PAPER NO. 80-4027

FLOOR HEATING OF GREENHOUSES

by

William J. Roberts
Dept. Chairman; Spec. in Agric. Engr.
Biological & Agric. Engineering Dept.
Cook College - Rutgers University
New Brunswick, New Jersey 08903

David R. Mears
Professor
Biological & Agric. Engineering Dept.
Cook College - Rutgers University
New Brunswick, New Jersey 08903

For presentation at the 1980 Summer Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

San Antonio Convention Center
San Antonio, TX
June 15-18, 1980

SUMMARY:

This paper presents the heat transfer coefficients for several floor heating systems used for greenhouse production. These include the flooded floor, plastic pipe embedded in porous concrete and plastic pipe in sand.

American Society of Agricultural Engineers

St. Joseph, Michigan 49085

FLOOR HEATING OF GREENHOUSES

William J. Roberts*   David R. Mears*

Introduction

There are many crops which are grown in containers directly on the floor in greenhouses. These include bedding plants, poinsettias and other pot plants which require minimum hand labor and vegetable transplants. All of these crops can benefit from soil heating systems which supply energy from the warm floor of the greenhouse. Greenhouse vegetables such as lettuce, tomatoes and cucumbers, and flowers such as roses and carnations which are grown directly in beds placed on the floor also respond favorably to warmer soils. This response has been well documented and as a result, benches have been used in greenhouses since their inception not only to put plants at a proper working height, but to enable the grower to utilize a heating system under the bench to provide warm root-zone temperatures. The elimination of costly fixed benches and the desire for a more flexible use of floor space has led to a significant interest in floor heating of greenhouses.

Research at Rutgers has developed several systems which provide heat to the greenhouse through the floor. These include: I. The Rutgers Solar System(8,9); II. Use of condensor cooling water from power plants(6,7); III. In-floor placement of plastic pipe for warming porous concrete floors(10); and IV. The use of plastic pipe and plastic grids in floors of various materials(3,4).

System Performances

I. The Rutgers Solar System has been reported in several publications and at various meetings(8,9). A key to the system is the use of the floor as the heat storage system as well as the primary heat exchanger for the greenhouse. Fig. 1 illustrates the construction of the floor which is composed of 0.5 mm vinyl, biocide treated swimming pool liner, placed over 2 cm of rigid foam insulation which also serves as a cushion for the liner. Gravel is placed on the liner to a depth of 22 to 30 cm. The floor is constructed with a cap of 7 cm of porous concrete which serves as the working surface(Fig.1). Water is stored in the area between the vinyl liner and the lower edge of the porous concrete cap. Approximately 500 liters of water can be stored per cubic meter of gravel which has a void space of 50%.

---

* Department Chairman and Specialist in Agric. Engineering; Professor, Biological & Agricultural Engineering Department, Cook College-Rutgers University, New Brunswick, New Jersey 08903.

Paper of the Journal Series, New Jersey Agricultural Experiment Station, Rutgers University, Biological and Agricultural Engineering Department, New Brunswick, New Jersey 08903, May 1980.

This work was performed as part of NJAES Project No. 03130, supported by the New Jersey Agricultural Experiment Station and Hatch Funds.

Water is pumped from the floor storage to the solar collector field and returns to the storage by gravity having been warmed in the collector. The energy collected is released during the subsequent heating period. When solar energy is inadequate, a floor pipe loop (Fig.1) connected to an auiliary water heater or boiler is activated to heat the floor to the desired temperature.

The heat transfer rate from the floor storage to the growing area has been determined over a wide range of operating conditions. A typical value is 8.23 W/m^2K, although it varies with the temperature difference between the storage and the greenhouse air temperature. Normal operating conditions would fall in the range of 23.9°C to 26.7°C storage temperature to 15.6°C to 18.3°C air temperature[8].

Cipolletti[1] working in a large research démonstration greenhouse determined the value to range from 8.8 W/m^2K for bare greenhouse floor to 5.1 W/m^2K when the floor was totally covered with a crop of bedding plants in tightly spaced flats. Air temperature was measured at 10 locations in the greenhouse. The floor storage temperature was also averaged from eight locations. During the time of the experiment, the heat loss from the structure was determined using a previously calculated U value. The experiment occurred at night after transient flow had ceased and during periods when the floor and storage temperature remained constant.

Therefore $Q_g = Q_f$

Heat loss greenhouse $Q_g = U_g\, A_g\, (T_i - T_o)$

Heat loss floor $Q_f = U_f\, A_f\, (T_f - T_i)$

$$\therefore U_f = \frac{U_g\, A_g\, (T_i - T_o)}{A_f\, (T_f - T_i)}$$

Data on a typical night for the week of April 14-21, 1980, indicates the following:

$U_g = 2.3\ W/m^2K$ $\qquad A_f = 5388\ m^2$

$A_g = 7339\ m^2$ $\qquad T_f = 20.5°C$

$T_i = 15°C$

$T_o = 4.4°C$

U_f is determined to be 5.9 W/m^2K

During the experiments, the measured floor losses were negligible since the system had been in operation for many months and the soil temperature was equal to the floor storage temperature. Heat flow downward was a maximum of 10% at startup when measured with a heat flow disk.

The thermal mass of the floor storage was determined using the auxiliary heating system during the day when the greenhouse ambient temperature was warmer than the floor storage. Fig. 2 shows the temperature variation in the system on a typical day. The porous concrete cap showed wide variation in temperature over time so it was separated from the storage when evaluating the thermal mass. The determination was made by observing the temperature change during a period and measuring the input energy.

The input energy from the auxiliary system was measured by recording the water flow on two integrating flow meters over a given period of time. Temperatures in the heat exchanger supplying energy to the floor storage were measured at inlet and outlet. Knowing the flow rate and change in temperature, the energy supplied to the floor system was determined.

The thermal capacity of the floor system was found to be 0.9 MJ/m^2K of floor area. This compares to a value of 1.2 MJ/m^2K if the entire floor volume were water instead of the rock-water combination.

There is much interest on utilizing passive heating in a greenhouse and there is little information available on this subject, especially for commercial greenhouses.

Passive gain to the floor system was also determined by Cipolletti(1) using a horizontal solarimeter and a net radiometer. These instruments were coupled to a data acquisition system. Incoming solar flux and flux absorbed by the floor were measured. Instantaneous values varied from 32% to 20% absorption for the bare floor. The average value for a bare floor was 26%. When the floor was covered with a full plant canopy, the total absorptivity was 65%. Walker 1965(11) reported that approximately 3% of the incoming radiation is used in the photosynthetic process, indicating that plant transpiration is a significant drain on the solar energy input.

A second test was conducted to determine the bare floor absorptivity. A section of floor was instrumented with thermocouples placed at varying depths. The change in temperature versus time was observed at these locations along with greenhouse and water storage temperature rise (Fig.2). When the surface of the porous concrete reached a point of thermal stability, the incident solar energy absorbed would equal the energy lost from the surface by natural convection. From ASHRAE 1965, an empirical convection coefficient was determined to be 5 W/m^2K and the corresponding absorptivity was found to be 21%. By using this absorptivity and calculated convection coefficient, the heat capacitance per cubic meter of porous concrete was determined.

A section of porous concrete which was removed from a greenhouse was measured and weighed to determine the density of the sample. From the thermocouples in the floor, the change in temperature versus time and incident solar flux were recorded. Conservation of energy determines that the absorbed solar flux has to equal the energy lost from the surface by convection plus the energy stored or released from the concrete mass. At a point during the day from 1700-1900 hours, shown in Fig. 2, the upper strata of porous concrete was losing energy only in one direction, through convection from the surface. Using the change in temperature at this point along with the incident absorbed solar flux and convective loss, a value for the heat capacitance per cubic meter could be solved directly from the following equation:

$$\alpha\ Q_s\ A_f = H_f\ A_f\ (T_s - T_g) + M\ C_p\ {}^{dT}/_{dt}$$

α = absorptivity

Q_s = solar flux

A_f = area floor

H_f = convective coefficient floor

A_f = area floor

T_s = surface temperature

T_g = greenhouse air temperature

M = mass of concrete

$^{dT}/_{dt}$ = change in surface temperature over time

C_p = specific heat of concrete

From this equation, the value of MC_p was found to be 1543 KJ/m^3K, which translates to a C_p of 835.9 J/K_g K when the measured density of the porous concrete was used. Kreith and Kreider, 1979[5] list the C_p of concrete as 837.4 J/K_g K, which is within 2% of the determined value.

In some instances of greenhouse production, porous concrete may not be needed, such as in the headhouse or work areas. The warm floor, of course, also has great merit for a residential or business application. Cipolletti[2] reported on the use of the warm floor for residential use. Fig. 3 shows the construction of the floor.

Using an electric hot water heater to supply the energy to the floor, temperature data was recorded and a U value for the Rutgers warm floor system capped with regular rather than porous concrete was determined. The small 3 m x 3 m instrument shed was well insulated, without windows and equipped with a weather sealed door. The overall heat transfer coefficient of the building was measured and found to be U = 0.403 W/m^2K. The experiment was performed 10 times and similar sets of data were analyzed. The floor temperature was maintained at 27°C. After temperature stabilization, the heat loss from the building was equal to the energy coming from the warm floor. The U_f was determined to be 4.93 W/m^2K. Losses to the soil were determined and the U value determined to be 2.45 W/m^2K. This value is abnormally high but attributed to flooding at the site during January and the edge effects of the small building which lacked sufficient insulation on the edges of floor-rock composite. It can be seen that the U values for the solid concrete and porous concrete are 4.93 and 8.80 W/m^2K respectively. In a residential situation, the addition of a floor covering would reduce the U value but in this case, higher floor water temperatures could be used. The obvious advantage of this heating system is that a low temperature solar collector or low temperature warm water source can effectively be used for heating a residential slab-on-grade house.

II. The use of condensor cooling water for greenhouse heating through the floor has been studied by Manning[6]. River water was heated to various temperatures and passed through a floor of similar construction as described above and shown in Fig. 1. Electrical energy was used in tests and the consumption recorded and temperatures measured in a greenhouse used for tomato production. The values of U for the bare porous concrete floor vary from 6.9 to 8.0 W/m^2K agreeing closely with Mears[8] and Cipolletti[1].

III. The use of porous concrete, that is, concrete with cement and aggregate and no sand, has become popular for greenhouse floors. Porous concrete allows excess irrigation water to drain through the floor without creating low spots which could damage a crop growing on the floor. Porous concrete controls weeds and provides a solid working surface suitable for light vehicular traffic. The use of plastic pipe embedded in the floor offers the opportunity to create a radiant heating system similar to that often used in industry and homes for slab buildings.

Many growers are using this system. Table 1 illustrates the results for one grower who has 4 years experience with the system. Observations indicate that ambient air temperatures can be lowered 3° to 6°C in double covered plastic film houses when bedding plants are grown on a warm floor in flats. Success with potted poinsettias has been observed by several growers when lower air temperatures were used with a significant energy savings of more than 20% because of lowered ambient temperatures.

Research at Rutgers was carried out by James(4) to determine the thermal properties of the porous concrete with embedded plastic pipe. Fig. 4 shows the construction of the test section in a 3.65 m x 3.65 m greenhouse. Plastic pipe was placed on 15 cm spacings and the plumbing arranged to allow for 15, 30, or 46 cm spacings during the tests. In addition, ICEMAT™ was placed in the floor as indicated. These mats are normally used in skating rinks to form ice for skating or ice hockey. The individual loops were 5.1 cm apart and were pinched off to achieve various spacings. Table 2 illustrates the heat transfer values of various spacings with a bare floor and with dry soil filled flats on the floor. Fig. 5 illustrates the change in U value with wider pipe spacings and with and without a cover of flats. Tables 3 and 4 show the influence of wetting the flats and wetting the floor prior to the test period. The wet flat-dry floor system would be the closest to a typical bedding plant operation. By wetting the floor as well, more energy can be delivered to the greenhouses if this practice does not adversely affect the growing system.

Temperature variation is indicated in Figs. 6, 7, and 8. As might be expected, the most uniform temperature is in the ICEMAT™ spacing, which approximates the flooded floor system. The temperature differences with the concrete are the greatest for the 46 cm pipe spacing and although there is a small temperature difference on the floor surface, the effective air temperature varies only slightly across the floor. This difference is even less when a flat of bedding plants is placed on the floor.

Table 3 further illustrates this by listing the profile of various temperatures throughout a given time period for a wet soil, wet flats condition.

Although no crops were grown in the test facility, growers who are using this technique have noticed no difference in plant growth as long as the warm water temperature was in the 32°C to 38°C range. The prevailing design now being used places the pipes on 30 cm to 41 cm spacings(10).

The warm floor is to be viewed as a supplement to the standard commercial greenhouse heating system with an average expected floor heating rate of 63 watts per square meter, using 32°C water in piping spaced 41 cm apart. Flow rate in the pipe is important and should be between 0.6 to 0.9 meters/sec. This velocity assures good heat transfer and helps eliminate air pockets in the system[10]. Fig. 9 illustrates a typical system for a 9.1 m x 29.3 m house using a double return header system to ensure uniform flow throughout the system.

IV. Several growers have tried to implement the floor heating system by embedding pipe in soil, sand, gravel or other materials. Research was conducted in an undergraduate research project by Giniger[3] to determine the heat loss coefficient for a sand floor. Plastic pipe spaced on 15 cm centers was laid under 10 cm of sand. The same test setup as James[4] was used to measure heat input and temperature. Table 5 shows the U values for various treatments in a series of preliminary tests on sand systems.

It is apparent that the trial using just the 4 cm sand without the cover showed the effects of the sand drying out over the course of the experiments. The value of the plastic cover is seen when the sand is moist and no drying occurs.

A grower rooting ivy made the following observations. Pipe was placed on 30 cm centers and placed beneath 15 cm of sand. Plastic film was placed over the sand after it had been thoroughly moistened. Flats with soil were placed on top of the plastic cover. Air temperature was maintained between 7°C to 10°C. Soil into which the ivy was being rooted was maintained at 20°C. Soil in an area of the greenhouse when no soil heating was used was observed to be 13.3°C. Ivy in the unheated soil area took 3 weeks longer to root.

Table 6 summarizes the heat transfer coefficients determined experimentally in the 4 types of floor systems discussed. There has been no attempt to make any economic judgement concerning cost of construction versus heat output or the physical performance of the floor. The advantage of the flooded floor is that the same heat output can be achieved with lower water temperatures which are readily available from low-cost solar collectors or warm water discarded from a power plant. The flooded floor also serves as storage as well as heat transfer surface.

The embedded pipe system has a lower initial cost but higher temperature water must be used to obtain heat outputs equivalent to the flooded floor. Also, if solar collectors are desired, more expensive collectors and an external storage area is required.

Grower response from all the systems described has been enthusiastically favorable. In some cases, management changes, that is, starting the crop later and running the greenhouse at lower ambient air temperatures, have resulted in 30% energy savings. The crop grown on the warm floor has responded favorably to warmer root temperatures and been ready for market even though it was planted later and grown at cooler ambient air temperature. More information is needed on the response of flowering crops to adjusted temperature regimes designed to conserve energy.

ACKNOWLEDGEMENTS

Research in this project has been funded in part by the New Jersey Agricultural Experiment Station, ARS/USDA Grant funded research, Public Service Electric and Gas Company and the Department of Energy.

REFERENCES

(1) Cipolletti, John, 1980. "Performance of the Kube Pak Greenhouse Solar Heating Demonstration." Unpublished Masters Thesis, Biological & Agricultural Engineering Department, Cook College-Rutgers University, New Brunswick, New Jersey, May 1980.

(2) Cipolletti, John, 1978. "Residential Applications of the Rutgers Solar Heating Systems for Greenhouses." Unpublished Special Studies Project, Biological & Agricultural Engineering Department, Cook College-Rutgers University, New Brunswick, New Jersey, May 1978.

(3) Giniger, Michael, 1980. "Embedded Plastic Pipe in a Sand Floor." Unpublished Special Studies Project, Biological & Agricultural Engineering Department, Cook College-Rutgers University, New Brunswick, New Jersey, May 1980.

(4) James, Mark F., 1980. "Thermal Performance of Embedded Pipe Porous Concrete Floor Heating Systems for Greenhouse Use." Unpublished Masters Thesis, Biological & Agricultural Engineering Department, Cook College-Rutgers University, New Brunswick, New Jersey 08903.

(5) Kreith, F. and J. F. Krieder, 1979. "Principles of Solar Engineering," McGraw-Hill Book Company, New York, New York.

(6) Manning, Thomas O., 1980. "Evaluation of a Phototype Greenhouse Designed for Utilization of Waste Heat." Unpublished Masters Thesis, Biological & Agricultural Engineering Department, Cook College-Rutgers University, New Brunswick, New Jersey 08903.

(7) Manning, T. O., D. R. Mears, R. McAvoy and B. Godfriaux, 1980. "Waste Heat Utilization in the Mercer Research Greenhouse." ASAE Paper No. 80-4031, San Antonio, Texas, June 15-19.

(8) Mears, D. R., W. J. Roberts, J. C. Simpkins and P. W. Kendall, 1977. "The Rutgers Solar Heating System for Greenhouses." ASAE Paper No. 77-4009, Raleigh, North Carolina, June 26-29.

(9) Roberts, W. J., J. C. Simpkins and P. W. Kendall, 1976. "Using Solar Energy to Heat Polyethylene Film Greenhouses." ASAE Paper No. 76-4011, Lincoln, Nebraska, June 27-30.

(10) Roberts, W. J. and D. R. Mears, 1979. "Floor Heating of Greenhouses." Publication of Cooperative Extension Service, Cook College-Rutgers University, Biological & Agricultural Engineering Department, New Brunswick, New Jersey 08903.

(11) Walker, J. N., 1965. "Predicting Temperatures in Ventilated Greenhouses." Transactions ASAE, Volume 8, No. 3.

TABLE I

Recorded Temperature °C* January 9,10, 1980

	Floor Heated Area			Alley	Foyer	Shop
	1800	2100	0800	0800	0800	0800
Outside	-1.1	-6.7	-16.1	-16.1	-16.1	-16.1
Soil Temp. Pot	16.6	16.1	17.7	-	-	-
Under Pot	17.7	17.2	19.4	11.7	13.3	3.9
30 cm Level	15.5	16.1	18.3	14.4	13.3	7.0
1.8 m Level	18.3	18.3	19.4	21.1	20.0	17.2

* Data gathered, George Schaeffer Range, Shenango Forks, New York

TABLE 2

Relationship Between Heat Transfer Values of Various Floor Pipe Spacings Embedded in Porous Concrete for Bare Floor and Floor Covered with Soil Flats (4)

	ICEMAT™			20 mm Polyethylene Pipe		
	(Full)4 cm	(3/4)6 cm	(1/4)15 cm	15 cm	30 cm	46 cm
Bare Floor	7.3	5.9	3.5	4.2	3.5	2.9
Dry Soil Flats	4.5	-	-	2.9	2.7	2.6

TABLE 3

TYPICAL TEMPERATURE PROFILES FOR A WET FLOOR, WET SOIL FLATS CONDITION[4]

Case 1: 30 cm polyethylene pipe spacing

Parameter	Temperature (°C)							
Outside Ambient	8	7	5	2	8	8	15	17
Greenhouse Ambient	13	13	11	8	14	14	19	21
Soil Flat	17	17	17	14	18	18	23	23
Floor Surface	24	25	24	23	25	25	27	28
2.5 cm Below Floor Surface	26	26	27	26	27	27	29	30
Water in Pipe	46	46	48	48	48	49	51	52
Time (a.m.)	12:00	6:30	12:00	6:30	12:00	6:30	12:00	6:30
Date	11/6/79		11/7/79		11/8/79		11/9/79	

Case 2: 46 cm polyethylene pipe spacing

Outside Ambient	-4	-5	-1	0	3	-1
Greenhouse Ambient	2	2	4	5	7	5
Soil Flat	10	11	9	11	12	10
Floor Surface	16	16	17	17	18	18
2.5 cm Below Floor Surface	18	17	19	19	20	19
Water in Pipe	43	42	43	43	45	45
Time	12:00	6:30	12:00	6:30	12:00	6:30
Date	12/3/79		12/4/79		12/5/79	

NOTE: Heat input rates were held constant for duration of each case.

TABLE 4

The Relationship Between U Values of 30 cm and 46 cm Polyethylene Pipe Spacings for Various Treatments(4)

Treatment	Pipe Spacing 30 cm	Pipe Spacing 46 cm
1) Bare dry floor, no flats U value (W/m^2K)	3.5	2.9
2) Dry Floor, dry flats U value (W/m^2K)	2.7	2.6
3) Dry floor, wet flats U value (W/m^2K)	3.1	2.5
4) Wet floor, wet flats U value (W/m^2K)	3.4	2.8

TABLE 5

15 cm Pipe Spacing in Sand(3)

Trial No.	Treatments: 10 cm of Sand	10 cm Sand With Plastic Cover	Flooded With Cover	Saturated With Cover
	U Value in W/m^2K			
1	6.18	4.03	8.51	9.07
2	5.33	3.97	8.51	9.30
3	5.33	4.14	9.07	-
4	4.71	3.69	10.20	-
5	4.82	-	9.64	-
6	4.59	-	-	-

TABLE 6

U Value in W/m^2K

Flooded Floor - Bare	8.8
Flooded Floor - Flats	5.1
Flooded Floor - Condenser Water	6.9 - 8.0
Flooded Floor - Solid Concrete	4.9
Embedded Pipe 15 cm spacing - Bare Floor	4.2
Embedded Pipe 15 cm spacing - Dry Flats	2.9
Embedded Pipe 30 cm spacing - Bare Floor	3.5
Embedded Pipe 30 cm spacing - Dry Flats	2.7
Embedded Pipe 30 cm Dry Floor-Wet Flats	3.1
Embedded Pipe 30 cm Wet Floor-Wet Flats	3.4
Embedded Pipe 46 cm - Bare Floor	2.9
Embedded Pipe 46 cm - Dry Flats	2.6
Embedded Pipe 46 cm Dry Floor-Wet Flats	2.5
Embedded Pipe 46 cm Wet Floor-Wet Flats	2.8
Full ICEMAT™ - Bare Floor	7.3
Full ICEMAT™ - Dry Flats	4.5
Dry Sand 15 cm spacing	5.2
Dry Sand Covered with plastic	4.0
Wet Sand flooded plus cover	9.2
Wet Sand plus cover	9.2

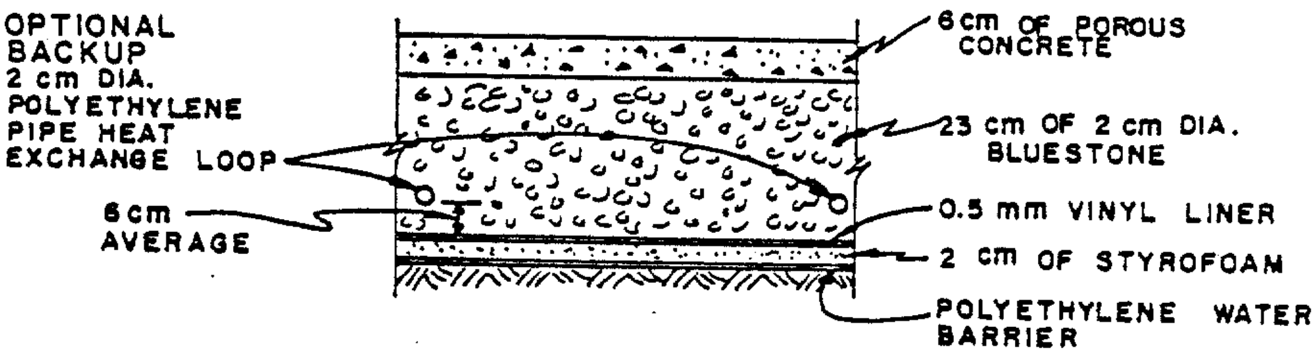

FIGURE-1 POROUS CONCRETE FLOOR CROSS SECTION

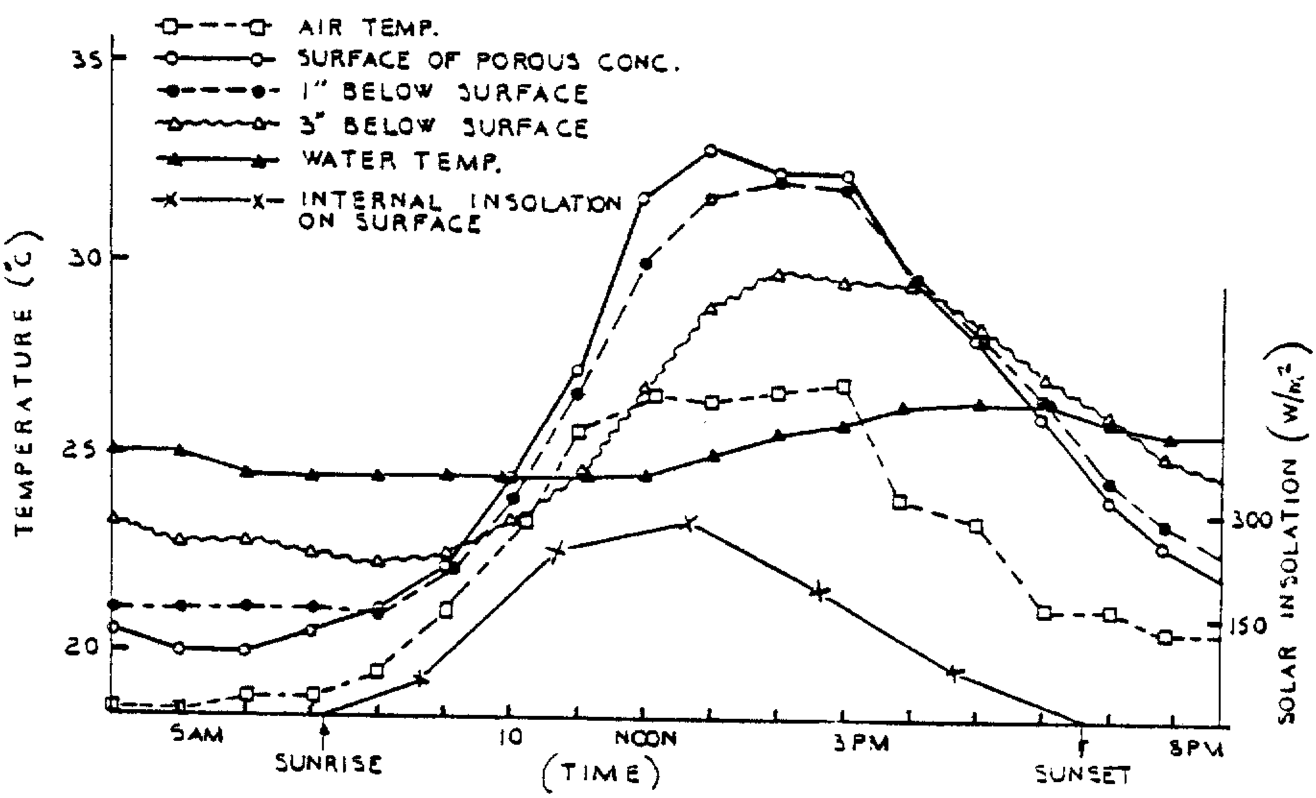

FIG. 2 TEMPERATURE VS. TIME AT VARIOUS DEPTHS IN POROUS CONCRETE

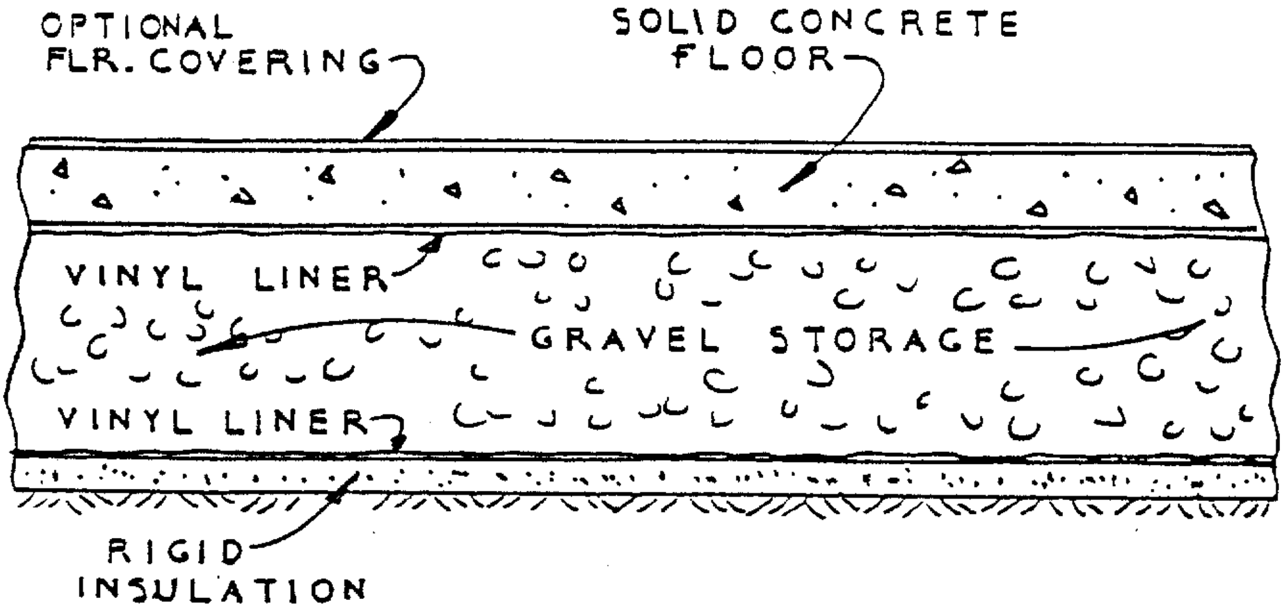

FIG. 3 VIEW OF FLOOR CROSS SECTION IN INSTRUMENT SHED

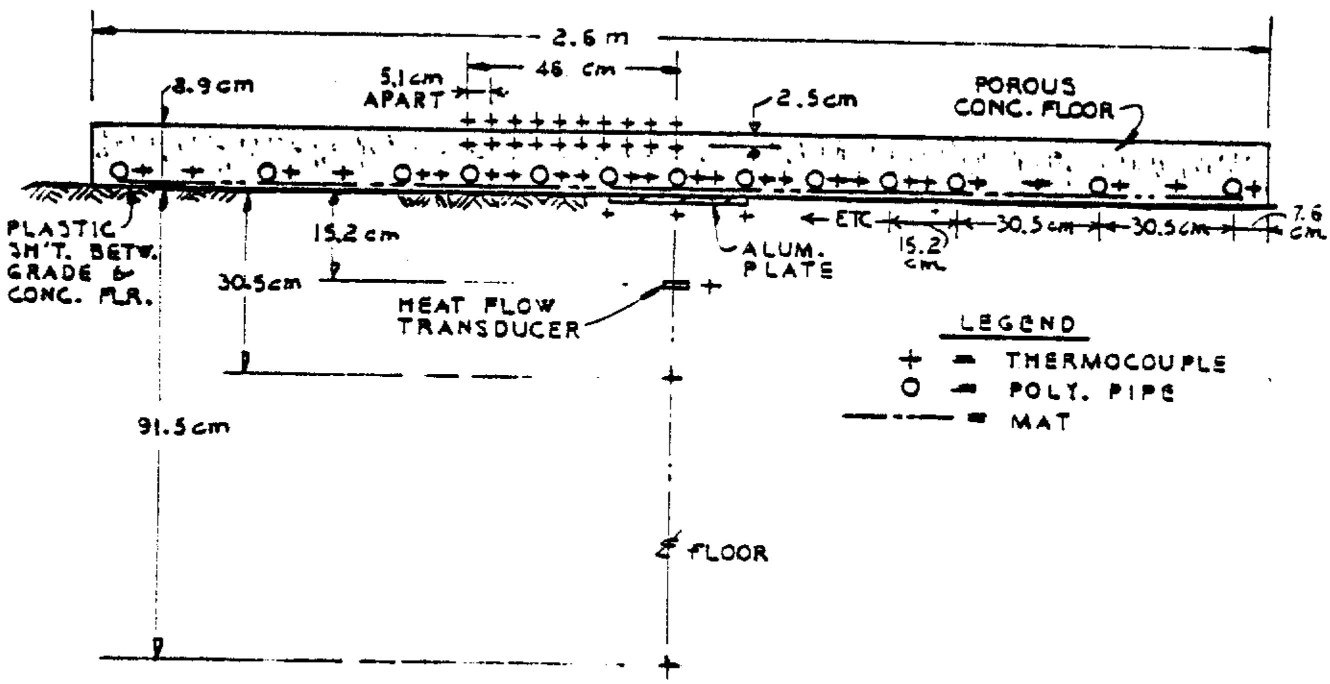

FIG. 4 CROSS SECTION OF POROUS CONCRETE FLOOR SHOWING PIPE, THERMOCOUPLE & MAT LOCATIONS

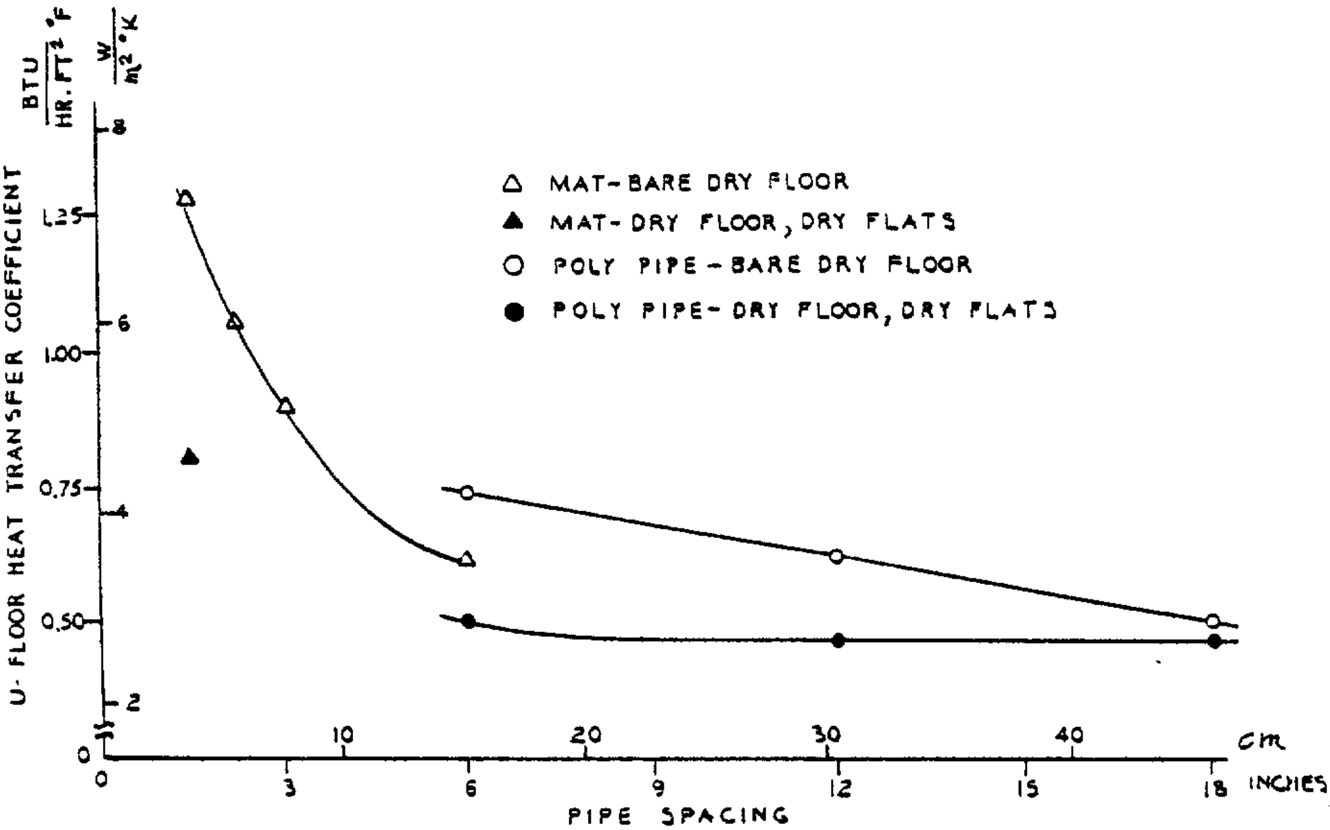

FIG. 5 RELATIONSHIP BETWEEN U-VALUES AND PIPE SPACINGS

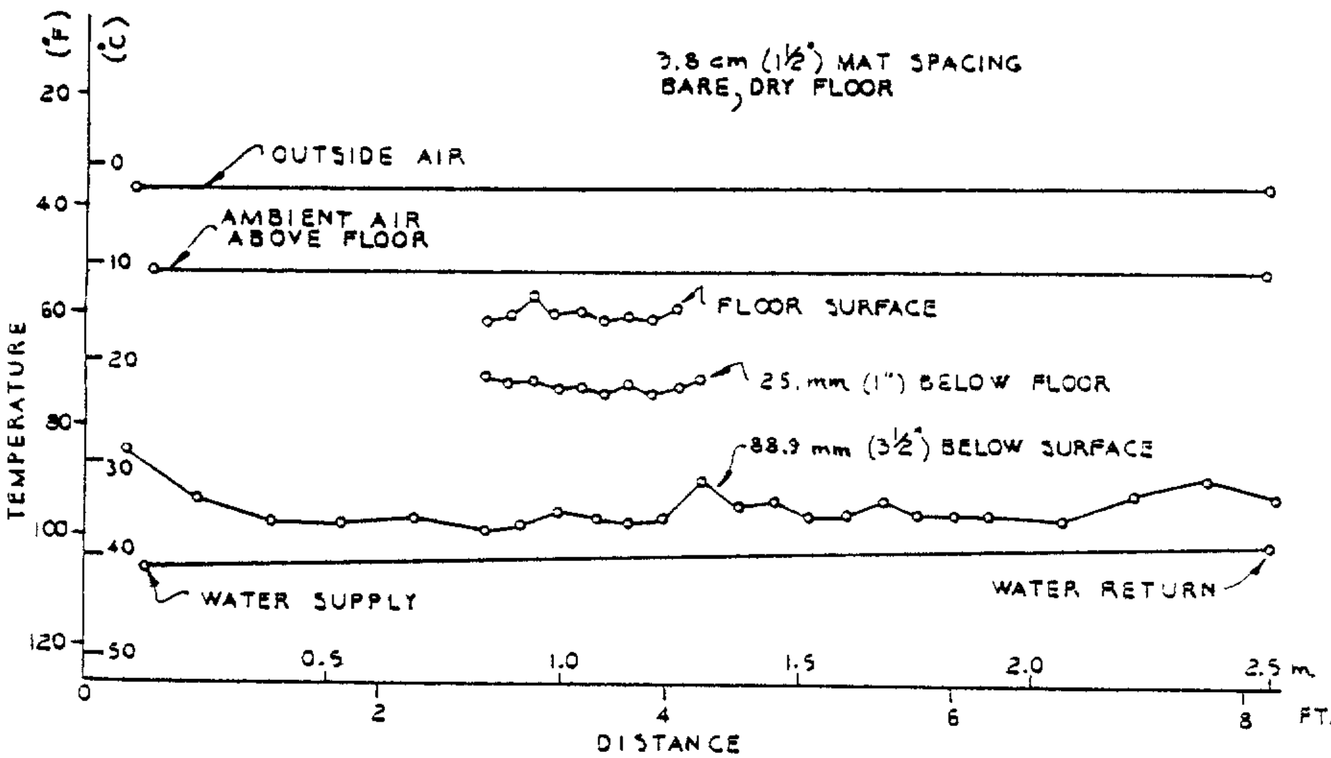

FIG. 6 TEMPERATURE PROFILE OF FLOOR CROSS SECTION FOR 3.8 cm (1½") FULL ICEMAT™ SPACING

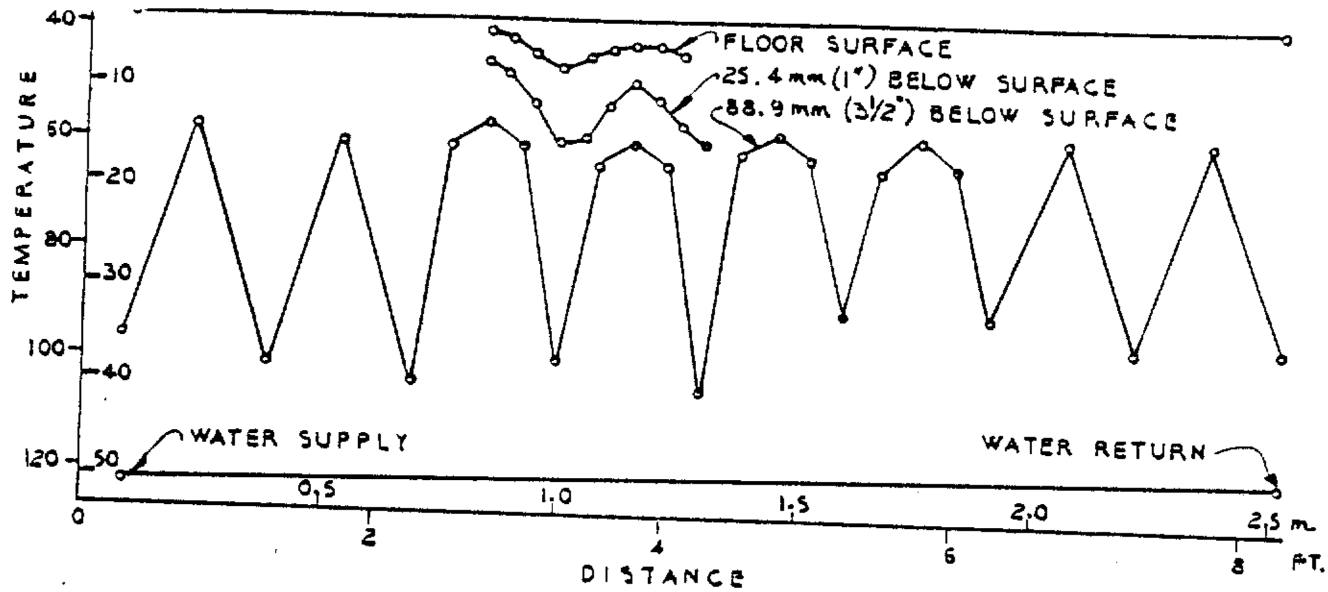

FIG. 7 TEMPERATURE PROFILE OF FLOOR CROSS-SECTION FOR 30 cm (12") POLYETHYLENE PIPE SPACING

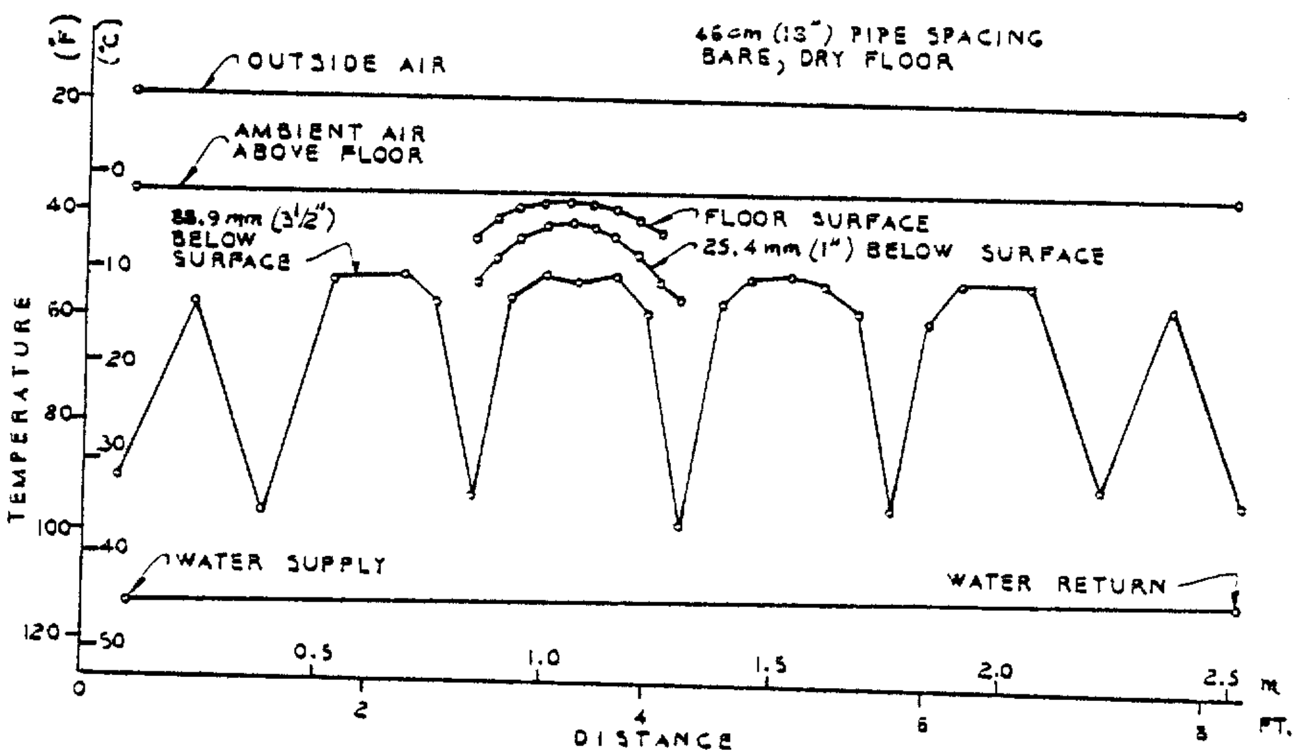

FIG. 8 TEMPERATURE PROFILE OF FLOOR CROSS-SECTION FOR 46 cm (18") POLYETHYLENE PIPE SPACING

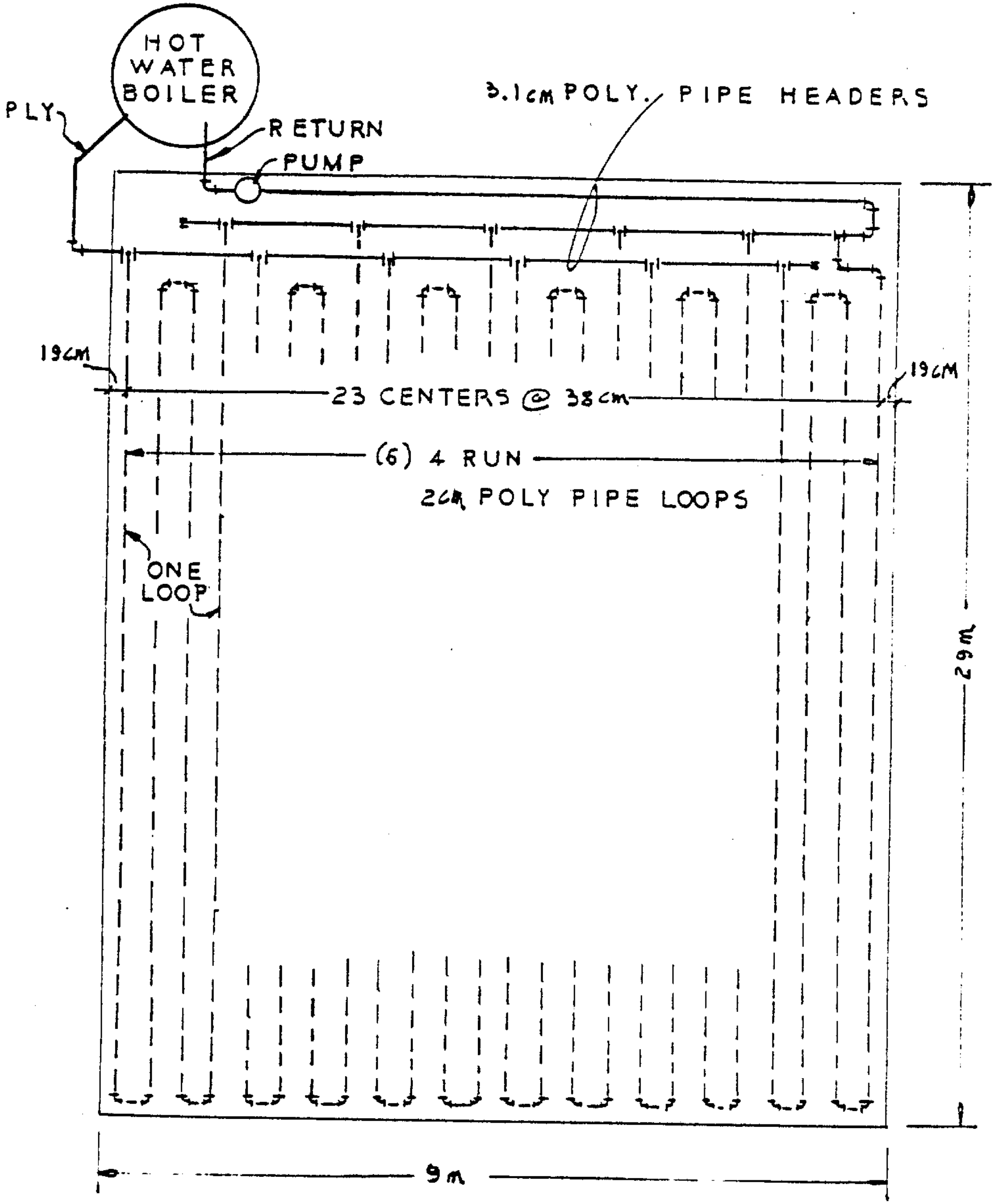

FIG. 9 FLOOR HEAT PIPE LOOP LAYOUT
FOR 9m X 29m LAYOUT