered to the bridge deck. Because of the pattern of power delivery earth heat is ideal for controlling preferential icing of bridge decks.

VIII. ALTERNATIVE ANALYSIS FOR TWO PROPOSED STRUCTURES IN LITTLETON, COLORADO

Two structures are planned in Littleton, Colorado (10 miles south of Denver) which are good candidates for bridge deicing (see Figure 11). The structures are planned to provide an overpass over two heavily trafficked railroad tracks for one-way couplets in downtown Littleton. The structures will have a significant grade with traffic signals at each end. Icing of these structures could create a significant hazard. The surface of the bridge planned for Main Street (westbound one-way) will be somewhat hidden from view of approaching motorists due to the vertical curve. Preferential icing (icing of bridge before approaches) would create an unusual hazard because the motorist will not see the surface of the bridge until the last minute. The problem is compounded by a 7% down grade (see Reference 20).

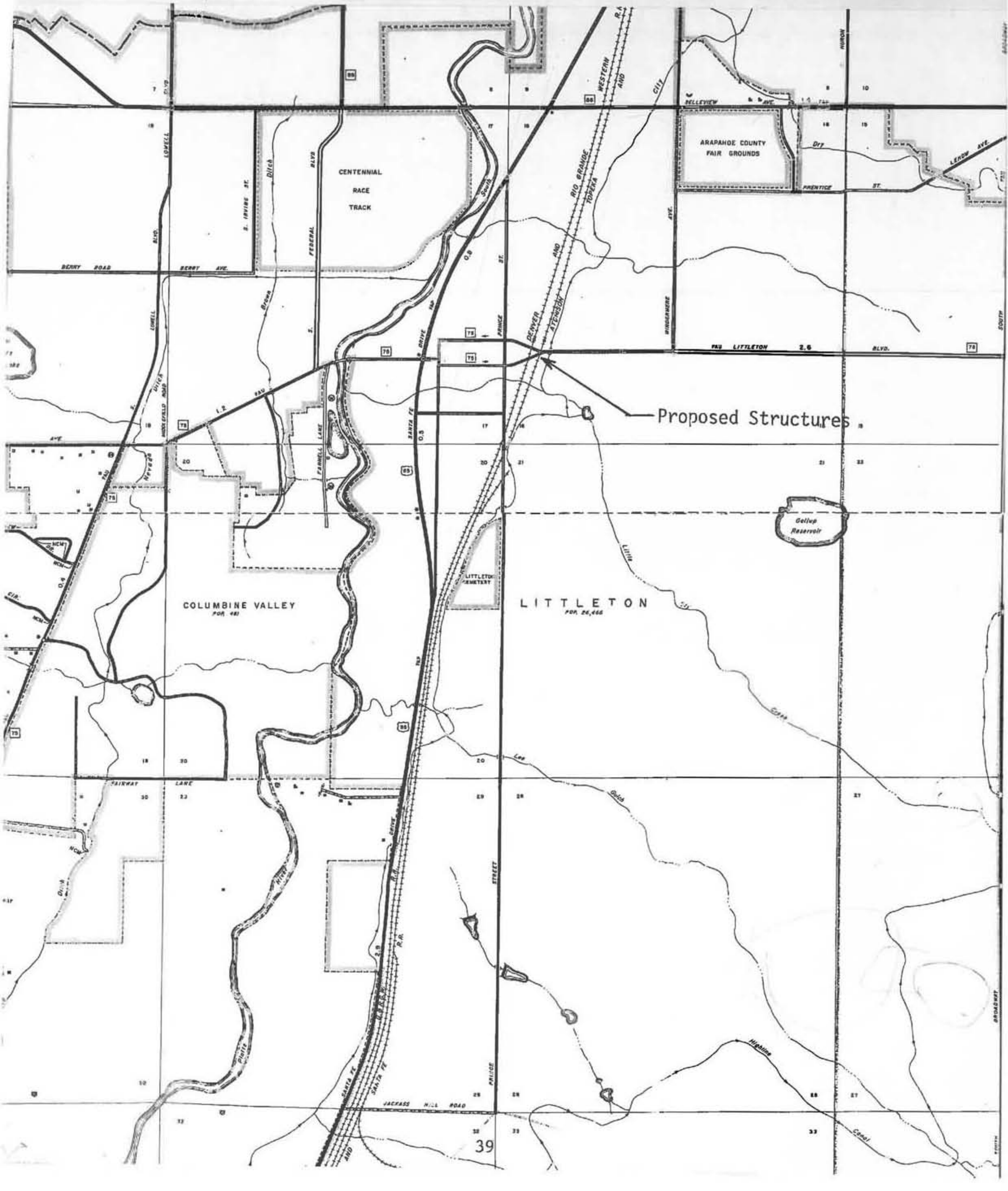
In order to demonstrate a procedure for considering alternate deicing systems for a structure, icing control methodology will be evaluated for these two structures. The Alamo Street structure is planned to be 36x178 feet long while the Main Street structure is 52x108 feet long for a total of 12,000 sq. ft. (1120 sq. m.) of surface to heat.

A. Heating With Ground Water.

Two possible ground water sources have been identified. The first source is the Larimie/Fox Hill aquifer which in this area is approximately 1500 feet (450 m) below the surface. Based on other wells in this area, temperature of this water is expected to be 75 deg. F (24 deg. C) (see Reference 21). The second source is the deep water bearing gravels of the

FIGURE 11

LOCATION MAP FOR LITTLETON BRIDGES



Platte River which is approximately 1/2 mile (800 m) from the structure and 50 feet (15 m) below the surface. Temperature of this water is 52 deg. F (11 deg. C). For either source it is expected that sufficient water can be derived from a single well to heat all 12,000 sq. ft. of both structures.

1. Deep ground water heat. The system based on deep aquifer water will require two 1500-foot (450 m) wells, one well to extract the water and a second well to reintroduce it back into the formation. The water will be circulated through heat pipe heat exchangers on the bridge and returned to the ground. These heat exchangers for the Main Street bridge will have 54-foot long condenser fingers spaced 18 inches apart. Two sets of exchangers can be mounted transverse to the traffic flow. The evaporator sections of the first set will be located near the lower abutment, and its fingers will run through the deck up grade to midway along the bridge. The second set will be mounted across the midsection of the bridge, and its condenser fingers will run in the surface of the deck up to the upper abutment. For the Alamo Street bridge three sets of exchangers can be mounted similarly to Main Street with 59-foot fingers spaced 18 inches apart. Cost of these heat exchanger configurations will be $7.00/sq. ft. (see Figure 5). According to Figure 4 this configuration will function adequately provided the available water is bove 72 deg. F (22 deg. C). Therefore, the expected 75 deg. water will be sufficient.

The assumption of Figure 4 is that 25% of the temperature difference is given up as the water passes through the system. This corresponds to 9.5 deg. F [(72-34 deg. F)x.25]. Since the water is actually 75 deg. F, an additional 3 deg. F drop is allowed for a total of 12.5 deg. F. Based on delivering 32 BTU/hr-sq. ft. (100 w/sq. m.) to 12,000 sq. ft. of bridge deck, the required flow rate is given as follows:

$$Q = \frac{(32\ \text{BTU/hr-sq.ft})\ (12{,}000\ \text{sq.ft})}{(1.0\ \text{BTU/15 deg F})\ (8.3\ \text{gal/lb})\ (60\ \text{min/hr})\ (12.5\ \text{deg F})}$$

$$Q = 62\ \text{gal/min.}$$

The power to pump this quantity of water through a head of 1500 feet with the overall efficiency of the pump and motor being 0.5 is computed as follows:

$$P = \frac{(1500\ \text{ft})\ (62\ \text{gal/min})\ (8.3\ \text{lb/gal})}{(60\ \text{sec/min})\ (\ .5)} \quad \frac{1\ \text{kw}}{738\ \text{ft-lb/sec.}}$$

$$P = 35\ \text{kw.}$$

Based on the Public Service Company (PSCo.) rate schedule for 1981, commercial power electrical cost to operate this pump for 2000 hours per year will be as follows:

Base annual service charge	$ 144
Demand charge for 35kw for 6 months	1,804
Energy charge for 70Mwh	1,166
Fuel cost adjustment 70Mwh assumed rate of $.007/kwh	490
Total Annual Cost	$ 3,604

The following is a cost summary for this system:

Quantity	Item	Source	Unit Cost	Cost
12,000 sq.ft.	2" polyurethane insulation	Ref.16	$ .87	$ 10,440
2	1500 ft. deep water wells	Local driller	90.000.00	180,000
2	50 H.P. pump (one replacement at 10 years)	Local driller	15,000.00	30,000
12,000 sq.ft.	Heat Exchangers	Fig. 5	7.00	84,000
12,000 sq.ft.	Heat exchanger installation	Fig. 5	1.00	12,000
1	Misc. plumbing & controls	Fig. 5		10,000
Net Capital Cost				326,440
20% Engineering & Contractor Profits				65,288
TOTAL CAPITAL COST				$391,728

Annual Maintenance Cost	$ 500	
Annual Electrical Cost	3,604	
Annual Total Operating Cost	4,104	
Operating cost for 20 years (See note, page 50)		55,775
TOTAL COST OF SYSTEM		$447,503
Unit Cost	$37.3 $/sq.ft	

2. Heating with Shallow Ground Water. Sources of shallow ground water in the area of the project were investigated. Because of the low permeability of the soil adjacent to the proposed structures, a single well producing a sufficient volume of water for heating is not possible. Water-bearing gravel beds of the Platte River were then explored. Two test holes were drilled in order to determine the temperature and volume of water available. No gravel beds were encountered at either hole. An existing well into these gravel beds was then investigated. This well was originally owned by the City of Littleton and was turned over to the Denver Water Board when it began supplying water to Littleton. The well has not been used for years but remains intact for a source of emergency water. The yield of this well was recorded as 1000 gal/min, and the water temperature measured during the winter of 1981 was 52 deg. F (11 deg. C).

This design will be based on a new well in this same area with 52 deg. F (11 deg. C) water temperature. There is a possibility of using this existing well, but costs to rejuvenate may approach constructing a new well. Because this water is considered part of the Platte, used water can be dumped into the storm sewer which will channel it back to the river. This is still considered a non-consumptive use, and no water rights are required.

The heat exchanger configuration for this system will be four rows with 27-foot-long fingers spaced at 6 inches for the Main Street Bridge. Six rows with 30-foot-long fingers will be used for the Alamo Street bridge. Based on Figures 4 and 5, this configuration costs $11.50/sq. ft. and will perform properly provided the water temperature is above 50 deg. F (10 deg. C). Since Figure 4 assumes 25% of the water temperature difference is lost through the loop, and since we have a 2 deg. F addition above 50 deg. F, 6 deg. F drop can be used to determine the flow rate as follows:

$$Q = \frac{(32\ \text{BTU/hr-sq.ft})\ (12{,}000\ \text{sq.ft})}{(1\ \text{BTU/lb F})\ (60\ \text{min/hr})\ (6\ \text{deg F})\ (8.3\ \text{lb/gal})}$$

$$Q = 129\ \text{gal/min.}$$

This 129 gal/min must be pumped through a head loss of 150 ft. (50 ft. of well and 100 ft. of friction loss and elevation change to bridge). Based on an overall efficiency of .4, the power required is given as follows:

$$P = \frac{(129\ \text{gal/min})\ (150\ \text{ft})\ (8.3\ \text{lb/gal})}{(60\ \text{sec/min})\ (.4)} \quad \frac{1\ \text{kw}}{7.38\ \text{ft-lb/sec}}$$

$$P = 9.1\ \text{kw}$$

Based on PSCo's 1981 rate structure, annual electrical cost to operate this pump for 2000 hours will be as follows:

Base Annual Service Charge	$ 144
Demand Charge for 9.1 kw for 6 months	469
Energy Charge for 18.2Mwh	303
Fuel Cost Adjustment for 18.2Mwh	127
Annual Electrical Cost	$1,043

Cost of major items are summarized below:

Quantity	Item	Source	Unit Cost	Cost
12,000 sq.ft.	2-inch polyurethane insulation	Ref.16	.87	$ 10,440
1	50 ft. well	Local driller		3,000
2*	Pumps	Ref.16	2,404	4,808
12,000 sq.ft.	Heat Exchangers	Fig. 5	11.5	138,000

3000 ft.	8" insulated water pipe	Local Public Works	42.00	126,000
1	Misc. Plumbing & controls			10,000

Net Capital Cost		$ 292,248
20% Engineering & Profit		58,450
TOTAL CAPITAL COST		$ 350,698
Annual Maintenance Cost	$ 500	
Annual Electrical Cost	1,043	
Total Annual Operating Cost	1,543	
Operating cost for 20 years (See note, page 50)		20,970
Total Cost of Heating System		$ 371,668
Unit Cost	31.0 $/sq.ft.	

It is interesting to note that almost $11/sq. ft. of this cost is due to the distance the bridge is away from the water. For the case when the water source is adjacent to the bridge, cost could be $20/sq. ft. For a bridge over a major river, this situation is usually available.

B. Heating With Domestic or Sanitary Sewer Water

Domestic Water Heating. There is one 30-inch domestic water line which crosses under the railroad tracks near where the construction will take place. Because the railroad tracks are to be depressed in this area, this pipe line will have to be relocated. This initially appeared to be an ideal situation for a heat source. As discussed in Section IV, sufficient water could be diverted through heat exchangers on the bridge decks to control preferential icing.

Temperature of this water was measured during the 1981-82 winter to determine the feasibility of using this water. The temperature of the water at an access point a few blocks from the proposed structure was 39 deg. F (4 deg. C). Based on Figure 4, this temperature is to cold to be a feasible heat source.

Sanitary Sewer Water Heating. One 8-inch sewer line passes near these structures. Since insufficient flow is available during the minimum demand period to sustain deicing control, a holding tank must be utilized. This tank will store water during peak demand periods to be used during minimum usage time. Temperature of this would vary, but it probably would never drop below the temperature of the surrounding earth of 52 deg. F (11 deg. C). The system will therefore be designed based on 52 deg. F water. Because the water temperatures are the same, the heat pipe configuration will be the same as that proposed for the shallow ground water case. For Main Street four rows with 27-foot-long fingers spaced at six inches will be used, and six rows with 30-foot-long fingers will be used for the Alamo structure. Just as in the shallow ground water case, 129 gal/min of flow will be required. This flow, however, need only be pumped through a 50-foot head, so the power required is computed as follows:

$$P = \frac{(129\ \text{gal/min})\ (50\ \text{ft})\ (8.3\ \text{lb/gal})}{(60\ \text{sec/min})\ (.4)} \quad \frac{1\ \text{kw}}{7.38\ \text{ft-lb/sec}}$$

$$P = 3.0\ \text{kw}$$

Based on PSCo's 1981 rate structure, annual electrical cost to operate this pump for 2000 hours will be as follows:

Base Annual Service Charge	$144
Demand Charge (3.0 kw for 6 months)	155
Energy Charge (6 Mwh)	100
Fuel Cost Adjustment	42
Annual Electrical Cost	$442

Cost of major items for this system are as follows:

Quantity	Item	Source	Unit Cost	Cost
12,000 sq.ft.	2" polyurethane	Ref.16	.87	$ 10,440
2	Pumps	Ref.16	1319	2,638
12,000 sq.ft.	Heat Exchanger	Fig. 5	165	138,000
1	90,000 gallon holding tank (used cost of ten 10,000 gallon tanks)	Ref.16		64,854
1	Misc. Plumbing & Controls			10,000
	Net Capital Cost			$225,932
	20% Engineering & Profit			45,146
	Total Capital Cost			$271,118

Annual Maintenance Cost	$	500	
Annual Electrical Cost		442	
Total Annual Operating Cost	$	942	
Operating cost for 20 years (See note, page 50)			12,802
Total Cost			$283,920

Unit Cost $23.7/sq.ft.

It is interesting to note that without the holding tank cost the unit cost would be $19/sq.ft. This could be the situation if a large sewer line were available.

D. Heating With Solar Energy.

Solar energy can be used to provide icing control on these Littleton bridges. In addition to cost there are other considerations for using solar energy. First, sufficient area must be available adjacent to structures to locate the water storage tank and solar collector panels. Next, solar collectors may be subject to vandalism; and finally, the massive array of solar panels may be considered unacceptable visual pollution.

A system for heating these two bridge decks with solar energy would consist of heat pipe exchangers, water tank thermal storage, flat plate solar collectors, one pump to circulate water through heat exchanger, one pump to circulate water through collectors, piping to interconnect everything, and a fence around the collector field. The heat exchanger configuration will be two rows of heat exchangers with 54-foot fingers spaced 18 inches apart for the Main Street structure and five rows of heat exchangers with 59-foot fingers spaced 18 inches apart for the Alamo bridge. Cost according to Figure 5 is $7.00/sq. ft. According to Figure 4 a minimum of 72 deg. F (22 deg. C) water must be available in order for this configuration to perform properly. If the temperature is only allowed to drop 9.5 deg. F (5 deg. C) as it passes through the heat exchanger while delivering 31 BTU/sq.ft.-hr, the required flow rate is given as follows:

$$Q = \frac{(31\ \text{BTU/sq.ft-hr})\ (12{,}000\ \text{sq.ft})}{(1\ \text{BTU/lb deg. F})\ (60\ \text{min/hr})\ (9.5\ \text{deg. F})\ 8.3\ \text{lb/gal}}$$

$$Q = 79\ \text{gal/min}$$

The power to pump this volume through a head of 50 feet is given as follows:

$$P = \frac{(79\ \text{gal/min})\ (50\ \text{ft})\ (8.3\ \text{lb/gal})}{(60\ \text{sec/min})\ (.35)} \frac{1\ \text{kw}}{738\ \text{ft-lb/sec}}$$

$$P = 2\ \text{kw}$$

Because the heat exchangers need 72 deg. F (22 deg. C) for proper performance, that temperature must be maintained in the water storage tank. Allowing 20 deg. F (9 deg. C) drop in water tank temperature during heat transfer, maximum temperature of water should be 92 deg. F (33 deg. C). As discussed in Section V 14.3 gal. of water storage is required for every square foot of bridge deck, or a 172,000 gal. storage tank is required. A tank 40x40 15 feet deep would provide this capacity. The tank will be composed of one- foot-thick reinforced concrete wall and floor with the ceiling made of ten 8x20-foot twin Ts bearing on the outside walls and a center wall.

The collector surface area must be 22% of the bridge deck area or 2640 sq. ft. This can be achieved with 110 3x8-foot flat plate collectors. Water in the storage tank will be circulated directly through the collectors with a 100 gal/min pump pumping into a 4" PVC insulated pipe routed through the collection field. One-half-inch PVC pipe will be taped off for each collector, and a metering system on each collector will be used to regulate the flow. Plumbing should be arranged to drain freely when the pump is not operating. This will prevent freeze-up of the collectors at night.

The panels will be mounted at a 55-degree angle and bolted to a series of strip footers 1x1 feet with length as required. Rocks will be placed between panels to control vegetation in the area. The entire area will be surrounded by a six-foot chain link fence.

The power to operate the 100 gal/min collector pump at a 50-foot head is computed as follows:

$$P = \frac{(100\ \text{gal/min})\ (50\ \text{ft})\ (8.3\ \text{lb/gal})}{(60\ \text{sec/min})\ (.4)} \quad \frac{1\ \text{kw}}{738\ \text{ft-lb/sec}}$$

$$P = 2.3\ \text{kw}$$

Assuming the collector pump will operate for 1000 hours per year and the bridge pump will operate for 2000 hours per year, total annual energy use will be 6300 kwh with a peak monthly demand of 4.3 kw. Based on PSCo's rate schedule, annual electrical cost will be $515.

The following is a list of major cost items for the solar bridge heating system.

Quantity	Item	Source	Unit Cost	Cost
12,000 sq.ft.	2" thick insulation	Ref 16	.87	$ 10,440
12,000 sq.ft.	Heat Exchangers	Fig. 5	7.00	84,000
2640 sq.ft.	Solar Collectors	Local Supplier	14.00	36,960
860 cu.yd.	Excavation	Ref.22	2.90	2,494
170 cu.yd.	Concrete	Ref.22	170.00	23,460
10	8x20 ft. Twin Ts	Ref.22	2000.00	20,000
445 sq.yd.	Waterproof Membrane	Ref.22	6.90	3,071
5600 sq.ft.	4" Insulation	Ref.16	1.74	9,744
360 ft	6-ft. Chain Link Fence	Ref.22	6.30	2,268
8100 sq.ft.	4" Agregate Base Coarse (175 tons)	Ref.22	7.57/ton	1,325
25 cu.yd.	672 ft. Strip Footer 1x1 ft.	Ref.22	138.00	3,450
2640 sq.ft.	Mounting Panels		4.00	10,560
1500 ft.	Insulation for 4" PVC	Ref.16	7.92	11,880
4	100 gal/min pumps	Ref.16	1100.00	4,400
1	Misc Plumbing & Controls			10,000
Net Capital Cost				$244,117
20% Engineering & Profit				48,823
TOTAL CAPITAL COST				$292,940
Annual Maintenance Cost		$ 500		
Annual Electrical Cost		515		
Total Annual Operating Cost		1,015		
Operating Cost for 20 years				$ 13,794
TOTAL COST				$306,734
	Unit Cost	$25.6/sq.ft.		

In addition to the hardware and operating cost, over 8000 sq. ft. of land with good solar exposure is required.

E. Heating With Earth Heat.

An earth heat system will be based on continuous heat pipes. The condenser ends will be cast into the concrete bridge deck while the evaporator ends will be buried in an adjacent field. The system will require a collection field at least as large as the area of the bridge deck with numerous wells drilled. Based on the average earth temperature of 52 deg. F, a system with 1/2" heat pipes spaced at 6-inch centers and one foot of evaporator pipe for every one square foot of bridge should provide adequate heat for preferential icing control. For every square foot of bridge deck this system design requires:

2 feet of 1/2-inch pipe in deck
1 foot of 3-inch pipe
1 foot of drilled and grouted well
1 foot of 1 inch insulated connecting pipe

Cost estimate of this system based on a unit area of bridge deck is estimated as follows:

Quantity	Item	Price Source	Unit Cost	Cost
1 ft.	3" black iron pipe	Ref.16	6.47	$ 6.47
1 ft.	3" black iron pipe welded & tested	Ref.16	13.97	13.97
2 ft.	1/2" steel pipe	Ref.16	2.86	5.72
1 ft.	1" black iron pipe	Ref.16	4.40	4.40
1 ft.	Insulating 1" pipe	Ref.16	2.71	2.71
5 ft.	Cleaning & Charging Pipe with Ammonia		.50	2.50
1 ft.	Drilling holes	Ref.22	9.00	9.00
1 sq.ft.	Urethane Insulation	Ref.22	.87	.87
Net Capital Cost				$45.64
20% Engineering & Profit				9.13
Total Cost				$54.77/sq.ft.

The unit cost estimated here is higher than that estimated by Ferrara (Reference 5) and that experienced by Wyoming at Spring Creek. These costs, however, did not include engineering costs. Compensating for the high initial cost is the total passive nature of this system. No annual operating costs are required; and although the other systems were based on 20 years of operating cost, this system could operate much longer without any additional expenses.

The system will require excavating and drilling on "adjacent land". Although no structures should be built on the heat pipe field, other uses such as a park or a parking lot are acceptable. The field should have reasonable solar exposure in the summer to facilitate annual recovery of earth heat. Underground utilities might pose a problem in this urban area. Installation or maintenance of these facilities could seriously damage the heat pipes.

Note: Annual costs are discounted at the rate of 4% over and above inflation, i.e., if inflation was 8%, this 4% interest would correspond to 12% market interest.

IX. CONCLUSIONS

Below is a table summarizing the unit costs of various heating systems for heating two structures in Littleton, Colorado based on 1981 prices.

Heating with deep ground water	$ 37/sq.ft.
Heating with shallow ground water	$ 31/sq.ft.
Heating with sanitary sewer water	$ 24/sq.ft.
Heating with solar collectors	$ 26/sq.ft.
Heating with earth heat	$ 55/sq.ft.

These costs include engineering and twenty years of operating cost. They can be used for planning or preliminary engineering activities. Costs could vary significantly from these due to cost and availability of material and appropriate skilled labor.

Not shown on this table is the concept of insulating the bottom side of the bridge deck to control preferential icing. This was studied for bridges near Vail, Colorado (Reference 19). Insulation alone is approximately $.87/sq. ft. but tends to be effective only for open girder bridges when the wind blows perpendicular to the bridge. For this case for the Dowd Junction Bridge near Vail, insulation reduced the time the deck temperature was significantly below that of the approach from 56 to 36% of the time. This study also showed that insulation is ineffective in controlling preferential icing on box girder bridges.

Heating with sanitary sewer water is the lowest cost system studied. Since a major cost of this system is the holding tank, significant cost saving could be realized if the tank size can be reduced. Continuous flow monitoring of the sewer line should be performed to determine the diurnal flow rates so possible reduction in holding tank size can be determined.

After heating with sewer water, heating with solar panels is the next alternative. This system, however, is not without problems. Acquiring land with good solar exposure at a reasonable cost may not be possible in this urban area. Also the visual pollution of a large solar collector field may not be acceptable to the public.

Heating with shallow ground water became high cost in this case due to the need to transport the water between the bridge and the water source. For the case where a large volume of shallow ground water is available adjacent to the bridge, cost in the order of $20/sq. ft. would be encountered. This would be the case where a bridge crosses over a river with deep water bearing gravels.

For the case of heating with deep well water, the cost of the well is a major part of the total cost. For larger structures the unit cost would be reduced significantly. In addition if dual use of the well could be arranged (winter deicing/summer irrigation), cost could be reduced further.

In conclusion, systems are available for controlling bridge deck preferential icing for as little as $20/sq. ft. This is still a major cost, and such systems should only be considered for critical locations where over $500,000 savings in realized accident cost can be expected over a 20 year period (based on 12,000 sq. ft. of bridge deck).

X. IMPLEMENTATION

In order to evaluate the cost effectiveness of bridge deck heating of the Littleton structures, accident records were investigated. Historical records of several similar bridges in the Denver area were examined. These bridges were: SH 93 over SH 58 in Golden, SH 95 (Sheridan Boulevard) over RR tracks near 86th Avenue, SH 75 (Broadway) over SH 285, Evans Avenue over SH 85 (Santa Fe Drive), and SH 2 (Colorado Boulevard) over I-25.

Over the past year, only one of the five bridges considered had documented icy bridge accidents. That bridge was the Evans Avenue over Santa Fe Drive bridge. During the last year, two property damage accidents, averaging a cost of $980, occurred when ice was present on the bridge. If we assume bridge heating in Littleton would eliminate two similar accidents a year for twenty years and save $1960 per year, total savings can be computed. Present value of this savings based on a 4% return above inflation would be $26,000. The estimate of savings is probably the upper limit because the Evans bridge is much longer than the proposed bridges and the lack of any icy bridge accidents on the other four bridges suggests a lower statistic.

Since the projected savings of $26,600 is far below the expected cost of $283,000, heating the Littleton bridge is not recommended. Heating bridges, however, may be cost effective in other areas of Colorado where the weather is more severe or for bridges with more hazardous geometry.

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APPENDIX A

COST ESTIMATES FOR HEAT PIPE HEAT EXCHANGERS

Costs of heat pipe heat exchangers are based on the following letter from SETA Corporation in September 1981. The letter gives four configurations at two different production levels. Since SETA Corporation has built and sold a substantial number of these since this letter, the higher volume costs will now be applicable even for a lower volume order. In order to determine the cost of other configurations per square foot costs were converted to cost per linear foot of exchanger. These costs are shown on the table below.

Cost Per Linear Foot of Exchanger ($)

Width (ft) / Spacing (in)	10	20	40	60
3	281.20	387.6	600.4	813.20
6	195.40	271.2	422.8	574.40
12	152.50	213.00	334.00	455.00
18	138.20	193.60	304.40	415.20

The four numbers in the box were obtained by multiplying the per square foot cost times the width. Since for 12-inch spacing it cost $121/ft (334-213) to add 20 feet of the condenser pipes, therefore, it should cost an additional $121/ft to increase width from 40 feet to 60 feet. Similarly, half of $121 could be saved if the width is reduced from 20 to 10 feet. This same rationale can be used for the other condenser pipe spacing.

For changing condenser pipe spacing it cost $19.40/ft (213.00-193.60) to add an additional 1/3 pipe per foot (18-inch spacing to 12-inch spacing) for 20-foot-wide exchangers. The cost to add an additional pipe per foot would be three times this amount or $58.20/ft. Adding this to cost of 12-inch spacing will give us the cost of heat exchangers with 6-inch spacing. Similarly, for 3-inch space an additional 3 pipe per foot would re required at $58.20/ft. each, or $174.60/ft additional cost over the 12-inch spacing. With this logic costs for the remainder of the configurations can be generated.

The cost per square foot can be determined by dividing each linear foot cost by the corresponding width, and the table below can be generated.

Cost Per Square Foot (Dollars)

Width / Spacing	10	20	40	60
3	28.12	19.38	15.01	13.55
6	19.54	13.56	10.57	9.57
12	15.25	10.65	8.35	7.58
18	13.82	9.68	7.61	6.92

80.0

SETA CORPORATION

P.O. Box 4057
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Phone: 307/742-6563

Kynric M. Pell, Ph.D., P. E.
President

John Nydahl, Ph.D.
Vice President

September 28, 1981

Mr. Harvey R. Atchison, Director
Department of Transportation Planning
Colorado Department of Highways
4201 East Arkansas Avenue
Denver, Colorado 802222

Dear Mr. Atchison:

We are pleased to have the opportunity to provide cost estimates for a manifolded heat pipe system. In order to cover a number of possible applications I will quote a variety of combinations as presented on the enclosed sheets. It should be noted that the coefficient of performance (0.4) mentioned in your letter of September 15, 1981 was the highest observed for the 6" spaced manifolds and is in addition not theoretically possible even with an idealized, "perfect", evaporator for 18" spaced condenser elements. In view of this I have provided quotes for 12" and 18" condenser spacings which can be expected to provide coefficients of performance between 0.2 and 0.3 depending on the number of units placed in series.

The quotes provided for 1/4 mile may be used for any lesser quantity in which case we will absorb the major portion of the capital cost of the equipment required to start up the production facility.

For quantities involved between 1/4 mile and 1 mile some automated equipment would be installed and a firm quote would depend on the quantity involved. For quantities involved beyond 2 miles an asymptotic limit for the 18" spacing, single header, of approximately $6.75/square foot is approached. The enclosed graph may be of some use in projecting costs.

I trust that the material provided is in a useful form, however; if additional information is required, please do not hesitate to call us.

Sincerely,

Kynric M. Pell, President

SETA CORPORATION

Enclosures:

KMP/abp

General Features of Design Common to Each Estimate

1. External epoxy coating (DOT Approved) of steel components which are to be placed in the slab. (Condensers)

2. Expansion joints which also have lateral flexibility to allow for manufacturing tolerance of the concrete sections at each manifold interface.

3. A "Y" section (capped) on 100 foot intervals in the header for cleaning of the primary flow circuit.

4. Interior surface coating of the primary flow header. The estimates assume an epoxy coating at a price of $1.50/linear foot. Tests to be conducted may indicate an alternate coating, however; any cost differential should not be large.

5. Use of 150 pound slip on, raised face flanges at the header interfaces.

6. Use of 1/2" ∅ (Seamless) Grade B steel for condenser fingers.

7. Use of 3" ∅ (ERW) Grade B steel for header

8. Use of 5" ∅ (Seamless) Grade B steel for manifold.

9. Price includes gaskets and bolts for field connection of the manifolds.

10. Estimate includes delivery of fabricated manifolds to a site within 30 miles of Glenwood Springs, Colorado.

11. The estimate includes labor to connect up the manifolds after placement, but <u>not</u> the labor required to set the manifold in place in the slab prior to pour.

12. Plumbing, pumping and related costs associated with providing and exhausting water for the manifolds is <u>not</u> included.

13. A field service nipple for possible recharge of the manifold with ammonia is provided.

14. Insulation of exposed portions of the manifolds is <u>not</u> included in the estimate. SETA is working on a novel insulation technique which should be very cost effective, however; we are not in a position to provide an estimate at this time.

15. This estimate was made September 28, 1981 in terms of entering into an agreement within 90 days of that date. No inflationary considerations are included.

Cost Estimates for Manifolded Heat Pipe Systems

Cost estimate for 1 mile (5280 feet) of 40 foot wide pavement assuming a superelevated road requiring a single header:

Assuming 18" condenser spacing	$7.61/square foot
Assuming 12" condenser spacing	$8.35/square foot

Cost estimate for 1 mile (5280 feet) of 40 foot wide pavement assuming a flat road requiring two headers:

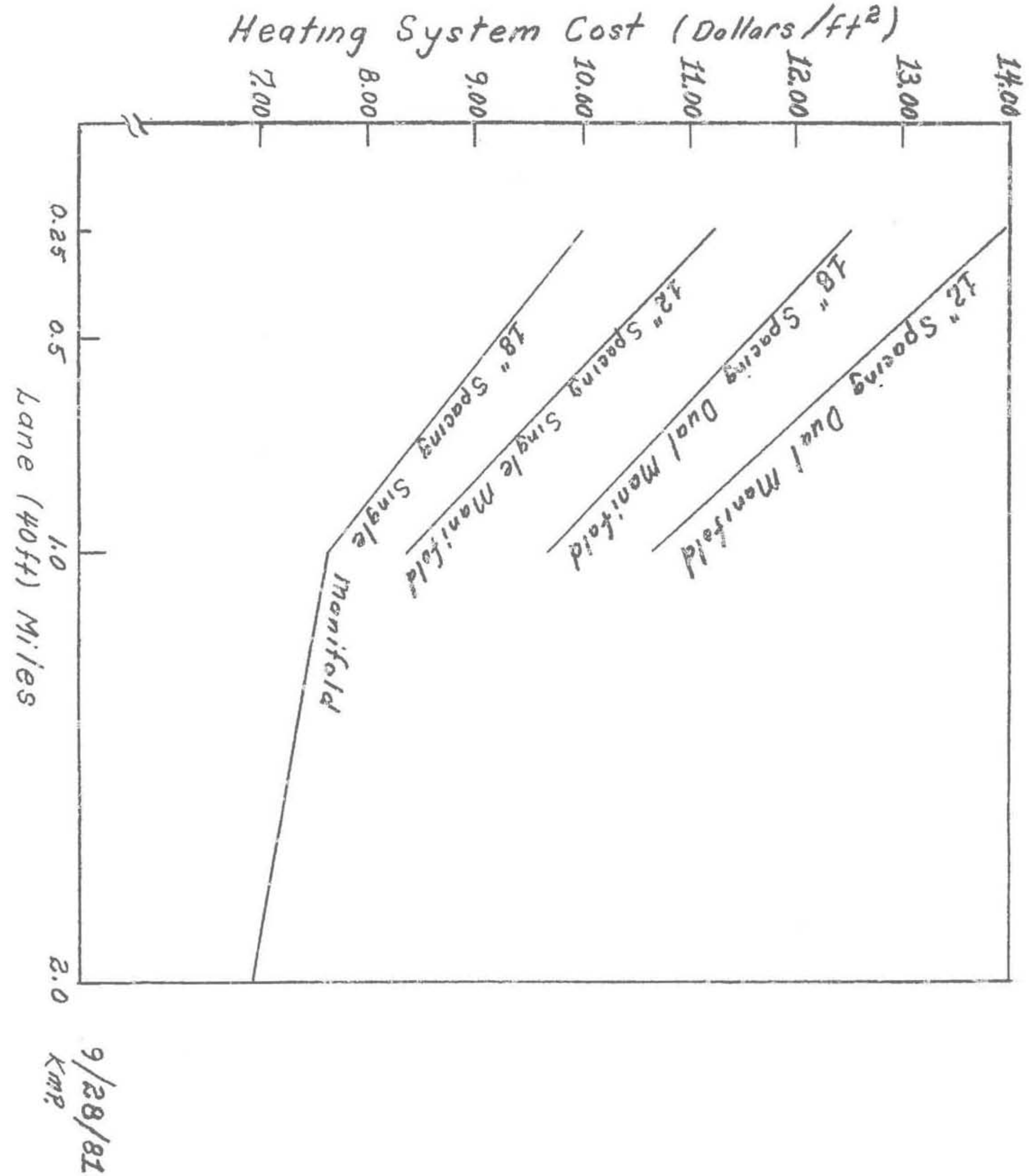
Assuming 18" condenser spacing	$9.68/square foot
Assuming 12" condenser spacing	$10.65/square foot

Cost estimate for 1/4 mile (1320 feet) of 40 foot wide pavement assuming a superelevated road requiring a single header:

Assuming 18" condenser spacing	$10.00/square foot
Assuming 12" condenser spacing	$11.21/square foot

Cost estimate for 1/4 mile (1320 feet) of 40 foot wide pavement assuming a flat road requiring two headers:

Assuming 18" condenser spacing	$12.52/square foot
Assuming 12" condenser spacing	$13.99/square foot



Heating System Cost (Dollars/ft²)
7.00
8.00
9.00
10.00
11.00
12.00
13.00
14.00
Lane (40ft) Miles
0.25
0.5
1.0
2.0
18" Spacing Single Manifold
12" Spacing Single Manifold
18" Spacing Dual Manifold
12" Spacing Dual Manifold
9/28/81
KMP

APPENDIX B

The amount of heat flux available from a water source can be expressed as follows:

$$q = \frac{C_p F_w f (T_w - T_d)}{A}$$

where

q = heat flux at surface

C_p = heat capacity of water

F_w = flow rate of water

f = fraction of total temperature difference that will result between inlet and outlet

T_w = inlet water temperature

T_d = temperature at surface of bridge deck

As an example consider a 10 l/s (160 gal/min) water source at 10°C (50°F). If we plan on dropping the water temperature 25% (f = .25) of the available difference for heating a 1000 m^2 (11,000 sq. ft) bridge deck, the heat flux available from the water is given by:

$$q = \frac{(1 \text{ cal/ml } ^{o}\text{C})(10 \text{ l/sec})(.25)(10^{o}\text{C} - 1^{o}\text{C})}{1000 \text{ m}} \left[\frac{1000 \text{ ml/l}}{.239 \text{ cal/watt sec}}\right]$$

(The last factor is for unit conversion.)

Therefore: $q = 94 \text{ w/m}^2$

Similarly for English units:

$$q = \frac{(1 \text{ BTU/16}^{o}\text{F})(160 \text{ gal/min})(.25)(50-33.8^{o}\text{F})}{11{,}000 \text{ ft}^2} \left[8.3 \text{ lb/gal}\right]$$

$$q = 30 \text{ BTU /hr ft}^2$$

APPENDIX C

Computation of pipe size for transporting of 1900 gal/min (120 l/sec) in a free flowing pipe:

Assume a steel pipe on a 1% grade. For a circular pipe running full, Manning's formula can be written as:

$$Q = \left(\frac{.4632}{n}\right) D^{8/3} \; S^{1/2}$$

where

Q = flow in ft^3/sec

n = Manning's roughness factor

D = inside pipe diameter in feet

S = grade of pipe

(see page 6-38, Reference 11)

For good steel pipe Manning's roughness factor is .012.

$$D = \left(\frac{Q\ n}{.4632\ S^{1/2}}\right)^{3/8}$$

Since 1900 gal/min equals 4.23 ft^3/sec and Manning's roughness factor is .012, D must be 1 foot for a 1% grade.

APPENDIX D

Computation of the effect of pipe diameter on heat transfer:

The convective film coefficient is given in Reference 12.

$$h \propto N_R^{.8} \; N_{P_r}^{1/3} \; k/D$$

where

h = convective film coefficient

N_R = Reynold's number DV/μ

N_{P_r} = Prantl number $\frac{C_p \mu}{k}$

k = thermal conductivity

D = diameter

V = average velocity of fluid

ν = kinemetic viscosity

C_p = heat capacity of fluid

The ratio of h's for 3" and 24" pipe is given by:

$$\frac{h \text{ (for 3")}}{h \text{ (for 24")}} = \frac{.023 \; N_R \text{ (for 3")}^{.8} \; N_{P_r}^{1/3} \quad k/3"}{.023 \; N_R \text{ (for 24")}^{.8} \; N_{P_r}^{1/3} \quad k/24"}$$

$$= \frac{24}{3} \left(\frac{N_R \text{ (for 3")}}{N_R \text{ (for 24")}} \right)^{.8}$$

for a flow rate of Q $\quad N_R = \frac{ND}{\nu} = \frac{4\,Q}{\pi D \nu}$

Therefore

$$\frac{h \text{ (for 3")}}{h \text{ (for 24")}} = \frac{24}{3} \left(\frac{24}{3}\right)^{.8} = 8^{1.8} = 42$$

This means for the same flow rate a 3" pipe is 42 times as efficient at transferring heat from the water than a 24" pipe.

APPENDIX E

Description of Program HEAT for Determining Heat Requirements

Program HEAT was written to determine the heat losses and gains from a horizontal surface based on meteorological data. This program uses wind speeds, temperatures, type of precipitation, cloud cover, and relative humidity data to determine the heat transfer. Heat required to melt ice and snow was not calculated in this program. It was also assumed that snow cover would be removed before it interfered with heat gains by snow plows and vehicle action. Four components of the heat transfer were considered as follows:

heat loss due to evaporation
heat transfer due to convection
heat transfer due to long wave radiation
heat gain due to sunlight

Evaporation was assumed to take place any time there was precipitation. The heat loss due to this evaporation was computed as follows (based on Reference 3):

$$Q_{ep} = h_{fg} \ (.0201 \ W_s + .055) \ (P_{vs} - P_{va})$$

where

Q_{ep} = heat loss due to evaporation at the surface in BTU/hr

h_{fg} = heat of vaporization of water in BTU/lb.

.0201 and .055 are imperical constants

W_s = wind speed in MPH

P_{vs} = saturated vapor pressure of water at surface the temperature in torr

P_{va} = partial pressure of water vapor in air in torr

Heat transfer due to convection was computed as follows (based on Reference 3):

$$Q_{cv} = (1 = 0.3 \ W_s)(T_s - T_a)$$

where

Q_{cv} = heat flux due to convection in BTU/hr-ft^2

W_s = wind speed in mph

T_s = temperature of surface in ^oF.

T_a = temperature of air in ^oF.

Heat loss due to long wave readiation was computed as follows (based on Reference 3):

$$Q_{rd} = \sigma \epsilon_s (T_s^4 - \epsilon_a T_a^4)(1 - .75\ S_k)$$

where

Q_{rd} = heat flux due to radiation in BTU/hr-ft^2

σ = Stefan Boltzmann constant (.173x10^{-8} BTU/hr-ft^2-^{o}F)

ϵ_s = emissivity of surface (.8 used)

ϵ_a = emissivity of air (.7 used)

T_s, T_a = temperature of surface and air in ^{o}F

S_k = cloud cover in tenths

The heat gain from the sunlight was computed as follows:

$$Q_{sun} = S_c C_a (1.2 - S_k) \sin \theta$$

where

Q_{sun} = heat flux from the sunlight

S_c = solar constant (442 BTU/hr ft^2)

C_a = coefficient of absorption for surface

S_k = cloud cover in tenths

θ = incident angle of sunlight based on time of day and time of year

The program was data based on every third hour of the day since this information is easily available from the National Weather Service. The format is as follows:

Column	Item
1-10	Location description
11-12	Year - 1900
13-14	Month (1-12)
15-16	Day of month (1-30)
17-18	Hour of day (0-23)
19-20	Tenth of cloud cover
21-24	Weather condition code same as reported by NWS
25-27	Ambient humidity
28-30	Relative humidity
31-32	Wind speed (knots)

Weather data is inputted on TAPE7 and the results are outputted on TAPE8. TS, CA, W and MAXPOW (surface temperature, solar absorption coefficient, and maximum flux that can be transferred by system) are entered in free format on INPUT.

The following is a listing of program HEAT followed by its output for various scenarios.

APPENDIX F

Calculation of ratio of incident solar radiation on tilted surface to that on a horizontal surface (from Reference 14):

$$I_{day} = -\frac{24}{\pi} I_p(1+.034 \cos \frac{2\pi n}{365})(\cos L \cos \delta_s \sin h_{sr} + h_{sr} \sin L \sin \delta_s)$$

where:

I_{day} = total daily solar radiation on a surface

I_p = peak solar radiation when surface is directly into sun

n = julian date (use 0)

L = latitude

δ_s = solar azimuth angle (use -23.5^o)

h_{sr} = sunrise hour angle in radians based on 15^o per hour from noon

Since sunrise for January 1 is 7:21 a.m., the hour angle will be -69.75^o. In radians this will be -1.2174.

For the horizontal surface case a latitude of 40^o will be used. For a surface tilted at 55^o a latitude of (40-55) -15^o will be used.

The ratio of radiation on a tilted surface to that on a horizontal surface is given as follows after dividing out like coefficients:

$$\frac{I_{day}\text{ (tilt)}}{I_{day}\text{ (hoz)}} = \frac{\cos(-15^o)\cos(-23.5^o)\sin(-1.2174) - 1.2174\sin(-15^o)\sin(-23.5^o)}{\cos(40^o)\cos(-23.5^o)\sin(-1.2174) - 1.2174\sin(40^o)\sin(-23.5^o)}$$

$$= 2.8$$