PAVEMENT HEATING

Project 7722

Progress Report 1970-1971

Developed by

New Jersey Department of Transportation
Division of Research and Development
Bureau of Instrumentation Services

by

Frank Winters, Principal Engineer

S. Robert Sasor, Assistant Engineer, Highway

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COMPLIMENTS OF

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NEW JERSEY DEPARTMENT OF TRANSPORTATION
1035 PARKWAY AVENUE
TRENTON, NEW JERSEY 08625

William T Cahill, Governor
John C Kohl, Commissioner of Transportation
Keith Rosser, Director of Planning and Research
David W Gwynn, Director, Div of Research and Development

ABSTRACT

To develop more economical means of melting snow and ice by pavement heating, a 3200 square foot experimental heated pavement, designed to utilize low temperature heat available in the earth, was constructed by the New Jersey Department of Transportation. Heat is extracted from the earth by means of three heat exchangers, each consisting of 2000 linear feet of 1-1/4" diameter wrought iron pipe buried 3' to 13' in the earth. By means of a circulating ethylene glycol solution, heat is transferred from the heat exchangers to a grid of pipes, embedded in the test pavement.

Results of operation for the winter of 1970-1971 indicated best snow melting on a section of the test pavement containing 3/4" and 1-1/4" wrought iron pipes spaced on 6-inch centers. Heat dissipation in this section was approximately 100 BTU's per square foot of surface area per hour producing a snow melting rate of 1/2 inch per hour per square foot. During the summer of 1970, the heat transfer cycle was reversed in order to store heat in the earth, for later use during the winter. Summer operation resulted in a maximum average temperature increase of 13°F in the earth of the test site above the normal earth. Rapid loss of heat during the fall reduced this temperature difference to 3°F by mid-December. There was no significant storage of heat resulting from operation of the system during the summer.

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I. INTRODUCTION

The presence of snow or ice on highways especially at interchanges, ramps and bridge decks often results in hazardous driving conditions and reduced traffic volumes. Conventional snow and ice control techniques may prove inadequate at these locations due to limited snow storage area; the time lag between ice and snow formation; plowing, salting and sanding operations and alternate freezing and thawing of plowed or unplowed snow across superelevated ramps.

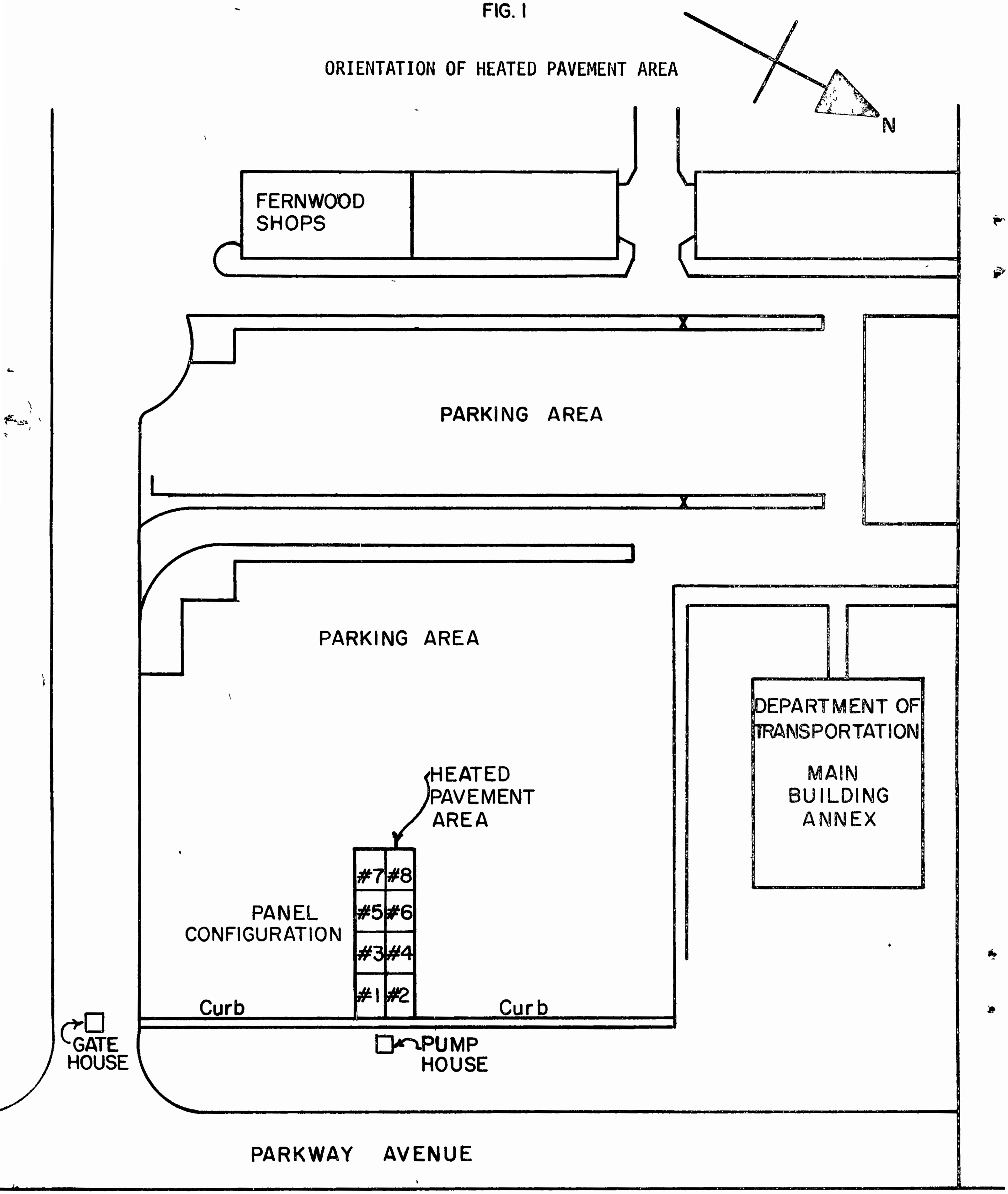
The ideal solution for the control of snow and ice at these problem locations is the use of a heated pavement, capable of melting any snow or ice forming on the roadway, however, the high installation and operating costs presently limit their use in New Jersey.

In order to investigate more economical sources of heat, an experimental heated pavement was constructed at the Fernwood Parking Lot adjacent to the main building of the New Jersey Department of Transportation (Fig. 1). Construction began on April 7, 1969 and was completed by December, 1969.

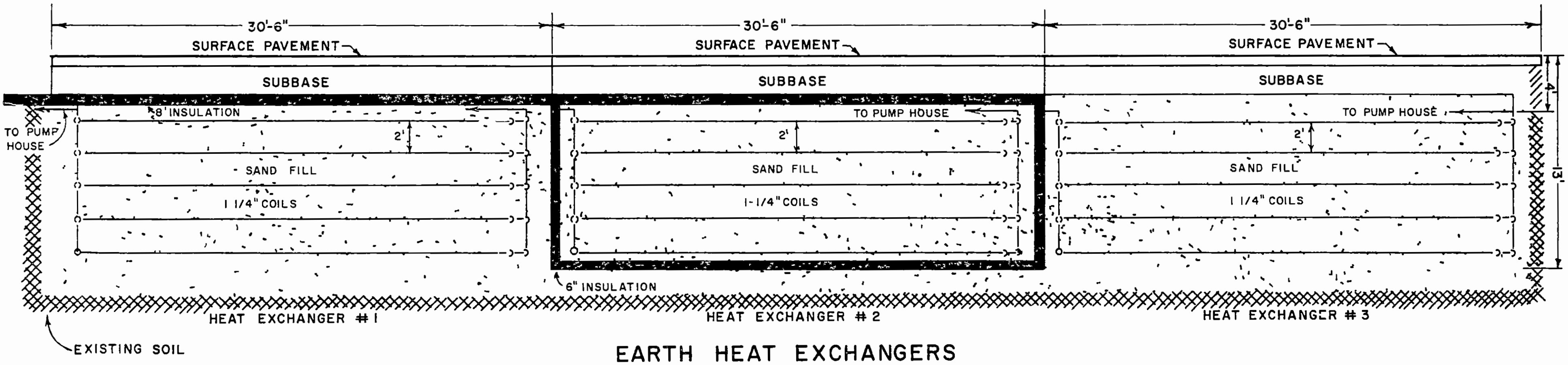
The primary objective was to utilize the heat available in the earth for use in melting snow and ice. To accomplish this objective, three heat exchangers, each consisting of 2000 linear feet of 1-1/4 inch wrought iron pipe, were installed in the earth prior to construction of the pavement surface. The earth beneath the pavement was excavated to a depth of 13 feet and 5 layers of pipe were installed with a horizontal and vertical spacing of two feet (Fig. 2). Heat was extracted from the earth by circulating an ethylene glycol solution through these heat exchangers and then to a grid of pipes embedded in the experimental pavement.

FIG. 1

ORIENTATION OF HEATED PAVEMENT AREA



SCALE 1 1/4" = 100'



EARTH HEAT EXCHANGERS

SECTION

FIGURE 2

The pavement consists of two parallel "lanes" each 13 feet wide and 123 feet long. One lane consists of 9-inch thick slabs of Portland Cement Concrete while the other lane consists of 7 inches of Bituminous Concrete on a 6-inch macadam base. Each lane is sub-divided into four panels each of which is independent of the other panels. Pipes with nominal diameters of 3/4 inch, 1 inch and 1-1/4 inch are embedded at depths of 2 inches and 4 inches in the concrete of Panels #1, 2, 3, 4, 5 and 6 (Fig. 3). In each of the above panels, the pipes are spaced on 6-inch, 12-inch and 18-inch centers as shown in Figure 4. To serve as a reference, Panels #7 and #8 (Fig. 5) contain vinyl insulated electric resistance wires embedded at a depth of 2 inches in the concrete. Each of these panels, evenly sub-divided into 3 sections, was designed to dissipate a known amount of heat of 20 watts (68 BTUH)*, 40 watts (136 BTUH) and 60 watts (204 BTUH) per square foot of surface area.

A report entitled Pavement Heating, March 1970, (#70-014-7722) prepared by the Division of Research and Development, describes the design, construction and results of operation during the winter of 1969-1970. The main conclusions reached were (1) that the pipes buried in the earth could extract heat at temperatures of 42°F to 52°F from the earth at a rate of 22 BTU per hour per one foot of pipe, and (2) the most effective melting of snow on the experimental pavement was on the Portland Cement Concrete panels which contained wrought iron pipes embedded at a depth of 2 inches and spaced on 6-inch centers. When supplied with heat from the earth, this above combination of factors produced a heat dissipation rate approximately 100 BTU per hour per square foot of surface area.

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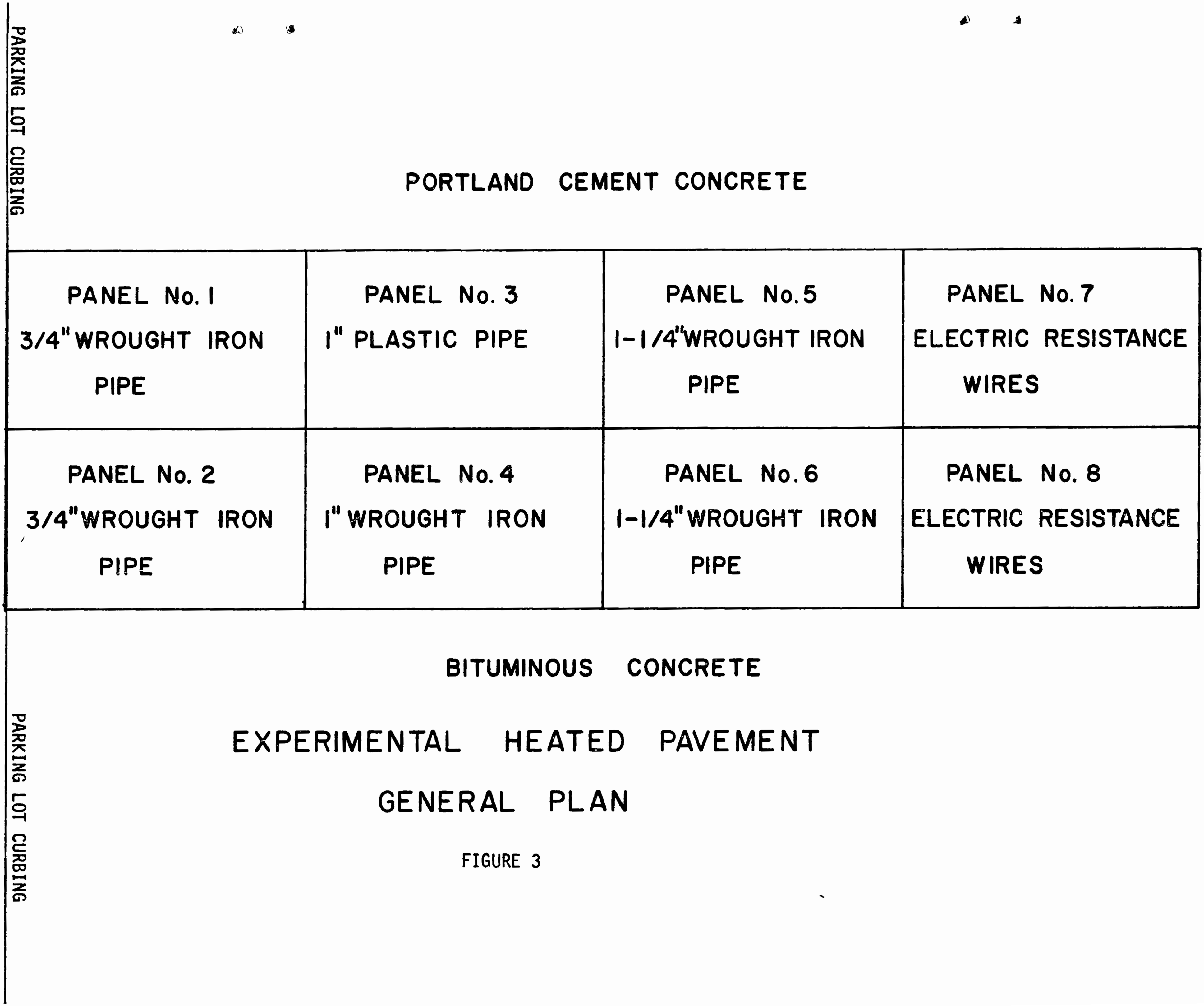
*British Thermal Units per Hour

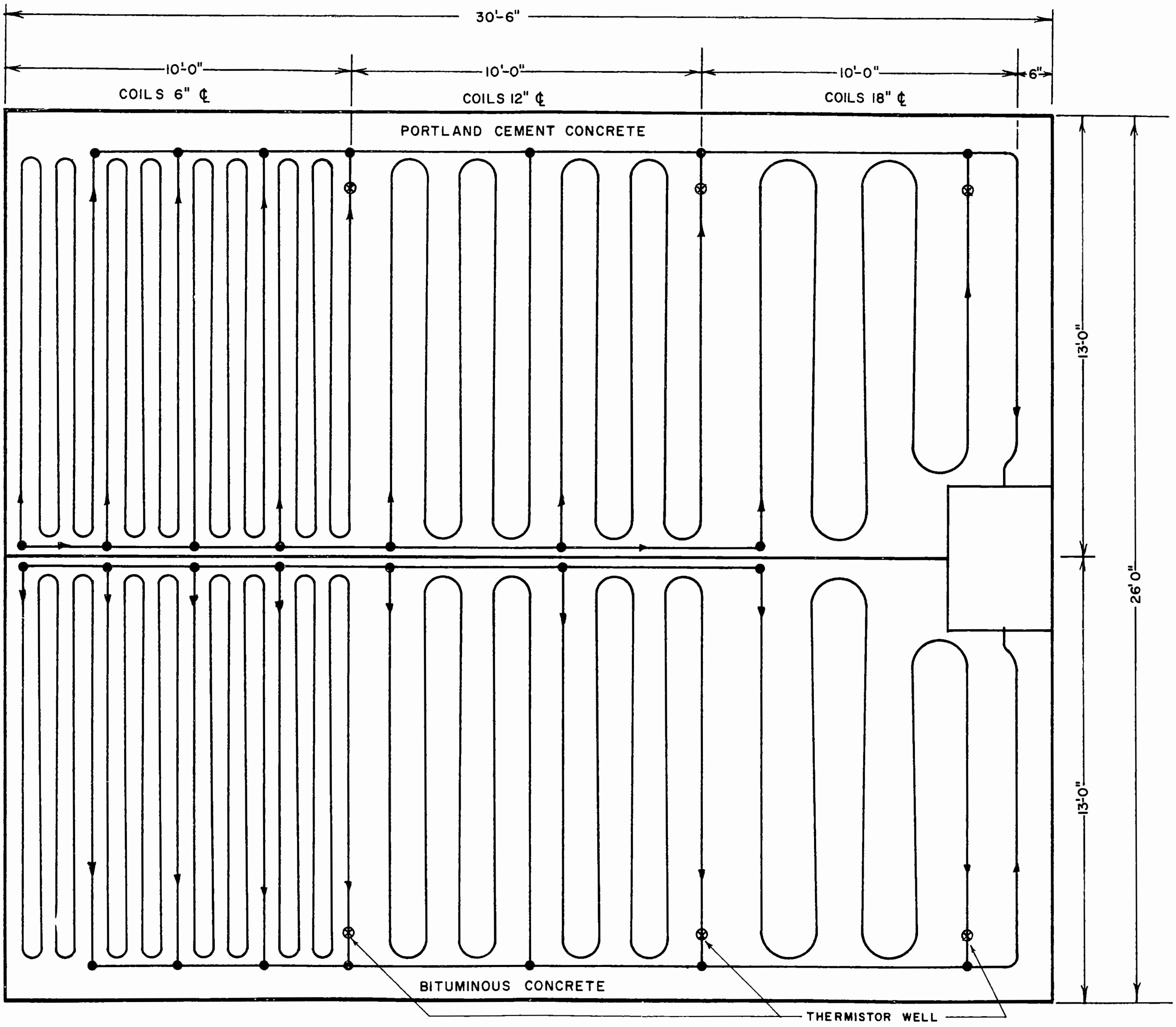


EXPERIMENTAL HEATED PAVEMENT

GENERAL PLAN

FIGURE 3

FIGURE 4



TYPICAL EMBEDDED PIPE PANEL

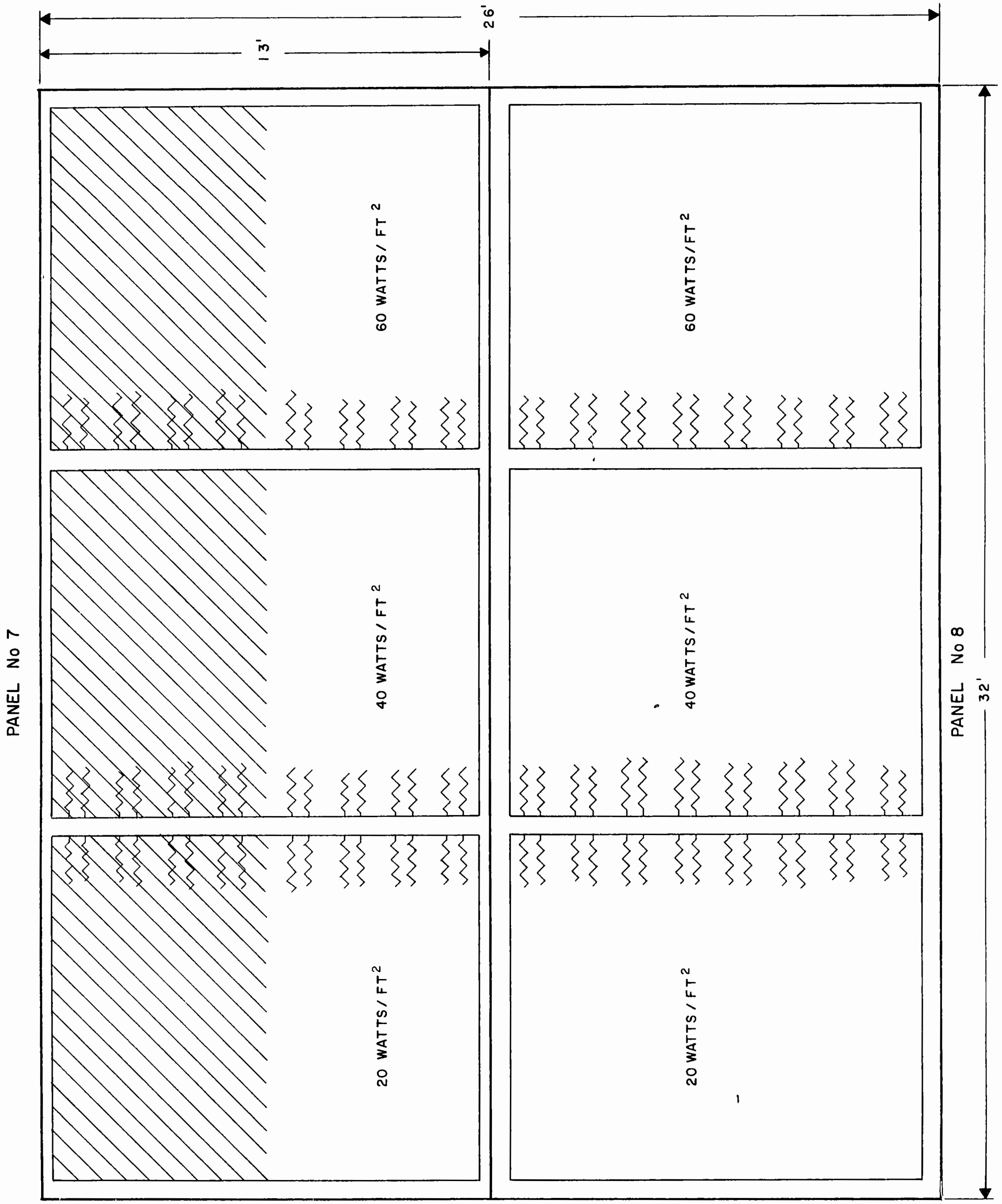
ELECTRICALLY HEATED PANELS

PANEL 7 PORTLAND CEMENT CONCRETE

PANEL 8 BITUMINOUS CONCRETE

▨ ← 2" INSULATION DIRECTLY BELOW CONCRETE

FIGURE 5



The primary objective of the work program for 1970-1971 was to store heat in the earth for later use during the winter season. To accomplish this objective, the system was run intermittently during the summer of 1970, when the pavement temperature often exceeded 100°F. Heat from the hot pavement was transferred to the earth, by means of the ethylene glycol solution, which was circulated through the pavement pipes and then to the heat exchangers.

To prevent the loss of this stored heat during the fall, a layer of polystyrene foam insulation had been installed during construction to partially enclose one section of buried pipes, (Heat Exchanger #1), and totally enclose a second section of buried pipes (Heat Exchanger #2), (Fig. 2).

Results of the 1971 summer heat storage operation; an evaluation of the use of insulation for heat retention; and the results of the 1970-1971 winter snow operation are presented in this report.

II. CONCLUSIONS

1. The operation of the heated pavement during the summer of 1970, for the purpose of storing heat in the earth, did not result in any significant increase in the temperature or heat capacity of the earth at the time of the first snowstorm on December 21, 1970.

2. The use of the polystyrene insulation, either partially or totally enclosing the heat exchangers, was not effective in reducing the loss of stored heat during the period of non-operation between the end of summer and beginning of the winter snow season.

3. For the winter of 1970-1971, the most effective melting, utilizing heat available in the earth, took place on the sections of the Portland Cement Concrete panels containing wrought iron pipes embedded at a depth of 2 inches and spaced on 6-inch centers. These factors produced a heat dissipation rate of 100 BTU per hour per square foot of surface area, which resulted in a snow melting rate of 1/2 inch per hour per square foot. Operating costs for one square foot of surface area for the winter were $.0015 for the embedded pipe heating system as compared to $.17 per square foot in an equivalent electrically heated area.

4. The polyvinyl chloride (PVC) plastic pipe embedded in Portland Cement Concrete (Panel #3) does not possess sufficient strength for use in an embedded pipe type of pavement heating system.

III. RECOMMENDATIONS

1. Operation of the present pavement heating system should continue for another year in order to:

   (a) evaluate the use of higher temperature fluids (150°F)

   (b) confirm the conclusions contained in this report

   (c) ascertain whether the system should be operated intermittently or continuously over the summer for the purpose of heat storage.

   (d) observe any structural failure of the pavement and pipes and any deterioration of the water-glycol solution used in the system.

2. A 33 kilowatt electric hot water heater should be purchased and installed in the pump house at the Fernwood site for use during the winter of 1971-1972. This heater would be used to supply higher temperature fluid (150°F) to two of the panels in order to compare the relative snow melting and heat dissipation rates with panels supplied with the present low temperature fluid (50°F).

3. Due to the possibility of breakage, the use of polyvinyl chloride (PVC) plastic pipe is not recommended for use in pavement heating systems designed for highway use.

IV. EVALUATION OF SUMMER OPERATION, 1970

During the summer of 1970, the pavement heating system was intermittently operated for 715 hours between June 4th and October 6th. The system was run selectively during this period with the only governing factor being that the output temperature of the fluid from the pavement pipes should exceed the output temperature of the fluid from the earth heat exchanger.

During operation, the ethylene glycol solution continuously circulated along a route through the pavement pipes, down to the buried earth heat exchanger, and back again to the pavement, at a rate that was varied from five gallons per minute to 20 gallons per minute. In the process, heat from the pavement was extracted by the fluid and transferred to the earth in the immediate vicinity of the underground heat exchanger. All three heat exchangers were operated for approximately the same number of hours, at approximately the same times, and under the same environmental conditions. Parking on the pavement above all the panels was not restricted.

By 1 September 1970, summer operation raised the average temperatures of the earth within Heat Exchangers #1 (HE1), #2 (HE2) and #3 (HE3) to a maximum of 81°F, 84°F and 81°F (Fig. 7, page 38), respectively, which represented an increase of 10°F (HE1), 13°F (HE2) and 10°F (HE3) above the control earth temperature.

The benefits of summer operation for 715 hours for 1970 were minimal due to the rapid rate of stored heat loss during non-operation in the fall (Fig. 8, page 39). The rate of stored heat loss during non-operation in the fall approached the rate of heat storage during operation in the summer, so that by December 17, 1970, the average temperatures of HE1 and HE2 were 1°F and 3°F higher and HE3 was 1°F lower than the control earth temperature (Fig. 7, page 38).

For maximum snow melting during winter operation, the heat dissipation rate to the pavement surfaces should be as high as possible. Since the rate of heat dissipation, dQ/dt, from the pavement pipes to the surface is directly proportional to the temperature difference, ΔT, between the pavement pipes and the surface, the only means of increasing the heat dissipation rate of an existing system is to maximize ΔT[1]. To increase this temperature difference the temperature of the circulating fluid must be increased, which, in this case, necessitates an increase in the temperature of the heat exchanger. Data for December 21, 1971, for HE3, indicates an earth temperature of 55°F (Fig. 7, page 38), and a circulating fluid temperature of 55°F (Table 4, page 48). Assuming a surface temperature of 32°F (temperature of melting snow) the temperature difference, ΔT, would be 23°F. An increase of 3°F in ΔT results in a 13% increase in dQ/dt, the heat dissipation rate. This percent increase is not considered significant and therefore the temperature increases of 1°F and 3°F, exhibited by the earth within HE1 and HE2, due to the summer operation were not considered significant. A 20°F earth temperature increase which would result in a doubling of the heat dissipation rate during winter operation would have been considered significant for this experiment.

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1. Report #4, NCHRP, Non Chemical Methods of Snow and Ice Control on Highway Structures.

V. EVALUATION OF INSULATION USED IN CONJUNCTION WITH HEAT EXCHANGERS #1 AND #2, 1970

With the realization that heat stored in the earth during the summer would probably be dissipated during the fall, the use of thermal insulation was an integral part of the design of Heat Exchangers #1 and #2.

The purpose of the insulation was to prevent the conduction of heat from the earth, within the heat exchangers, upward to the air or outward to the surrounding earth.

Heat Exchanger #1 (HE1) was insulated with an 8-inch layer of an expanded polystyrene insulation placed above the heat exchanger, as shown in Figure 2, page 3 and Figure 6, page 37. This insulation was intended to prevent the conduction of heat to the air.

Heat Exchanger #2 (HE2) was also covered with an 8-inch layer of insulation and in addition had a 6-inch layer of insulation placed to completely enclose the earth within the heat exchanger as shown in Figure 2, page 3 and Figure 6, page 37. This insulation was intended to prevent the conduction of heat to the air and to the surrounding earth.

Heat Exchanger #3 (HE3) was not insulated in order to serve as a control.

The objective was to raise the temperature of the earth within all the heat exchangers at least 20°F higher than the control earth temperature by the time of the first snowfall and to maintain this temperature difference throughout the winter.

Graphical analysis of the temperature data presented in Figure 7, page 38, indicates the average temperature of the earth within the heat exchangers as a function of time.

As shown in this graph, a maximum temperature of 84°F was attained on August 12, 1970 within HE2, which was completely enclosed by insulation. This increase of 13°F above the control earth temperatures falls short of the desired increase of 20°F. HE1 and HE3 show an increase of approximately 9°F above the control earth temperature.

During the time between October 6, 1970 and December 21, 1970, when the system was not operated either for heat storage or snow melting, the earth temperature within all three heat exchangers decreased rapidly. By the middle of December, 1970 the earth temperature within HE2 was only 3°F above the control earth temperature and HE3 was actually 2°F below the control. The fact that HE3 was below the control earth temperature was probably due to the different type of soil in which the control temperature sensors were located.

For the duration of the winter snow season, from December 21, 1970 to April 7, 1971, the earth temperatures within all the heat exchangers were usually less than the earth control temperatures. The insulation was effective in maintaining a 2°F to 4°F increase in the temperature of HE1 and HE2 above HE3 for the first 8 weeks of operation, after which the pattern reversed and the earth temperature within HE3 exceeded HE1 and HE2 by several degrees.

Since the insulation was <u>not effective</u> in maintaining the earth temperature, within the heat exchangers, at a desired level of

20°F above the control earth temperature and since the earth temperature within the uninsulated heat exchangers exceeded the temperature within the insulated heat exchangers after March 1, 1971, it can be concluded that the insulation was not effective in reducing the loss of stored heat during the fall of 1970.

VI. WINTER OPERATION, 1970-1971

A. Snow Storm Operating Procedure, 1969-1970 and 1970-1971

During the winter, daily weather forecasts were obtained from the Division of Maintenance. If snow was forecast, the system was activated in anticipation of snowfall. If non-forecast snow began to fall, the system was turned on as soon as assigned personnel arrived at the Fernwood test site.

To prevent the heated pavement area from being snow-plowed, and to restrict the travel of automobiles over the heated panels, traffic cones and snow alert signs were placed around the pavement heating area. The system was activated from the pump house. Only the pipes embedded in the pavement at a depth of two inches were put in operation for both winters. Soon after activation occurred, the pressure of the glycol solution within the piping system was checked and the glycol-water flow rates were adjusted (if required), read, and recorded.

Throughout the entire snowstorm, visual observations of the pavement surface condition for each section of each panel were entered in a log book. To supplement these written observations, daytime photographs of all panels were taken.

The calibration of the Digitec system was checked and the equipment was programmed to sample and print out temperature data on an hourly schedule. Prior to 2/17/71, this temperature data was manually recorded in a log book.

After snowfall had ended, the system was operated until one of the following three conditions existed. Firstly, all the snow that fell on the panels was melted; secondly, it became evident that no more snow would be melted by the system; and thirdly, automobile traffic over the panels had made meaningful data collection difficult.

B. Evaluation of Winter Operation, 1970-1971 and Comparison with Winter Operation, 1969-1970

This section contains an evaluation of the results of winter operation 1970-1971 with a comparison made between winter operation for the past two winters.

The notation used in this discussion and in the "Account of Snow Storms 1970-1971" is explained in Table 1.

TABLE 1

PANEL NOTATION

Embedded Pipe Panels

Notation	Panel Number	Type of Pipe	Type of Concrete	Pipe Diameter	Pipe Spacing
P1 (6")	1	wrought iron	P.C.C.*	3/4"	6"
P1 (12")	1	wrought iron	P.C.C.	3/4"	12"
P1 (18")	1	wrought iron	P.C.C.	3/4"	18"
P2 (6")	2	wrought iron	B.C.**	3/4"	6"
P2 (12")	2	wrought iron	B.C.	3/4"	12"

* P.C.C. - Portland Cement Concrete

** B.C. - Bituminous Concrete

Notation	Panel Number	Type of Pipe	Type of Concrete	Pipe Diameter	Pipe Spacing
P2 (18")	2	wrought iron	B.C.	3/4"	18"
P3 (6")	3	plastic - U.P.V.C.***	P.C.C.	1"	6"
P3 (12")	3	plastic - U.P.V.C.	P.C.C.	1"	12"
P3 (18")	3	plastic - U.P.V.C.	P.C.C.	1"	18"
P4 (6")	4	wrought iron	B.C.	1"	6"
P4 (12")	4	wrought iron	B.C.	1"	12"
P4 (18")	4	wrought iron	B.C.	1"	18"
P5 (6")	5	wrought iron	P.C.C.	1 1/4"	6"
P5 (12")	5	wrought iron	P.C.C.	1 1/4"	12"
P5 (18")	5	wrought iron	P.C.C.	1 1/4"	18"
P6 (6")	6	wrought iron	B.C.	1 1/4"	6"
P6 (12")	6	wrought iron	B.C.	1 1/4"	12"
P6 (18")	6	wrought iron	B.C.	1 1/4"	18"

Electrically Heated Panels

Notation	Panel Number	Type of Concrete	Heat Output
P7 (20W)	7	P.C.C.	20 watts/ft^2 (68 BTUH/ft^2)
P7 (40W)	7	P.C.C.	40 watts/ft^2 (136 BTUH/ft^2)
P7 (60W)	7	P.C.C.	60 watts/ft^2 (204 BTUH/ft^2)
P8 (20W)	8	B.C.	20 watts/ft^2 (68 BTUH/ft^2)
P8 (40W)	8	B.C.	40 watts/ft^2 (136 BTUH/ft^2)
P8 (60W)	8	B.C.	60 watts/ft^2 (204 BTUH/ft^2)

*** U.P.V.C. - Unplasticized Polyvinyl Chloride

According to climatological data for the Trenton area, the snowfall for the winter of 1969-1970 was 26.6 inches and 22.7 inches for the winter of 1970-1971.[2] The heated pavement was operated for approximately 200 hours during the winter of 1969-1970 and 105 hours for the winter of 1970-1971.

The increased usage of the system during the winter of 1969-1970 resulted from longer hours of operation after melting of snow had ceased. During the second year of operation, experience indicated that the system could be deactivated after it became evident that no further melting would take place.

Comparative analysis of visual observations recorded during the various snowstorms of 1970-1971 indicated that the best melting occurred on the P.C.C. panels containing wrought iron pipes embedded at a depth of two inches and spaced on 6-inch centers. The rate of melting of these sections was determined by dividing the total snow accumulation by the length of time necessary to melt all snow on the surface. Since an observer was not always present at the exact time all the snow melted on any given section, it was not possible to accurately determine this value for each storm, although in most instances the melting rates on P1 (6") and P5 (6") were at least greater than .2 inches of snow per hour. Analysis of the best observations during storm #5 and #8 indicate a melting rate of .7 inches per hour [P1 (6")] and .5 inches per hour [P5 (6")], respectively. The average calculated heat dissipation

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[2] Climatological Data, U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service.

rates for P1 (6") and P5 (6"), when snow covered, were 92 BTUH/ft^2 and 116 BTUH/ft^2 of surface area although a maximum of 186 BTUH/ft^2 for P5 (6") was calculated for storm #2, December 22, 1970 (Table 5, page 49).

The results shown in Table 5 indicate that the highest heat dissipation rate was in the section of Bituminous Concrete containing wrought iron pipes on 6-inch centers, P2 (6"), however, these results are considered to be erroneous. These rates do not agree with the average heat dissipation rate of 24 BTUH/ft^2 for P4 (6") which is a similar design nor do they correlate with the poor snow melting rates observed on the pavement surface for this section. A defective thermistor (TW-10) monitoring the output fluid temperature of P2 (6") would account for this result. An effort will be made to determine if this thermistor is defective.

For the winter of 1970-1971 comparison of visual observations of snow melting on the embedded pipe panels with the electrically heated reference panel, P7, show that the melting rates for P1 (6") and P5 (6") are greater than the 20 watt/ft^2 section of P7 but less than the 40 watt/ft^2 section. This indicates that P1 (6") and P5 (6") are approximately equivalent to a 30 watt/ft^2 (102 BTUH/ft^2) electrically heated panel. This value of 30 watt/ft^2 (102 BTUH/ft^2) correlates well with the calculated average heat dissipation rate of 92 BTUH/ft^2 and 116 BTUH/ft^2 for P1 (6") and P5 (6"), respectively.

Comparison of visual observations for the winter of 1969-1970 and the winter of 1970-1971 indicate that the melting patterns appear identical and the relative melting abilities of all panels were the same.

The average heat dissipation rates for P1 (6") and P5 (6") for the winter of 1969-1970 were 96 BTUH/ft^2 and 108 BTUH/ft^2, respectively, which agree closely with the rates given above for the winter of 1970-1971.

In summary, the most effective melting took place on the P.C.C. panels containing wrought iron pipes embedded at a depth of 2 inches and spaced on 6-inch centers. This combination of factors produced an average heat dissipation rate of 100 BTUH/ft^2 which resulted in a snow melting rate of approximately 1/2 inch per hour per square foot.

C. Account of Snow Storms 1970-1971

1. December 21, 1970 (5.5 hours)*

A light snow, melting on contact with the pavement, began to fall at 4:20 P. M. The entire system was activated at 4:55 P. M. Snow continued to fall for the next five hours and finally ceased at approximately 10:00 P. M. During this period the air temperature dropped several degrees from 34°F (4:35 P. M.) to 32°F (8:00 P. M.), and slush began to form on several panels, notably P2 (18") and P4 (18"), while the snow melted on contact with the other panels.

At 10:00 P. M., Panels #1, 3, 5, 6, 7 and 8 were wet and clear of all snow and slush, and P7 (60W) and P8 (60W) were 98% dry.** At this same time, slush still remained on P2 (18") and

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* Hours the system operated during a particular storm.

** For explanation of percentage dry and percentage clear and wet refer to Appendix, page 46.

P4 (18"), while P2 (6", 12") and P4 (6", 12") were clear and wet.

The best melting had occurred on P7 (60W) and P8 (60W). The slowest melting took place on Panels 2 and 4 both constructed of Bituminous Concrete. All other panels were equal in melting ability.

2. December 22, 1970 (4.8 hours)

About 6:00 A. M., light hail and snow began to fall and continued throughout the morning.

On arrival at the Fernwood test site at 8:45 A. M., all panels except P7 (40W, 60W) were covered with 1/4 inch of snow. All systems were turned on at 8:50 A. M.

By 10:07 A. M., P7 (60W) and P8 (60W) were clear and wet, and P1 and P5 had produced sufficient melting to change the snow covering them to slush. P5 had produced better melting than P7 (20W) which was still snow covered. Snow covered all other panels to a depth of 1/2 inch.

The snowfall ended at about 11:15 A. M., and was followed by light rain. Total accumulation of snow was measured as approximately one inch.

At 1:05 P. M., Panels #1, 3, 5, 7 and 8 were for the most part clear and wet with only slight instances of slush, while P2, P4, and P6 were snow covered with localized melting occurring only directly above the buried pipes.

The system was deactivated at 1:40 P. M.

Air temperature for the storm was measured as 33°F at 9:00 A. M., 32.5°F at 11:00 A. M., and 32.9°F at 1:00 P. M.

The best snow melting had occurred on P7 and P8, both of which melted snow at an approximate rate of 1/2 inch per hour per square foot. P5 (6") and P1 (6") performed the best of the embedded pipe panels. P5 (6") melted snow at a rate of 1/2 inch per hour and P1 (6") at a rate of greater than 1/4 inch per hour.

3. December 31, 1970 - January 1-2, 1971 (5.1 hours)

The system was turned on at 1:30 P. M., with no snow falling at the time. Snow began falling sometime between 11:00 P. M. (12/31/70) and 1:00 A. M. (1/1/71).

By 11:45 A. M. (1/1/71), there was a snow accumulation of 4" with heavy snowfall still continuing. P7 (40W, 60W) and P8 (60W) were partially clear, but all other sections and panels showed no signs of melting. The air temperature was 28°F.

Snow stopped falling at approximately 3:00 P. M., the afternoon of January 1, 1971.

At 7:30 A. M. (1/2/71), P7, P1 (6") and P8 (40W, 60W) were clear. All other areas and panels were snow covered with melting directly above the buried pipes (Fig. 10, page 41). Air temperature was 21.6°F.

At 12:00 Noon (1/2/71) P3 and P4 were turned off due to a sharp pressure drop in that particular system. P7 and P8, P5 (6") and P1 (6") were totally clear and dry, whereas all other pavement surfaces were clear and wet directly above the buried pipes with slush covering the pavement between pipe centers. Air temperature was 32.9°F.

By 4:00 P. M. (1/2/71), P1 (12"), P5 (12"), P2 (6") and P6 (6") were now clear. P3 and P4 showed little if any additional melting. Air temperature was 32.9°F. (See Fig. 11, page 41).

The system was deactivated at 4:35 P. M. (1/2/71).

P7 (40W, 60W) and P8 (40W, 60W), P1 (6"), and P5 (6") were observed to have the most satisfactory melting. P7 (60W) and P8 (60W) melted 4 inches of snow in 12 hours. P5 (6") and P1 (6") melted 4 inches of snow in less than 30 hours.

NOTE: This was the last time Panel #3 was operated this winter. From this time on Panel #3 served as a control panel. A leakage developed in this Panel from a breakage occurring in the plastic pipe. This leakage was discovered as a result of a pressure drop in the system servicing Panel #3 and #4. It was traced to the layer of plastic pipe in Panel #3 that lies two inches below the concrete surface. A more exact location of this leakage could only be determined by excavation of the panel.

4. January 13-14, 1971 (14.1 hours)

Light snow mixed with sleet started falling between 7:30 P. M. and 9:00 P. M. (1/13/71). The system was activated at 12:15 A. M. (1/14/71), with outside air temperature being 27°F.

By 1:05 A. M., there had been no significant melting and all panels were covered with a hard crust of snow and sleet.

At 10:30 A. M., the next morning, snowfall (total accumulation 1") had stopped and a light rain was falling. Outside air temperature was 33.5°F. P7, P8, P1 (6"), P4 (6"), and P5 (6") were wet and 100% clear of snow and ice. All other areas and panels were either snow or snow and ice covered. P7 and P8 were turned off at 10:50 A. M. and the other panels turned off at 2:23 P. M.

At 2:30 P. M., all panels except P2 (12", 18"), P3, and

P4 (18") were clear of snow and slush. P2 (12"), P2 (18"), and P4 (18") were slush covered, and the control P3 was still mostly snow covered.

Electrical panels #7 and #8 showed the best melting and were both clear and 65% dry by this time. Of the embedded pipe panels P1 (6"), P4 (6"), and P5 (6") melted snow most effectively.

5. January 24-25, 1971 (3.6 hours)

Snowfall was intermittent on the 24th of January. Snowfall lasted from 4:00 P. M. to 6:00 P. M., stopped for a period of two hours, then resumed from 8:00 P. M. to 11:30 P. M. for a total accumulation of two inches. At 11:30 P. M., Panels 4, 5, 6, 7, and 8 were turned on.

At 9:55 A. M. (1/25/71), Panels #1 and #2 were activated while Panels #4, 5, 6, 7 and 8 were turned off. At this time, P7 (40W, 60W) and P8 (40W, 60W) were clear but still wet. P5 (6", 12"), P4 (6"), and P6 (6") were 90% clear and wet. P5 (18"), P4 (12", 18"), and P6 (12", 18") were partially snow covered.

P1, P2 and P3 were completely covered with 2 inches of snow. Air temperature was 35.6°F.

By 1:00 P. M. that afternoon, P4, P5, P6 and P1 (6") were 100% clear and wet. P1 (12", 18") was clear directly above pipe centers with slush existing between pipe centers.

P2, though mostly snow covered, was clear and wet above the 18" pipe spacing where cars had driven over it. P3 (control) was snow covered. Air temperature was 39°F. The system was completely deactivated at 1:05 P. M. (1/25/71). The best melting occurred on

P7 and P8. The best performing pipe section was P5 (6"). This buried pipe panel melted snow at better than .20 inches per hour.

P1 (6") which was activated 10 1/2 hours after the other panels melted snow at a rate of .7 inches per hour, however, the air temperature was above 35°F.

6. February 17, 1971 (2.7 hours)

The system was activated at 4:35 P. M. (2/17/71), with a very light snow falling at the time. Air temperature was 36.2°F. Snow was melting on contact with the pavement surface and all panels were wet.

The snow gradually changed to rain which ceased at 7:20 P. M. (2/17/71). At 7:20 P. M., all panels were clear and wet. Air temperature was measured at 36.7°F.

All systems were turned off at 7:20 P. M. (2/17/71).

There was no accumulation of snow on any panels or on the adjoining parking lot.

7. March 3, 1971 (3.5 hours)

A light snow was falling at the Fernwood test site at 10:00 A. M. Air temperature was 32.5°F. P1 and P5 were slush covered, P3 was slush and snow covered, and P2, P4 and P6 were snow covered (Fig. 12, page 42). The total snow accumulation was 1.5". The system was activated at 10:15 A. M.

By 1:45 P. M., the air temperature had risen to 33.1°F and the snow had changed to rain. At this time, P1 and P5 were wet and clear of snow and slush. P3 (control), P4 and P6 were partially covered with slush and P2 was completely covered by slush (Fig. 13, page 42).

The system was deactivated at 1:45 P. M. after 3 1/2 hours of operation.

P1 and P5 melted snow at a rate greater than 1/3 inch per hour, and once again these two panels produced better snow melting than any of the other pipe panels.

NOTE: P7 and P8 were covered by parked automobiles throughout this entire storm so no conclusive visual observations of P7 and P8 could be made.

8. March 4, 1971 (6 hours)

Snowfall began between 4:00 A. M. and 5:00 A. M. (3/4/71). The snowfall was accompanied by high winds which caused drifting.

The system was activated at 9:00 A. M., at which time all panels were snow covered to a depth of 2 inches. Air temperature was 28.8°F. The snowfall ceased sometime between 10:00 A. M. and 11:00 A. M., and with drifting the final accumulation approached 3 inches.

At 11:00 A. M., all panels were fully snow covered except P7 (60W) and P8 (60W) which were 80% clear and wet, and P7 (40W) and P8 (40W), which were 60% clear and wet (Fig. 16, page 44). Melting was observed on P1 (6"), P5 (6") and P5 (18") (Fig. 14, page 43). Air temperature was 29.7°F.

An hour later, at 12:00 noon, P2, P3 and P4 were still snow covered though the depth of snow had been reduced to 1/2 - 3/4 inch on P2 and P4, and 1 - 1 1/2 inches on P3. P1 (6") was 50% clear and wet, while P1 (12", 18") was concealed by 1/2 inch of snow (Fig. 15, page 43). All sections of P6 were 50% clear and wet.

P5 (6"), P5 (12") and P5 (18") were 70%, 30% and 40% clear and wet, respectively. P7 (40W, 60W) and P8 (40W, 60W) were almost 100% clear and wet; P7 (20W) and P8 (20W) were 50% clear and wet (Fig. 17, page 44). Air temperature was 29.1°F.

At 2:00 P. M. all sections of panels #1, 2, 5 and 6 were at least 90% clear and wet. P7 (40W, 60W) and P8 (40W, 60W) were clear and dry. P7 (20W) and P8 (20W) were 100% clear and wet. P4 (12", 18") were 100% clear and wet, whereas P4 (6") was mostly slush covered. P3 was completely covered by slush. Air temperature was 29.9°F.

The system was deactivated after 6 hours of operation, at 3:00 P. M., at which time these final qualitative observations were made. Panels #1, 2, 5 and 6 were wet and 100% clear of snow and slush. P7 and P8 were 100% clear and dry. P3 and P4 (6") were covered with slush. P4 (12", 18") were wet and 100% clear. Air temperature was 29.4°F.

P7 (60W) and P8 (60W) once again surpassed all of the other panel areas in snow melting ability. The 60 watts/ft^2 electrical areas of these panels melted 3" of snow in four hours for a melting rate of 3/4 inch per hour. Of the embedded pipe panels, P5 (6", 12") and P1 (6") melted snow at the fastest rate. P5 (6", 12") and P1 (6") melted 3 inches of snow in six hours for a snow melting rate of 1/2 inch per hour.

In order to obtain a more accurate estimate of snow melting rates, more frequent visual observations were made during this snow storm. The snow melting rates presented here are therefore considered to be the most accurate ones determined for this winter.

NOTE 1: Automobile traffic passed over Panels #3, 4, 5, 6, 7 and 8 sometime between 11:00 A. M. and 12:00 Noon.

NOTE 2: Before this storm it was discovered that the thermistor used to measure outside air temperature had been placed close to an opened window of the Fernwood gate house. Heat escaping from the window may have influenced outside air temperature readings taken previous to this storm. If the thermistor had been effected, it would have indicated readings higher than actual outside air temperature. This misplacement of thermistor was corrected, so that outside air temperatures, for this storm and the ones following it, are accurate.

9. April 6-7, 1971 (13.7 hours)

Heavy wet snow began falling about 8:00 P. M. the evening of April 6, 1971.

At 10:05 P. M., that same evening, panels #1, 2, 4, 7 and 8 were turned on. P5 and P6 had been operated continuously since March 16, 1971, so these panels were already operational when the rest of the system was activated. All of the panels were covered with snow to a depth of three inches except P5 which was covered by 1.5 inches of snow. Air temperature was 32.3°F.

Overnight the snowfall ceased.

At 8:30 A. M. (4/7/71) the next morning, P7 (40W, 60W), P8 (40W, 60W) and P5 (6") were 100% clear and wet. P7 (20W) and P8 (20W) were 90% clear and wet. P5 (12") was 50% clear and wet, and P5 (18") was 25% clear and wet (Fig. 18, page 45). P1 and P6 were completely covered with 1/4 - 1/2 inch slush and 1 1/2 - 2 inches of slush, respectively. P3 (control) and P4 were covered by two inches of wet snow, and P2 was covered by one inch of wet snow.

By 10:05 A. M. the wet snow covering P2, P3 and P4 had been reduced to slush. Slush still covered P6. P1 (6") and P5 (6") were 100% clear and wet, whereas, P1 (12", 18") and P5 (12", 18") were 80% clear and wet. P7 (40W, 60W) and P8 (40W, 60W) were clear and 10% dry, P7 (20W) and P8 (20W) were 100% clear and wet. Air temperature was 45.9°F.

At 11:45 A. M., the system was deactivated. The air temperature was 49.3°F. By this time, all panels except P3 and P4 were 100% free of slush and snow. P3 and P4 were still 25% covered with wet snow. P7, P8, P1 (6") and P5 (6", 12") were completely dry (Fig. 19, page 45). All other areas and panels were 100% clear and wet.

P7, P8 and P5 (6") showed the best melting. P5 (6") melted snow at a rate greater than .30 inch per hour, and P1 (6") melted snow at a rate greater than .25 inch per hour. As in all other storms P5 (6") and P1 (6") exceeded all other buried pipe panels in effectiveness of snow melting.

NOTE: Considerable automobile traffic traversed P3 and P4 during this storm.

VII. OPERATIONAL COSTS

During the winter of 1969-1970, the pavement heating system was operated for 208.5 hours at an hourly rate of $0.05 per kilowatt hour, for a total cost of $5.63 for the embedded pipe panels, and $300.24 for the electrically heated panels. Operational costs per square foot of pavement surface area are shown in Table 2.

TABLE 2

OPERATING COST

Winter 1969-1970

Hours Operated: 208.5 Hourly Electricity Charge: $0.05/kw-hr.

Panels	Sections	Cost ($)	Cost ($/ft^2)
Embedded Pipe	All	$ 5.63	$0.0024
Electrical	20 watts/ft^2	$ 50.04	0.19
	40 watts/ft^2	100.08	0.38
	60 watts/ft^2	150.12	0.57
	Subtotal	$300.24	
	Total	$305.87	

During winter 1970-1971, the system was operated 104.9 hours at an hourly rate of $0.06 per kilowatt hour, for a total expense of $184.69. Of this, $181.29 was required to operate the electrical panels, while $3.40 was needed for the embedded pipe panels. Operational costs per square foot are shown in Table 3.

TABLE 3

OPERATING COST

Winter 1970-1971

Hours Operated: 104.9 Hourly Electricity Charge: $0.06/kw-hr.

Panels	Sections	Cost ($)	Cost ($/ft^2)
Embedded Pipe	All	$ 3.40	$0.0015
Electrical	20 watts/ft^2	$ 30.21	0.12
	40 watts/ft^2	60.42	0.23
	60 watts/ft^2	90.66	0.35
	Subtotal	$181.29	
	Total	$184.69	

The operating cost of the electrical panels relfects the amount of electricity required by the resistance wires. The operating cost of the embedded pipe panels is for the electricity used by the 1/6 HP circulating pumps.

For purposes of storing heat, the pavement heating system was operated for 715 hours during summer 1970. All three heat exchanger-panel systems were run at a total cost of $15.44 ($0.0066/ft^2) for electricity for the circulating pumps.

VIII. INSTRUMENTATION

The temperature of the earth, pavement, and ethylene glycol solution were monitored with 120, Model 401 Digitec Thermistors, that were placed in the earth, pavement and pipes of the system. The locations of the thermistors in the heat exchangers are shown in Figure 9, page 40. All thermistors are connected to a multi-conductor cable which runs from the heated pavement area to the Fernwood gatehouse. At the gatehouse, the cable was linked to a digital registering and recording system. This registering and recording system is composed of a Digitec digital thermometer, digital clock, multiplexer, and printer, with an overall system accuracy of ± 0.3°F. Pavement surface temperatures, heat exchanger temperatures, air temperatures, control soil temperatures, and ethylene glycol fluid temperatures, were sampled and recorded at 60 minute intervals during snow storms. One hundred data points were sampled during the full cycle of the system. The time of the reading, coded position of the thermistor, and temperature of the thermistor under consideration, are automatically recorded on paper tape by the printer. This Digitec system first worked effectively during the snow storm of March 3, 1971. Previous to this automated recording of temperature readings, the reading registered by the digital thermometer was manually entered in a log book.

The panel input and output temperatures of the ethylene glycol solution were measured in the pumphouse by six Trerice alcohol thermometers entered in a log book, prior to the date of February 17, 1971. On this day, the Trerice Thermometers were replaced by six Model 401 Digitec Thermistors. These six thermistors were connected to the multi-conductor cable running to the gatehouse so that they too could be automatically read. The Digitec Thermistor and digital thermometer (accuracy ± 0.3°F) provide a more exact measurement of these input and output temperatures than did the Trerice Thermometers (accurate to ± 1°F).

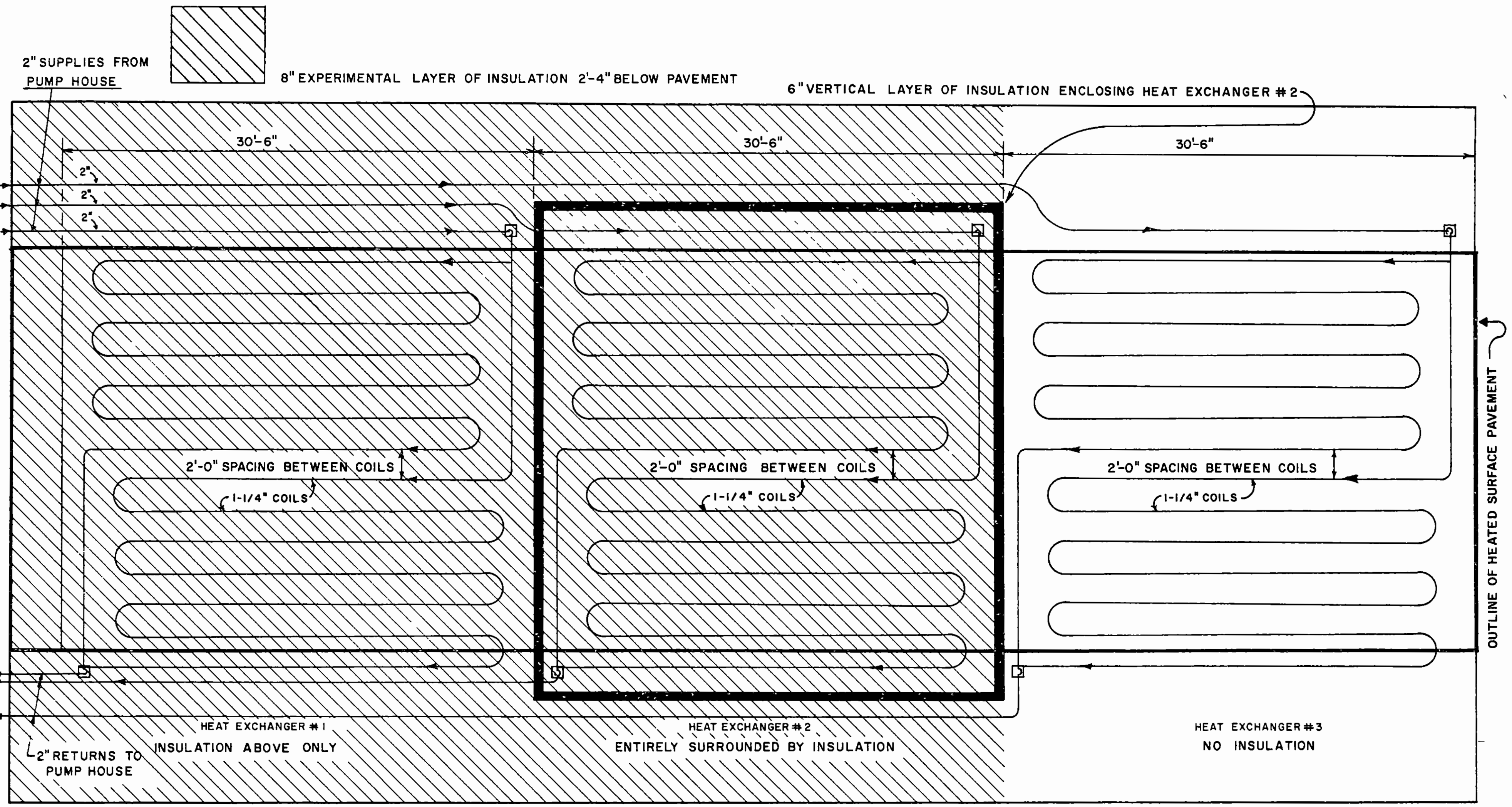
The flow rate of the ethylene glycol solution through the system was measured with three Wallace and Tiernan, Inc. glass tube, variable area flow meters, accurate to ± 0.5 gallons per minute.

IX. PROBLEMS

Two major problems have occurred since the installation of this system. Firstly, several thermistors have failed due to damage to wire or thermistor, resulting in short circuits and open circuits. In these cases no worthwhile temperature data can any longer be gathered. Several thermistors indicate temperature readings lower than true temperature. An increase in resistance of the thermistor and its leads, possibly caused by a bad splice or wire damage, could cause these lower readings. Before winter 1971-1972, all thermistors will be checked; those in error will be noted, and those that can be repaired, will be.

The second problem encountered was a leakage which developed in Panel #3. This leakage, caused by a break in the rigid plastic pipe two inches below the concrete surface of Panel #3, required that this panel be disconnected from service after January 2, 1971. Location and repair of the break can only come about after this panel is excavated. Until this time, Panel #3 is being used as a control panel.

APPENDIX



EARTH HEAT EXCHANGER

PLAN

FIGURE 6

FIG. 7

AVERAGE EARTH TEMPERATURE WITHIN HEAT-EXCHANGERS (OCT. 1, 1969 - MAY 12, 1971)

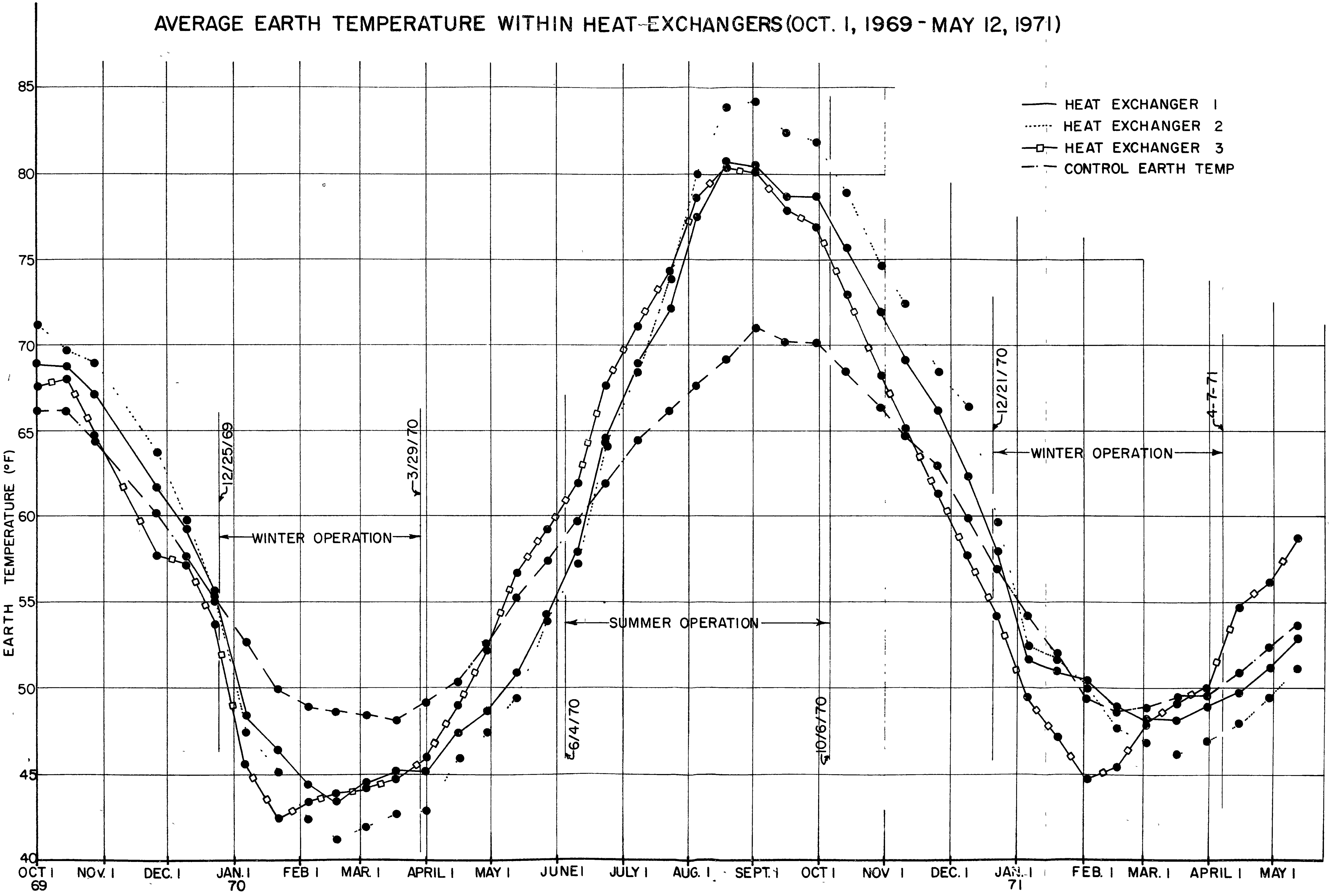
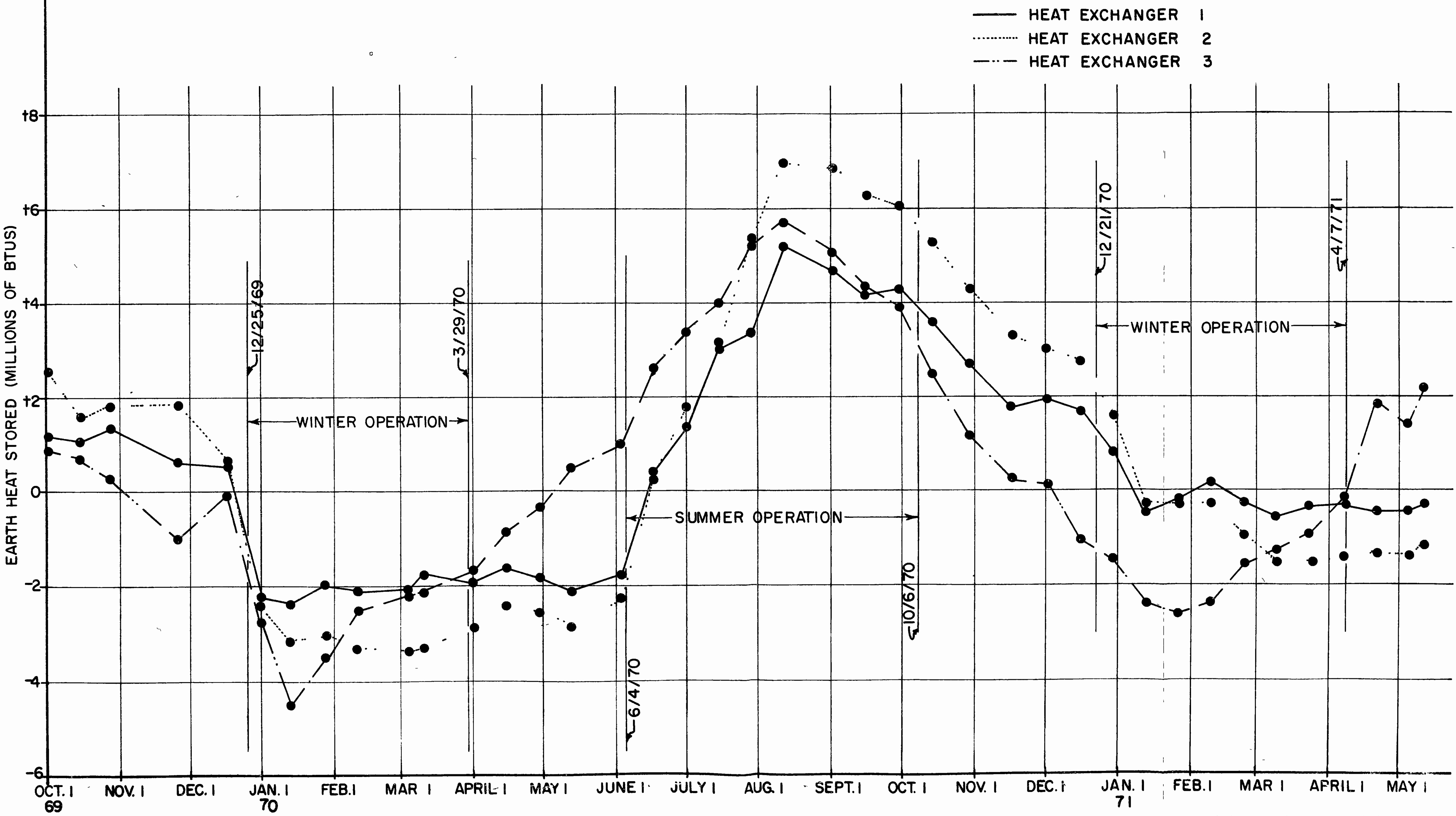


FIG. 8

HEAT STORED IN THE EARTH WITHIN HEAT EXCHANGERS
(OCT. 1, 1969 - MAR. 12, 1971)



SECTIONED VIEW OF EXPERIMENTAL AREA

X - TEMPERATURE SENSOR (THERMISTOR)

O - 1 1/4" IRON PIPE

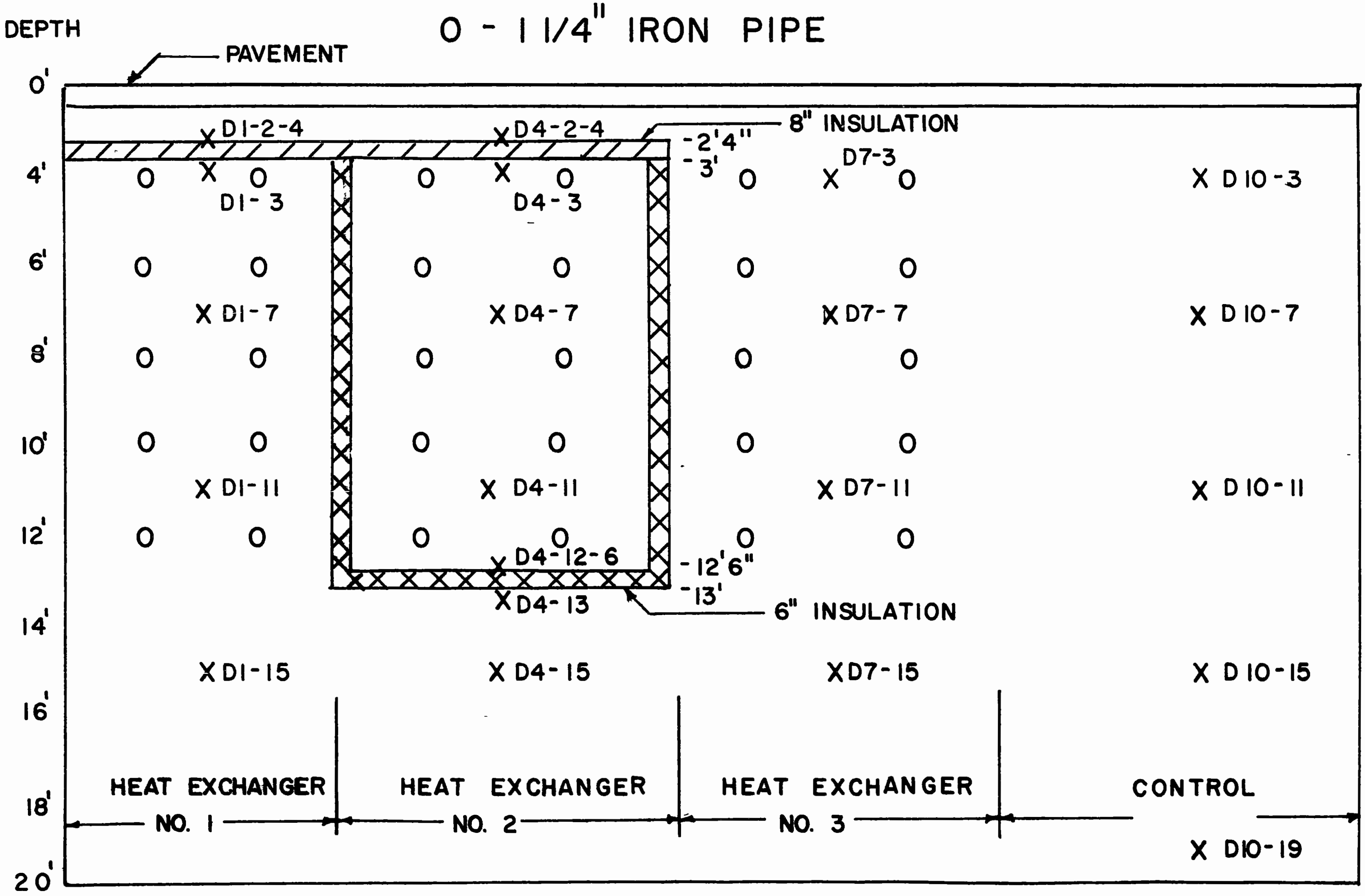


FIG. 9

FIGURE 10. STORM #3

Panel #3 (Portland Cement Concrete) & Panel #4 (Bituminous Concrete)
7:30 A. M. - January 2, 1971
(Operated 42 hours) (Air Temp. 21.6°F)

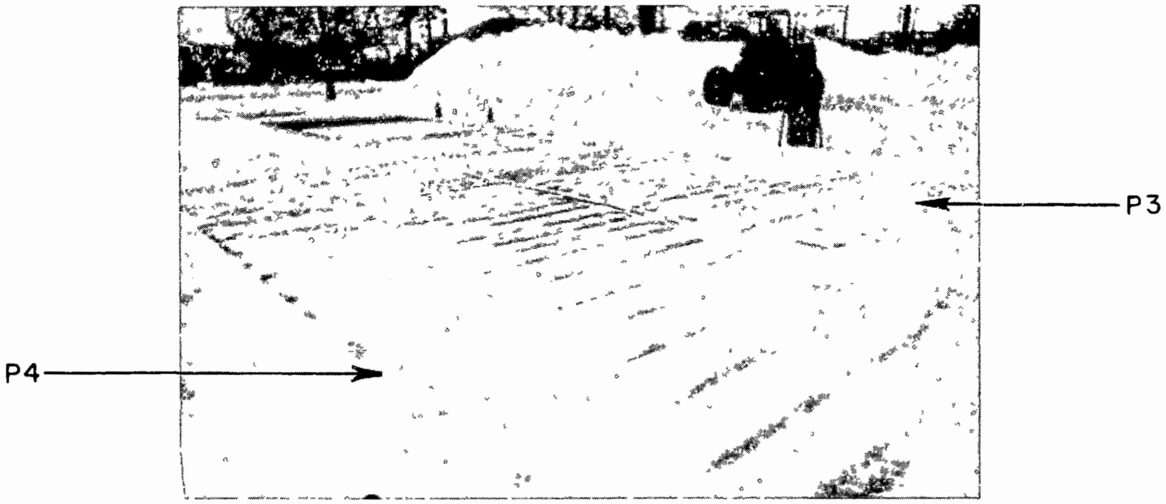


FIGURE 11. STORM #3

Panel #3 (Portland Cement Concrete) & Panel #4 (Bituminous Concrete)
4:15 P. M. - January 2, 1971
(Operated 50 hours) (Air Temp. 35.0°F)

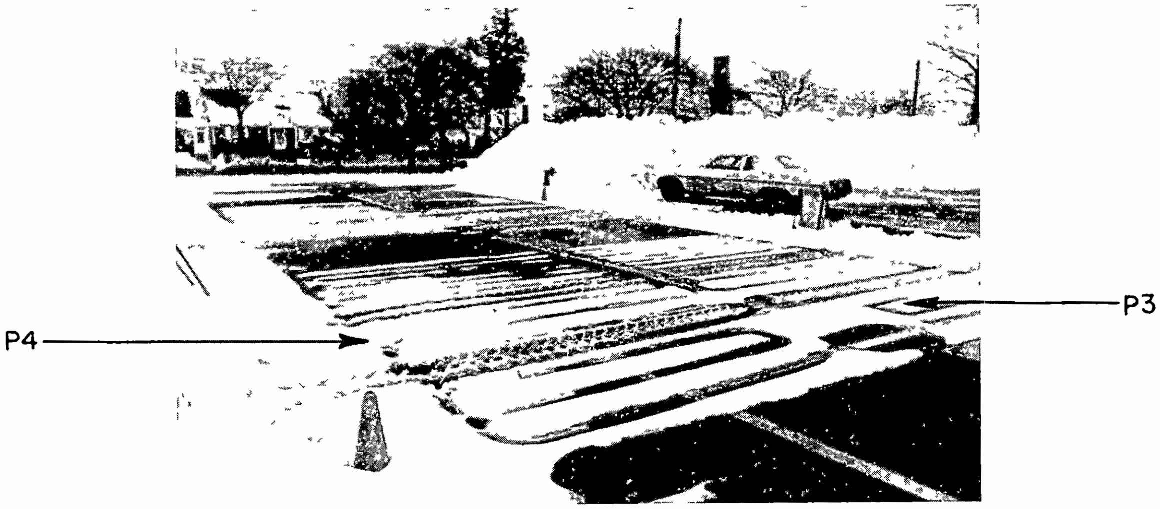


FIGURE 12. STORM # 7

Overall View --- Panels #1 & #2 nearest the observer
10:15 A. M. - March 3, 1971
(Just Activated) (Air Temp. 32.5°F)

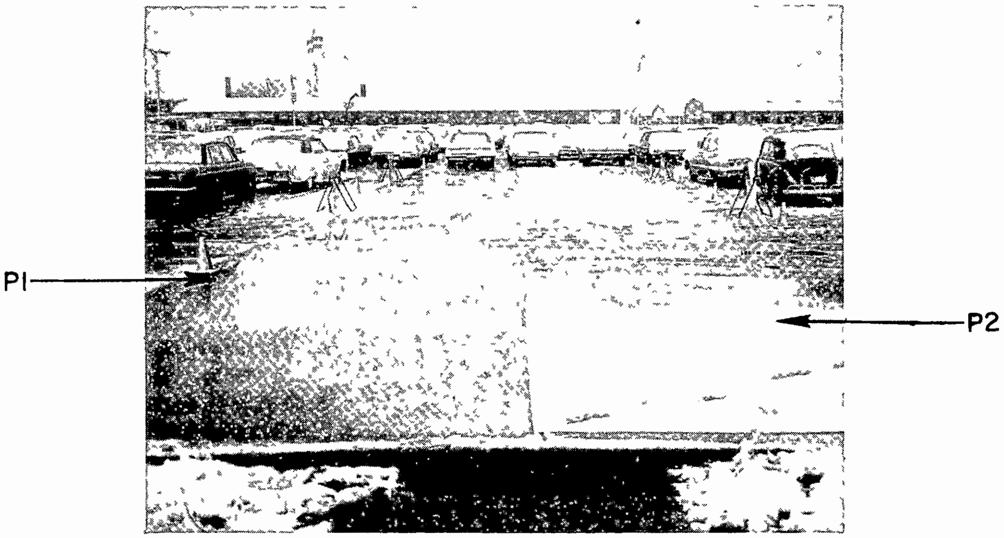


FIGURE 13. STORM #7

Overall View --- Panels #1 & #2 nearest the observer
1:45 P. M. - March 3, 1971
(Operated 3.5 hours) (Air Temp. 33.1°F)

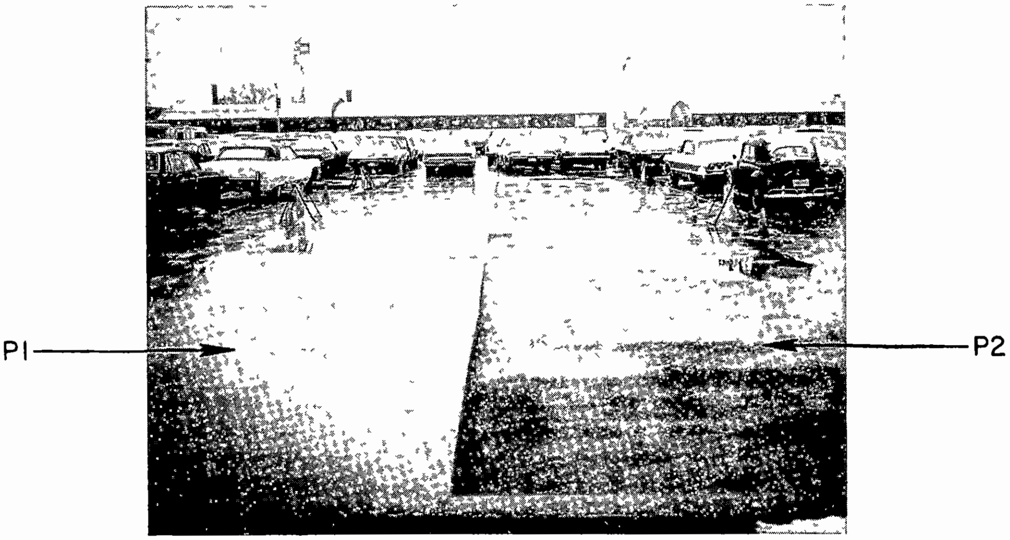


FIGURE 14. STORM #8

Panel #1 (Portland Cement Concrete) & Panel #2 (Bituminous Concrete)
11:00 A. M. - March 4, 1971
(Operated 2 hours) (Air Temp. 29.7°F)

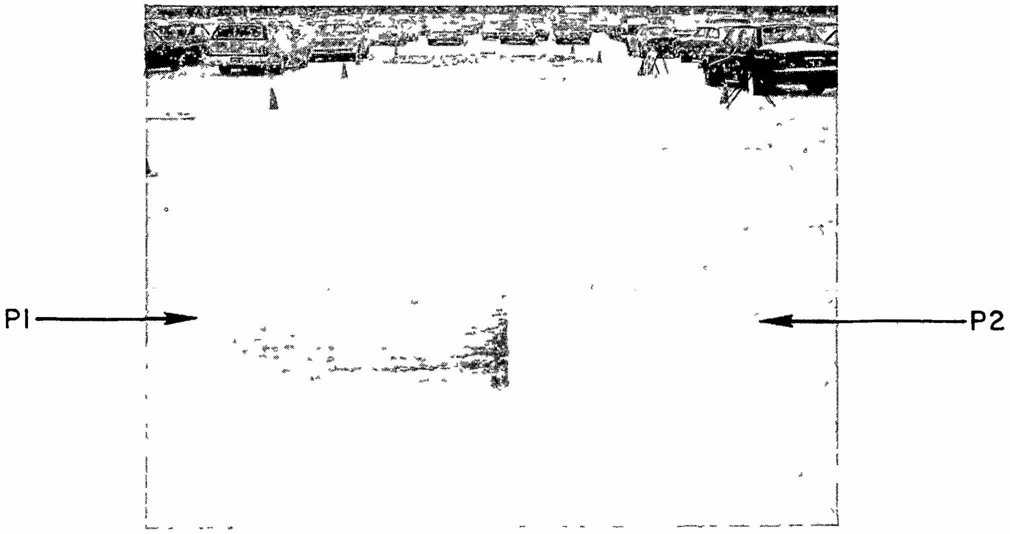


FIGURE 15. STORM #8

Panel #1 (Portland Cement Concrete) & Panel #2 (Bituminous Concrete)
12:00 Noon - March 4, 1971
(Operated 3 hours) (Air Temp. 29.1°F)

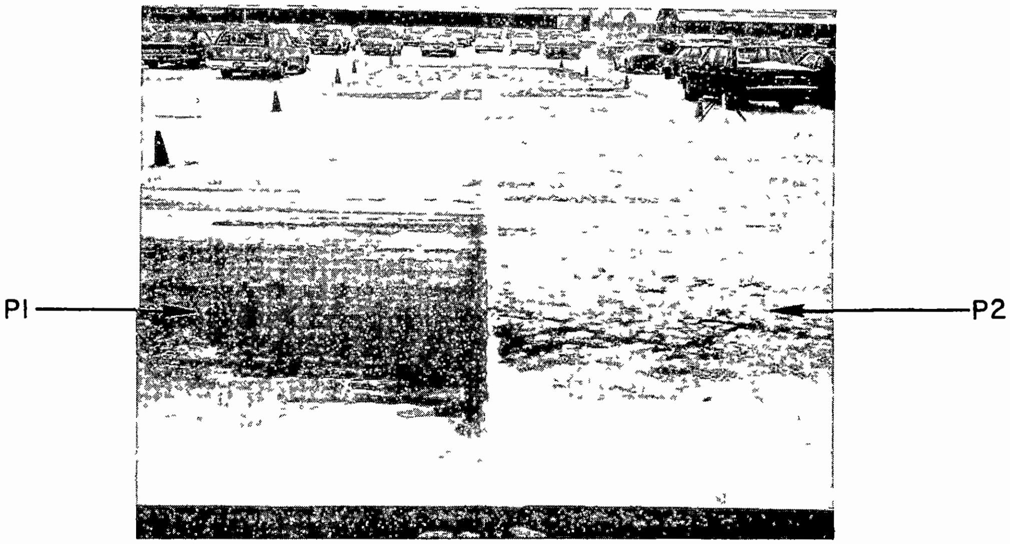


FIGURE 16. STORM #8

Panel #7 (Portland Cement Concrete) & Panel #8 (Bituminous Concrete)
11:00 A. M. - March 4, 1971
(Operated 2 hours) (Air Temp. 29.7°F)

FIGURE 17. STORM #8

Panel #7 (Portland Cement Concrete) & Panel #8 (Bituminous Concrete)
12:00 Noon - March 4, 1971
(Operated 3 hours) (Air Temp. 29.1°F)

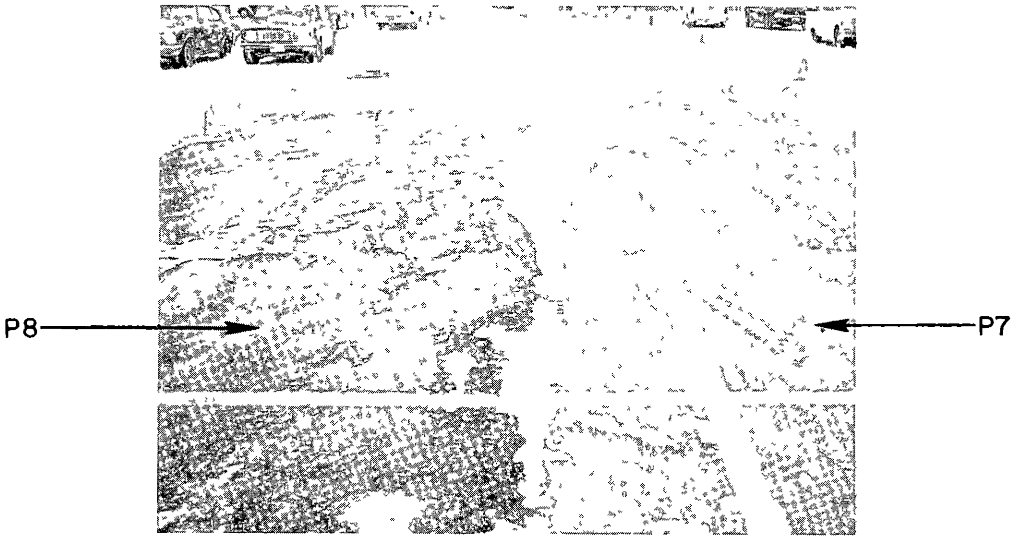


FIGURE 18. STORM #9

Panels #5, #6, #7, and #8
8:30 A. M. - April 7, 1971
(Operated 10.5 hours) (Air Temp. 37.0°F)

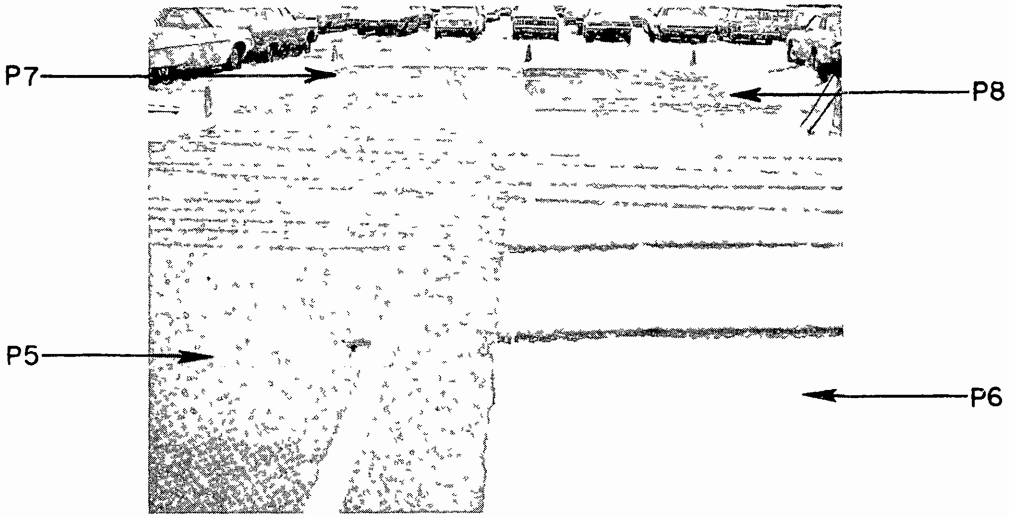
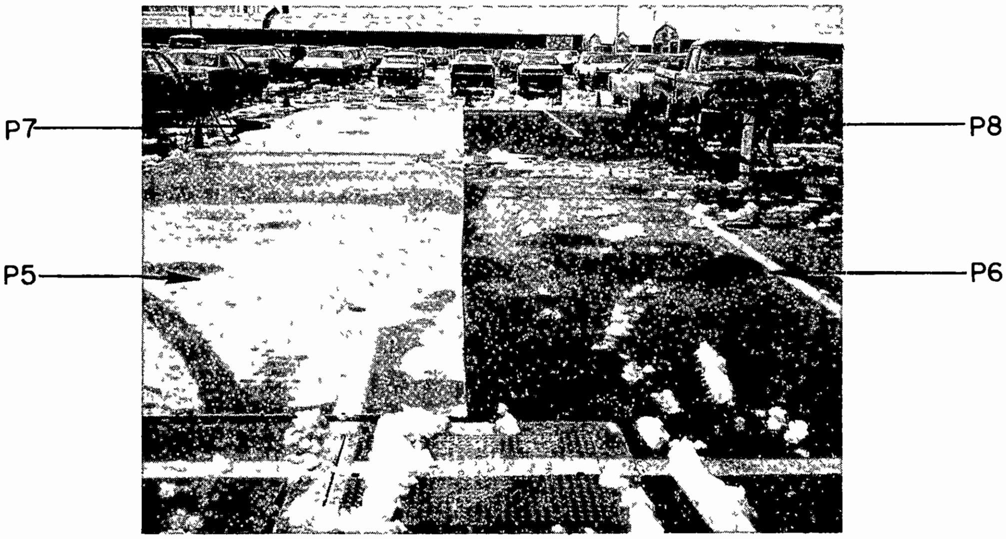


FIGURE 19. STORM #9

Panels #5, #6, #7, and #8
11:45 A. M. - April 7, 1971
(Operated 13.5 hours) (Air Temp. 49.3°F)



Terminology Used in "Account of Snow Storms 1970-1971"

Percentage Dry

The expression "P2 is x% dry" indicates that x% of the pavement surface area of P2 is dry and clear of snow, slush or ice.

Percentages Clear and Wet

When used in this report the expression "P1 (6") is x% clear and wet" means that x% of the pavement surface area of P1 (6") is wet and clear of snow, slush or ice. As a further example, "80% clear and wet" indicates that 20% of the pavement surface area of a panel is still covered by snow, slush or ice.

Figure 20 provides an illustration of the above terminology. This Figure shows Panels #1 and #2, with Panel #1 closest the viewer. P1 (6") is "100% clear and wet", P1 (12") is "50% clear and wet", and P1 (18") is "20% clear and wet". P2 is snow covered.

FIGURE 20

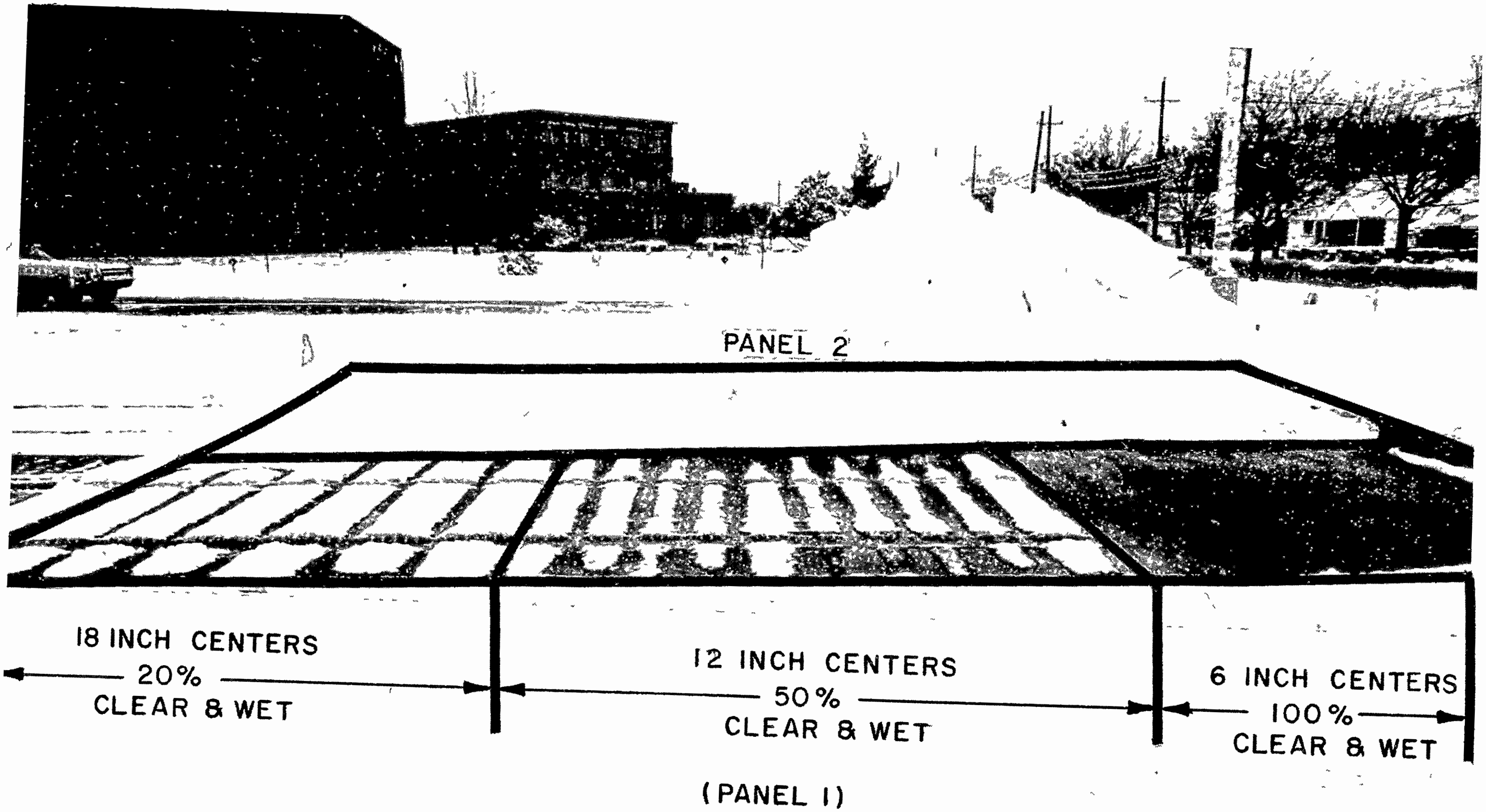

PANEL 2
18 INCH CENTERS
20%
CLEAR & WET
12 INCH CENTERS
50%
CLEAR & WET
6 INCH CENTERS
100%
CLEAR & WET
(PANEL 1)

TABLE 4

TEMPERATURE OF HEAT EXCHANGER FLUID

Date	Heat Exchanger #1		Heat Exchanger #2		Heat Exchanger #3	
	Temperature °F	Operational Hours	Temperature °F	Operational Hours	Temperature °F	Operational Hours
12/21/70	58°	5.5	61°	5.5	55°	5.5
12/22/70	58°	10.5	61°	10.5	55°	10.5
1/1/71	54°	47	56°	47	51°	47
1/2/71	52°	61.5	54°	61.5	49°	61.5
1/14/71	51°	75.5	51.5°	75.5	47°	75.5
2/17/71	51°	81.5	49.5°	89	46.5°	89
3/3/71	49°	85	47°	92	46°	92
4/6/71	47°	98.5	48°	106	46.5°	106

TABLE 5: HEAT DISSIPATION RATES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION			HEAT DISSIPATION (BTUH/FT.^{2})		
							PIPE DIAMETER			PIPE DIAMETER		
							3/4"	1"	1-1/4"	3/4"	1"	1-1/4"
1.	Dec. 21, 1970	12/21/70	8:10 p.m. (3 hours)	32.0	PORTLAND CEMENT	6"	CW	CW	CW	NO THERMISTOR READINGS (TW) TAKEN		
						12"	CW	CW	CW			
						18"	CW	CW	CW			
					BITUMINOUS	6"	CW	CW	CW	NO THERMISTOR READINGS (TW) TAKEN		
						12"	CW	CW	CW			
						18"	CW	CW	CW			
2.	Dec. 22, 1970	12/22/70	11:00 a.m. (2 hours)	32.5°F	PORTLAND CEMENT	6"	50%CW,SL	SC,M	80%CW,SL	177	147	186
						12"	SC,M	SC,M	SC,M	114	58	85
						18"	SC,M	SC,M	SC,M	64	41	63
					BITUMINOUS	6"	SC	SC	SC	181	111	109
						12"	SC	SC	SC	---	76	34
						18"	SC	SC	SC	44	32	15
3.	Dec. 31, 1970 Jan. 1-2 1971	1/1/71	12:10 p.m. (23 hrs.)	28.0	PORTLAND CEMENT	6"	SC	SC	SC	NO THERMISTOR READINGS (TW) TAKEN		
						12"	SC	SC	SC			
						18"	SC	SC	SC			
					BITUMINOUS	6"	SC	SC	SC	NO THERMISTOR READINGS (TW) TAKEN		
						12"	SC	SC	SC			
						18"	SC	SC	SC			

CW - Clear and Wet
CD - Clear and Dry
SL - Slush
SC - Snow Covered
M - Melting Above Pipes
I - Ice
--- Temperature Data Unreliable

TABLE 5: HEAT DISSIPATION RATES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	1"	1-1/4"	HEAT DISSIPATION (BTUH/FT.^{2}) PIPE DIAMETER 3/4"	1"	1-1/4"
4.	Jan. 13-14, 1971	1/14/71	1:30 p.m. (13.5 hrs.)	36.5	PORTLAND CEMENT	6"	CW	SL	95%CW	80	NOT OPERATIONAL	74
						12"	CW	SL	95%CW	69		46
						18"	CW	SL	95%CW	35		44
					BITUMINOUS	6"	CW	CW	95%CW	139	40	55
						12"	SL	CW	95%CW	---	35	18
						18"	SL	SL	95%CW	26	14	2
5.	Jan. 24-25, 1971	1/25/71	1:05 p.m. (13 hrs.)	39.0°F	PORTLAND CEMENT	6"	CW	SC	CW	122	NOT OPERATIONAL	
						12"	SL	SC	CW	84		
						18"	SL	SC	CW	42		
					BITUMINOUS	6"	SC	CW	CW	154	NOT OPERATIONAL	
						12"	SC	CW	CW	---		
						18"	SC	CW	CW	26		
6.	Feb. 17-18, 1971	2/17/71	7:00 p.m. (3 hrs.)	36.4	PORTLAND CEMENT	6"	CW	CW	CW	162	NOT OPERATIONAL	163
						12"	CW	CW	CW	104		76
						18"	CW	CW	CW	58		52
					BITUMINOUS	6"	CW	CW	CW	241	67	19
						12"	CW	CW	CW	---	47	43
						18"	CW	CW	CW	44	4	24

CW - Clear and wet
CD - Clear and dry
SL - Slush
SC - Snow Covered
M - Melting above pipes
I - Ice
--- Temperature Data Unreliable

TABLE 5. HEAT DISSIPATION RATES

STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	1"	1-1/4"	HEAT DISSIPATION (BTUH/FT.^{2}) PIPE DIAMETER 3/4"	1"	1-1/4"
7. March 3, 1971	3/3/71	11:00 a.m. (1 hour)	33.1°F	PORTLAND CEMENT	6"	SL	SL	SL	100	NOT OPERATIONAL	125
					12"	SL	SL	SL	70		56
					18"	SL	SC	SL	31		40
				BITUMINOUS	6"	SC	SC	SC	127	17	---
					12"	SC	SC	SC	---	22	21
					18"	SC	SC	SC	19	---	7
	3/3/71	12 noon (2 hrs.)	33.1	PORTLAND CEMENT	6"	SL	SL	SL	82	NOT OPERATIONAL	102
					12"	SL	SL	SL	62		50
					18"	SL	SC	SL	26		36
				BITUMINOUS	6"	SC	SC	SC	120	11	---
					12"	SC	SC	SC	---	19	20
					18"	SC	SC	SC	17	---	7
	3/3/71	1:00 p.m. (3 hrs.)	33.1	PORTLAND CEMENT	6"	CW	50%CW,SL	CW	68	NOT OPERATIONAL	89
					12"	CW	50%CW,SL	CW	59		47
					18"	CW	50%CW,SL	CW	24		35
				BITUMINOUS	6"	SL	50%CW,SL	SL	119	9	---
					12"	SL	50%CW,SL	SL	---	19	18
					18"	SL	50%CW,SL	SL	16	---	-5

CW - Clear and wet
CD - Clear and dry
SL - Slush
SC - Snow covered
M - Melting above pipes
I - Ice
--- Temperature Data Unreliable

TABLE 5: HEAT DISSIPATION RATES

STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	1"	1-1/4"	HEAT DISSIPATION (BTUH/FT.^{2}) PIPE DIAMETER 3/4"	1"	1-1/4"
8. March 4, 1971	3/4/71	10:00 a.m. (1 hour)	29.1	PORTLAND CEMENT	6"	SC	SC	SC	96	NOT OPERATIONAL	133
					12"	SC	SC	SC	73		62
					18"	SC	SC	SC	34		43
					6"	SC	SC	SC	127	20	---
				BITUMINOUS	12"	SC	SC	SC	---	23	22
					18"	SC	SC	SC	21	---	7
	3/4/71	11.00 a.m. (2 hrs.)	29.7	PORTLAND CEMENT	6"	SC,M	SC	SC,M	89	NOT OPERATIONAL	128
					12"	SC	SC	SC	71		61
					18"	SC	SC	SC,M	33		42
					6"	SC	SC	SC	122	12	---
				BITUMINOUS	12"	SC	SC	SC	---	20	22
					18"	SC	SC	SC	19	---	7
	3/4/71	12 noon (3 hrs.)	29.1	PORTLAND CEMENT	6"	50%CW,SL	SC	70%CW,SL	85	NOT OPERATIONAL	123
					12"	SC	SC	30%CW,SL	69		58
					18"	SC	SC	40%CW,SL	33		41
					6"	SC	SC	50%CW,SL	119	11	---
				BITUMINOUS	12"	SC	SC	50%CW,SL	---	19	21
					18"	SC	SC	50%CW,SL	19	---	6

CW - Clear and Wet
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SC - Snow Covered
M - Melting Above Pipes
I - Ice
--- Temperature Data Unreliable

TABLE 5 : HEAT DISSIPATION RATES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	1"	1-1/4"	HEAT DISSIPATION (BTUH/FT.^{2}) PIPE DIAMETER 3/4"	1"	1-1/4"
8.	March 4, 1971 (Cont.)	3/4/71	1:00 p.m. (4 hrs.)	30.6°F	PORTLAND CEMENT	6"	50%CW,SL	SL	80%CW,SL	71	NOT OPERATIONAL	92
						12"	90%CW,SL	SL	70%CW,SL	63		53
						18"	SL	SL	70%CW,SL	29		37
					BITUMINOUS	6"	CW	CW	90%CW,SL	114	9	---
						12"	80%CW,SL	90%CW,SL	90%CW,SL	---	18	18
						18"	80%CW,SL	90%CW,SL	90%CW,SL	17	---	5
		3/4/71	2:00 p.m. (5 hrs.)	29.9°F	PORTLAND CEMENT	6"	90%CW,SL	SL	90%CW,SL	59	NOT OPERATIONAL	96
						12"	90%CW,SL	SL	90%CW,SL	56		46
						18"	90%CW,SL	SL	90%CW,SL	26		34
					BITUMINOUS	6"	90%CW,SL	CW	95%CW,SL	110	8	---
						12"	90%CW,SL	CW	95%CW,SL	---	14	14
						18"	90%CW,SL	CW	95%CW,SL	14	---	3
		3/4/71	3:00 p.m. (6 hrs.)	29.4°F	PORTLAND CEMENT	6"	CW	40%CW,SL	98%CW,SL	85	NOT OPERATIONAL	104
						12"	CW	30%CW,SL	98%CW,SL	63		54
						18"	CW	30%CW,SL	98%CW,SL	33		39
					BITUMINOUS	6"	CW	CW	CW	133	23	---
						12"	CW	CW	CW	---	20	20
						18"	CW	CW	CW	19	---	7

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TABLE 5: HEAT DISSIPATION RATES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION			HEAT DISSIPATION (BTUH/FT.^{2})		
							PIPE DIAMETER			PIPE DIAMETER		
							3/4"	1"	1-1/4"	3/4"	1"	1-1/4"
9.	April 6-7, 1971	4/7/71	10:39 a.m. (12.5 hrs.)	45.9°F	PORTLAND CEMENT	6"	CW	SL	CW	25	NOT OPERATIONAL	45
						12"	80%CW,SL	SL	90%CW,SL	51		38
						18"	80%CW,SL	SL	80%CW,SL	22		41
					BITUMINOUS	6"	SL	SL	SL	116	3	---
						12"	SL	SL	SL	---	18	26
						18"	SL	SL	SL	18	---	6

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TABLE 6: PAVEMENT SURFACE TEMPERATURES

STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	1"	1-1/4"	SURFACE TEMPERATURES (°F) PIPE DIAMETER 3/4"	1"	1-1/4"
1. Dec. 21, 1970	12/21/70	8:10 p.m. (3 hrs.)	32.0	PORTLAND CEMENT	6"	CW	CW	CW	44.1	37.6	41.9
					12"	CW	CW	CW	35.2	32.5	35.8
					18"	CW	CW	CW	37.9	32.5	34.3
					6"	CW	CW	CW	39.6	34.1	43.6
				BITUMINOUS	12"	CW	CW	CW	37.6	35.0	38.0
					18"	CW	CW	CW	35.3	32.8	36.2
	12/21/70	10:08 p.m. (5 hrs.)	32.0	PORTLAND CEMENT	6"	2%CD	CW	CW	46.0	40.3	43.6
					12"	2%CD	CW	CW	37.6	35.0	38.0
					18"	2%CD	CW	CW	35.3	32.8	36.2
					6"	CW	CW	CW	42.0	42.5	41.3
				BITUMINOUS	12"	CW	CW	CW	34.5	35.0	35.7
					18"	SL	SL	CW	34.0	34.1	34.5
2. Dec. 22, 1970	12/22/70	11:00 a.m. (2 hrs.)	32.5	PORTLAND CEMENT	6"	50%SL,CW	SC,M	80%CW,SL	38.5	33.4	34.3
					12"	SC,M	SC,M	SC,M	32.9	32.4	32.8
					18"	SC,M	SC,M	SC,M	32.5	32.4	32.5
					6"	SC	SC	SC	37.8	37.0	36.8
				BITUMINOUS	12"	SC	SC	SC	33.7	33.8	33.7
					18"	SC	SC	SC	33.3	33.6	33.8

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I - Ice
** Panel Not in Operation

TABLE 6: PAVEMENT SURFACE TEMPERATURES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER			SURFACE TEMPERATURES (°F) PIPE DIAMETER		
							3/4"	1"	1-1/4"	3/4"	1"	1-1/4"
2.	Dec. 22, 1970 (Cont.)	12/22/70	1:00 p.m. (4 hrs.)	32.9	PORTLAND CEMENT	6"	CW	CW	CW	44.6	38.2	42.7
						12"	SL	SL	80%CW	33.1	32.5	33.0
						18"	SL	SL	30%CW	32.6	32.5	33.8
					BITUMINOUS	6"	SC,M	SC,M	SC,M	38.6	37.9	37.3
						12"	SC,M	SC,M	SC,M	34.1	34.2	33.8
						18"	SC,M	SC,M	SC,M	33.6	33.8	34.0
3.	Dec. 31, 1970 Jan. 2, 1971	1/1/71	12.10 p.m. (23 hrs.)	28.0	PORTLAND CEMENT	6"	SC	SC	SC	37.5	33.1	33.8
						12"	SC	SC	SC	33.0	32.3	32.7
						18"	SC	SC	SC	32.5	32.9	32.4
					BITUMINOUS	6"	SC	SC	SC	37.7	37.4	36.6
						12"	SC	SC	SC	33.8	33.6	33.4
						18"	SC	SC	SC	32.9	32.8	33.9
		1/2/71	7:45 a.m. (42.5 hrs.)	21.6	PORTLAND CEMENT	6"	100%CD	SC,I,M	SL	39.8	34.9	34.6
						12"	SL	SC,I,M	SC,M	34.8	33.8	35.5
						18"	SC,I	SC,I,M	SC,M	35.2	32.7	34.4
					BITUMINOUS	6"	SC,M	SC,I,M	SC,I,M	40.7	34.1	38.1
						12"	SC,M	SC,I,M	SC,I,M	34.1	33.7	34.5
						18"	SC	SC,I,M	SC,I,M	31.8	33.1	34.9

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TABLE 6: PAVEMENT SURFACE TEMPERATURES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	1"	1-1/4"	SURFACE TEMPERATURES (°F) PIPE DIAMETER 3/4"	1"	1-1/4"
3.	Dec. 31, 1970 Jan. 2, 1971 (Cont.)	1/2/71	12:37 p.m. (47 hrs.)	32.9	PORTLAND CEMENT	6"	100%CD	SL	CD	53.4	34.7	48.6
						12"	SL	SL	SL	33.5	32.7	33.3
						18"	I,SL	SC,M	SL	34.2	32.5	33.1
					BITUMINOUS	6"	CW	SL	CD	43.1	44.8	39.1
						12"	SC,M	SL	SL	34.4	37.0	34.9
						18"	SC	SC,M	SL	33.5	33.4	34.3
		1/2/71	4:20 p.m. (51 hrs.)	35.0	PORTLAND CEMENT	6"	CD	SL	CD	48.5	**35.2	43.1
						12"	70%CW	SL	CD	36.9	**32.2	36.3
						18"	75%CW,I	SC,M	SL	32.3	**32.6	32.7
					BITUMINOUS	6"	90%CW	SL	100%CW	41.7	**40.1	40.8
						12"	SL	SL	SL	34.5	**34.8	35.0
						18"	I	SC,M	SL	34.0	**34.5	34.3
4.	Jan. 13-14, 1971	1/14/71	10:15 a.m. (10 hrs.)	33.5°F	PORTLAND CEMENT	6"	100%CW	SC	100%CW	44.3	**31.3	40.7
						12"	SL	SC	SL	32.6	**30.7	32.4
						18"	SL	SC	SL	32.1	**30.4	33.6
					BITUMINOUS	6"	SC,M	100%CW	SC,I	36.4	36.6	36.6
						12"	SC	SC	SC,I	33.0	33.2	33.1
						18"	SC	SC	SC,I	32.8	32.6	34.2

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TABLE 6: PAVEMENT SURFACE TEMPERATURES

STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	1"	1-1/4"	SURFACE TEMPERATURES (°F) PIPE DIAMETER 3/4"	1"	1-1/4"
4. Jan. 13-14, 1971 (Cont.)	1/14/71	1:30 p.m. (13 hrs.)	33.5	PORTLAND CEMENT	6"	100%CW	SL	95%CW	48.8	**31.8	44.3
					12"	100%CW	SL	95%CW	39.8	**31.8	40.3
					18"	100%CW	SL	95%CW	32.5	**32.1	40.0
				BITUMINOUS	6"	CW	CW	95%CW	42.7	46.3	44.2
					12"	SL	CW	95%CW	33.3	34.3	34.7
					18"	SL	SL	95%CW	33.0	33.1	42.8
5. Jan. 24-25, 1971	1/25/71	10:00 a.m. (10.5 hrs.)	35.6	PORTLAND CEMENT	6"	SC	SC	90%CW	**37.5	**31.0	43.4
					12"	SC	SC	90%CW	**31.8	**30.8	38.3
					18"	SC	SC	SL	**31.8	**30.7	36.5
				BITUMINOUS	6"	SC	90%CW	90%CW	**31.9	42.8	40.2
					12"	SC	SL	SL	**31.9	33.2	36.1
					18"	SC	SL	SL	**31.8	32.6	33.8
	1/25/71	1:05 p.m. (13.5 hrs.)	39.0	PORTLAND CEMENT	6"	CW	SC	CW	43.9	**35.7	**44.9
					12"	SL	SC	CW	32.5	**31.8	**43.9
					18"	SL	SC	CW	31.7	**32.1	**43.5
				BITUMINOUS	6"	SC	CW	CW	34.8	**48.1	**46.4
					12"	SC	CW	CW	32.0	**45.4	**46.2
					18"	SC	CW	CW	33.9	**42.1	**46.6

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TABLE 6: PAVEMENT SURFACE TEMPERATURES

STORM NUMBER AND STORM DATES	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER			SURFACE TEMPERATURES (°F) PIPE DIAMETER		
						3/4"	1"	1-1/4"	3/4"	1"	1-1/4"
6. Feb. 17-18, 1971	2/17/71	7.00 p.m. (3 hrs.)	36.4°F	PORTLAND CEMENT	6"	CW	CW	CW	43.9	**32.9	39.6
					12"	CW	CW	CW	35.3	**32.0	36.0
					18"	CW	CW	CW	34.2	**32.1	42.7
					6"	CW	CW	CW	35.9	38.7	43.9
				BITUMINOUS	12"	CW	CW	CW	32.3	35.7	35.5
					18"	CW	CW	CW	34.5	46.0	36.7
7. March 3, 1971	3/3/71	11:00 a.m. (1 hour)	33.1°F	PORTLAND CEMENT	6"	SL	SL	SL	40.5	**34.2	35.8
					12"	SL	SL	SL	32.9	**32.3	34.6
					18"	SL	SC	SL	37.0	**32.5	40.3
					6"	SC	SC	SC	35.2	35.2	40.9
				BITUMINOUS	12"	SC	SC	SC	34.0	33.6	33.6
					18"	SC	SC	SC	34.8	39.9	34.5
	3/3/71	12 noon (2 hrs.)	33.1°F	PORTLAND CEMENT	6"	SL	SL	SL	44.2	**35.1	39.3
					12"	SL	SL	SL	35.6	**32.6	37.5
					18"	SL	SC	SL	36.9	**32.5	40.9
					6"	SC	SC	SC	36.2	36.7	41.5
				BITUMINOUS	12"	SC	SC	SC	34.1	33.7	33.8
					18"	SC	SC	SC	36.5	39.8	34.6

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TABLE 6: PAVEMENT SURFACE TEMPERATURES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER 3/4"	PAVEMENT SURFACE CONDITION PIPE DIAMETER 1"	PAVEMENT SURFACE CONDITION PIPE DIAMETER 1-1/4"	SURFACE TEMPERATURES (°F) PIPE DIAMETER 3/4"	SURFACE TEMPERATURES (°F) PIPE DIAMETER 1"	SURFACE TEMPERATURES (°F) PIPE DIAMETER 1-1/4"
7.	March 3, 1971 (Cont.)	3/3/71	1:00 p.m. (3 hours)	33.1°F	PORTLAND CEMENT	6"	CW	50%CW,SL	CW	45.5	**36.5	40.3
						12"	CW	50%CW,SL	CW	37.3	**33.5	38.3
						18"	CW	50%CW,SL	CW	37.9	**32.6	41.1
					BITUMINOUS	6"	SL	50%CW,SL	SL	36.6	38.5	41.9
						12"	SL	50%CW,SL	SL	34.3	33.9	34.1
						18"	SL	50%CW,SL	SL	36.8	39.8	36.3
8.	March 4, 1971	3/4/71	10:00 a.m. (1 hour)	29.1	PORTLAND CEMENT	6"	SC	SC	SC	40.3	**32.4	33.9
						12"	SC	SC	SC	32.8	**32.3	33.1
						18"	SC	SC	SC	32.7	**32.4	40.7
					BITUMINOUS	6"	SC	SC	SC	35.1	34.5	41.5
						12"	SC	SC	SC	33.5	33.2	33.2
						18"	SC	SC	SC	33.4	39.8	33.8
		3/4/71	11:00 a.m. (2 hours)	29.7	PORTLAND CEMENT	6"	SC,M	SC	SC,M	40.6	**32.5	34.2
						12"	SC	SC	SC	32.9	**32.3	33.2
						18"	SC	SC	SC,M	32.8	**32.4	41.1
					BITUMINOUS	6"	SC	SC	SC	35.8	35.2	42.0
						12"	SC	SC	SC	33.7	33.4	33.4
						18"	SC	SC	SC	33.6	39.7	33.8

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TABLE 6: PAVEMENT SURFACE TEMPERATURES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITION PIPE DIAMETER			SURFACE TEMPERATURES (°F) PIPE DIAMETER		
							3/4"	1"	1-1/4"	3/4"	1"	1-1/4"
8.	March 4, 1971 (Cont.)	3/4/71	12 noon (3 hours)	29.1	PORTLAND CEMENT	6"	50%CW,SL	SC	70%CW,SL	40.7	**32.6	34.5
						12"	SC	SC	30%CW,SL	33.2	**32.4	33.2
						18"	SC	SC	40%CW,SL	32.8	**32.4	41.3
						6"	SC	SC	50%CW,SL	36.2	35.5	42.4
					BITUMINOUS	12"	SC	SC	50%CW,SL	34.0	33.6	34.4
						18"	SC	SC	50%CW,SL	33.6	39.8	34.1
		3/4/71	1:00 p.m. (4 hours)	30.6	PORTLAND CEMENT	6"	50%CW,SL	SL	80%CW,SL	43.3	**32.5	36.8
						12"	90%CW,SL	SL	70%CW,SL	34.2	**33.3	33.2
						18"	SL	SL	70%CW,SL	33.2	**32.6	42.9
						6"	CW	CW	90%CW,SL	36.4	35.8	43.7
					BITUMINOUS	12"	80%CW,SL	90%CW,SL	90%CW,SL	34.0	35.1	34.4
						18"	80%CW,SL	90%CW,SL	90%CW,SL	34.1	41.1	37.2
		3/4/71	2:00 p.m. (5 hours)	29.9	PORTLAND CEMENT	6"	90%CW,SL	SL	90%CW,SL	48.0	**32.9	43.6
						12"	90%CW,SL	SL	90%CW,SL	40.2	**38.7	35.6
						18"	90%CW,SL	SL	90%CW,SL	34.8	**32.9	48.0
						6"	90%CW,SL	CW	95%CW,SL	36.6	36.1	48.8
					BITUMINOUS	12"	90%CW,SL	CW	95%CW,SL	39.5	41.5	42.8
						18"	90%CW,SL	CW	95%CW,SL	36.3	45.9	42.0

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TABLE 6: PAVEMENT SURFACE TEMPERATURES

	STORM NUMBER AND STORM DATE	DATE OF OBSERVATION	TIME (HOURS IN OPERATION)	AIR TEMPERATURE (°F)	TYPE OF CONCRETE	PIPE SPACING	PAVEMENT SURFACE CONDITIONS PIPE DIAMETER 3/4"	1"	1-1/4"	SURFACE TEMPERATURE (°F) PIPE DIAMETER 3/4"	1"	1-1/4"
8.	March 4, 1971 (Cont.)	3/4/71	3:00 p.m. (6 hours)	29.4	PORTLAND CEMENT	6"	CW	40%CW,SL	98%CW,SL	48.3	**34.8	42.2
						12"	CW	30%CW,SL	98%CW,SL	39.8	**38.2	39.7
						18"	CW	30%CW,SL	98%CW,SL	36.1	**35.4	47.8
						6"	CW	CW	CW	41.0	38.1	38.6
					BITUMINOUS	12"	CW	CW	CW	41.2	41.8	41.6
						18"	CW	CW	CW	38.7	46.1	40.4
9.	April 6-7, 1971	4/6/71	11:00 p.m. (1 hour)	33.5	PORTLAND CEMENT	6"	SC	SC	SC	41.1	**33.1	34.1
						12"	SC	SC	SC	33.6	**32.9	-----
						18"	SC	SC	SC	33.5	**33.2	40.2
						6"	SC	SC	SC	36.4	36.2	40.8
					BITUMINOUS	12"	SC	SC	SC	35.1	35.0	-----
						18"	SC	SC	SC	35.5	43.1	35.4
		4/7/71	10:39 a.m. (12.5 hrs.)	45.9	PORTLAND CEMENT	6"	CW	SL	CW	46.3	**39.0	58.6
						12"	80%CW,SL	SL	90%CW,SL	39.4	**32.8	52.7
						18"	80%CW,SL	SL	80%CW,SL	37.0	**37.5	49.8
						6"	SL	SL	SL	37.0	42.5	50.2
					BITUMINOUS	12"	SL	SL	SL	36.4	36.3	55.8
						18"	SL	SL	SL	37.0	47.0	49.8

CW - Clear and wet
CD - Clear and dry
** Panel Not in Operation
SL - Slush
SC - Snow Covered
-----Temperature Data Unreliable
M - Melting above pipes
I - Ice

Method of Calculation

I. CALCULATION OF AVERAGE TEMPERATURES OF HEAT EXCHANGERS

1. Average temperatures of the two readings at 3 ft., 7 ft. and 11 ft.

   a. For Heat Exchanger #1 use:

      D 1-3 + D 2-3; D 1-7 + D 2-7; D 1-11* + D 2-11

   b. For Heat Exchanger #2 use:

      D 4-3 + D 5-3; D 4-7 + D 5-7; D 4-11* + D 5-11

   c. For Heat Exchanger #3 use:

      D 7-3 + D 8-3; D 7-7 + D 8-7; D 7-11 + D 8-11

      * Discard this reading - appears to be erroneous

II. CALCULATION OF HEAT STORED IN HEAT EXCHANGERS

1. Average two readings at 3 ft., 7 ft. and 11 ft. in Heat Exchanger

   Ex. $\frac{D\ 1\text{-}3 + D\ 2\text{-}3}{2} = \text{Average}$

2. Subtract the control reading (D10) at 3 ft., 7 ft. and 11 ft. from the average temperature at each depth, respectively.

   Ex. $\frac{D\ 1\text{-}3 + D\ 2\text{-}3}{2} - D\ 10\text{-}3 = \Delta T_3$

3. Divide each Heat Exchanger into layers using an average T for each layer.

   Thus: 3' to 5' use $\Delta \overline{T}_3$ at 3'
   5' to 9' use $\Delta \overline{T}_7$ at 7'
   9' to 12.5' use $\Delta \overline{T}_{11}$ at 11'

4. Calculated heat stored, Q, for each layer and sum Q for all three layers.

   Ex. $Q_{total} = Q_{3-5} + Q_{5-9} + Q_{9-12.5}$

   where $Q_{3-5} = \rho c \Delta \overline{T}_3 \, [(5'-3') \times 32' \times 30']$

   $Q_{5-9} = \rho c \Delta \overline{T}_7 \, [(9'-5') \times 32' \times 30']$

   $Q_{9-12.5} = \rho c \Delta \overline{T}_{11} \, [(12.5'-9') \times 32' \times 30']$

where ρ = earth density = 110 lb/ft^3 (known)

c = earth specific heat = 0.5 (assumed)

III. CALCULATION OF HEAT DISSIPATION RATES

$$\dot{Q} = \dot{V}\,(60 \times \rho \times C_g \times C_h \times \Delta T)/A$$

where $\dot{Q}$ = heat dissipation rate [(BTUH)/ft^2]

$\dot{V}$ = volumetric flow rate = [1.07 gal/min]

ρ = density of water = [8.3 $\frac{\text{lbs}}{\text{gal}}$]

C_g = specific gravity of circulating fluid

C_h = specific heat of circulating fluid

ΔT = temperature drop [°F]

A = surface area of slab [ft^2]

and 60 = $\frac{\text{minutes}}{\text{hour}}$ is the time conversion

IV. CALCULATION OF HEAT LOSS DURING STORMS

$$Q = \dot{Q}\,(t)\quad(A)$$

where Q = heat loss [BTU]

$\dot{Q}$ = heat dissipation rate [(BTUH)/ft^2]

t = total time of operation [hr]

A = surface area [ft^2]

V. CALCULATION OF RATES OF HEAT STORAGE

$$\dot{Q}_s = \frac{Q_2 - Q_1}{T}$$

where $\dot{Q}_s$ = rate of heat storage [BTUH]

Q_2, Q_1 = heat stored at times 2 and 1, respectively

T = time interval - between times 2 and 1

VI. SAMPLE CALCULATION

Heat dissipation rates for storm of March 3, 1971, Panel #1 (6" pipe spacing)

$$\dot{Q} = \dot{V}\ (60 \times \rho \times C_g \times C_h \times \Delta T)/A$$

where $\dot{Q}$ = heat dissipation rate (BTUH/ft^2)

$\dot{V} = 1.07 \pm .04$ gallons per minute

$\rho = 8.3$ lbs/gal

$C_g = 1.073$, $C_h = .840$

$\Delta T = 6.5 \pm .42°\text{F}$

$A = 124.50\ \text{ft}^2$

$$\dot{Q} = (1.07 \pm .04)\ (60 \times 8.3 \times 1.073 \times .840)\ (6.5 \pm .42)/(124.50)$$

$$\dot{Q} = 100.3 \pm 10.5\ \text{BTUH/ft}^2$$