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Technical Report

ABOVEGROUND UTILIDOR PIPING SYSTEMS FOR COLD-WEATHER REGIONS

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13. ABSTRACT

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Sewage lines						
Corrugated metal arches						
Pipe supports						
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Computer program						

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FOREWORD

The piping of freezable liquids in cold-weather regions, especially in polar regions, requires special techniques and equipment. The Naval Civil Engineering Laboratory has conducted studies on two types of piping systems. One system, the utilidor, utilizes an insulated enclosure that houses two or more pipes; usually one pipe contains hot water or steam, which supplies heat for the utilidor interior and the other pipes. This system is best suited for permanent facilities. The other system, the single-line preassembled piping system, utilizes a single pipe which is electrically heated and insulated. Two or more individually heated and insulated pipes can be used to accomplish the same liquid distribution pattern obtained with the utilidor. This system is suitable for both permanent and temporary or advanced based facilities.

This report discussed the utilidor system and compares it with the single-line preassembled piping system. Detailed information on the single-line system can be found in Technical Report R-733, "Single-Line, Heat-Traced Piping System for Polar Regions," by C. R. Hoffman, dated June 1971.

INTRODUCTION

The severe environment and difficult terrain in polar regions present special problems in the design of piping systems for freezable liquids such as water and sewage. Also, the remoteness of these areas with their high labor and transportation costs requires different design considerations for piping than those for more temparate regions. When steam or hot water is distributed between buildings in polar or other cold-weather regions, all freezable liquid lines are often placed in a common enclosure, or utilidor, with the hot line serving as a heat source for the unheated lines. Where practical, utilidors have been considered to date to be more economical for distributing freezable liquids than separate, insulated, heat-traced lines.

This report presents the results of an investigation on an aboveground utilidor piping system for Navy application at permanent facilities in cold-weather regions. It covers the requirements and the design concept for such a system and presents the evaluation of a 32-foot-long test section based on this concept. Also, the thermal analysis required for specific application of this concept is presented, and a cost-effectiveness comparison is made with the individual, single-line, preassembled, electrically heat-traced piping system advanced by the Naval Civil Engineering Laboratory (NCEL).

This development relates to the technological capabilities and objectives outlined in the Naval Technological Forecast, Section 536-33, "Polar Utilities."[1]

BACKGROUND

In 1965, NCEL began investigating systems for the distribution of freezable liquids in polar regions. The initial effort was directed toward a single, preassembled, insulated, electrically heat-traced piping system[2] which could be field cut and installed at temperatures to -30°F with maximum flexibility of design. Results of this work were successful, and in July 1968 in-service evaluation began at Point Barrow, Alaska, on more than 2,000 feet of this piping system. Also, current plans call for installing several hundred feet of this piping at McMurdo Station, Antarctica, in 1971.

In March 1967, the Northwest Division of the Naval Facilities Engineering Command (NORWESTDIVNAVFAC) requested that NCEL investigate composite utilidor (multiline) distribution systems to determine the most suitable and least costly above-grade design approach for Naval polar facilities. This request was based on the need for about 2,300 feet of multiline piping carrying water, sewage, and medium-temperature hot water (MTW) to future facilities at the Naval Arctic Research Laboratory (NARL), Point Barrow, Alaska. This investigation was undertaken in June 1968.

ABOVE-GRADE UTILIDOR REQUIREMENTS FOR NAVY APPLICATION

No single Navy utilidor design for polar or other cold-weather regions is likely to meet the requirements at all locations because of variations in terrain and differences in the facilities being served. The most adaptable configuration for general Naval application was determined to be an insulated, weatherproof pipe enclosure supported on pilings above the ground. Such a system is unaffected by surface ground water, does not disturb natural permafrost, and is adaptable to level or rolling terrain.

In addition to the usual piping system requirements, which include a heated line, a utilidor system for polar regions must be:

1. Easy to assemble with minimum labor and mechanical equipment
2. Adaptable to all types of terrain
3. Suitable for installation and operation at prevailing temperatures
4. Unaffected by winds, water, or blowing snow
5. Lightweight and easy to adapt and repair
6. Resistant to damage by natural and man-induced forces

Also, for economy in heating the utilidor, the enclosure should:

1. Have minimum exterior surface area to reduce heat loss and wind load
2. Contain fewest enclosure panels to minimize the loss of heat and air infiltration through panel connections

3. Contain fewest enclosure-supporting elements and through-metal connectors to minimize conducted heat loss
4. Have internal partitions to minimize thermal convection and stratification

DESIGN APPROACH

The development of a utilidor for Navy application included surveying existing systems, formulating a design concept, and optimizing the principal design elements.

Existing Utilidors in Northern Canada

Before formulating a utilidor design concept for Navy use, a state-of-the-art survey was conducted and an inspection was made of selected utilidor systems operating in northern Canada. The details of this survey are contained in Appendix A.

During the Canadian inspection one system was found that closely approximated the general utilidor requirements for Navy application as well as those for the future facilities at NARL. This system, located at the new community of Inuvik, NWT, was studied in detail both on-site and from drawings obtained from the Canadian manufacturer. Because of the similarities between the Inuvik and Point Barrow requirements, the Inuvik utilidor was used as a basis for an improved engineering design concept for Navy application.

Briefly, the Inuvik utilidor is an aboveground system containing a potable waterline, sewerline, and two medium-temperature hot water (MTW) lines from a central heating plant. These four lines are enclosed in an insulated, rectangular structure supported at 10-foot intervals on wood piles set into the permafrost (Figure 1). Cost of the system installed with Canadian labor and materials was between $200 and $225 per linear foot. A cost factor study by NORWESTDIVNAVFAC indicates that an installation of similar design at Point Barrow would cost approximately $400 per linear foot with U.S. labor and material. Of this figure, direct labor and material for fabrication would be about one-third of the total.

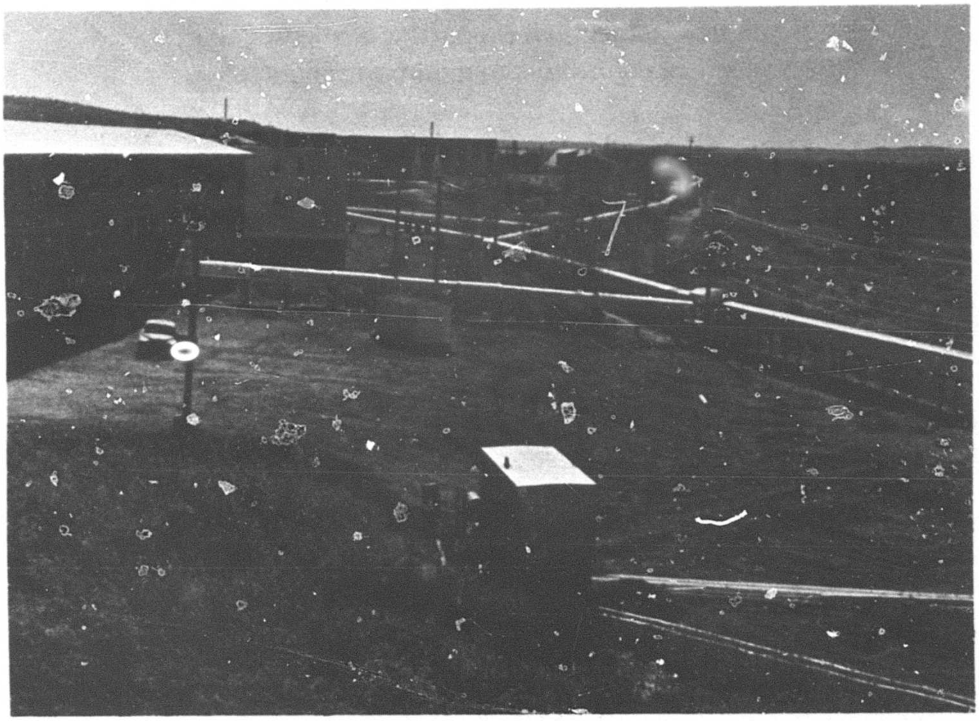


Figure 1. Above-grade utilidor at Inuvik, NWT, Canada

Utilidor Design Concept

Examination of the various construction features of the Inuvik utilidor indicated that the assembly and construction costs might be reduced by simplifying the structural design and prefabricating more parts for faster on-site assembly. Specifically, this could be accomplished by:

1. Increasing the length of the basic modular element to provide fewer parts and to reduce the number of supporting piles
2. Simplifying expansion anchors and eliminating poured-concrete anchor pile-caps
3. Changing the enclosure cross section from a rectangle composed of four panels to a semicircle of two parts. This in turn would (a) reduce the number of joints through which heat and moisture leaks could occur,

(b) decrease the number of fasteners for the enclosure assembly, and (c) provide a structural shape of greater strength with fewer framing members

With these guidelines, conceptual drawings were prepared for a five-pipe above-grade utilidor system. These drawings were as general as possible, but, where specific fluid flow or temperature conditions were required, values as applicable to NARL were used. These parameters, as suggested by NORWESTDIVNAVFAC, were:

Ambient air temperature	-56°F to 54°F
Wind velocity	30 mph
Maximum potable waterflow	15 fps
MTW supply temperature	250°F
MTW return temperature	210°F
Optimum potable water temperature . .	40°F to 50°F
Maximum potable water temperature .	70°F
Maximum sewage temperature	90°F
Raw water pipe size	8 inches
Maximum MTW pipe size	6 inches
Approximate length of utilidor	2,300 feet

Optimized Utilidor Design

Following the conceptual study, a design approach was selected for an above-grade utilidor for Navy application. For straight runs a 27-foot-long module designed for two-pile support at 27-foot intervals was selected. Work sketches were prepared in sufficient detail to determine the method and relative difficulty in providing other needed system elements, such as pile bents, anchors, 90-degree turns, expansion joints, valving, service connections, and fire hydrants. Appendix B lists the sketch identification.

Since the design study indicated that there would be no difficulty in developing all of the elements required for a complete system, the basic module was detailed as a five-pipe system for test and evaluation in the NCEL cold chamber. It consisted of a prefabricated, knockdown, 27-foot-long steel foundation (Figure 2) covered with three 5-foot-wide by 9-foot-long insulated wooden floor panels. Also, pipe brackets and support rollers were attached to the foundation crossmembers at 9-foot intervals (Figure 3). The top of the utilidor was formed with two 13.5-foot-long corrugated metal arches with 2 inches of polyurethane insulation sprayed on the interior surface (Figure 4). Six bolts per 13.5-foot sections were used to hold the arch and floor panels in place and to compress a soft gasket which covered the joint between arch sections for a weathertight enclosure. As shown in Figure 4, the MTW supply and return lines were located at the outer edges of the five-pipe test module.

In selecting the arch cover it was considered important to have the 13.5-foot-long sections light in weight so that two men could remove a section if required without special weight-handling equipment. On the other hand it was important that the cover not deform easily, delaminate the urethane insulation during rough handling, or be susceptible to vandalism. To determine the most suitable corrugated arch for the system, three different arch materials were selected for test and evaluation. These were:

20-gage galvanized steel with standard 2-2/3 x 1/2-inch corrugation

16-gage aluminum with 2-2/3 x 1/2-inch corrugation

16-gage aluminum with 6 x 1-inch corrugation, which is only available in aluminum

DESIGN EVALUATION

A 32-foot-long section of the utilidor was fabricated for test and evaluation in the NCEL cold chamber. It consisted of a basic 27-foot-long module and two 2.5-foot-long sections representing adjacent modules. The test section was assembled in the cold chamber at a temperature near 70°F and subjected to temperatures down to -45°F to determine (1) the suitability of the selected materials, (2) the success of the design in reducing field assembly time, (3) the heat loss through the utilidor enclosure, and (4) the interior steady-state temperature distribution at different exterior temperatures.

Materials

The materials used in fabricating the test section required little evaluation except for the corrugated metal arch with the spray-applied urethane insulation and the gasket and joint sealing materials.

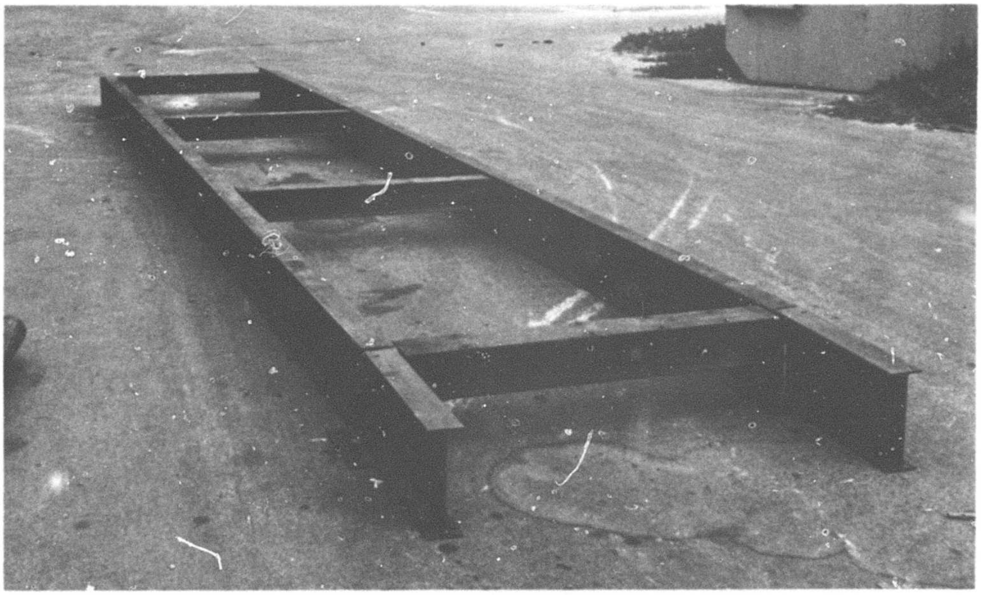


Figure 2. Steel foundation for experimental utilidor.

Figure 3. Experimental utilidor with insulated floor panels and pipe supports in place.

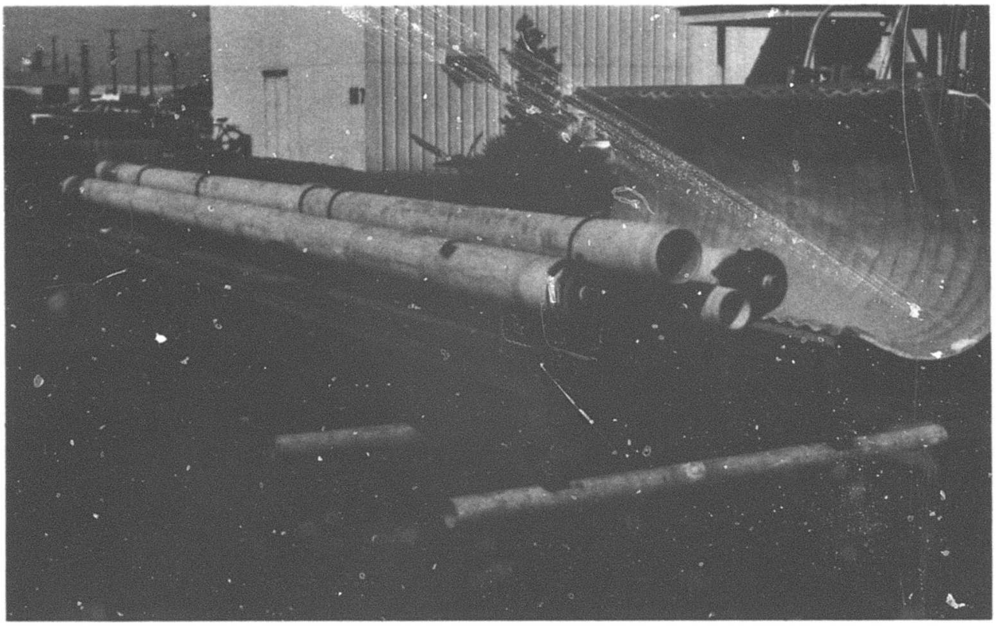


Figure 4. Experimental utilidor and cover arch with spray-applied urethane insulation ready for assembly.

Insulated Arch. The arch cover for the utilidor (Figure 5) consisted of a rolled corrugated metal section with a nominal 27-1/2-inch inside radius and a 5-1/4-inch straight tangent section on each side to raise the peak of the arch. A 2 x 2 x 1/4-inch structural angle was riveted longitudinally along the outside of the arch, 1/2 inch above the bottom edge. This angle, which contained boltholes, provided a means for attaching the arch to the floor panels and stiffened the bottom of the arch. The 1/2-inch of corrugation below the angle was specified to provide a narrow contact area and a high unit-compression on the 1/2-inch-thick gasket on the floor panels.

Upon receipt, inspection of the two aluminum arches and the one galvanized-steel arch showed that the quality of fabrication desired for the design had not been achieved. Figure 5 shows the galvanized-steel arch with the irregularity of its edge extending beyond the structural angle. This irregularity was most obvious on the steel arch where the dimension varied as much as 1-1/4 inches, but it was also typical of the two aluminum arches. Discussion with the representatives of the fabricators indicated that better workmanship could be provided particularly if the 5-1/4-inch straight tangent section on each side of the arches was rolled to the same radius as the arch. This would permit use of common culvert and conveyor-cover fabrication techniques.

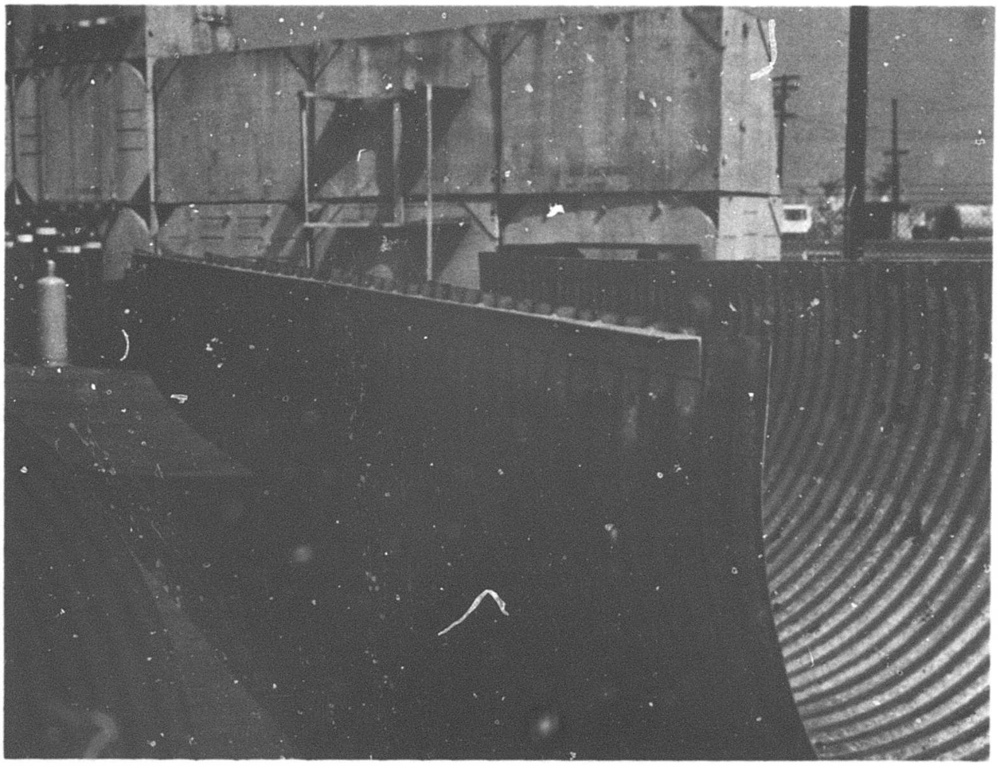


Figure 5. Corrugated utilidor cover before application of urethane insulation.

Comparisons were made of the flexibility of the three different arches, but no significant differences were observed. Figure 6 shows the typical twisting that occurred when one corner of the steel arch was raised until the opposite side was off the ground.

The irregular corrugated edge was trimmed where possible, and the interior surface was painted with an iron oxide primer for greater adhesion of the urethane insulation. During the spray application of the 2-lb/ft^3 rigid urethane foam insulation it was observed that a smoother, more uniform application could be obtained by spraying across the corrugations rather than parallel to them (Figure 7). It was also found that to achieve the specified insulation thickness at the edge and ends of the arch, a temporary bulkhead was required to create a corner to hold the spray. Buildup of the 2-inch insulation thickness was gaged with an awl and was averaged between the peaks and valleys in the corrugation. Generally it took three passes of the urethane spray gun to achieve the required thickness.

Upon completion of the low temperature tests, the arch sections were tested to measure the rigidity imparted by the urethane foam and to check the adequacy of the adhesion between the metal arch and the insulation.

It was found that one corner of the deep corrugated aluminum arch could be raised only 12 inches before the other corner on the same side came off the ground. This compares to the 58-inch lift, as shown in Figure 6, that was achieved before the insulation was applied. With the corrugated-steel arch the height was 22 inches. When three corners of either arch were restrained, the fourth corner could be raised 40 inches without damaging the insulation. Further raising of the one corner resulted in 1/8-inch-wide circumferential cracks in the insulation but no prominent separation from the metal. Next the arches were raised on a forklift and dropped from an elevation of 9 feet so that one edge struck the ground. Additional circumferential and longitudinal cracks were observed, but no complete separation of the insulation from the metal arch was obtained. The cracks produced by this handling did not appear to substantially reduce the usefulness of the arch as a utilidor cover although slightly greater heat loss might be expected.

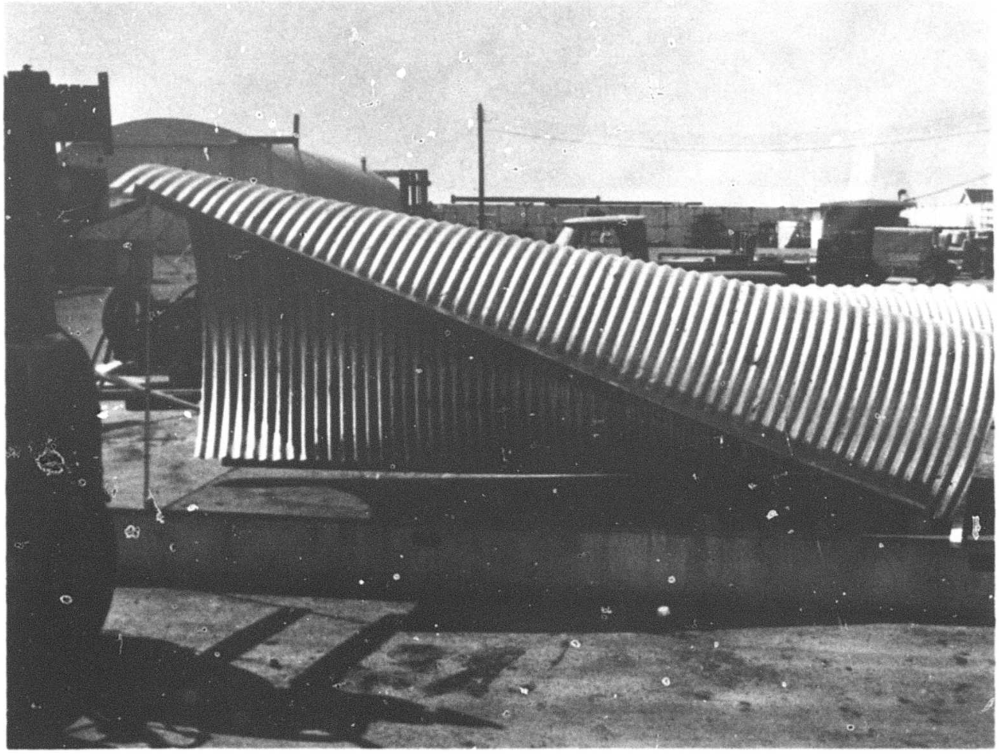


Figure 6. Typical flexibility of uninsulated metal arch.

Gaskets and Seals. The areas in the utilidor requiring gaskets or seals to provide a weathertight closure were the 1-1/2-inch space between the floor panels, the joint between the floor panel and arch, and the 1/2-inch joint between arches. As seen in Figure 3, a 3-3/4-inch-wide by 1/2-inch-thick neoprene gasket was applied to the top of the floor panels to seal against the arch. This material performed well with the corrugated arch compressing the gasket to form an effective seal.

Figure 7. Urethane insulation on interior of corrugated arch. Upper right sprayed parallel to corrugations, foreground sprayed across corrugation.

A 2-inch-thick, mastic-impregnated, flexible urethane foam material was selected for sealing the joint at the ends of the floor panels and arches. One large piece was applied at approximately 70°F to the joint between arches in conjunction with an 8-inch-wide metal band. At the conclusion of the tests the gasket had adhered so tightly that it was necessary to cut the metal band to give access to the joint (Figure 8). Also, contrary to manufacturer's reports, this material became so rigid at 32°F that it could not be compressed except in very small pieces and was, therefore, considered unsatisfactory.

A second method of sealing the joint between arch sections was investigated and found to be moderately successful. The ends of a 10-inch-wide band of heat-shrinkable polyethylene containing a heat-softened wax-like mastic on one side (Figure 9) were secured to the floor panel with a wood batten and nails. A 12-inch-wide by 1-inch-thick bat of fiber glass was used under the band on one side of the arch. Heat was applied with an electric heat gun and a small butane torch which caused the polyethylene to shrink in length only. A reasonably good appearing seal was achieved with the heat-softened mastic between the band and arch. The section over the fiber glass bat was unsatisfactory because the polyethylene did not exert sufficient tension when shrinking to compress the fiber glass. This type of band could be used to seal the joint between the arch sections; however, the band cannot be reused, and it does not provide sufficient thermal insulation for the gap between arch sections. Also, the band requires a large gentle heat source to produce adequate shrinkage without it burning.

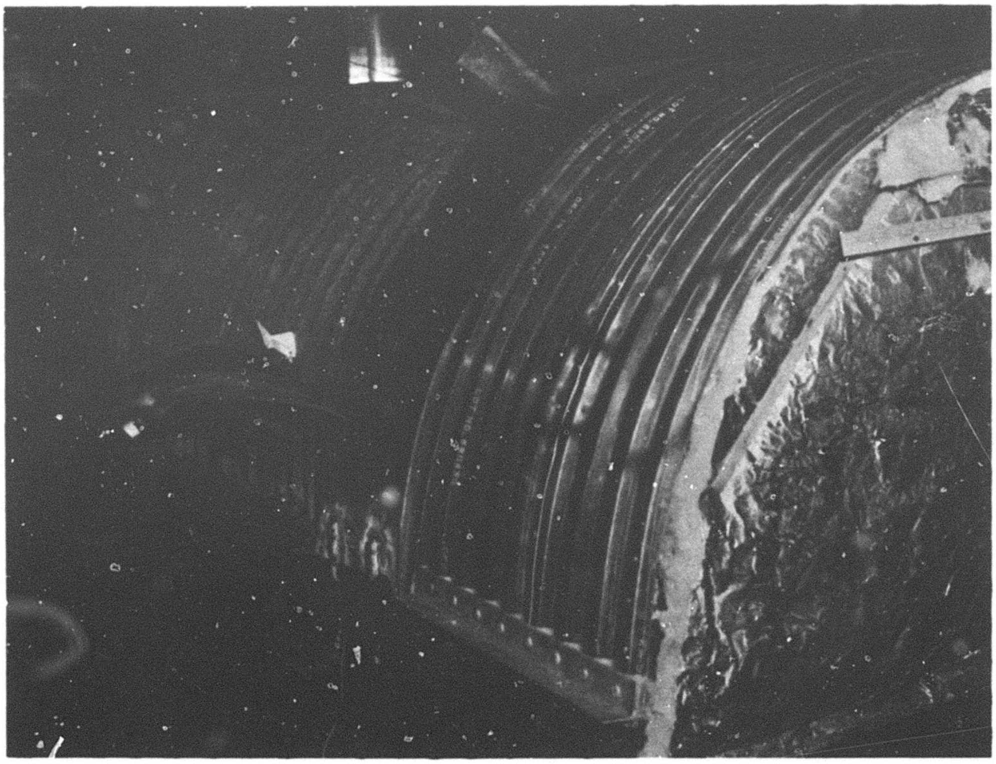


Figure 8. Metal band over joint cut to remove sticky gasket material.

Assembly

For assembly of the utilidor test section in the NCEL cold chamber at near 70°F, the bolted steel foundation was elevated on 8-inch-high wood blocks to simulate pilings and to provide space for air circulation during the low temperature tests. The two 5-inch-diameter steel MTW heating lines were covered with 2 inches of preformed canvass-jacketed fiber glass insulation to control the heat loss from these lines. Also the ends of the arch section were insulated and butted against the cold chamber walls to minimize the heat loss in this area during the tests. Figure 10 shows the experimental utilidor in the final stages of assembly. Several observations were made during the assembly that would improve the design and reduce the field assembly time.

Foundation. As designed, the 27-foot-long by 5-foot-wide foundation consisted of two 12B14 I-beam longitudinal members and three 6WF15.5 crossmembers that were assembled with 12 clip angles and 24 bolts. In addition, four 10-foot-long diagonal tie rods and turnbuckles were required for the assembly. During the trial assembly it was found that the oversized boltholes, which were required to compensate for dimensional tolerances, permitted considerable two-dimensional adjustment in locating the crossmembers. The precise position of the crossmembers could not be determined until the floor panels were installed; at this point access to the tightening nuts was lost unless a crawl space was available under the utilidor.

To correct this problem and to reduce the field assembly time, the foundation module should be delivered to the construction site as a welded assembly. While such a module would weigh approximately 1,000 pounds and would require a larger shipping space than the knockdown foundation, it would substantially reduce the costly on-site labor requirements.

Floor Panels and Pipe Supports. As designed, the brackets and rollers supporting the utilidor pipes were attached to a 1/4-inch-thick steel plate which in turn was bolted through the floor panels into the crossmembers of the steel foundation. The floor panels were designed so that there was a 1-1/2-inch space between the ends to accommodate the bolt and nuts on the pipe support roller. This spacing is undesirable because of the thermal insulation and moisture sealing required; it could be eliminated if the pipe supports were redesigned for no bottom projection.

Heat Loss and Temperature Distribution

Because of space and equipment limitations and other practical considerations, the thermal studies were conducted under static conditions with no fluid flow in the various pipe systems. The temperature and heat loss conditions in the MTW heating lines were simulated by installing a 25-foot-long, 600-watt, thermostatically controlled electric heating element in each pipe and filling the pipes with water. The other three pipes were also plugged and filled with water to provide a more realistic temperature–time response.

Figure 9. Heat-shrinkable polyethylene band being applied over arch joint.

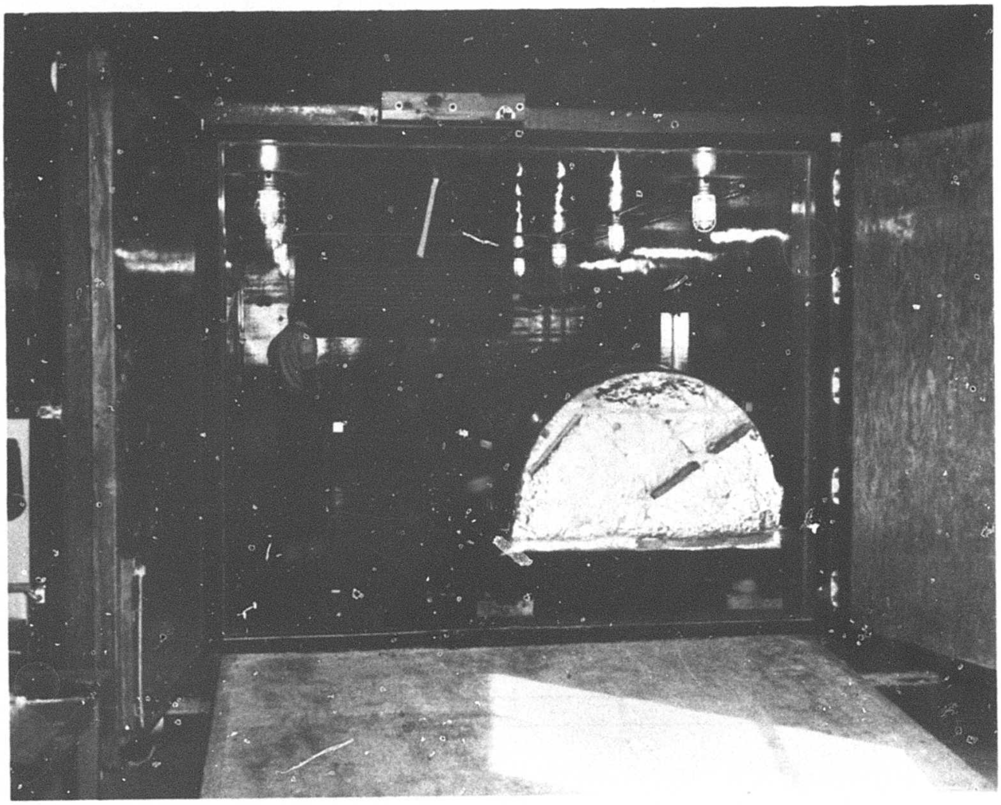


Figure 10. Experimental utilidor in final stage of assembly.

Thermocouples were installed on each of the pipes to measure their temperature and aid in adjusting the thermostat on the MTW heating lines. Eight other thermocouples were installed in the utilidor, four at each end, to measure air temperatures at different locations (Figure 11). Other instrumentation included hour meters to measure the operating time of each of the two heating elements and a watt-hour meter to measure total power consumed.

Measurements of the utilidor heat loss and temperature balance were made at five different ambient temperatures ranging from -45°F to 73°F. Each temperature was maintained for at least 48 hours or until 24 hours of data were obtained at a stabilized operating condition.

The heat lost through the utilidor enclosure is shown in Figure 12; it ranged from 98 Btuh per linear foot at -45°F to 82.2 Btuh per linear foot at 10°F. Also shown are the hours of operation of each heating element in the MTW lines during the 24-hour test period. The nonlinearity of the plot results from the nonlinear conductivity of urethane insulation.

L1 – 5-in.-diam steel pipe; 2-in.-diam fiber glass insulation; hot water supply

L2 – 6-in.-diam transite pipe; water or sewerline

L3 – 8-in.-diam transite pipe; water or sewerline

L4 – 3-in.-diam steel pipe; waterline

L5 – 5-in.-diam steel pipe; 2-in.-diam fiber glass insulation; hot water return

TC1-TC4 – Thermocouples located 4 feet from end of utilidor; projected 6 inches

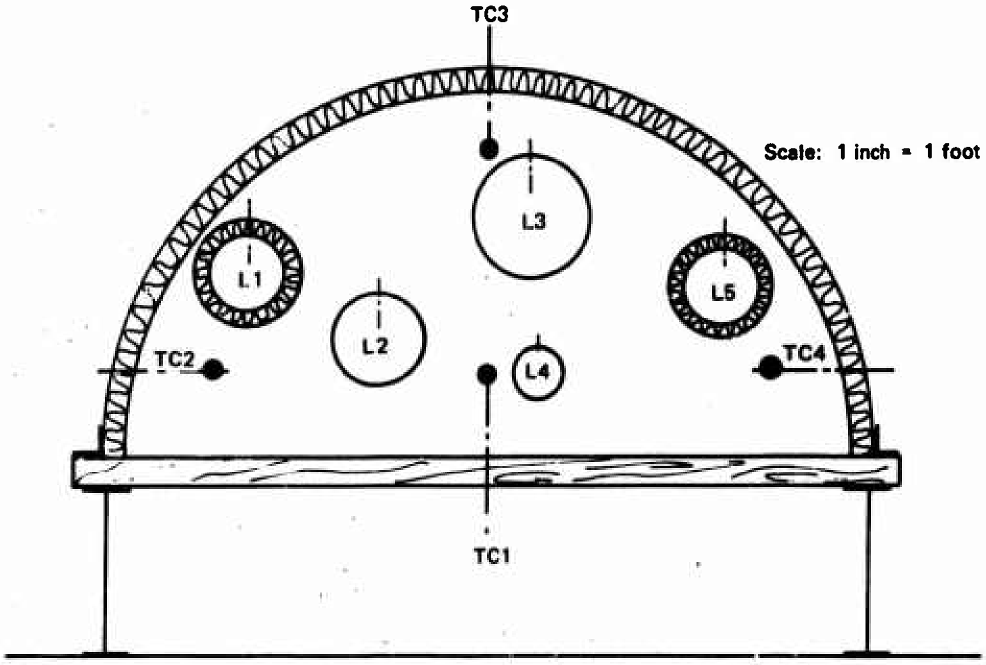


Figure 11. Location of thermocouples and piping in utilidor.

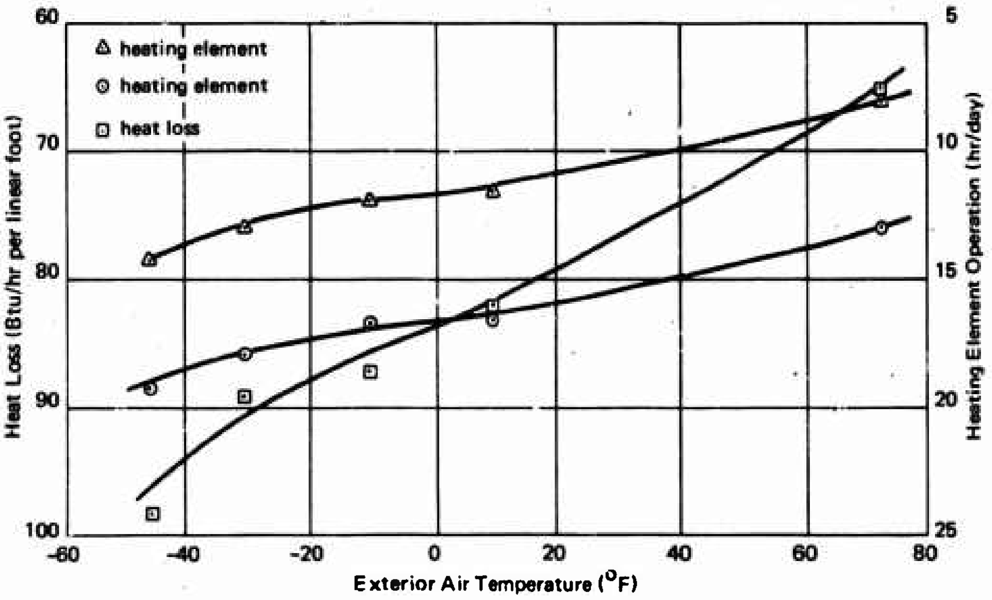


Figure 12. Heat loss and heating element operating time for utilidor.

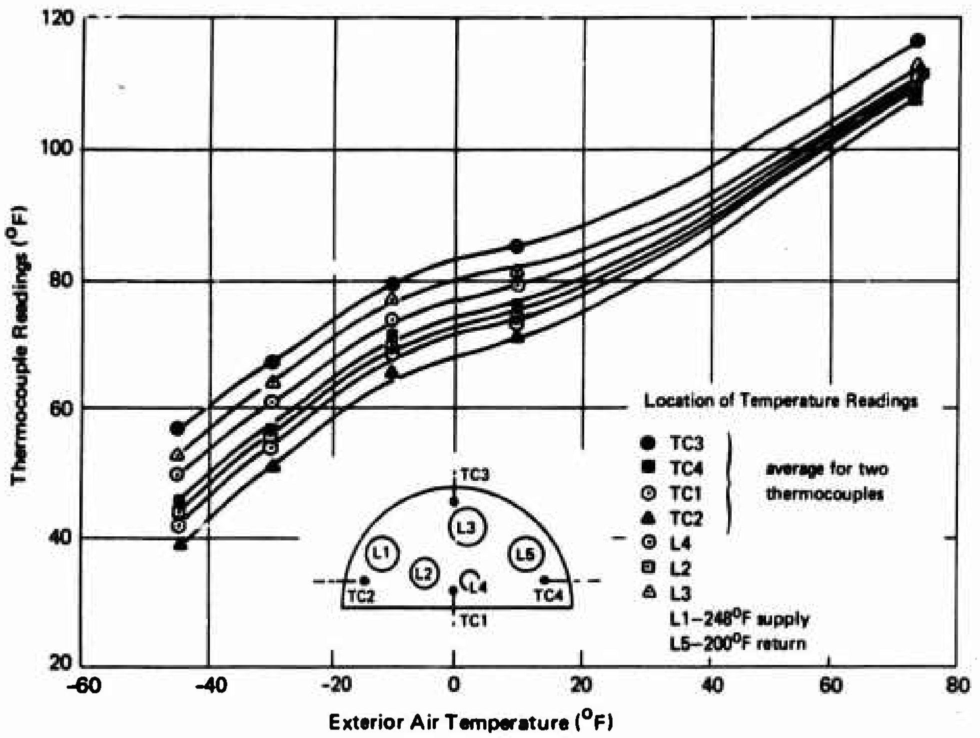


Figure 13. Air and pipe temperatures within utilidor at different exterior temperatures.

Figure 13 shows the average air and pipe temperature at different locations within the utilidor at different outside air temperatures. The average of all air temperatures ranged from 46°F at -45°F to 112°F at 73°F. As would be expected, air stratification was greatest at the lower outside temperatures. At -45°F it was 18°F, at -30°F it was 16°F, at -10°F it was 13°F, and at 10°F it was 14°F.

THERMAL ANALYSIS

A basic problem in utilidor design is to permit sufficient heat to escape from the MTW heated lines to the utilidor interior to prevent the pipes from freezing during the coldest weather without causing the temperatures of the other liquids being distributed to be undesirably high during warm weather. Before a utilidor design for a particular site can be finalized, the thermal performance of the utilidor must be carefully analyzed at both extremes of the ambient operating conditions.

A general analysis was made on the thermal performance of an utilidor, and it is presented in Appendix C. A computer program was prepared for predicting the thermal performance of various multiline utilidor designs over a wide range of boundary conditions; it is given in Appendix D.

The validity of the analytical study and computer program was tested by applying them to the low temperature tests on the 32-foot-long utilidor test section. The theoretical results compared favorably with the data collected from the test section.

The analytical study was also applied to a 2,300-foot-long system proposed for Point Barrow, Alaska, where the ambient air temperature ranges from -56°F to 54°F. The study indicates that all temperatures within the utilidor are acceptable under all operating conditions when the ambient air temperature is -56°F. However, at the 54°F ambient air temperature, the exit temperature of the potable water will be greater than the desired 50°F maximum if the potable waterflow is less than 18 gpm. After different solutions were considered, it was determined that the thermal performance of the utilidor could be improved during low flow operation if the potable waterline were insulated.

Further comparisons indicate the computer program to be sufficiently accurate to serve as a useful tool for designing and analyzing utilidors to be used under a variety of operating and environmental conditions.

COST EFFECTIVENESS

In designing a liquid distribution system for a specific area, consideration must be given to using a single-line system where pipes are individually insulated, jacketed, and heat-traced to prevent freezing. An investigation of single-line systems by NCEL[2] revealed a commercially available, preassembled, insulated, electrically heat-traced piping system that can be cut with simple tools to any desired length without destroying the heating element. Tests on this piping system showed it to be well suited for Navy polar application.

A cost-effectiveness comparison between parallel pipes of the preassembled, single-line system and an equivalent multiline utilidor system, using the limited data available, indicated the single-line system to be less expensive for one to three pipelines but more expensive for four to six pipelines that include a heated line. A comparison of effectiveness, which considers intangibles such as reliability, ease of installation, maintenance, expansion, and effect on traffic patterns, tended to indicate a utilidor system constructed at-grade to be the most effective of six possibilities considered, followed closely by parallel, single-line systems constructed at-grade.

When cost and effectiveness were combined (Figure 14), the single-line system appeared to be more cost effective for one to six lines than an equivalent utilidor constructed both at-grade and above-grade. This greater effectiveness was more evident for one to three lines than for four to six lines where differences in the cost-effectiveness rating were only 4 to 8%. This small difference in four- to six-line systems may readily be offset in favor of a utilidor by other considerations, such as esthetics, which were not included in the study. In addition, a usual consideration for an utilidor system is that at least one of the fluids in the system be at an elevated temperature (water or steam) to provide utilidor heat. This hot line may not exist when three lines (potable water, sewer, and nonpotable fire main) or less are in parallel, but it is almost certain to exist where four to six lines are in parallel.

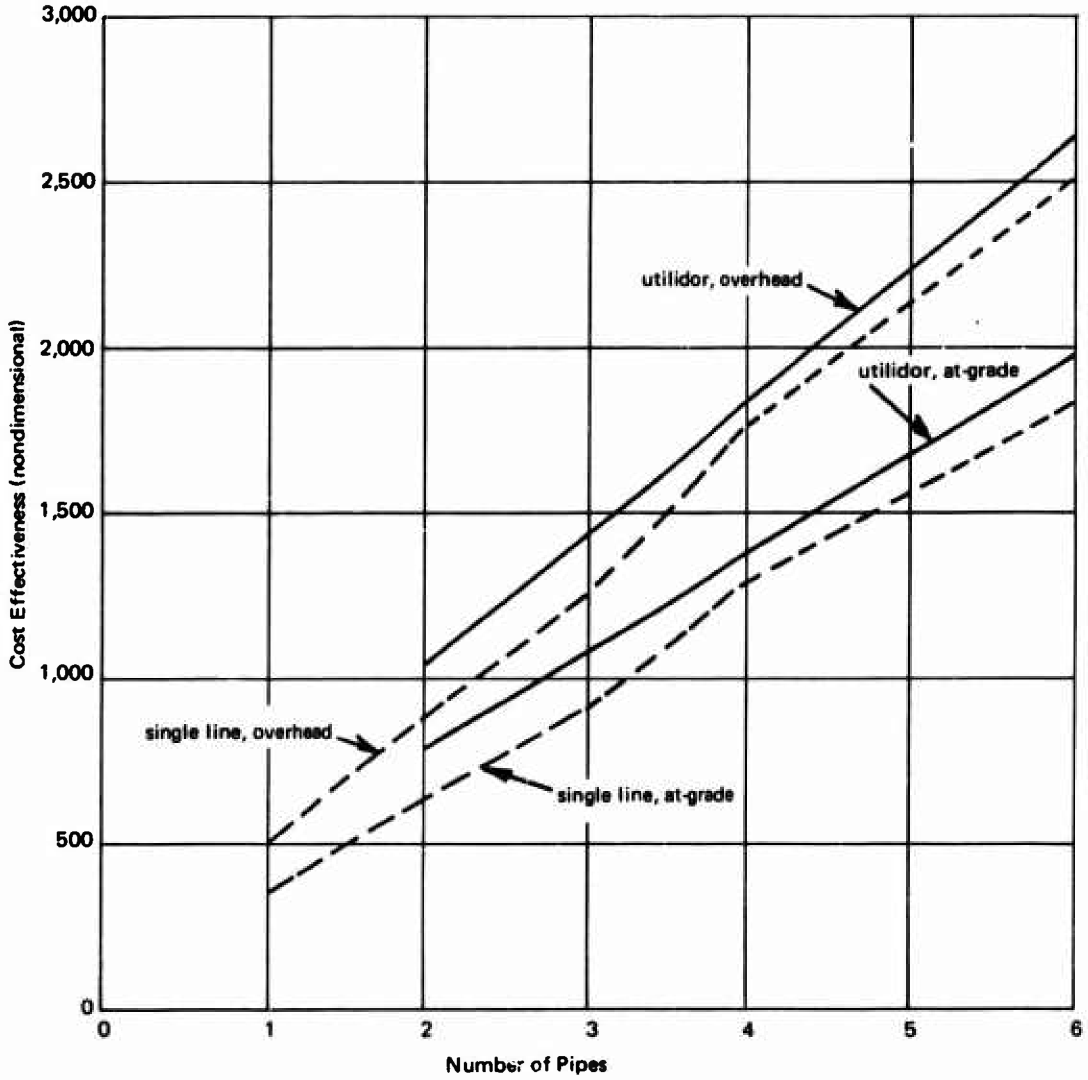


Figure 14. Cost-effectiveness comparison of single-line and multiline utilidor distribution systems.

CONCLUSIONS AND RECOMMENDATIONS

1. While no single utilidor design is suitable for all cold-weather locations because of variations in requirements and terrain, the above-grade utilidor design approach advanced in this report meets the current Navy requirements for utilidors.

2. The design approach is sufficiently advanced to permit detailed designing of an above-grade utilidor system for specific locations; however, when developing such a design, the thermal performance of the utilidor must be carefully analyzed for both extremes of the ambient air temperature at the site using the computer program provided. The system must be such that freezing will not occur during the lowest ambient air temperature and undesirably high temperatures for the liquids being distributed will not be produced during the highest ambient air temperature.

3. While single-line, preassembled, insulated, electrically heat-traced piping systems are most cost effective for one to six distribution lines for freezable liquids, this advantage is so slight for four- to six-line systems that the availability of an inexpensive source of heat (heated liquid or steam) or an intangible consideration (such as esthetics) may warrant the use of a utilidor system for a specific Naval facility.

ACKNOWLEDGMENTS

Dr. C. K. Smith of NCEL prepared the thermal performance analysis shown in Appendix C. Mr. N. F. Shoemaker, NCEL, programmed the analysis for the computer.

Appendix A

SURVEY OF EXISTING UTILIDOR SYSTEMS IN NORTHERN CANADA

INTRODUCTION

Before developing the requirements and selecting a design approach for utilidor piping systems at Naval polar facilities where a steam or hot waterline is included in the freezable-liquid distribution system, a state-of-the-art survey was conducted to obtain information on design and operational problems of existing utilidor systems. As part of this study a trip was made to Canada in June 1968 to discuss utilidor systems with the Department of Indian Affairs and Northern Development and the Northern Canada Power Commission at Ottawa, Ontario. In addition, visits were made to Fort Churchill, Manitoba, and Inuvik, NWT, to inspect composite multipipe utilidors which have been in use for several years.

UTILIDOR SITES

Ottawa

The Canadian Department of Indian Affairs and Northern Development, dealing with the welfare of the Canadian Indian and Eskimo, and the Northern Canada Power Commission, a public utility, are actively concerned with the development of freeze-protected water and sewer utilidor systems. A few large utilidor systems have been built in Canada which operate successfully, but the greatest need is for a low-cost system which can be installed and operated with local labor. Electrical power is generally not available in quantity so that it could be used for continuous freeze protection; instead, one of the fluids in the system is circulated through a closed pipe loop with heat being added to the fluid at the pumping station as required to maintain a temperature above freezing. In most cases, potable water is the continuously circulated fluid; however, at Frobisher Bay, NWT, sewer effluent is circulated. Figures A-1, A-2, and A-3 illustrate in cross section the utilidors at Rankin Inlet, Frobisher Bay, and Fort McPherson, NWT, respectively. These systems, which cost from $14 to $35 per foot in Canadian dollars, have been in use from 1 to 12 years. They are small systems serving only a relatively few families. Figure A-4 illustrates a new small utilidor system for water and sewage in the native housing area at Inuvik, NWT; it utilizes recirculated warm water to prevent freezing.

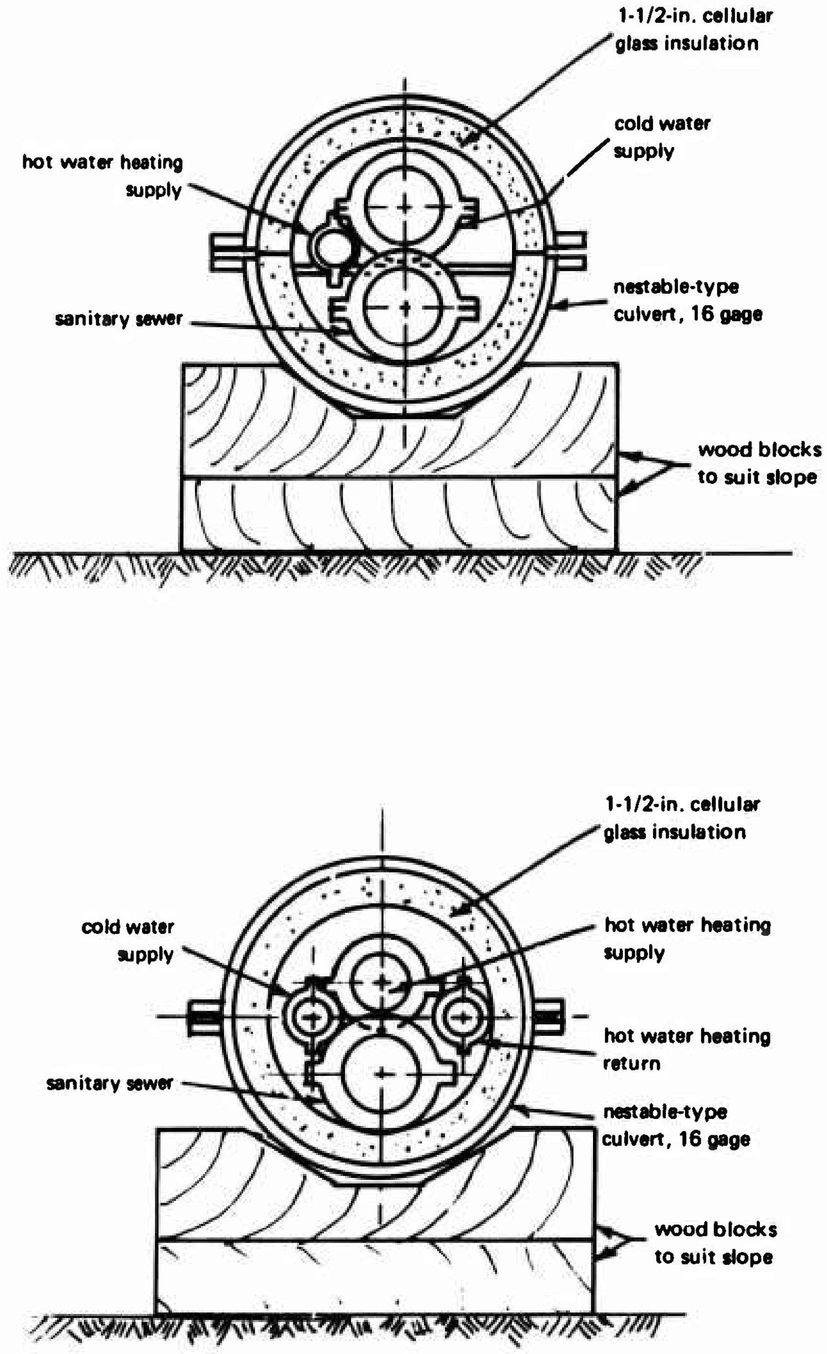
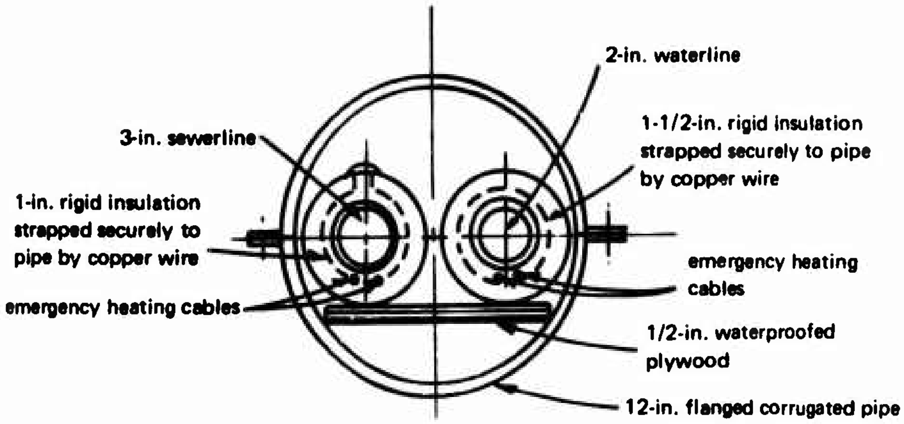


Figure A-1. Utilidors at Rankin Inlet, NWT. (Designed by the Technical Services Branch, Department of Indian Affairs & Northern Development.)

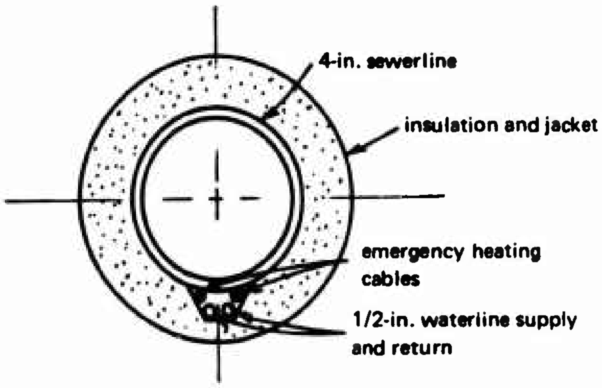


(a) Section of Circulating Pipes and Protective Casting

NOTES:

Provide 1/2-in. holes in bottom of corrugated pipe for drainage at low points. Provide 4-in. drain connection from corrugated pipe to free outlet at lowest point in line.

Drainage of 2-in. and 3-in. lines when required will be by removing victaulic coupling at location desired.



(b) Section of House Connection (not to scale)

Figure A-2. Utilidors at Frobisher Bay, NWT. (Designed by the Technical Services Branch, Department of Indian Affairs & Northern Development.)

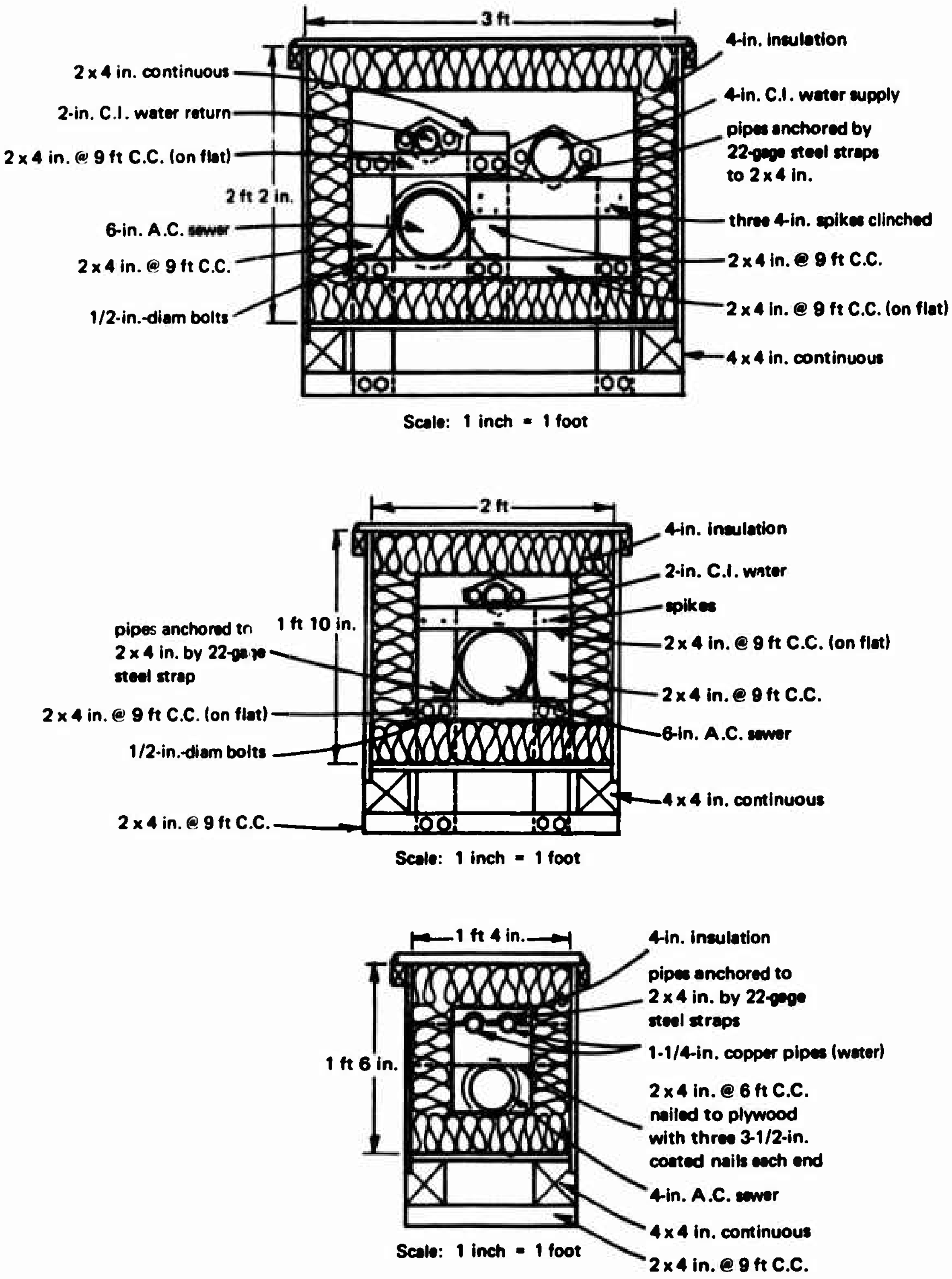


Figure A-3. Utilidors at Fort McPherson, NWT. (Designed by the Department of Public Works for Department of Indian Affairs & Northern Development.)

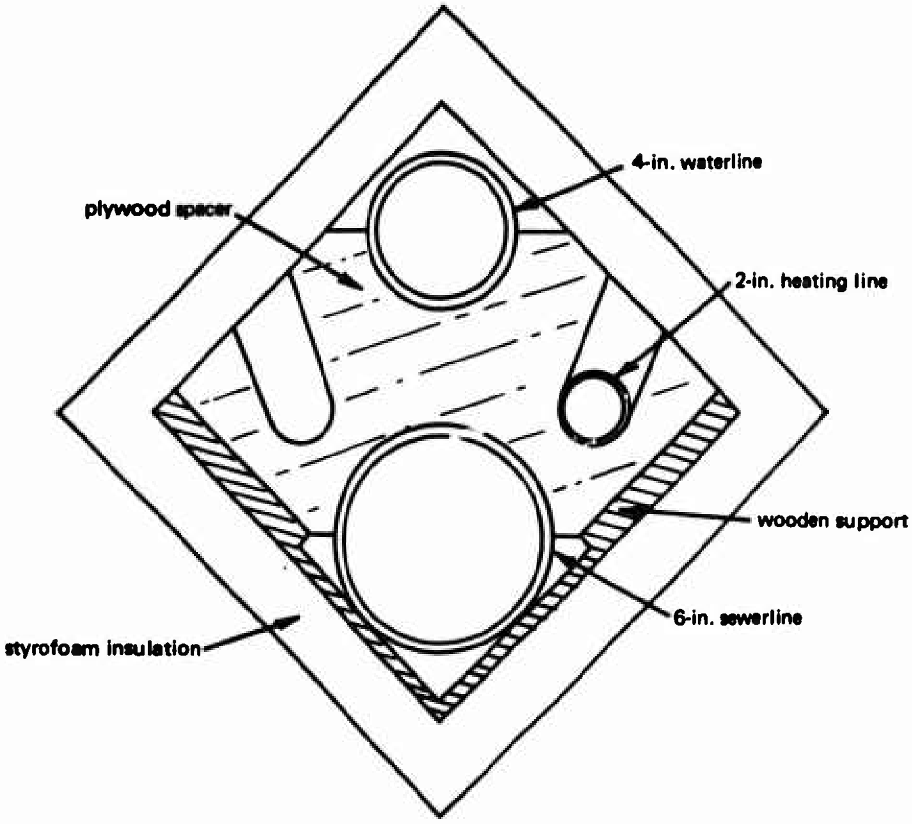


Figure A-4. Cross section of new utilidor for Inuvik, NWT. (Designed by The Northern Canada Power Commission for Department of Indian Affairs & Northern Development.)

Fort Churchill

The facilities at Fort Churchill, Manitoba, were built for the Canadian Army but are now occupied by civilians associated with a government medical and educational program for residents of northern Canada. The buildings are mostly two-story barracks with interconnecting corridors and are constructed on gravel fill placed over rock out-croppings (Figure A-5). The water, sewage, central heating, and nearly all electric lines are located in below-grade, concrete-walled utilidors which were constructed before the gravel fill was placed. Where possible, the utilidors are located under the connecting corridors between buildings. In other areas, the utilidor is covered with 4-inch-thick wood decking which serves as entry walkways to some buildings (Figure A-6). The steam-heating lines are welded steel pipe with fiber glass insulation. The waterlines are copper, and the sewerlines are cast iron with bolted bell joints. In some areas, the walls of the utilidor are insulated with either rigid fiber glass board or rigid excelsior board. Fire hydrants are located in small houses over the utilidor (Figure A-7).

Figure A-5. Rock outcrop covered with gravel fill at Fort Churchill.

Figure A-6. Utilidor under entry to building at Fort Churchill.

Figure A-7. Fire hydrant in small house over utilidor at Fort Churchill.

Because of below-grade construction, this system is affected little by changing weather conditions. Freezing has occurred in isolated areas and has been usually corrected by removing the insulation from the heating line to increase the air temperature of the utilidor at these points. When snow over the utilidor melts, water, which may leak through the wood cover, drains away through the gravel bottom of the trench.

The Department of Public Works of Canada, which operates the Fort Churchill facilities, has had little trouble with the utilidor system. The most frequent maintenance problem is associated with pipe expansion. Both bellows-type and sleeve-type expansion joints are used. In general, the sleeve-type joint is preferred and gives good service through an annual maintenance program.

Sewage from Fort Churchill is dumped onto the ice in Hunson Bay through an insulated but unheated pipe (Figure A-8). A large inverted box with no floor at the end of the sewer line prevents the pipe from freezing by stopping cold winds from blowing into the end of the pipe. No difficulty has been experienced with the outfall either from line freezing or buildup of frozen sewage below the discharge structure.

Inuvik

The new Canadian town of Inuvik, NWT, located on the Mackenzie River, 125 miles above the Arctic Circle, has a population of about 3,000 people; it has been constructed entirely since 1955. The west, or native, section of Inuvik contains about 1,100 people and is serviced by the low-cost water and sewer utilidor illustrated in Figure A-4.

The eastern and central sections include the federal and better-quality private housing, schools, hospitals, and business district. This area is serviced by an extensive utilidor system (Figure A-9) that was selected as the most suitable one from several design and fabrication proposals submitted to the Northern Canada Power Commission by various Canadian manufacturers. The utilidor is basically a four-pipe system containing 6-inch steel, high-temperature, water heating supply and return lines, and 8-inch asbestos-cement sewer and treated potable waterlines. A portion of the utilidor also contains a 4-inch steel line for carrying untreated river water to the reservoir lake above the town. Figure A-10 shows the arrangement of pipes within the utilidor which is made with a welded-steel frame and aluminum panels containing 3 inches of fiber glass insulation. Service connections to residences and small commercial and public buildings are made using a smaller utilidor of similar construction (Figure A-11).

The terrain on which the town is built rises gently from the river into low hills. To accommodate the uneven ground and the grade required for the gravity sewerline, the utilidor is supported on untreated wood piling set in 10-foot-deep drilled holes. The utilidor was constructed in 10-foot modules with adjoining modules supported on common pilings, two pilings at one end and one piling at the other end (Figure A-12). At points where the utilidor changes direction, 10-inch WF steel piling or 6-inch well casing are used to resist expansion forces in the lines. Figures A-13, A-14, and A-15 show some of these rigid steel structures. Concrete pile caps, cast in-place, are used as anchors at the corners and every 40 to 100 feet on straight runs. Figures A-16 and A-17 show typical concrete caps on wood pilings. Branch connections and valving in the main utilidor are housed in enclosures large enough to permit routine maintenance without removing wall panels (Figure A-18). Valves and firehose connections are located periodically throughout the system and are accessible behind an easily removed insulated enclosure (Figure A-19).

Sewage in Inuvik is discharged into a lagoon formed by diking off a shallow natural lake approximately one-half mile from the center of town. An 8-inch steel line with polystyrene insulation and aluminum jacketing supported on wood pilings (Figure A-20) carries the sewage to the lagoon (Figure A-21).

The utilities at Inuvik are operated and maintained by the local office of the Northern Canada Power Commission. During an inspection and discussion of the system, a number of pertinent facts were revealed regarding operation and maintenance.

Fabrication Cost. The average cost of the initial utilidor was $200 to $225 per foot in Canadian dollars using domestic labor and materials. This included tricone roller-rock-bit drilling and pile placement estimated at $100 per pile. Recent additions to the system cost about the same with savings in design cost being offset by increased labor and materials cost.

Freezing. Both the waterlines and sewerlines have frozen on occasion as the result of air stratification in the utilidor and chimney effects which cause low points in the utilidor to be particularly cold. It has been recommended that, in future designs, waterlines and sewerlines be placed above the heating lines and bulkheads be placed periodically throughout the system to control interior air circulation.

Operating Cost. It is estimated that 15 to 20% of the high-temperature water heating system capacity is used to prevent freezing in the utilidor.

Expansion. The steel heating lines present the greatest expansion problem. Bellows-type expansion joints are considered satisfactory if alignment is maintained on adjoining pipe sections. Sleeve-type joints are also satisfactory but require periodic maintenance.

Pile Heaving. Insufficient placement depth has resulted in pile heaving in some areas. When this occurs, the top of the pile is cut off, and the system is realigned (Figure A-22).

Vandalism. Substantial damage has been done to the utilidors by both children and adults. The tops of the utilidors are tempting walkways for children and have been dented in some areas. The original thin aluminum jacketing over the insulation on the sewerline is easily damaged (Figure A-23), and an additional corrugated cover has been banded in-place (Figure A-20).

High Water Temperature. The 300°F water in the heating mains is used in operating sterilizers at the Inuvik hospital and for producing steam in other areas. This use requires maintaining the same heating line temperature winter and summer. As a result, summer temperatures within the utilidor exceed 100°F, and undesirably warm potable water is produced. High water usage in the summer is partially attributed to persons running the taps in an attempt to obtain a cooler supply.

Figure A-8. Sewage outfall line and outfall house at Fort Churchill.

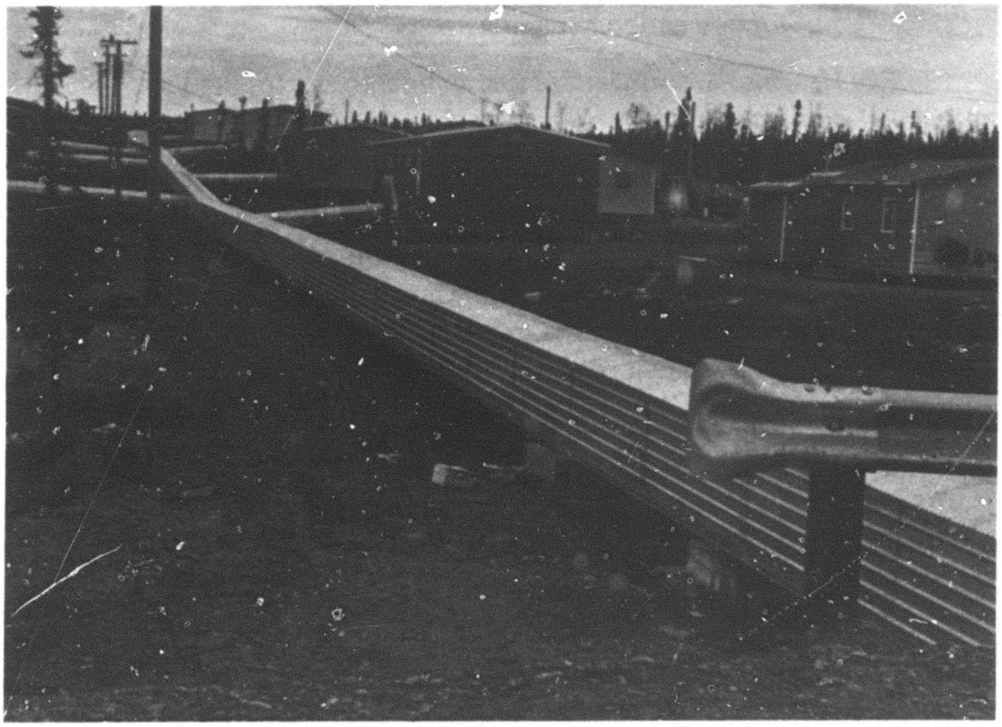


Figure A-9. Portion of utilidor system at Inuvik, NWT.

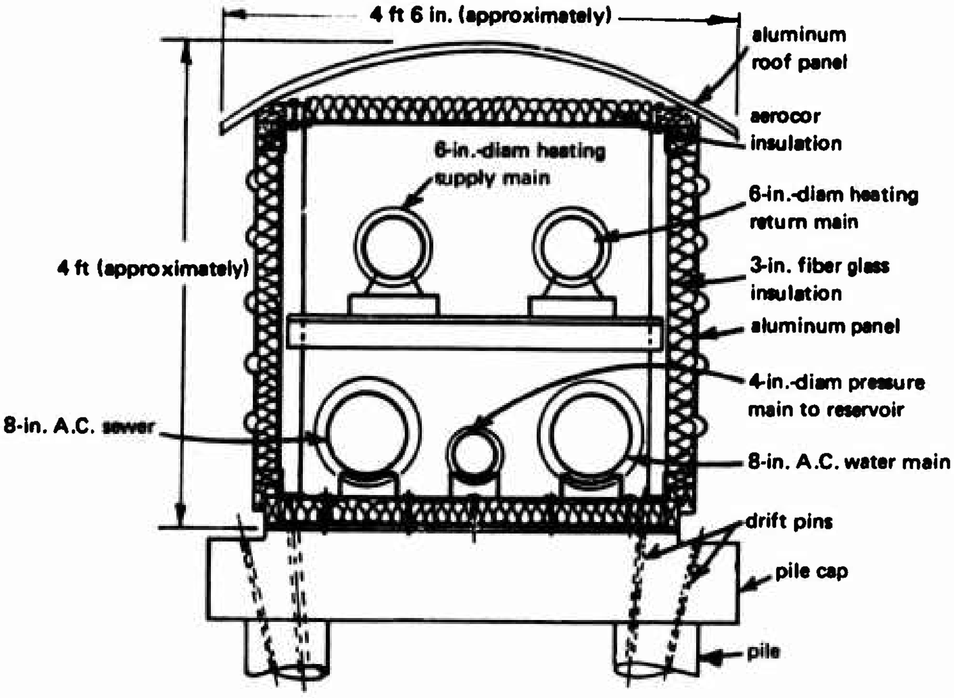


Figure A-10. Cross section of main utilidor at Inuvik, NWT.

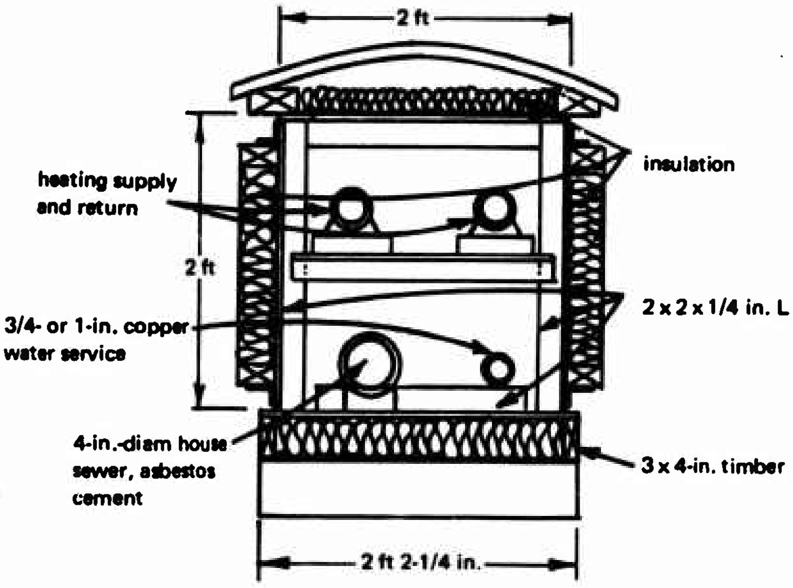


Figure A-11. Utilidor for service branch connections at Inuvik, NWT.

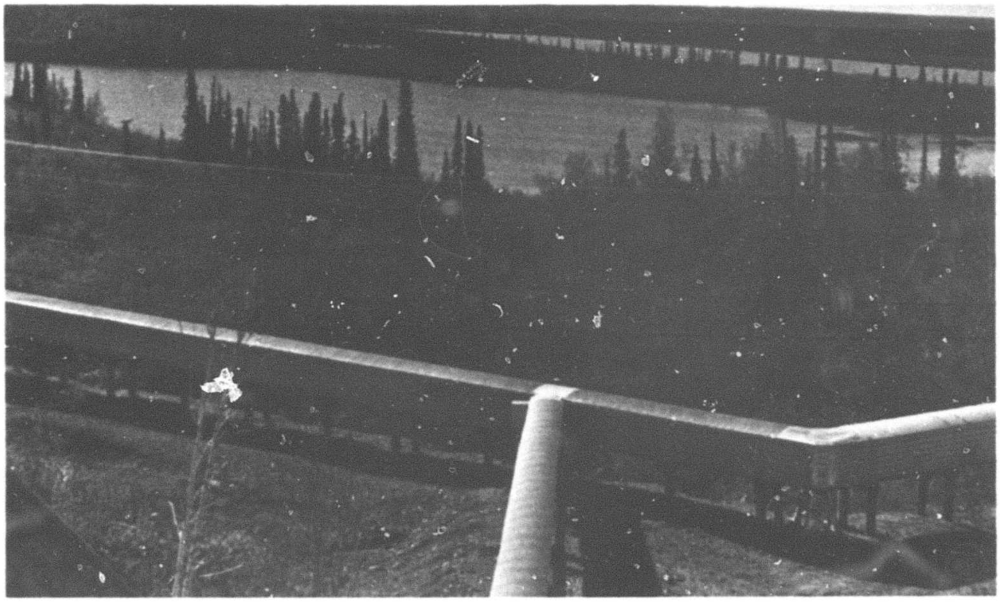


Figure A-12. General view of utilidor showing pile spacing.

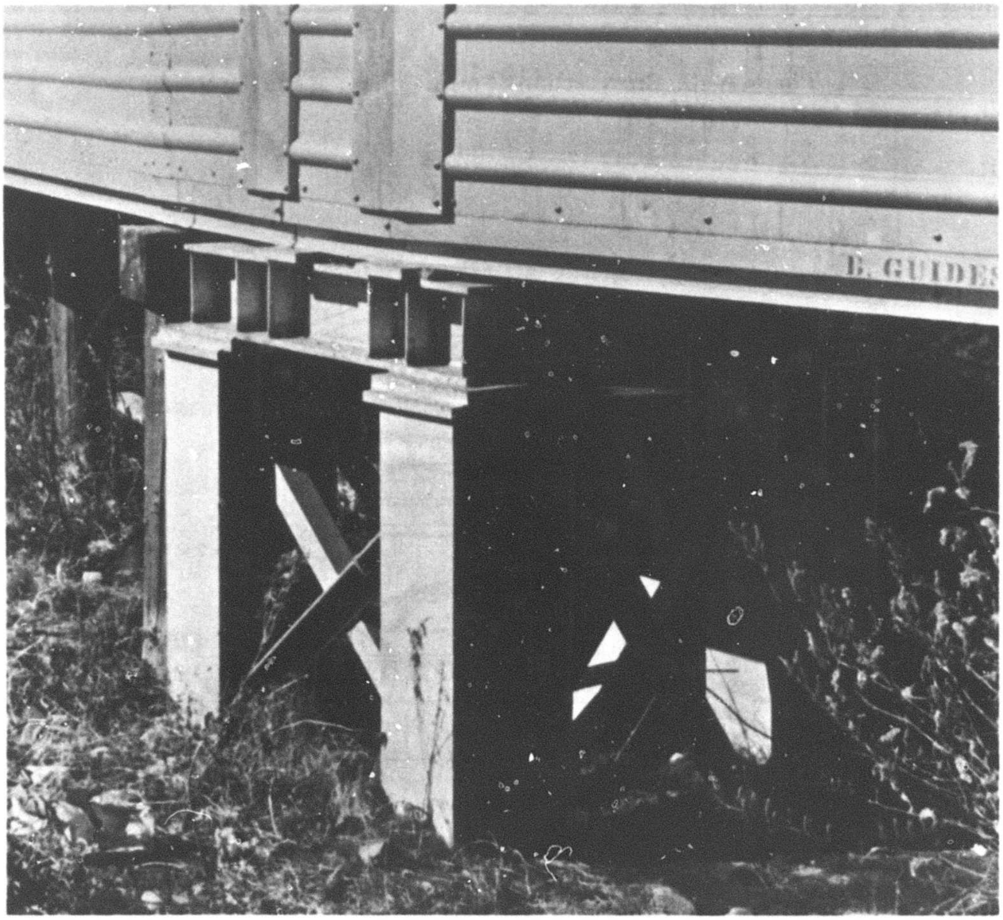


Figure A-13. Typical 10-inch WF anchor piling.

Figure A-14. Anchor piling.

Figure A-15. Anchor on 6-inch well casing.
All fabrication done on site.

Figure A-16. Typical concrete anchor points on wood piling.

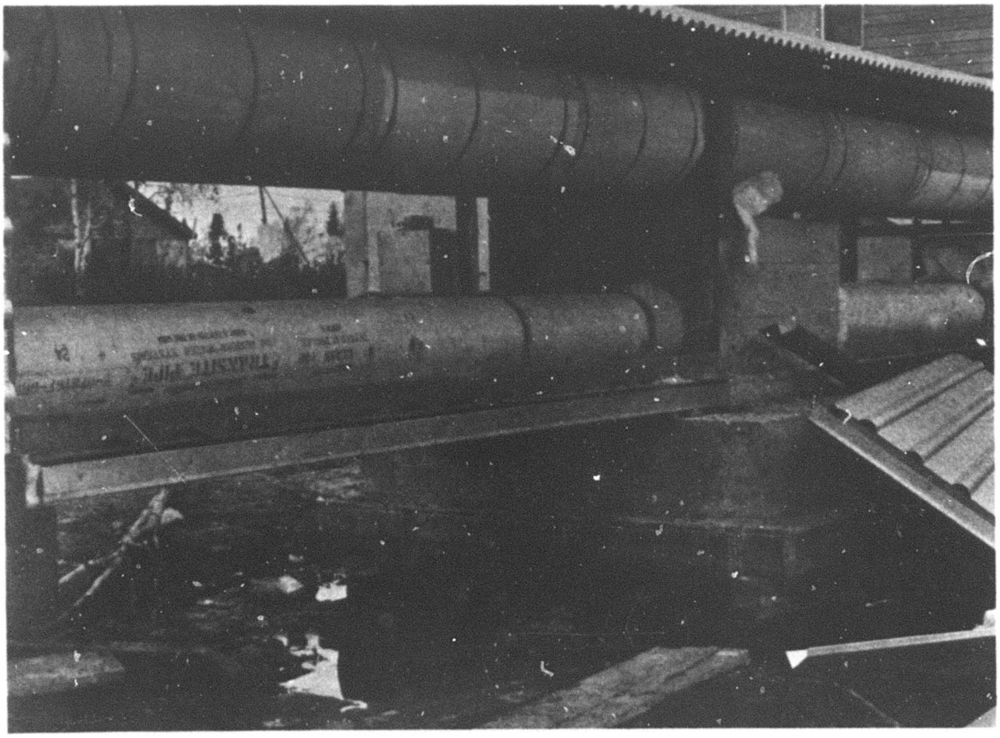


Figure A-17. Anchor point on straight section of utilidor. Concrete block on three wood pilings.

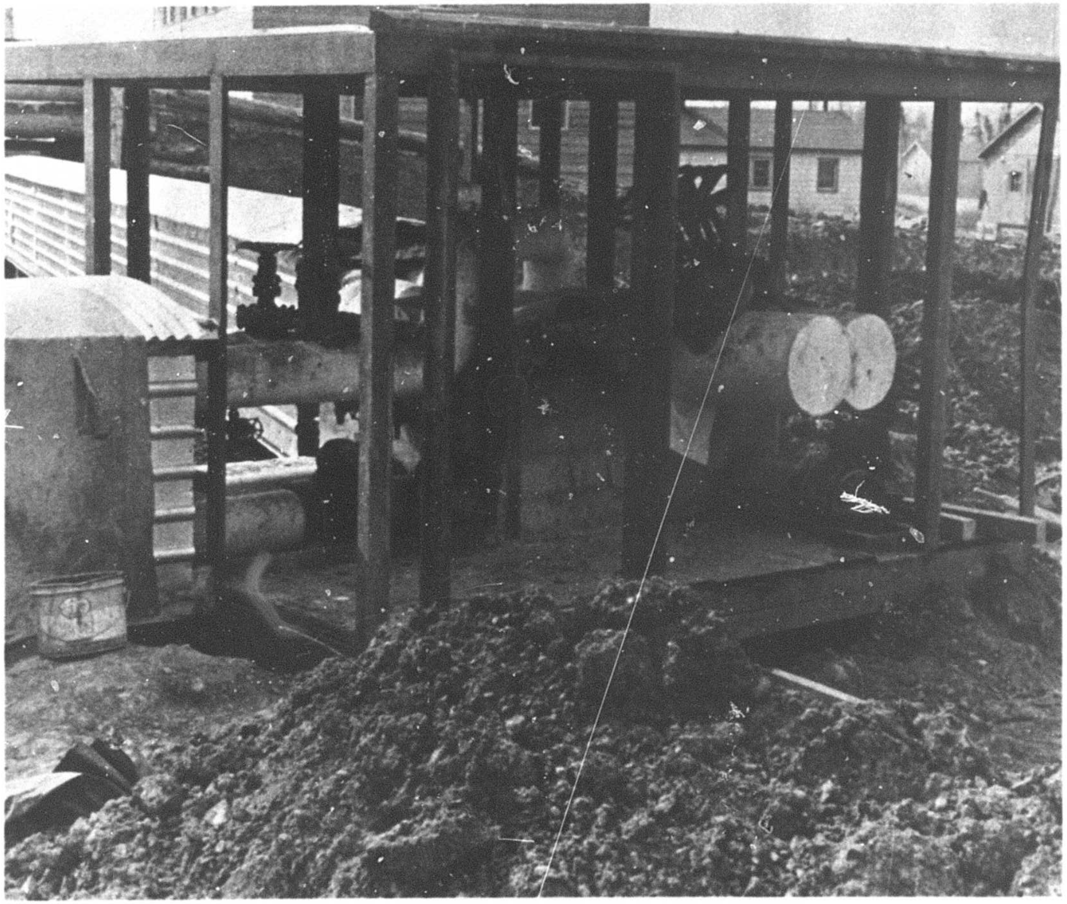


Figure A-18. Valve house under construction.

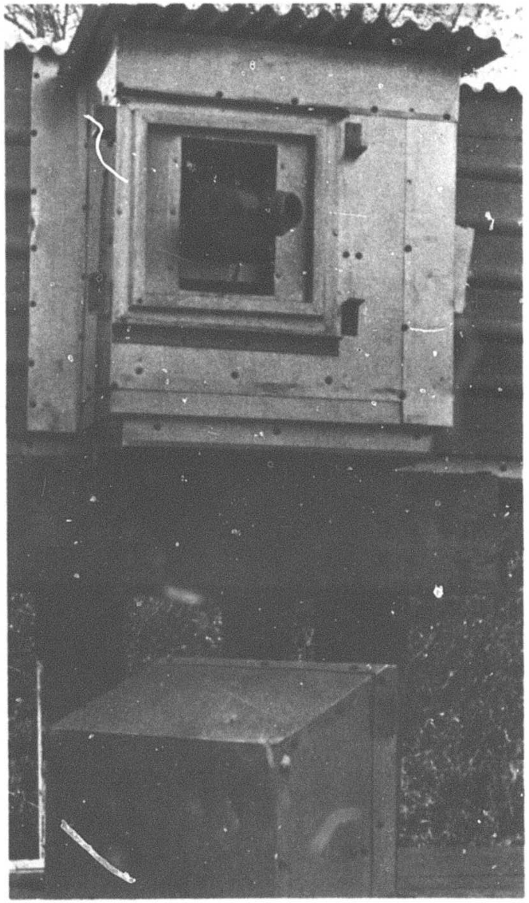


Figure A-19. Firehose connection; insulated enclosure removed.

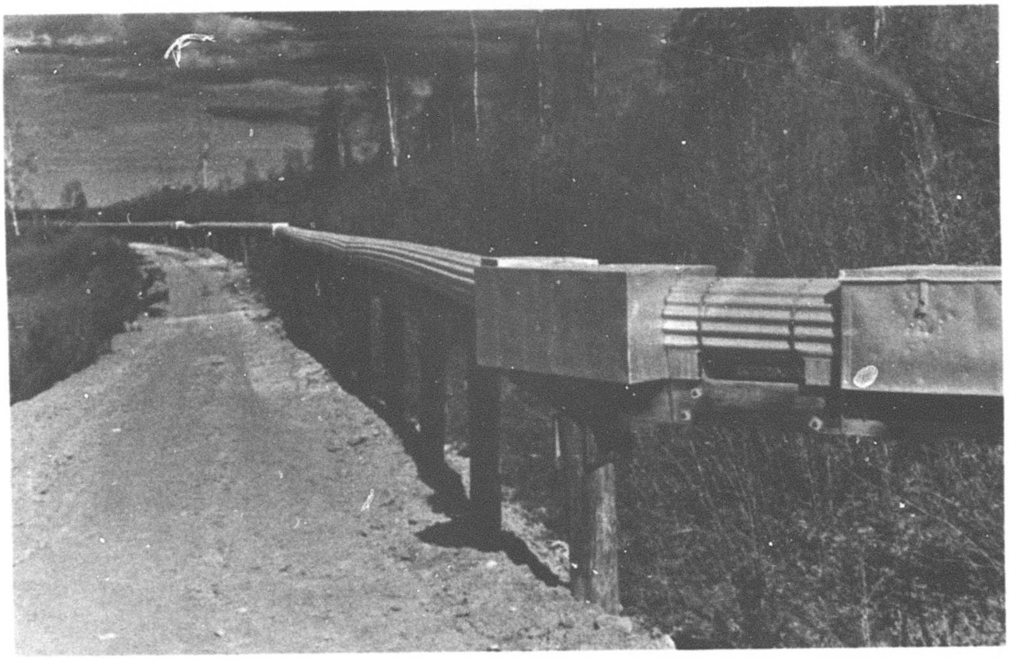


Figure A-20. Eight-inch sewerline with polystyrene insulation and extra corrugated aluminum cover.

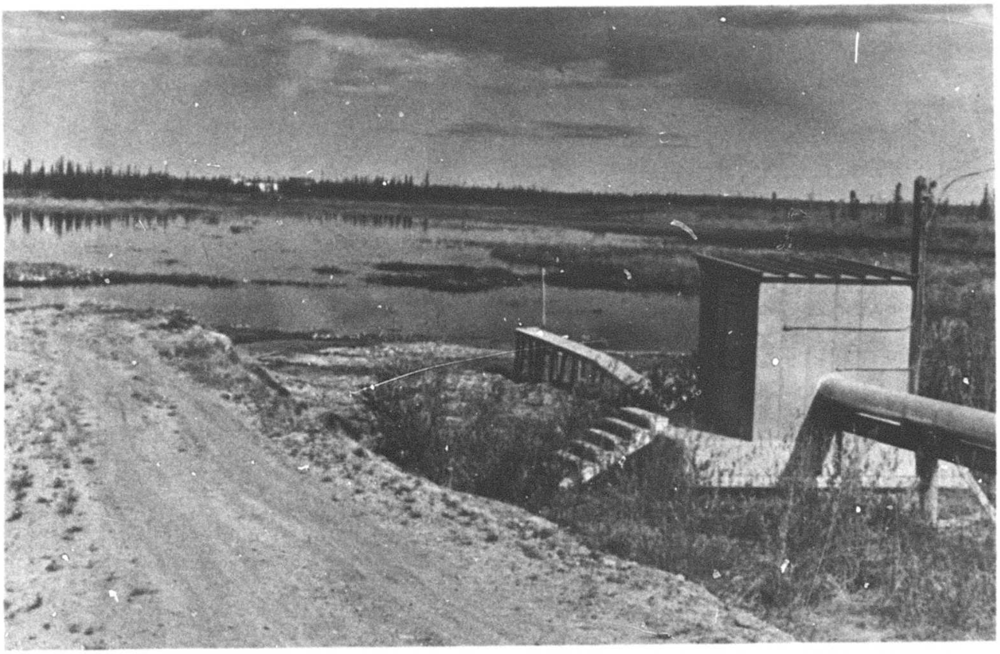


Figure A-21. Sewage lagoon at Inuvik, NWT.

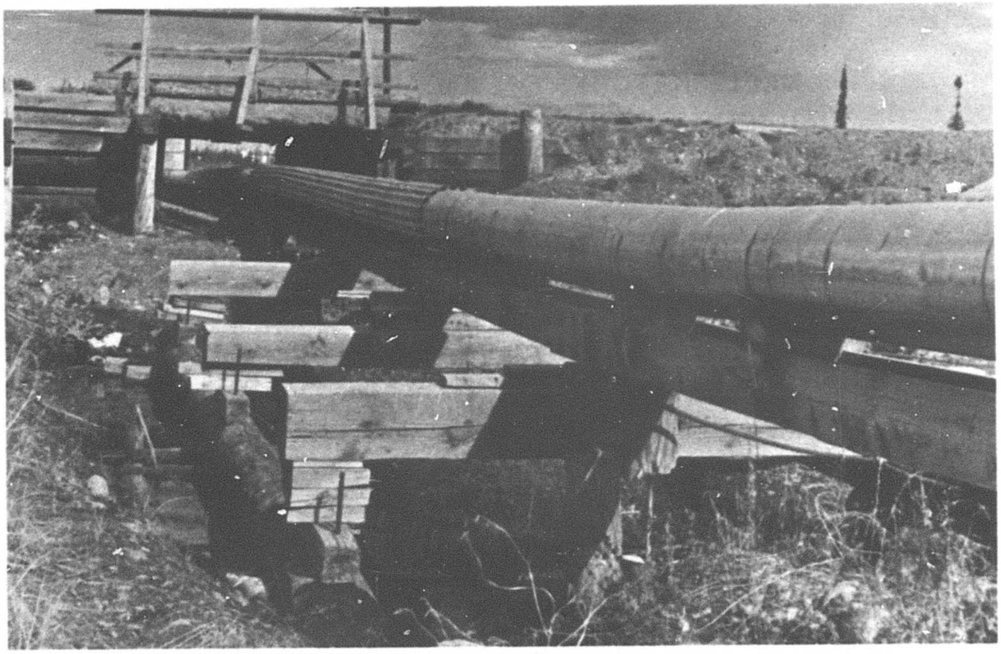


Figure A-22. Realignment necessary on sewerline due to pile heaving. Note cut pile.

Figure A-23. Sewerline to sewage lagoon at Inuvik, NWT. Urethane insulation and aluminum jacket damaged by vandals.

Appendix B

NCEL SKETCHES ON AN ABOVE-GRADE UTILIDOR DESIGN FOR NAVY APPLICATION

Sketch Number	Title
SK 1105	Typical Utilidor Module
SK 1106	Typical Straight Run Anchor and Pile Bent
SK 1107	90° Bend and Anchors
SK 1110	Fire Hydrant Service
SK 1112	Utilidor Valving
SK 1123	Utilidor Service Connection

The above sketches are dated January 1969; they are on file at NCEL.

Appendix C

THERMAL ANALYSIS OF ABOVE-GRADE UTILIDOR*

DESIGN PARAMETERS

The design of a utilidor involves the consideration of many different combinations of pipe size, piping array and geometric relationship, casing shape, and piping and casing insulations. It is useful to examine the manner in which an acceptable system must operate and, as a result, to identify those simplifications which are sufficiently valid to justify their use in a general analysis.

For circulation of hot water for heating service, the hot waterline must make two passes through the utilidor, an external load being served between passes. This line is the primary heat source in the utilidor. In order for the heat transferred in the utilidor to be small in comparison with that in the external load, the temperature drop in the hot water during each pass must be much smaller than that in the external load; otherwise an uneconomically large fraction of the total heat input to the hot water would be dissipated in the utilidor. In addition, the temperature of the air inside the utilidor casing must be much less than that of the circulating hot water to prevent undesirable overheating of the other service lines in the casing. Therefore, the temperature of the primary heat source inside the utilidor is very nearly constant over the entire length.

The ambient air outside the utilidor casing is usually the primary heat sink in the system. At a very high flow rate in one of the service lines other than the hot waterline, the ambient air may become secondary to that line as a sink. However, in such an event, the liquid flowing through that line will undergo very little temperature change because of its high mass flow rate.

Also, a primary objective in the design must be to prevent the temperatures of the flowing liquids from either increasing or decreasing substantially under all combinations of operating and environmental conditions. Large temperature drops cannot be allowed since at least one fluid normally enters the utilidor at a temperature only about $10^{\circ}F$ above its freezing point. Allowing the temperatures to rise is undesirable for several reasons: it would waste energy which could otherwise be delivered to the external heating load, the potable water could become too warm for drinking purposes, and the sewage temperature could rise to an undesirable value. Consequently, in an acceptable

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* Extracted from Reference 3.

system design, the primary heat sink or sinks must undergo little or no temperature change along the length of the utilidor. Therefore, the temperatures and thermal impedances associated with each of the service lines and the casing will be essentially constant throughout a utilidor run. On this basis, it is concluded that the temperature of the air inside the utilidor casing can be treated as a constant in the analysis.

GENERAL ANALYSIS

The analysis which follows considers the general case of a utilidor having an arbitrary shape and containing "n" lines, one of the lines being the hot waterline that makes two passes. Input quantities involve the liquid properties, flow rates, and inlet temperatures; the pipe and insulation sizes and properties for each line; the utilidor casing length, surface area, properties, and thicknesses; the external heating load; and the ambient air temperatures to which the utilidor is exposed. The analytical approach is one in which a value for the temperature of the air inside the utilidor is assumed, the heat which would be transferred to or from each line and through the casing at that air temperature is calculated, the assumed air temperature is corrected by an amount which will decrease the heat imbalance, and the process is repeated. Using this iterative procedure, the imbalance approaches zero, and the calculated air temperature converges on its real value. When the air temperatures calculated in two successive iterations differ by an acceptably small amount, the last calculated value and its corresponding liquid temperatures are the values being sought.

Interior and exterior surface coefficients are both included for all lines because either or both can control heat transfer if the line is not well insulated. The exterior of the casing is exposed to weather, and the combined free and forced convection coefficient at the outer surface would be expected to be 3 to 9 Btu/hr ft^2 $^\circ$F. By contrast, the primary mode of heat transfer to or from the innermost surface of the casing is natural convection, and the natural convection coefficient can become small for a small surface ΔT or for a large perimeter of the utilidor cross section. Therefore, although the thermal impedances at both the internal and external surfaces will normally be negligible compared with that of the casing insulation, it was decided to include the internal coefficient to avoid the possibility of error in certain cases. If one should want to account for the exterior coefficient, it can be done very easily by dividing the computed heat flux through the casing by the exterior surface coefficient and subtracting the resulting ΔT from the value of ambient air temperature used in the computation; the computed results are then valid for the resulting adjusted value of ambient temperature.

Examining the n^{th} line in the vicinity of the liquid inlet to the utilidor, the heat transferred is*

$$Q_n = (UA)_n (T_{in} - T_u) = (hA)_{3n} (T_{3n} - T_u)$$

from which

$$\frac{1}{(UA)_n} = \frac{(T_{in} - T_u)}{(hA)_{3n} (T_{3n} - T_u)} \tag{1}$$

For thermal resistances in series radially, as shown in Figure C-1,

$$\frac{L}{(UA)_n} = \frac{1}{D_{1n} h_{1n}} + \frac{\ln(D_{2n}/D_{1n})}{2 k_{2n}} + \frac{\ln(D_{3n}/D_{2n})}{2 k_{3n}} + \frac{1}{D_{3n} h_{3n}} \tag{2}$$

In addition, by definition,

$$\frac{(hA)_{3n}}{L} = \pi D_{3n} h_{3n} \tag{3}$$

Substitution of Equations 2 and 3 into Equation 1 yields

$$\frac{1}{D_{1n} h_{1n}} + \frac{\ln(D_{2n}/D_{1n})}{2 k_{2n}} + \frac{\ln(D_{3n}/D_{2n})}{2 k_{3n}} = \frac{1}{D_{3n} h_{3n}} \left(\frac{T_{in} - T_u}{T_{3n} - T_u} - 1 \right) \tag{4}$$

For streamline flow inside circular tubes ($N_{Re_n} < 2{,}100$), the Nusselt number has minimum asymptotic values of 3.66 for the constant wall temperature case and 4.36 for the constant heat flux case.[4] Therefore, a value of 4 was selected for use in this analysis. For turbulent flow ($N_{Re_n} > 10{,}000$), the Nusselt number is given by[5]

$$N_{Nu_n} = 0.023 N_{Re_n}^{0.8} N_{Pr_n}^{1/3} = \frac{h_{1n} D_{1n}}{k_{1n}}$$

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* See Nomenclature on foldout at end of report for definition of symbols.

Therefore,

$$\left.\begin{aligned}\frac{1}{D_{1n}h_{1n}} &= \frac{0.25}{k_{1n}} && \text{if } N_{Re_n} < 2{,}100\\ &= \frac{43.5}{k_{1n}N_{Re_n}^{0.8}N_{Pr_n}^{1/3}} && \text{if } N_{Re_n} > 10{,}000\end{aligned}\right\} \tag{5}$$

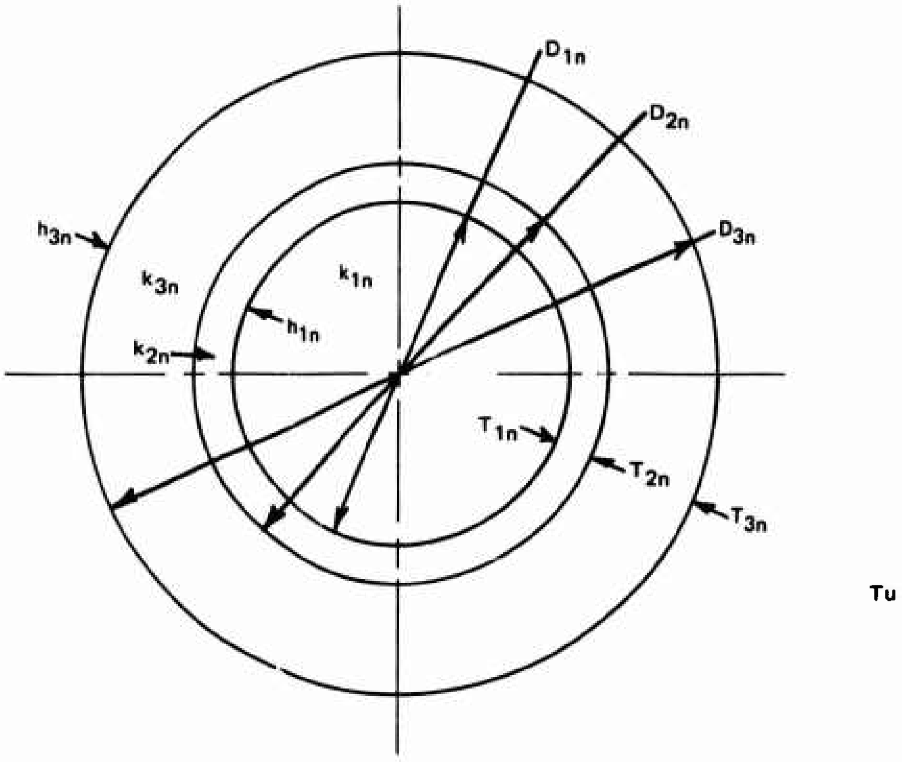

Figure C-1. Cross section through Line n.

Heat transfer from the exterior of the line is by natural convection of the air inside the utilidor casing. To identify the empirical relationship which should be used to calculate h_{3n}, it is first necessary to examine the range of possible values for the product of the Grashof and Prandtl numbers at the exterior of the line. This product is given by

$$P_n = D_{3n}^3(|T_{3n} - T_u|)\left(\frac{\rho^2 g\beta c_p}{\mu k}\right)_{air}$$

For air temperatures between 0 and 300^{O}F, the air properties term is always between 3.1 x 10^5 and 3.1 x 10^6 ft^{-3} ^{O}F$^{-1.5}$ The values of D_{3n} will range from about 0.2 to 1 foot. Therefore, $10^3 < P_n < 9.4 \times 10^6$ for $(|T_{3n} - T_u|)$ between 0.4 and 300^{O}F.

The appropriate relationship for calculation of the natural convection coefficient is then[4]

$$h_{3n} = 0.27 \left(\frac{|T_{3n} - T_u|}{D_{3n}} \right)^{0.25} \tag{6}$$

which is valid for $10^3 < P_n < 10^9$. The absolute value of the temperature difference is employed because h_{3n} must be a positive real number regardless of the direction of heat transfer.

Substituting Equation 6 into Equation 4 and rearranging,

$$B_n E_n (|T_{3n} - T_u|)^{0.25} (T_{3n} - T_u) + (T_{3n} - T_u) - (T_{in} - T_u) = 0 \tag{7}$$

where
$$B_n = \frac{1}{D_{1n} h_{1n}} + \frac{1n(D_{2n}/D_{1n})}{2k_{2n}} + \frac{1n(D_{3n}/D_{1n}}{2k_{3n}} \tag{8}$$

with $1/D_{1n}h_{1n}$ calculated according to Equation 5 and

$$E_n = 0.27 D_{3n}^{0.75} \tag{9}$$

It is physically impossible for the quantities $(T_{3n} - T_u)$ and $(T_{in} - T_u)$ to be of opposite sign, because T_{3n} must lie between T_{in} and T_u. Therefore, letting

$$X_n = (|T_{3n} - T_u|) \tag{10}$$

Equation 7 can be rewritten as

$$B_n E_n X_n^{1.25} + X_n - (|T_{in} - T_u|) = 0 \tag{11}$$

Solving Equation 11 for X_n and substituting into Equation 6,

$$M_n = \frac{1}{D_{3n} h_{3n}} = \frac{1}{E_n X_n^{0.25}} \tag{12}$$

Equation 2 can then be rewritten as

$$(UA)_n = \frac{\pi L}{B_n + M_n} \tag{13}$$

Use of Equation 13 is strictly valid only near the entrance to the line, because the value of M_n is based on the liquid inlet temperature. However, because h_{3n} is a weak function of X_n and $(T_{in} - T_u)$, Equation 13 can be applied with very little error over the entire length of the line even if the liquid temperature changes markedly during passage through the utilidor.

For one pass of liquid through the nth line, the log mean temperature difference between the liquid and the air inside the utilidor casing is

$$(LMTD)_n = \frac{T_{in} - T_{on}}{\ln(T_{in} - T_u) - \ln(T_{on} - T_u)}$$

where T_{in} and T_{on} are the liquid inlet and outlet temperatures, respectively, for that pass. The heat exchanged between the liquid and the air inside the casing is then

$$Q_n = (UA)_n (LMTD)_n = \frac{(UA)_n (T_{in} - T_{on})}{\ln(T_{in} - T_u) - \ln(T_{on} - T_u)} \tag{14}$$

This exchange of heat causes a liquid temperature change according to

$$Q_n = W_n c_{pn} (T_{in} - T_{on}) \tag{15}$$

Solving Equation 14 and 15 simultaneously for T_{on},

$$T_{on} = T_u + (T_{in} - T_u) e^{-(UA)_n / W_n c_{pn}} \tag{16}$$

If the line makes a second pass through the utilidor, it is necessary to use in Equation 16 a second-pass inlet temperature equal to the first-pass outlet temperature minus the temperature change due to removing heat from the liquid between the first and second passes. The latter temperature change is

$$F_n = \frac{Q_{rn}}{W_n c_{pn}} \tag{17}$$

The utilidor casing can have virtually any closed cross-sectional shape. The combined thickness of the casing wall and insulation is small when compared with the casing perimeter in multiple line systems. Heat transfer to the interior surface is by natural convection of the air inside the casing, while that at the exterior is by combined free and forced convection because the exterior is exposed to the wind; therefore, the thermal resistance at the outer surface is small when compared with the insulation and inner surface resistances and can be neglected. The total thermal resistance of the casing is then

$$\frac{1}{U_c} = \frac{1}{h_{ic}} + \frac{t_{c12}}{k_{c12}} + \frac{t_{c23}}{k_{c23}} \qquad (18)$$

The heat transferred through the casing is

$$Q_c = h_{ic} A_c (T_u - T_{ic}) = (UA)_c (T_u - T_a)$$

from which

$$\frac{1}{U_c} = \frac{T_u - T_a}{h_{ic}(T_u - T_{ic})} \qquad (19)$$

Solving Equations 18 and 19 simultaneously to eliminate U_c,

$$\frac{t_{c12}}{k_{c12}} + \frac{t_{c23}}{k_{c23}} = \frac{1}{h_{ic}}\left(\frac{T_u - T_a}{T_u - T_{ic}} - 1\right) \qquad (20)$$

Empirical relationships for calculation of h_{ic} have been identified only for certain simple shapes. Therefore, it is necessary that the surface be interpreted as a combination of simple shapes. For purposes of this analysis, the concept of an "equivalent square" shape having the same perimeter as the actual casing shape was selected. The dimension of each side of this equivalent square is then

$$P = \frac{A_c}{4L} \qquad (21)$$

It is assumed that one side of the square is parallel to the ground. For plane surfaces, the general expression for the natural convection coefficient is[4]

$$h = S\left(\frac{|\Delta T|}{P}\right)^{0.25} \qquad (22)$$

with **S** = 0.27 for heated plate facing up, or cooled plate facing down

= 0.12 for cooled plate facing up, or heated plate facing down

= 0.29 for vertical heated or cooled plate

Averaging the value of **S** over the square section, and combining Equations 21 and 22,

$$h_{ic} = 0.35\left(\frac{L}{A_c}\right)^{0.25}(|T_u - T_{ic}|)^{0.25} \tag{23}$$

Substituting Equation 23 into Equation 20 and rearranging,

$$B_c E_c X_c^{1.25} + X_c - (|T_u - T_a|) = 0 \tag{24}$$

where

$$X_c = |T_u - T_{ic}| \tag{25}$$

$$B_c = \frac{t_{c12}}{k_{c12}} + \frac{t_{c23}}{k_{c23}} \tag{26}$$

$$E_c = 0.35(L/A_c)^{0.25} \tag{27}$$

The argument for use of absolute values of the temperature differences is the same as that advanced earlier for the individual lines. Solving Equation 24 for X_c and substituting that value into Equation 23,

$$M_c = \frac{1}{h_{ic}} = \frac{1}{E_c X_c^{0.25}} \tag{28}$$

Equation 18 can then be rewritten in the form

$$U_c A_c = \frac{A_c}{B_c + M_c} \tag{29}$$

At this point, sufficient information has been produced to determine whether the assumed value of T_u is correct and, if not, the correction that should be made to T_u for the next trial.

For the assumed T_u, the residual overall heat imbalance is the net heat transfer between the lines and the air inside the casing, minus the heat transfer to the utilidor environment; that is,

$$R = \sum_n [W_n c_{pn} (T_{in} - T_{on}) - Q_{rn}] - U_c A_c (T_u - T_a) \qquad (30)$$

If R is zero, the assumed value of T_u and the corresponding values of the other temperatures calculated are correct. If R does not equal zero, the value of T_u should be altered as follows and the calculation repeated.

The correction being sought, ΔT_u, is one which will produce a change ΔR such that

$$R_{j+1} = R_j + (\Delta R)_j \rightarrow 0 \qquad (31)$$

where the subscript "j" indicates the j^th^ trial. If the trial value of $(T_u)_j$ is altered by an amount $(\Delta T_u)_j$, the heat imbalance represented by Equation 30 will be altered by an amount approximately equal to

$$(\Delta R)_j = -(\Delta T_u)_j \left[(U_c A_c)_j + \sum_n p_n (U_n A_n)_j \right] \qquad (32)$$

Substituting Equation 32 into Equation 31,

$$(\Delta T_u)_j = \frac{R_j}{(U_c A_c)_j + \sum_n p_n (U_n A_n)_j} \qquad (33)$$

The value of T_u to be assumed for the next trial is, therefore,

$$(T_u)_{j+1} = (T_u)_j + (\Delta T_u)_j \qquad (34)$$

APPLICATION TO A FOUR-LINE SYSTEM

Many of the utilidors in service or under consideration use a four-line system to provide hot water heating, potable water, sewage, and raw water services. The hot water line makes two passes (supply and return) through the utilidor. The potable waterline and raw waterline each make a single pass with flow in the direction of the hot water supply, while the sewage line makes a single pass with flow in the direction of the hot water return. Designating the two-pass hot waterline as Line 1 and the single-pass potable water, sewage, and raw waterlines as Lines 2, 3 and 4, respectively, the general analysis presented in the preceding section leads to the following.

For the particular design to be considered, the input quantities are the flow rates and inlet temperatures; the pipe and insulation sizes and properties; the casing length, surface area, properties, and thicknesses; the external heating load; and the temperature of the utilidor environment.

To begin the calculations for a specific case, the Reynolds number

$$N_{Re_n} = \frac{1.275 W_n}{D_{1n} \mu_n} \tag{35}$$

is calculated for each of the four lines. Because relationships for prediction of heat transfer coefficient in transition flow do not exist, all Reynolds numbers must be less than 2,100 or greater than 10,000. All input values are then available for calculation of $(1/D_{1n}h_{1n})$, B_n, E_n, F_1 ($F_2 = F_3 = F_4 = 0$ for the system being considered), B_c, and E_c according to Equations 5, 8, 9, 17, 26, and 27, respectively; these quantities are essentially independent of T_u for a specific design.

At this point, a first trial value of T_u is assumed, and the following procedure is iterated to converge on an actual predicted value of T_u. The procedure is:

1. Calculate X_1 according to

$$B_1 E_1 X_1^{1.25} + X_1 - (|T_{i1} - T_u|) = 0$$

2. Calculate

$$M_1 = 1/E_1 X_1^{0.25}$$

3. Calculate

$$(UA)_1 = \pi L/(B_1 + M_1)$$

4. According to Equations 16 and 17, the outlet temperature from the second pass of Line 1 with heat removed between the first and second passes is

$$T_{o1} = T_u + \left\{ \left[(T_{i1} - T_u)\, e^{-(UA)_1/W_1 c_{p1}} \right] - \frac{Q_{r1}}{W_1 c_{p1}} \right\} e^{-(UA)_1/W_1 c_{p1}}$$

Lines 2, 3, and 4 all make single passes and are calculated according to:

5. $B_n E_n X_n^{1.25} + X_n - (|T_{in} - T_u|) = 0$

6. $M_n = 1/E_n X_n^{0.25}$

7. $(UA)_n = \pi L/(B_n + M_n)$

8. $T_{on} = T_u + (T_{in} - T_u)\, e^{-(UA)_n/W_n c_{pn}}$

The corresponding equations for the casing are:

9. $B_c E_c X_c^{1.25} + X_c - (|T_u - T_a|) = 0$

10. $M_c = 1/E_c X_c^{0.25}$

11. $(UA)_c = A_c/(B_c + M_c)$

12. For the assumed value of T_u, the heat imbalance in the system would be

$$R = W_1 c_{p1}(T_{i1} - T_{o1}) - Q_{r1} + W_2 c_{p2}(T_{i2} - T_{o2}) + W_3 c_{p3}(T_{i3} - T_{o3})$$
$$+ W_4 c_{p4}(T_{i4} - T_{o4}) - (UA)_c(T_u - T_a)$$

13. The approximate error in the assumed value of T_u is

$$(\Delta T_u) = R/[(UA)_c + 2(UA)_1 + (UA)_2 + (UA)_3 + (UA)_4]$$

14. Correct the previous value of T_u by the amount (ΔT_u) and repeat the calculations beginning at Step 1. As (ΔT_u) becomes smaller with each successive trial, all the temperatures calculated approach their actual predicted values.

A number of sample calculations using this technique have shown that the value of (ΔT_u) is very nearly zero after only three or four iterations even if the initial assumed value of T_u is much too high or too low.

Because the calculating procedure is iterative and a large number of cases must be examined to identify the best design for a specific application, this analysis was programmed in IBM 1620 Fortran II-D language. This program and its nomenclature are described in Appendix D.

LATERAL BRANCH CIRCUITS

The analysis in its present form applies specifically to the case of a single utilidor run without branches. To use the program for analysis of cases which involve lateral branch circuits, it is necessary to analyze the individual run segments parametrically and search for temperature matches at the branch points.

SOLAR HEATING

The effects of solar heating on utilidor performance during the summer are dependent on the specific utilidor configuration, orientation, and location as well as the external surface convective coefficient, the solar absorptivity and thermal emissivity of the casing outer surface, and the thermal lags in the system. Orientation relative to the incident radiation is dependent on the time of day and the solar declination on that day. It is very difficult to account in detail for all these items in a manner that is sufficiently general to be of practical value. However, there is a simple technique which can be used to account for solar heating in summer.

NCEL measurements made in mid-July at Port Hueneme, California, on internally insulated aluminum and galvanized steel utilidor casings of the design shown in Figure C-2 indicate that solar heating of the metal surface raises the average temperature of the surface by a maximum of 26°F. By painting the surface with one coat of white paint to obtain a much lower ratio of solar absorptivity to thermal emissivity, the casing average temperature rise attributable to solar heating was reduced to a maximum of 13°F. The corresponding values for polar regions would be less because of the greater geographical latitude. Therefore, one can account conservatively for solar heating by entering the computer code in Appendix D with an ambient air temperature value equal to the actual air temperature plus 26°F for an unpainted metal casing surface or plus 13°F for a nonmetallic white casing surface.

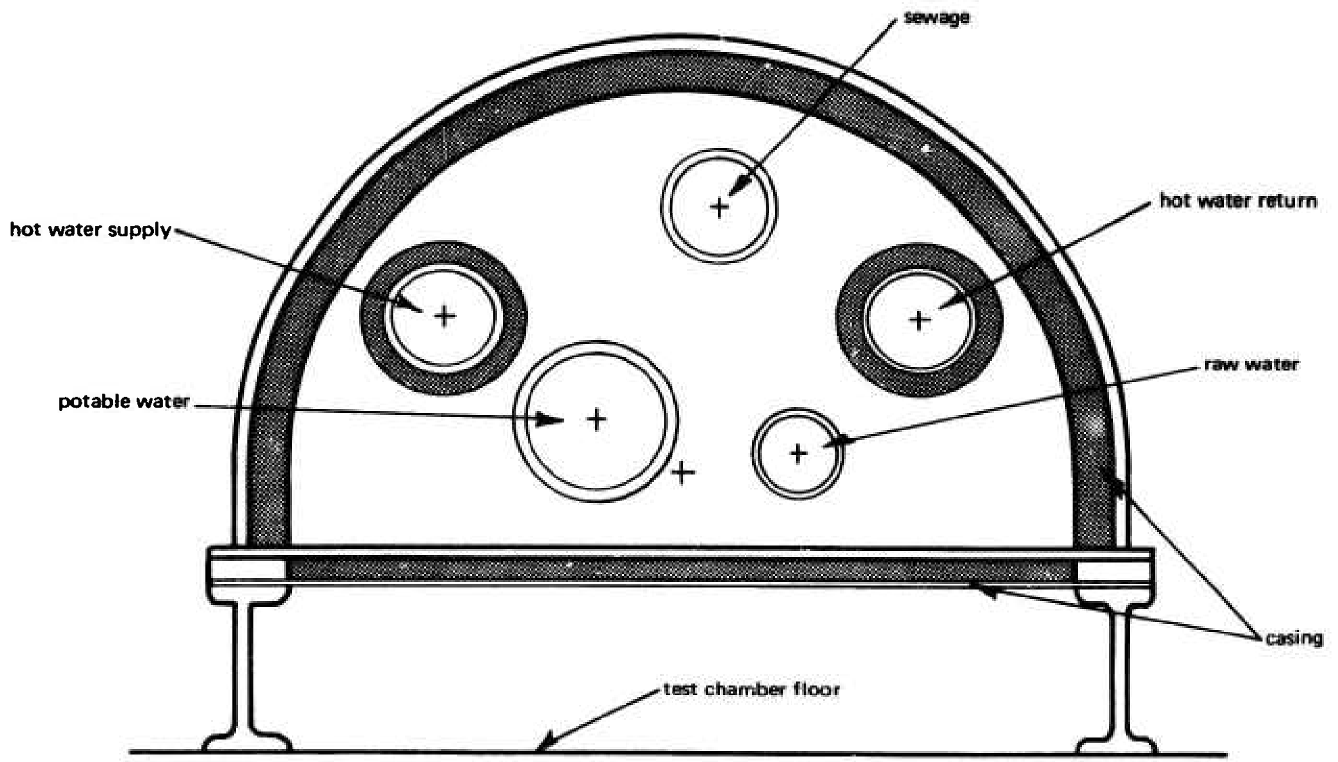

Figure C-2. Cross section of utilidor test section.

Appendix D

COMPUTER PROGRAM FOR UTILIDOR

The analysis presented in Appendix C for a four-line system, in which Line 1 makes two passes and the remaining three lines each make a single pass through the utilidor, was programmed for the computer in IBM 1620 Fortran II-D language. Running time on the IBM 1620 at NCEL is approximately two to three minutes per case.

NOMENCLATURE

Inputs

W(1)	Mass flow rate of fluid in Line 1	(lb/hr)
W(2)	Mass flow rate of fluid in Line 2	(lb/hr)
W(3)	Mass flow rate of fluid in Line 3	(lb/hr)
W(4)	Mass flow rate of fluid in Line 4	(lb/hr)
D1(1)	Inside diameter of Line 1	(ft)
D2(1)	Outside diameter of Line 1	(ft)
D3(1)	Outside diameter of insulation on Line 1*	(ft)
D1(2)	Inside diameter of Line 2	(ft)
D2(2)	Outside diameter of Line 2	(ft)
D3(2)	Outside diameter of insulation on Line 2*	(ft)
D1(3)	Inside diameter of Line 3	(ft)
D2(3)	Outside diameter of Line 3	(ft)
D3(3)	Outside diameter of insulation on Line 3*	(ft)
D1(4)	Inside diameter of Line 4	(ft)

---

* Set D3 = D2 for any uninsulated line.

D2(4)	Outside diameter of Line 4	(ft)
D3(4)	Outside diameter of insulation on Line 4*	(ft)
RN(1)	Reynolds number of flow in Line 1**	
RN(2)	Reynolds number of flow in Line 2**	
RN(3)	Reynolds number of flow in Line 3**	
RN(4)	Reynolds number of flow in Line 4**	
PN(1)	Prandtl number of fluid in Line 1	
PN(2)	Prandtl number of fluid in Line 2	
PN(3)	Prandtl number of fluid in Line 3	
PN(4)	Prandtl number of fluid in Line 4	
SP(1)	Specific heat of fluid in Line 1	(Btu/lb-^{O}F)
SP(2)	Specific heat of fluid in Line 2	(Btu/lb-^{O}F)
SP(3)	Specific heat of fluid in Line 3	(Btu/lb-^{O}F)
SP(4)	Specific heat of fluid in Line 4	(Btu/lb-^{O}F)
TK(1,1)	Thermal conductivity of fluid in Line 1	(Btu/hr-ft-^{O}F)
TK(1,2)	Thermal conductivity of fluid in Line 2	(Btu/hr-ft-^{O}F)
TK(1,3)	Thermal conductivity of fluid in Line 3	(Btu/hr-ft-^{O}F)
TK(1,4)	Thermal conductivity of fluid in Line 4	(Btu/hr-ft-^{O}F)
TK(2,1)	Thermal conductivity of Line 1 pipe wall	(Btu/hr-ft-^{O}F)
TK(2,2)	Thermal conductivity of Line 2 pipe wall	(Btu/hr-ft-^{O}F)
TK(2,3)	Thermal conductivity of Line 3 pipe wall	(Btu/hr-ft-^{O}F)

---

* Set D3 = D2 for any uninsulated line.

** Must be <2,100 or >10,000.

TK(2,4)	Thermal conductivity of Line 4 pipe wall	(Btu/hr-ft-°F)
TK(3,1)	Thermal conductivity of insulation on Line 1*	(Btu/hr-ft-°F)
TK(3,2)	Thermal conductivity of insulation on Line 2*	(Btu/hr-ft-°F)
TK(3,3)	Thermal conductivity of insulation on Line 3*	(Btu/hr-ft-°F)
TK(3,4)	Thermal conductivity of insulation on Line 4*	(Btu/hr-ft-°F)
TC12	Thickness of casing insulation	(ft)
TC23	Thickness of casing wall	(ft)
CK12	Thermal conductivity of casing insulation	(Btu/hr-ft-°F)
CK23	Thermal conductivity of casing wall	(Btu/hr-ft-°F)
EL	Casing length	(ft)
AL	Total surface area of casing	(ft^2)
QC	Heat removed from Line 1 fluid between passes through casing	(Btu/hr)
TI(1)	Inlet temperature of Line 1 fluid	(°F)
TI(2)	Inlet temperature of Line 2 fluid	(°F)
TI(3)	Inlet temperature of Line 3 fluid	(°F)
TI(4)	Inlet temperature of Line 4 fluid	(°F)
TA	Ambient air temperature	(°F)
TU	Initial assumption of air temperature inside casing	(°F)

Outputs

ZT(1)	Outlet temperature from first pass of Line 1 fluid	(°F)

---

* Assign value of 1,000 if specified line is uninsulated.

TRI	Inlet temperature to second pass of Line 1 fluid	(°F)
TRO	Outlet temperature from second pass of Line 1 fluid	(°F)
ZT(2)	Outlet temperature of Line 2 fluid	(°F)
ZT(3)	Outlet temperature of Line 3 fluid	(°F)
ZT(4)	Outlet temperature of Line 4 fluid	(°F)
TU	Calculated temperature of air inside casing	(°F)
DELTA	Overall heat imbalance	(Btu/hr)

INPUT AND INITIALIZATION PROGRAM

```
ZZJOB
ZZFORX5
C***INPUT***
      DIMENSION W(4),D1(4),D2(4),D3(4),RN(4),PN(4),TK(3,4),SP(4),TI(4),
     1ZN(4),ZT(4),B(4),C(4),E(4)
      COMMON W,D1,D2,D3,RN,PN,TK,SP,TI,ZN,ZT,B,C,E,EL,AL,QC,TA,TU,TC12,
     1 TC23,CK12,CK23,BC,EC,F
      DO 2 I=1,4
      READ 1,  W(I)
    2 PUNCH 1,  W(I)
    1 FORMAT(F15.3)
      DO 3 I=1,4
      READ  1,  D1(I)
      PUNCH 1,  D1(I)
      READ 1,  D2(I)
      PUNCH 1,  D2(I)
      READ 1,  D3(I)
    3 PUNCH 1,  D3(I)
      DO 4 I=1,4
      READ 1,  RN(I)
    4 PUNCH 1,  RN(I)
      DO 5 I=1,4
      READ 1, PN(I)
    5 PUNCH 1,  PN(I)
      DO 6 J=1,3
      DO 6  I=1,4
      READ 1,  TK(J,I)
    6 PUNCH 1,  TK(J,I)
      DO 7  I=1,4
      READ  1,  SP(I)
    7 PUNCH 1,  SP(I)
      READ 1, EL
      PUNCH 1, EL
      READ 1, AL
      PUNCH 1, AL
      READ 1, QC
      PUNCH 1, QC
      DO 8 I=1,4
      READ 1,  TI(I)
    8 PUNCH 1,  TI(I)
      READ 1,  TA
      PUNCH 1,  TA
      READ 1, TU
      PUNCH 1, TU
      READ 1, TC12
      PUNCH 1,  TC12
      READ 1,  TC23
      PUNCH 1,  TC23
      READ 1,  CK12
      PUNCH 1,CK12
      READ 1,CK23
      PUNCH 1,  CK23
C***CALCULATE CONSTANTS***
      DO  10  I=1,4
      IF(RN(I)-2100.) 11,12,12
   11 Y  =  .25/TK(1,I)
      GO TO 15
   12 IF(RN(I)-10000.) 14, 14, 13
   14 STOP
   13 Y = 43.5/(TK(1,I)*RN(I)**.8*PN(I)**.333333)
   15 B(I)=Y+LOGF(D2(I)/D1(I))/(2.*TK(2,I))+
     1LOGF(D3(I)/D2(I))/(2.*TK(3,I))
      C(I)=W(I)*SP(I)
   10 E(I)=.27 * D3(I)**.75
      F=QC/(W(1)*SP(1))
      BC=TC12/CK12+TC23/CK23
      EC=.35*(EL/AL)**.25
      CALL LINK(SNEAK)
      END
```

UTILIDOR THERMAL ANALYSIS ROUTINE

```
ZZJOB
ZZFOR
*LDISKSNEAK
      DIMENSION W(4),D1(4),D2(4),D3(4),RN(4),PN(4),TK(3,4),SP(4),TI(4),
     1ZN(4),ZT(4),B(4),C(4),E(4),ZUA(5)
      COMMON W,D1,D2,D3,RN,PN,TK,SP,TI,ZN,ZT,B,C,E,EL,AL,QC,TA,TU,TC12,
     1 TC23,CK12,CK23,BC,EC,F
   24 DO 20 I=1, 4
      IF(W(I))27,26,27
   26 X=0.
      GO TO 21
   27 X=ROOTF(E(I', B(I), TI(I), TU)
      IF(X)21, 21, 22
   21 ZUA(I) =0.
      ZN(I)=0.
      GO TO 20
   22 ZM = 1./(E(I)*X**.25)
      ZUA(I) = 3.1415927*EL/(B(I)+ZM)
      IF(C(I))25,23,25
   23 ZN(I)=0.
      GO TO 20
   25 ZN(I)=EXPF(-ZUA(I)/(C(I)))
   20 ZT(I)=TU + (TI(I) - TU)*ZN(I)
      TRI = ZT(1) - F
      TRO=TU+(TRI-TU)*ZN(1)
      X=ROOTF (EC, BC, TA, TU)
      IF (X) 31, 31, 32
   31 ZUA(5)=0.
      GO TO 33
   32 ZM= 1./(EC*X**.25)
      ZUA(5)=AL/(BC+ZM)
   33 DELTA=C(1)*(TI(1)-TRO)-ZUA(5)*(TU-TA)-QC
      DO 333 I=2,4
  333 DELTA=DELTA + C (I)*(TI(I)-ZT(I))
      DTU=DELTA/(2.*ZUA(1)+ZUA(2)+ZUA(3)+ZUA(4)+ZUA(5))
      IF(ABSF(DTU)-.25)50,50,40
   40 TU=TU+DTU
      GO TO 24
   50 PUNCH 200,ZT(1), TRI, TRO, ZT(2), ZT(3), ZT(4),TU,DELTA
  200 FORMAT (E15.8)

      END
```

SUBROUTINE FOR COMPUTATION OF VALUE OF X

```
ZZJOB
ZZFOR
*LDISKROOTF
      FUNCTION ROOTF(E,B,T,TU)
      AA=E*B
      CC=ABSF(T-TU)
      X=CC/(AA+1.)
      IF(X)8,5,8
    8 DX=(X-X**.8)*.5
      IF(DX)7,2,2
    7 DX=-DX
    1 X=X+DX
      GO TO 3
    2 X=X-DX
    3 ER=AA*X**1.25+X-CC
      IF(2.*DX/X-.0001 )5,5,4
    4 DX=DX*.5
      IF(ER)1,5,2
    5 ROOTF=X
      RETURN
      END
```

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5. B. Gebhart. Heat transfer, McGraw-Hill, 1961.

A

NOMENCLATURE

A_c	Total surface area of casing (ft^2)
A_{3n}	Total area of outermost surface of Line n (ft^2)
B_c	Combined thermal resistance of casing wall and insulation (hr ft^2 °F/Btu)
B_n	Thermal resistivity from fluid to outermost surface of Line n (hr ft °F/Btu)
$c_{p,\ air}$	Specific heat of air (Btu/lb °F)
c_{pn}	Specific heat of fluid in Line n (Btu/lb °F)
D_{1n}	Inside diameter of pipe in Line n (ft)
D_{2n}	Outside diameter of pipe in Line n (ft)
D_{3n}	Outside diameter of insulation on Line n (ft)
E_c	Function defined by Equation 27
E_n	Function defined by Equation 9
F_n	Temperature change due to heat removal from fluid between passes through Line n (°F)
g	Constant of proportionality (4.17×10^8 ft/hr^2)
h	Convective heat transfer coefficient (Btu/hr ft^2 °F)
h_{ic}	Convective heat transfer coefficient at inner surface of casing (Btu/hr ft^2 °F)
h_{1n}	Convective heat transfer coefficient at inner surface of Line n pipe (Btu/hr ft^2 °F)
h_{3n}	Convective heat transfer coefficient at outermost surface of Line n (Btu/hr ft^2 °F)
$(hA)_{3n}$	Product of h_{3n} and A_{3n} (Btu/hr °F)
j	Subscript integer indicating j^{th} trial value of T_u
k_{air}	Thermal conductivity of air (Btu/hr ft °F)

k_{c12}	Thermal c (Btu/hr ft
k_{c23}	Thermal c
k_{1n}	Thermal c ft °F)
k_{2n}	Thermal c hr ft °F)
k_{3n}	Thermal c (Btu/hr ft
L	Utilidor c
$(LMTD)_n$	Log mean liquid in L (°F)
M_c	Overall th (hr ft^2 °F,
M_n	Thermal re Line n (hr
N_{Nu_n}	Nusselt nu
N_{Pr_n}	Prandtl nu
N_{Re_n}	Reynolds r
P	Side dimer defined by
P_n	Product of air at outer
p_n	Number of
Q_c	Heat transf
Q_n	Heat transf
Q_{rn}	Heat remov (Btu/hr)
R	Residual he

Pd

2	Thermal conductivity of casing insulation (Btu/hr ft °F)
3	Thermal conductivity of casing wall (Btu/hr ft °F)
	Thermal conductivity of fluid in Line n (Btu/hr ft °F)
	Thermal conductivity of Line n pipe wall (Btu/hr ft °F)
	Thermal conductivity of insulation on Line n (Btu/hr ft °F)
	Utilidor casing length (ft)
TD)$_n$	Log mean temperature difference between liquid in Line n and air inside utilidor casing (°F)
	Overall thermal resistance of casing wall (hr ft^2 °F/Btu)
	Thermal resistivity at outermost surface of Line n (hr ft °F/Btu)
$_n$	Nusselt number for flow in Line n
n	Prandtl number of fluid in Line n
$_n$	Reynolds number for flow in Line n
	Side dimension of equivalent square section defined by Equation 21 (ft)
	Product of Grashof and Prandtl numbers for air at outermost surface of Line n
	Number of passes of Line n through utilidor
	Heat transferred through utilidor casing (Btu/hr)
	Heat transferred to or from Line n (Btu/hr)
	Heat removed from Line n fluid between passes (Btu/hr)
	Residual heat imbalance (Btu/hr)

S	Coefficient in Equation 22
T_a	Ambient air temperature (°F)
T_{ic}	Temperature at innermost surface of casing (°F)
T_{in}	Inlet temperature of Line n fluid (°F)
T_{on}	Outlet temperature of Line n fluid (°F)
T_u	Temperature of air inside utilidor casing (°F)
T_{3n}	Temperature of outermost surface of Line n (°F)
t_{c12}	Thickness of casing insulation (ft)
t_{c23}	Thickness of casing wall (ft)
$(UA)_c$	Product of overall heat transfer coefficient and surface area of casing (Btu/hr °F)
$(UA)_n$	Product of overall heat transfer coefficient and surface area of Line n (Btu/hr °F)
U_c	Overall heat transfer coefficient of casing (Btu/hr ft^2 °F)
W_n	Mass flow rate of fluid in Line n (lb/hr)
X_c	Absolute value of difference between T_u and T_{ic} (°F)
X_n	Absolute value of difference between T_u and T_{3n} (°F)
β_{air}	Mean coefficient of volume expansion for air (1/°F)
μ_{air}	Viscosity of air (lb/hr ft)
μ_n	Viscosity of fluid in Line n (lb/hr ft)
ρ_{air}	Density of air (lb/ft^3)