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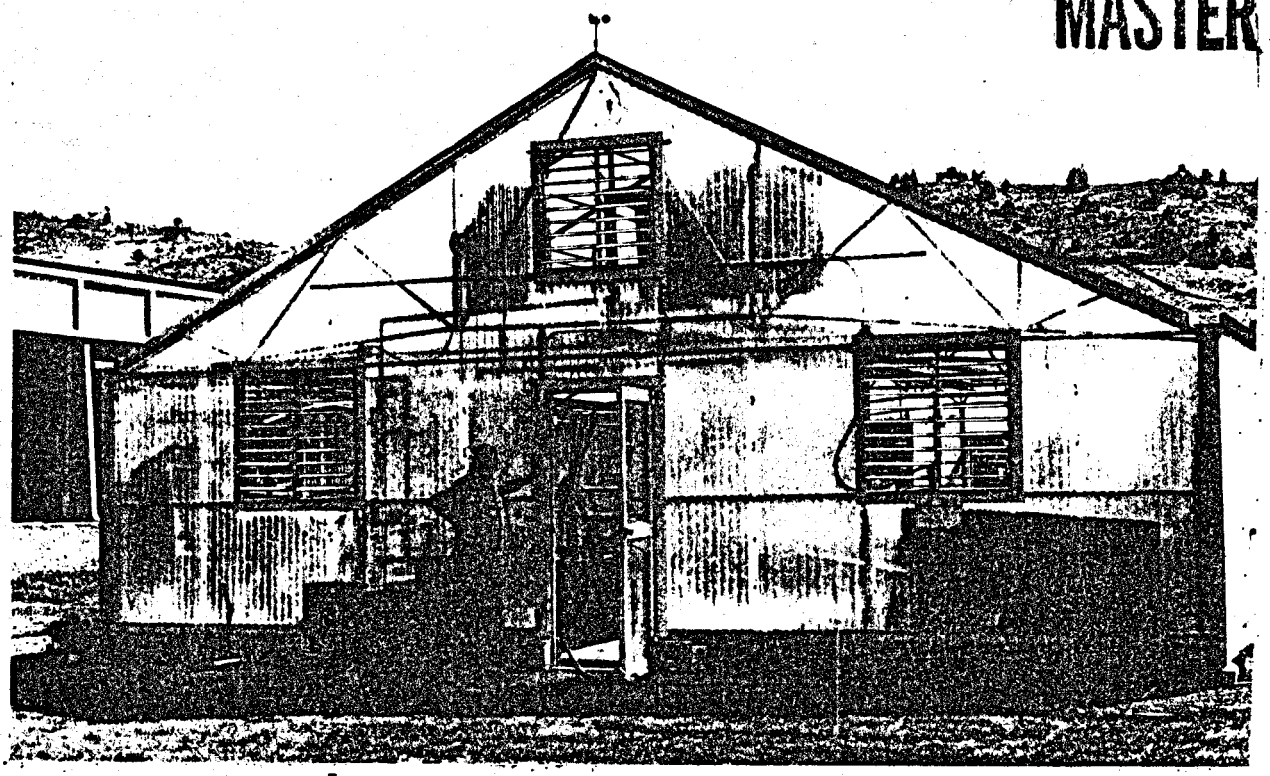
GEOTHERMAL HEATING SYSTEMS FOR GREENHOUSES

MASTER



Technical Report

Prepared by

Jay F. Silva
Project Engineer

William C. Johnson
Project Director

Geo-Heat Center
Oregon Institute of Technology
Klamath Falls, Oregon 97601

Prepared for the
Pacific Northwest Regional Commission
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FORWARD

The geothermally heated greenhouse on the Oregon Institute of Technology (OIT) campus was financed by the Agricultural Experiment Station of Oregon State University and was constructed by OIT personnel. The greenhouse came into being by a directive statement from the 1975 Oregon Legislative Assembly to the two institutions. The greenhouse was to be used to test and demonstrate the best use of geothermal energy for heating greenhouses. The structure was jointly used by the two institutions until 1979 when OIT assumed full responsibility for its operation.

In 1978, funding was received by the Geo-Heat Utilization Center at OIT from the Pacific Northwest Regional Commission to equip the structure with materials and instruments for testing purposes. The goal of the testing process was to identify the efficiency of different configurations of heat-exchange systems.

INTRODUCTION

There is an abundance of information on greenhouse heating for closed systems using fossil fuels and electricity. However, this report presents ways to utilize low-temperature geothermally heated water for a flow-through system. The use of geothermal energy for this system is the waste heat discharged from the space heating at Oregon Institute of Technology which consists of almost 500,000 square feet of floor space and the geothermal water pumped directly from the campus wells.

The information collected and analyzed for this report is from data developed from operating a greenhouse on the Oregon Institute of Technology campus from December 1979 to April 1980. This report does not consider the cooling of the greenhouse which is important during the summer months.

Methods for calculating heating requirements of greenhouses using geothermal energy were developed from the analyses of the data obtained.

FACILITY

The greenhouse on the Oregon Institute of Technology campus is a package unit built by Conley Construction of Portland, Oregon. Its frame is welded steel tubing and is covered with fiberglass 3/16 inches thick. The overall dimensions are 60 feet x 30 feet. Sides in 60-feet direction are 7.17 feet high, with the roof peak at 14 feet at the ends.

The heating units provided with the greenhouse are two (Modine) radiator/fan units, 2.5 feet x 2.5 feet, Model No. HS 1110 (the new equivalent is HS 258 with a rating of 200,000 Btu per hour at 22 gpm, 200°F water and 60°F entering air). The heaters are located at one end of the greenhouse near the ceiling and are so oriented to blow warm air into a single fan (FAN-JET Convection Tube Unit), Figures 1 and 2, which is directly connected to a large plastic tube 30 inches in diameter, running the length of the greenhouse, with holes to distribute the air uniformly, Figure 3. As part of this project, perimeter heating pipes were added in the form of three rows of finned pipe extending along both sides and one end of the house, making 125 feet in each row. Each row is continuous but valved at both ends so that they can be operated in series or in parallel, Figure 4. Thus, either 125 feet of triple pipe (total flow divided three ways), or 375 feet of single pipe carries the total flow for the perimeter heaters.

The perimeter heat pipes are 1-1/4 inches O.D. and have spiral round copper fins spaced 1/3 inch apart. The fin O.D. is 2-1/4 inches, Figure 4.

The greenhouse has available two types of geothermal water. One is primary water from the well, which is 192°F; however, by the time it enters the greenhouse, temperature varied from 167° to 183°F. The other source is secondary water, the water which is wasted in heating the campus, then discharged, and

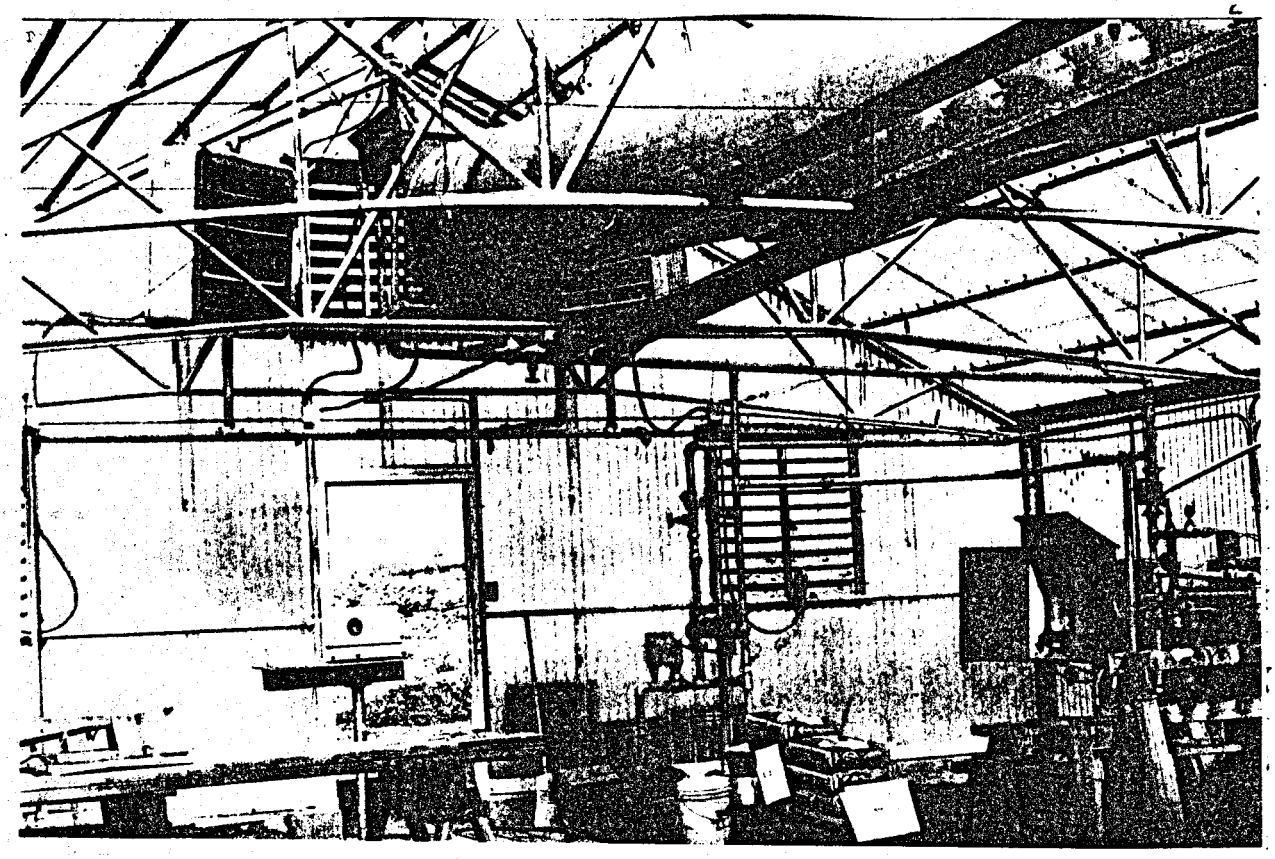


Figure 1. Radiator fan units, top center, and fan-jet unit

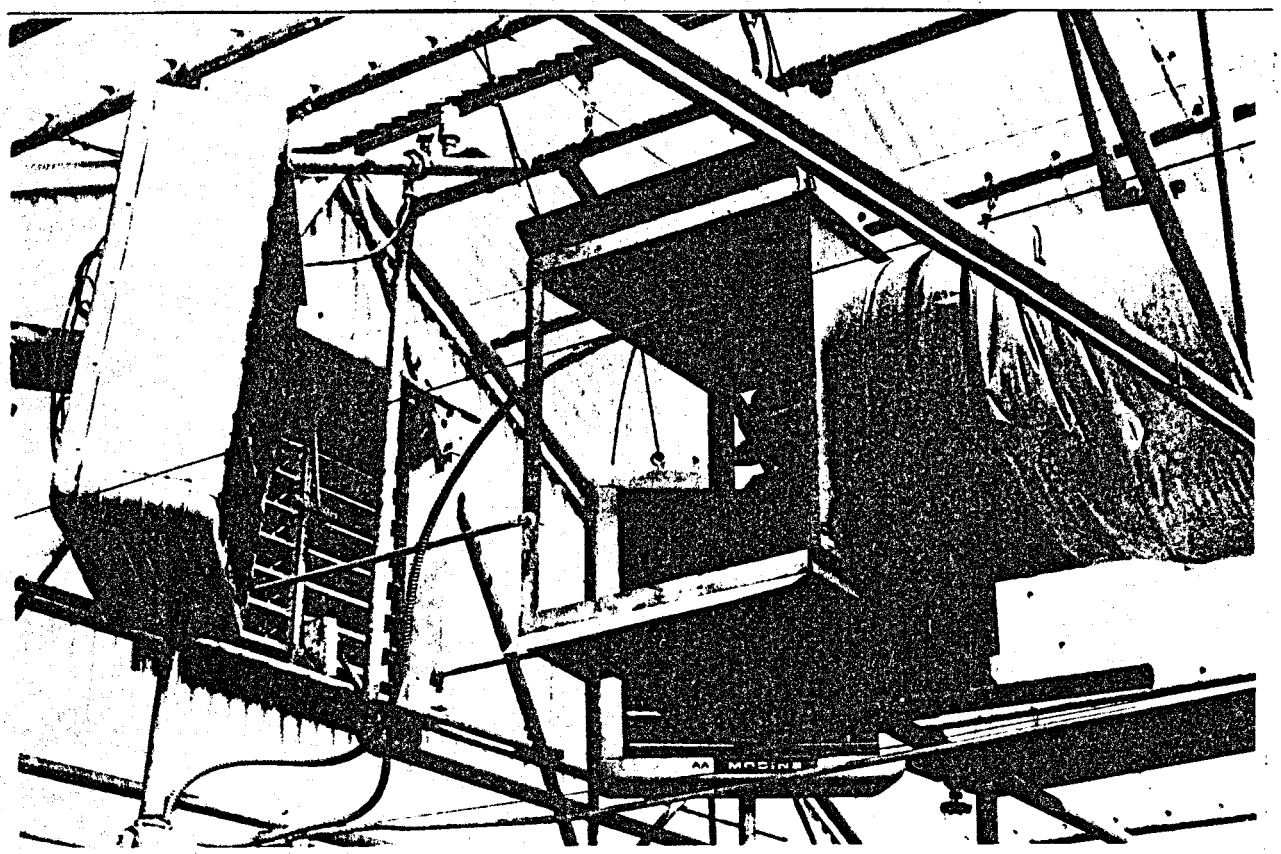


Figure 2. Radiator fan units, rear left and center; fan-jet unit, center

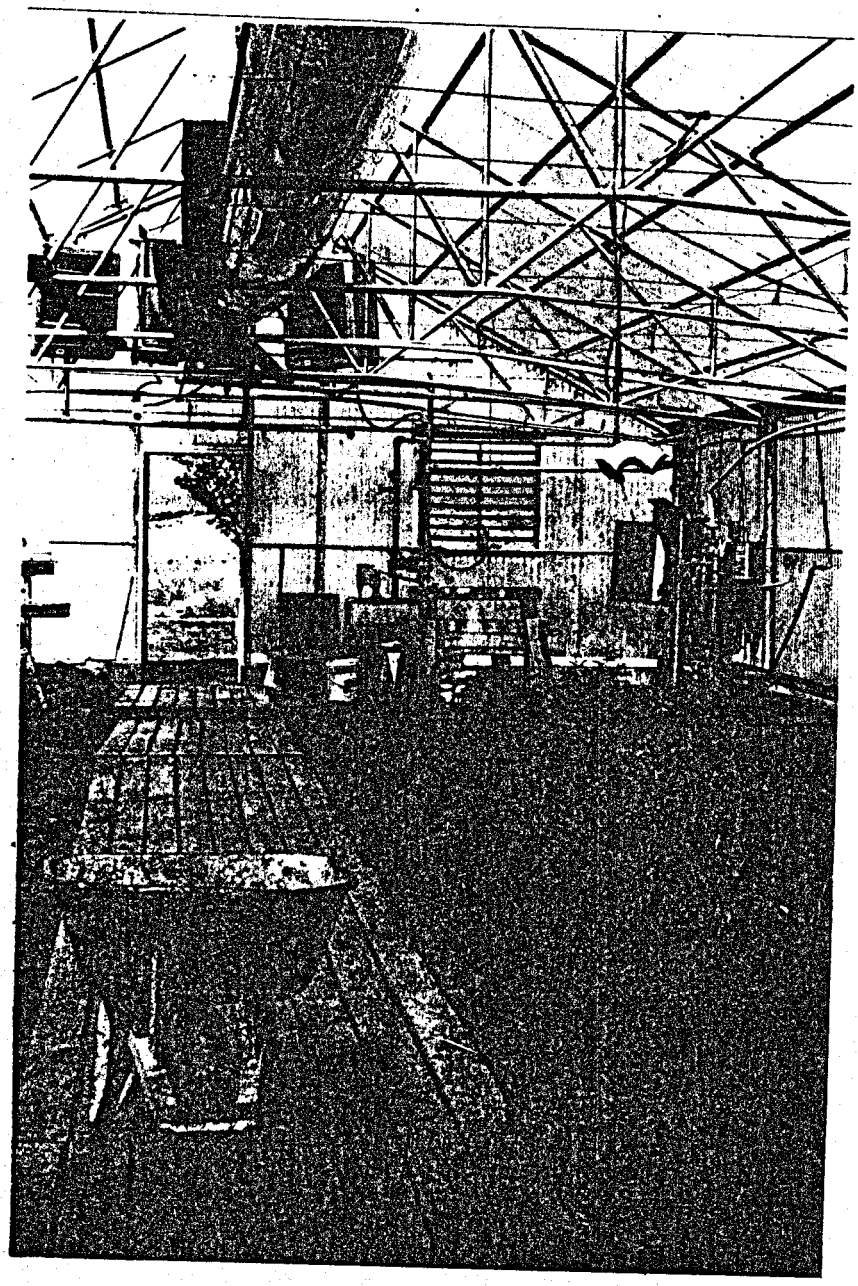


Figure 3. Plastic tube for heat distribution, top center

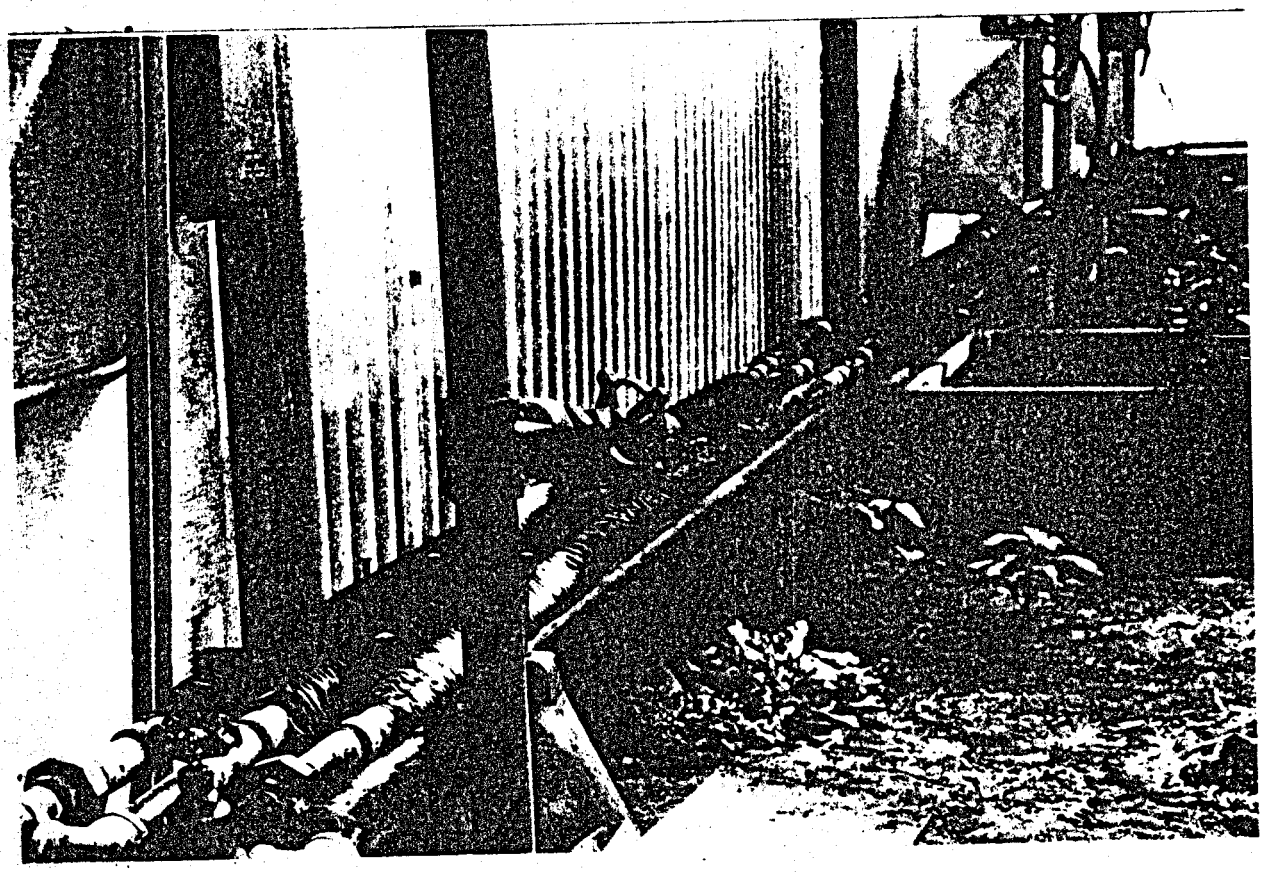


Figure 4. Perimeter heat pipes (3)

entered the greenhouse at 123° to 155°F. This water is pumped from the waste ditch for greenhouse use. The geothermal water quality is of potable quality and has only limited corrosion effects on iron pipe. The amount of this water varies with campus demand.

The monitoring equipment consists of two 10-inch chart temperature 24-hour recorders, one for "inflow" water temperature and one for the discharge temperature after circulating through the heat exchangers, Figures 5 and 6. A 10-inch dual pen 7-day recorder was used to monitor water flow and ambient wind speed at site, Figure 5. Two 4-1/2 inch chart temperature, 7-day recorders were used to monitor temperatures inside and outside the greenhouse, Figures 7 and 8. A 7-day mechanical pyranograph was used to record the sun's radiation intensity in cal/cm^2/min to evaluate the impact of solar radiation, Figure 8. A nutating disc water meter was used to measure the total discharge of hot water from the greenhouse, Figure 6. These instruments provided the data to determine the most efficient use of geothermal energy.

The flowmeter at the inlet of the system did not function because scale and other materials fouled it continually, so all flow data used was an average over a period of 8 to 15 hours during intensive operation monitoring. When inflow varied, anomalies in the data were reflected at the time of data analyses.

The control system designed and built in the Oregon Institute of Technology Electronics Department for the greenhouse controlled flow and selected primary or secondary water to meet programmed inputs, provided for closed-circuit circulation of hot water until an established temperature is reached. When the water is discharged, the cycle is repeated with a new hot water supply. The controller also opens and closes louvers and turns on/off both cooling and heating fans. A schematic of this controller will be provided on request, Figure 9.

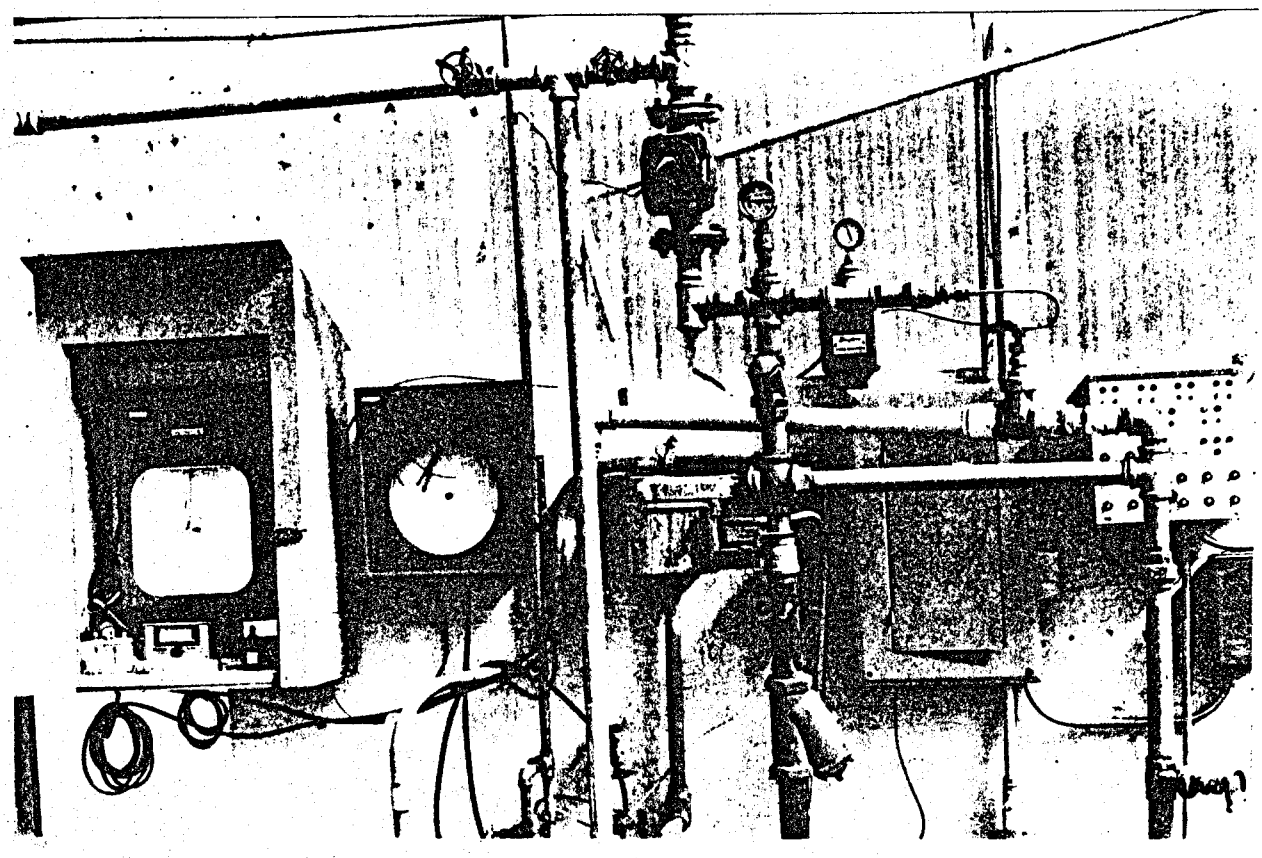


Figure 5. Inflow water temperature recorder, center; dual-pen recorder for wind, speed, and water flow

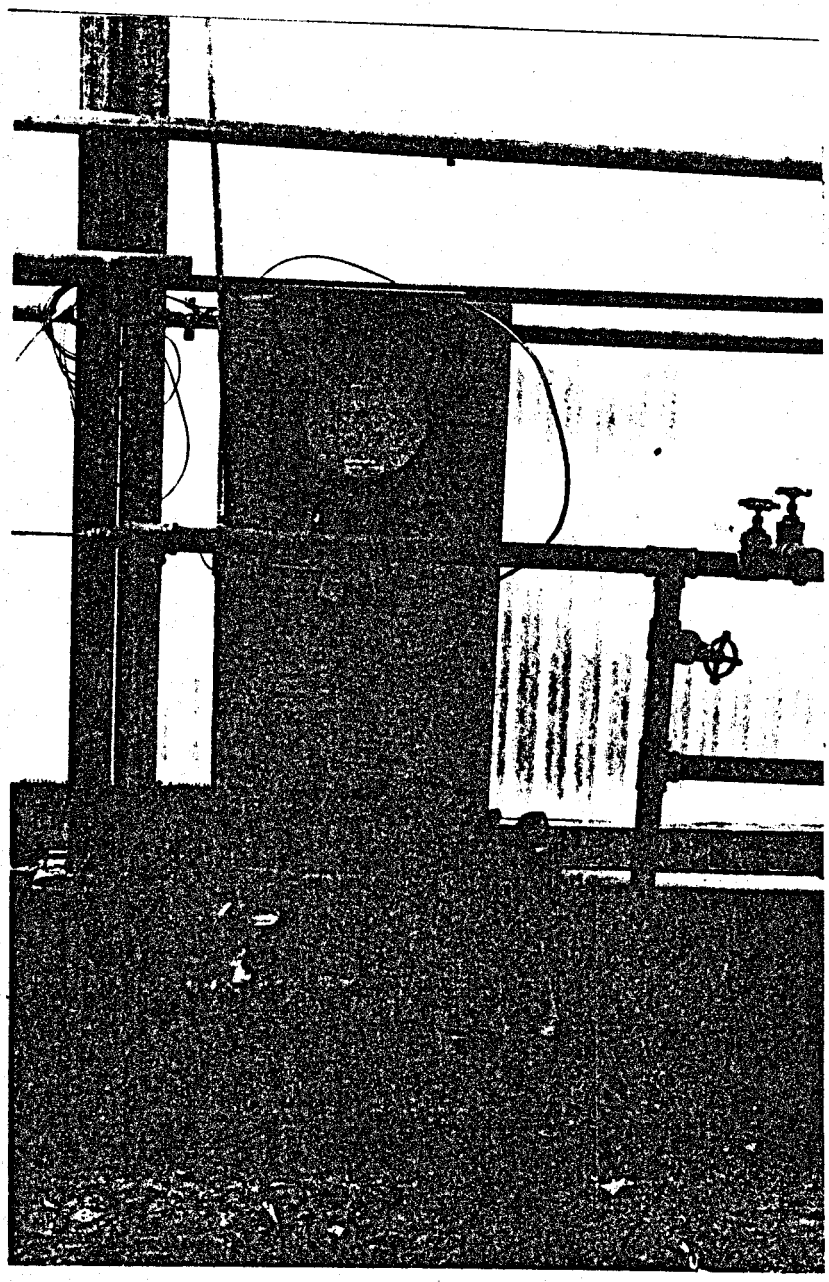


Figure 6. Outflow water temperature recorder, top, nutating-disc water meter, bottom of photo

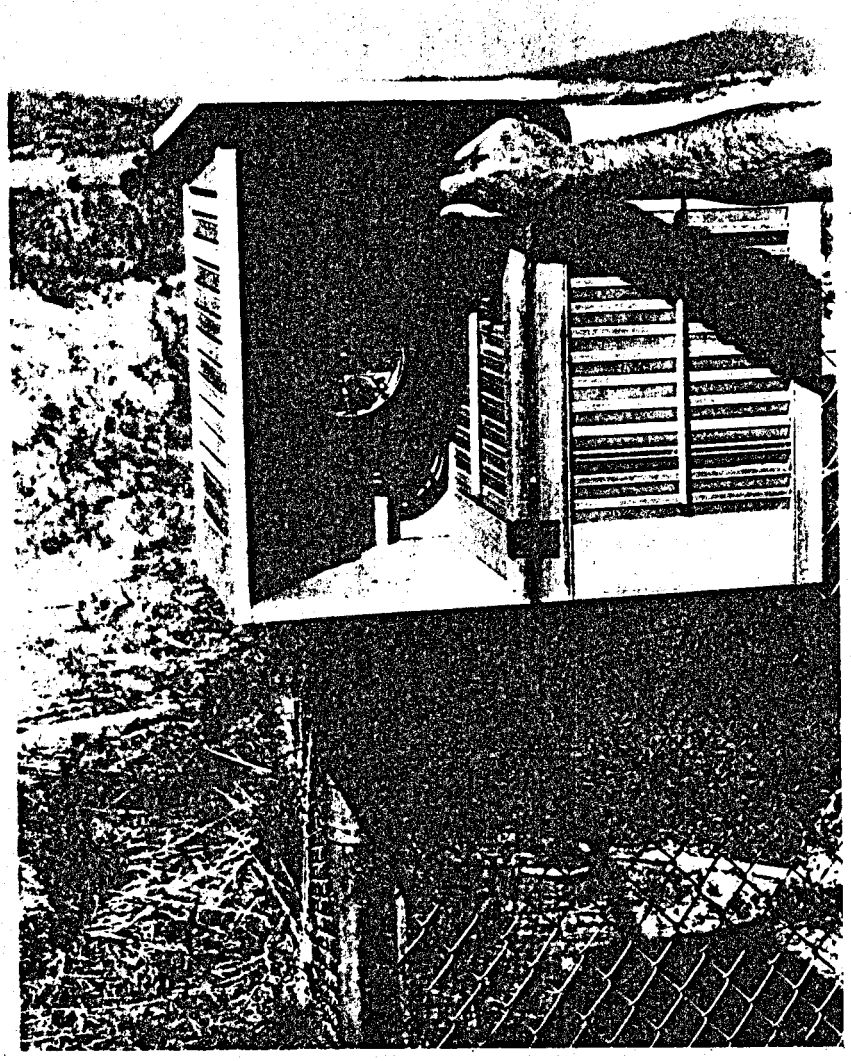


Figure 7. Outside temperature recorder

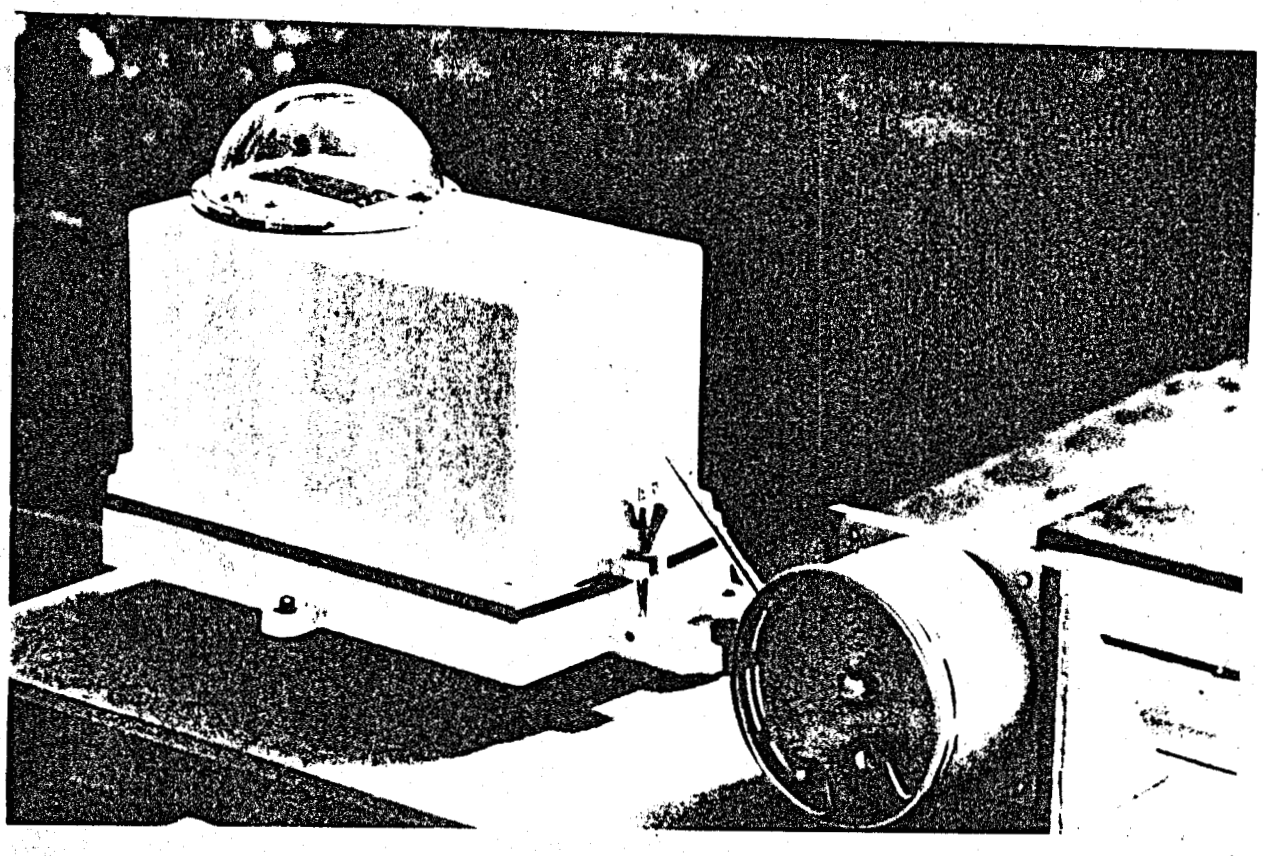


Figure 8. Pyranograph, left, inside temperature recorder

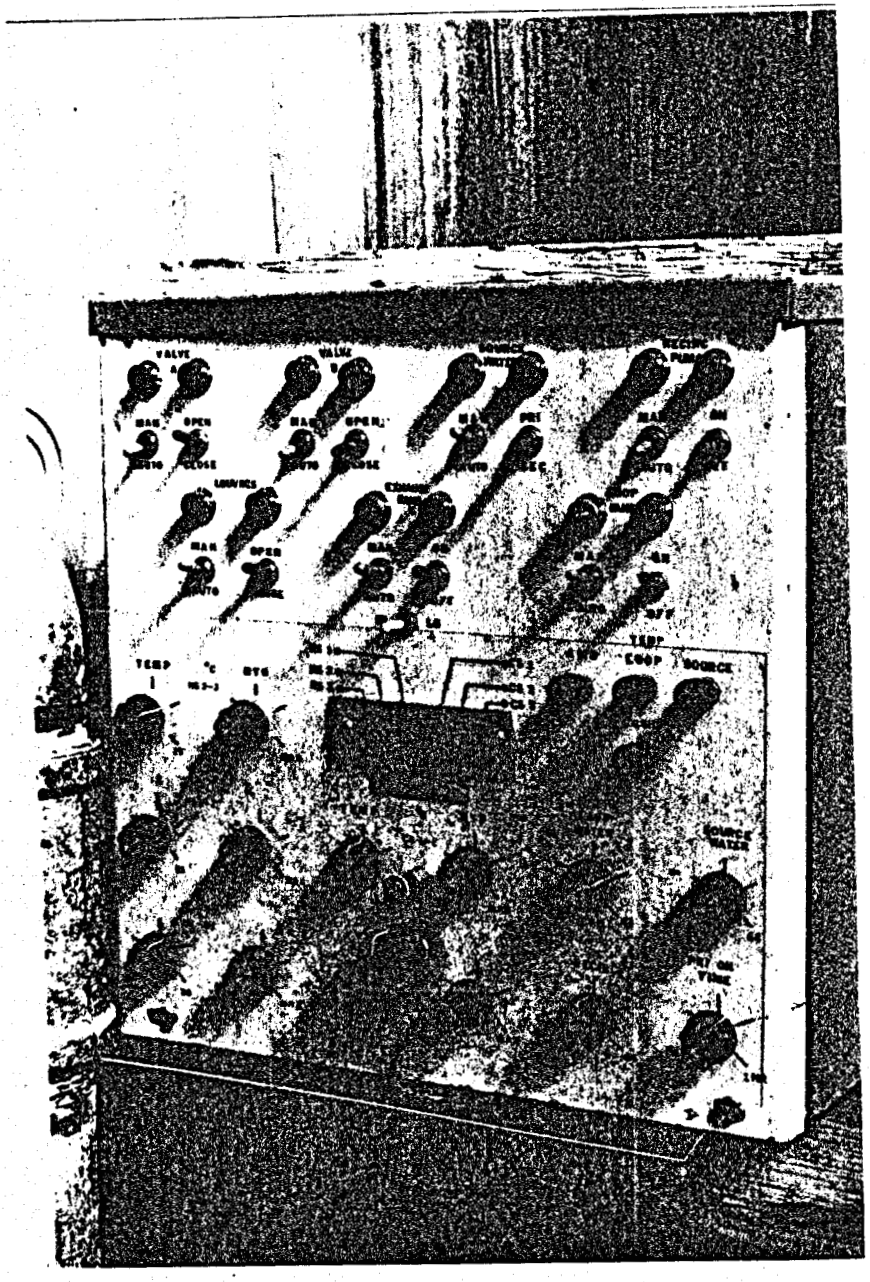


Figure 9. Greenhouse controller

The greenhouse is oriented with the long direction being in the east-west direction, the only near building being about 130 feet to the north. The greenhouse receives no shade from buildings or trees which are important factors to consider in determining a heat budget.

GREENHOUSE OPERATION BASICS

Desired nighttime temperatures for greenhouses range from 50° to 65°F, and daytime temperatures from 60° to 75°F[1]. If a heating system will maintain the minimum desired temperature at night, then there will only be a limited problem with the daytime requirement, even on a cloudy day because of solar radiation.

The basic elements needed for the supply of geothermal energy are an adequate available hot water supply, heat exchangers, and a method of distributing the heat by forced air where natural convection is not adequate. These elements could vary from a simple on/off thermostat manually changed for day/night operation to a multimode controller with programmed changes in the temperature from night to day.

Cooling generally consists of ventilation fans and openings to exhaust hot air and draw in fresh air. Some form of shade or heat reflecting material may also be used.

From a horticultural standpoint, the problem (regarding temperature) is to maintain the environment at the optimum temperature day and night and for the particular plants being grown. Other parameters not considered are humidity, light, and soil used. Nonoptimum conditions considered are unexpected extremes in which a plant might "survive to grow another day"--namely freezing. No horticultural observations were considered in this report.

---

[1]Pierce, J. H., Greenhouse Grow How, Plants Alive Books, Doubleday, 1977.

DATA COLLECTION

Some functions of the controller tended to overlap, and harmonic cycling was observed, Chart 1. Consequently, all intensive monitoring for heating efficiency was done with the controller set on manual operation, Charts 2 and 3.

The data analyzed for this report were collected during the night hours. It is the period of the day when the greatest amount of heat is needed for a greenhouse and the conditions that a designer must use for a heat-efficient design for a specific geographic area.

All tests for efficiency were conducted when the louvered windows were closed, the cooling exhaust fans were turned off, and the interior circulating fans operating. The water recycling system was off, allowing the water to flow through the system.

Variations during operation analyzed included type of water, radiator/fan units and/or perimeter heaters in the circuit and whether in parallel or series, and the flow through the three perimeter heaters to be in parallel or series. Fourteen configurations of these variables were considered, Table 1.

A test under one of these configurations was accomplished by adjusting controller and valves around 9 p.m., checking or replacing all charts, and noting the gallons from water meter, time, and configuration on the outflow temperature chart. The following morning (about 8 a.m.), the gallons and time were again noted on the chart, valves and controller readjusted. A steady state period for greenhouse and outside temperatures was decided upon (approximately midnight to 6 a.m.) and then all charts were read, averaged, and noted on the outflow chart for that period, Charts 2 and 3.

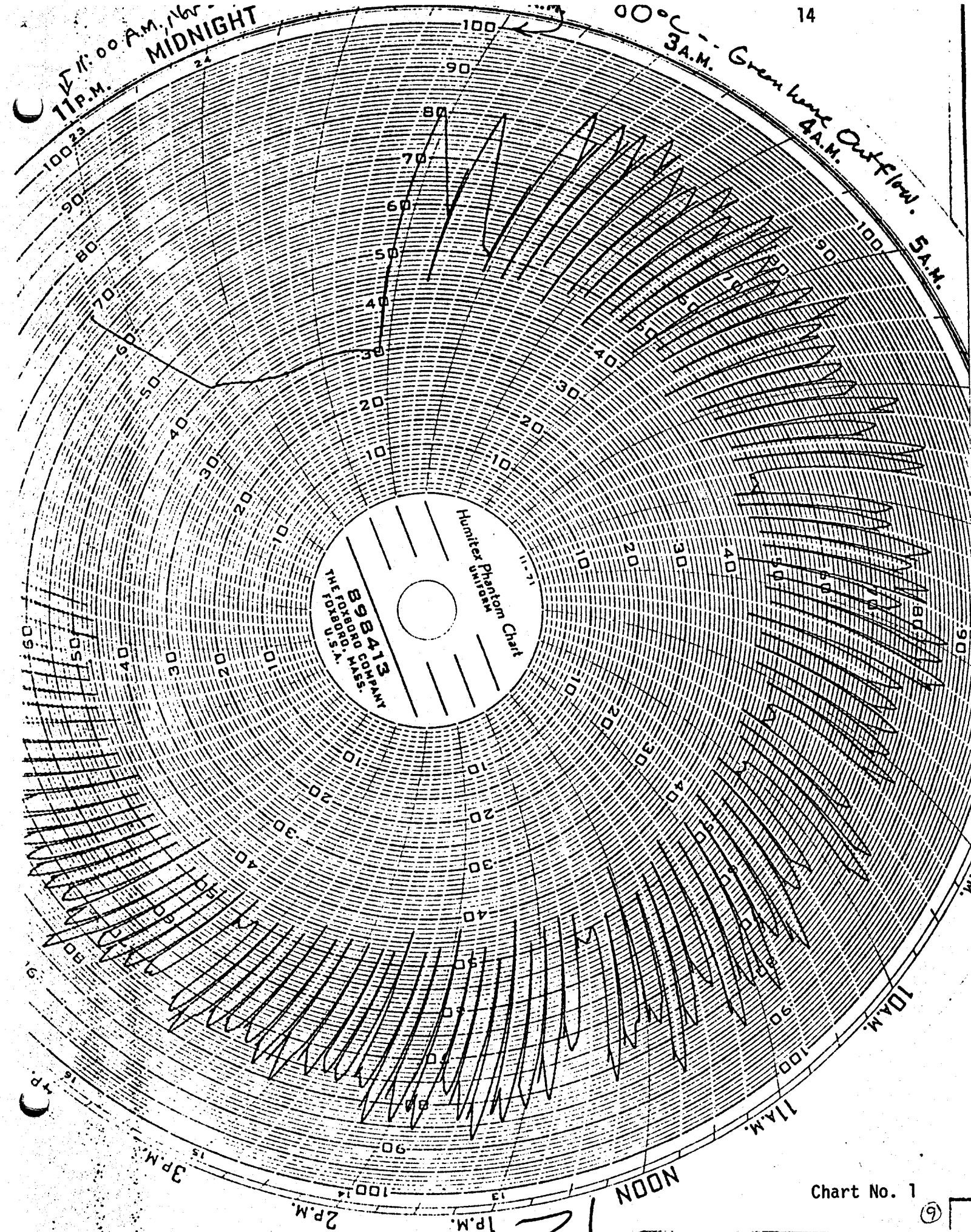

11:00 A.M.
MIDNIGHT
11P.M.
3A.M.
4A.M.
5A.M.
10A.M.
11A.M.
NOON
1P.M.
2P.M.
3P.M.
Humitex Phantom Chart
UNIFORM
898413
THE FOXBORO COMPANY
FOXBORO, MASS.
U.S.A.

Chart No. 1

(9)

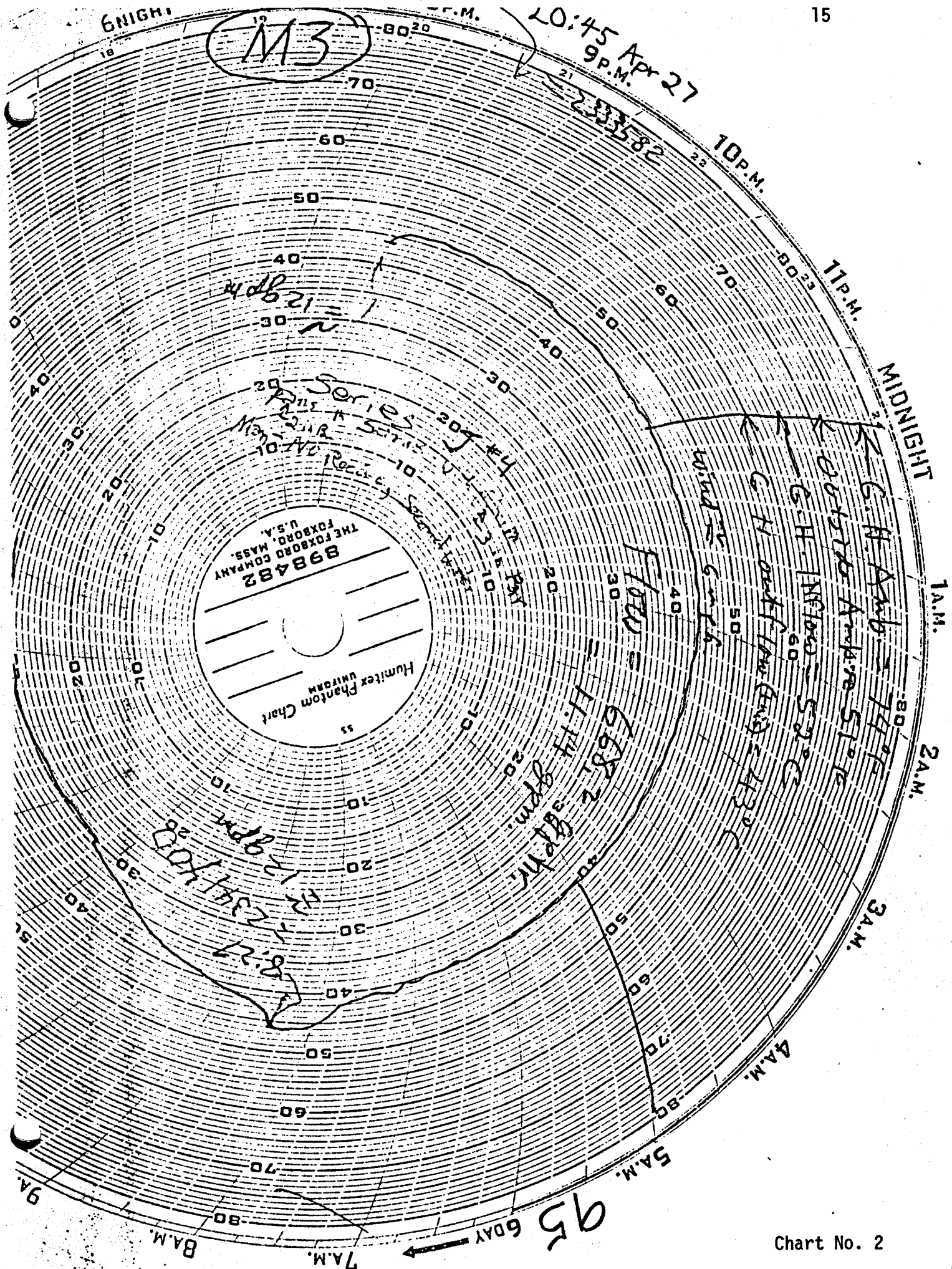

M3
20:45 Apr 27
9P.M.
10P.M.
11P.M.
MIDNIGHT
1A.M.
2A.M.
3A.M.
4A.M.
5A.M.
6DAY
7A.M.
8A.M.
9A.
Series J #4
Humitex Phantom Chart
UNIFORM
898482
THE FOXBORO COMPANY
FOXBORO, MASS.
U.S.A.

Chart No. 2

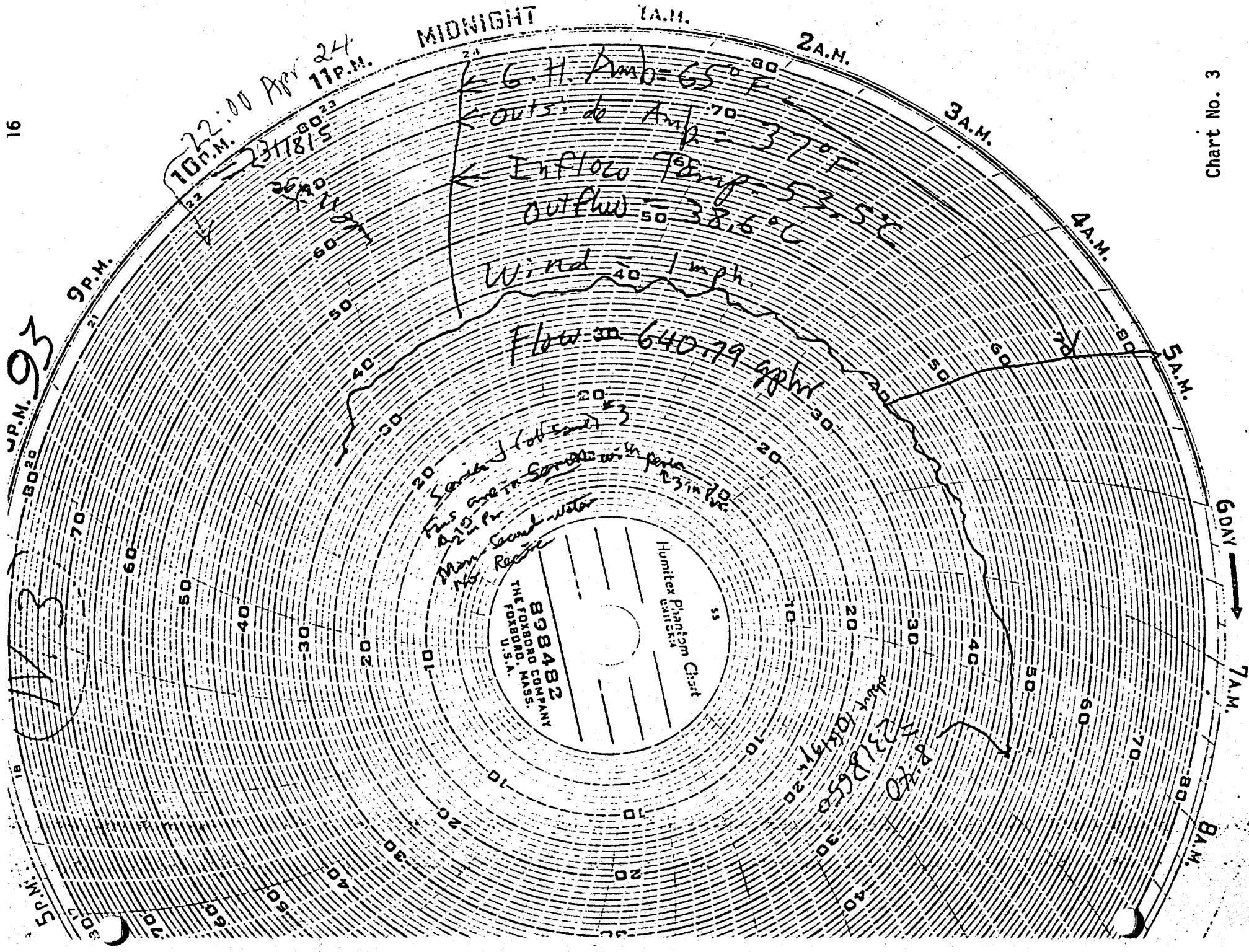

MIDNIGHT
1A.M.
2A.M.
3A.M.
4A.M.
5A.M.
6DAY
7A.M.
8A.M.
9P.M.
10P.M.
11P.M.
G.H. Amb = 65°F
outside Amb = 37°F
Inflow Temp = 53.5°C
outflow = 38.6°C
Wind = 1 mph.
Flow = 640.79 gphr
Humitex Phantom Chart
898482
THE FOXBORO COMPANY
FOXBORO, MASS.
U.S.A.

Chart No. 3

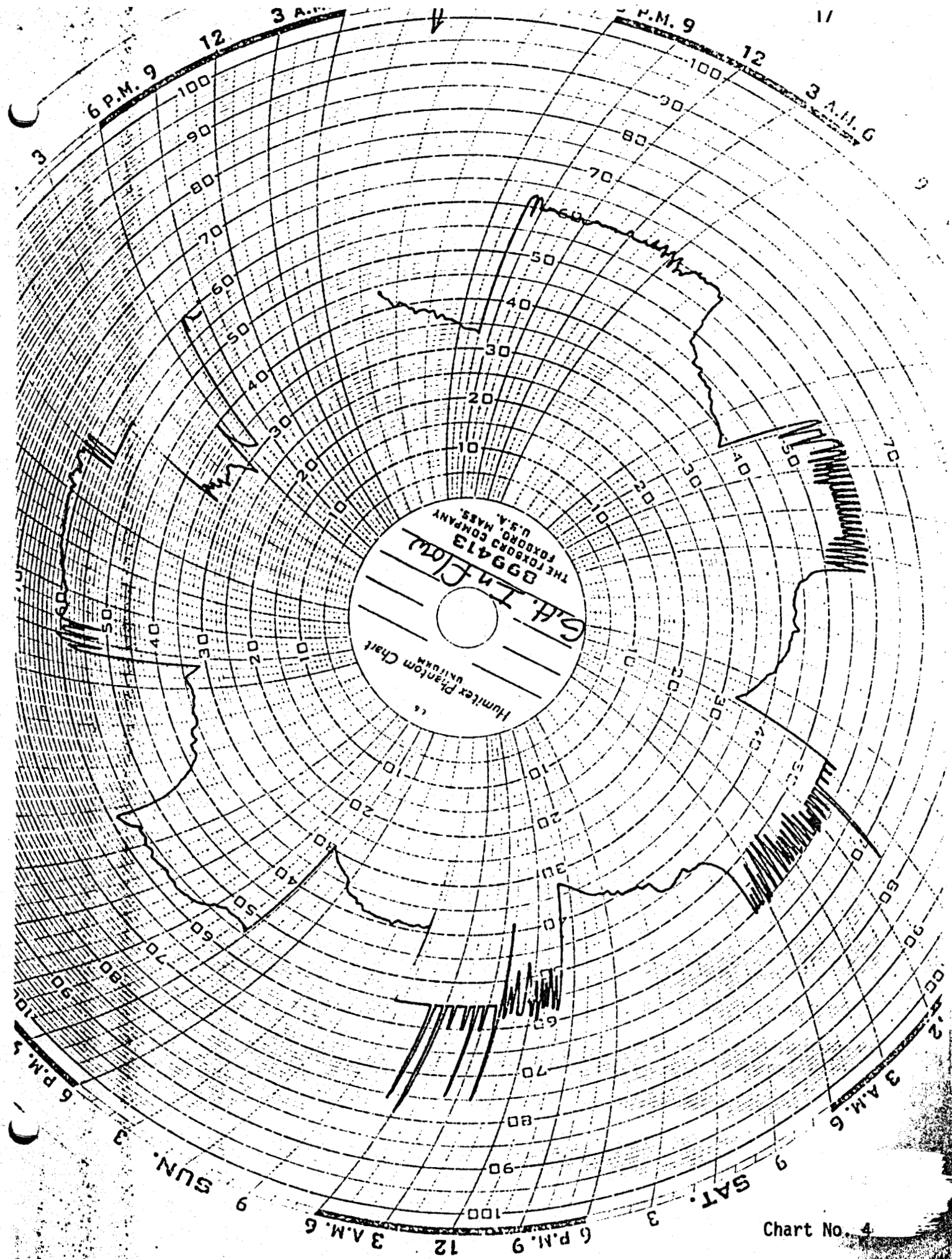

Humitex Phantom Chart
UNIFORM
THE FOXBORO COMPANY
FOXBORO, MASS.
U.S.A.
SAT.
SUN.

Chart No. 4

TABLE 1.

WATER CIRCULATION CONFIGURATIONS
USED TO DETERMINE HEATING EFFICIENCY

Config. Design	Sec./Pri. Water	**Radiator-Fans (Par./Series) With Perim. Heating	*Perim. Heaters (3) Pipes in Par. or Series	No. of Tests
M1	Sec.	Par.	Par.	2
M2	Sec.	Par.	Series	7
M3	Sec.	Series	Par.	13
M4	Sec.	Series	Series	2
M5	Pri.	Par.	Par.	1
M6	Pri.	Par.	Series	3
M7	Pri.	Series	Par.	1
M8	Pri.	Series	Series	2
M9	Sec.	Fan rads only		3
M10	Sec.	Perim. only Fans circulate air only, no water through radiator/fan units	Series	1
M11	Sec.	Perim. only	Par.	1
M12	Pri.	Fan rads only		1
M13	Pri.	Perim. only	Series	0
M14	Pri.	Perim. only	Par.	1

*The two fan radiators were always in parallel (Winter, 1979/80).
**Division of the flow between fan radiators and the perimeter heaters was by manual valve with no way of measuring the proportion of total flow through each when in parallel.

Water flows were averaged between night and morning readings of the nutating disc water meter, and a stopwatch spot-check of waterflow was sometimes noted on the chart. These daily greenhouse outflow water charts then contained the data for one test, were numbered consecutively, and the data compiled, Table 2.

TABLE 2.

Measurements Obtained During Tests to Determine Energy Consumption

Btu/Hr.

Chart No.	Date 1980	Configu-ration	Outside Amb. °C *	Gr. Hse. Amb. °C	Inflow Water Temp. °C	Outflow Water Temp. °C	Δ Ta (ambient) °C	Δ Tw (water) °C	Wind ~ mph	Gal./ Min.	Btu Per Hr. Per Sq. Ft. of G.H.
56	Feb. 11	M2	-2.2	11.7	66	37	13.9	29	Neg.	4.32	32.2
57	12	M2	-0.6	16.7	67.5	39.2	17.2	28.3	Neg.	4.8	34.9
58	13	M2	1.7	17.8	68.3	44.5	16.1	23.8	5	5.86	35.8
59	14	M2	3	17	67.7	42.8	13.9	24.9	5	5.15	32.9
60	15										
61	19	M2	5.6	20.6	68	49.4	15	18.6	5	8.27	39.5
62	20	M2	1.1	18.9	68.5	44.7	17.8	19.8	8	8.31	42.2
63	21	M2	1.7	17.2	67	46.8	15.6	20.2	8	7.42	38.5
64	22	M6	-1.8	19.9	79.3	48.9	21.7	30.4	3	6.82	53.2
65	23	M6	5	21.3	80.8	50.3	16.3	30.5		5.87	69.3
66	24	M6	6.1	21.1	81.3	49.5	15	31.8		5.58	45.6
67	25	M6	6.7	19.4	83	47.2	12.8	35.8		3.5	32.2
68	26	M8	8.9	21.1	83	40.84	12.2	42.16	15	3.57	38.7

* Average temperature during test period.

TABLE 2 (continued).

Measurements Obtained During Tests to Determine Energy Consumption

Btu/Hr.

Chart No.	Date 1980	Configu-ration	Outside Amb. °C *	Gr. Hse. Amb. °C	Inflow Water Temp. °C	Outflow Water Temp. °C	Δ Ta (ambient) °C	Δ Tw (water) °C	Wind ~ mph	Gal./ Min.	Btu Per Hr. Per Sq. Ft. of G.H.
69	Feb. 28	M8	0.6	19.4	83.8	40.8	10.5	43	3	4.83	53.3
70	29		3.9	17.8	58.6	39.28	13.9	19.32	7	7.05	35
71	Mar. 2	M9	5	17.6	58.2	38.64	12.6	19.56	1	5.31	26.7
72	3	M10	-0.6	7	57	44.5	7.5	12.5	3	3.64	11.7
73	4										
74	5	M4									
75	13										
76	23	M5	-0.6	18.2	79.7	44.4	18.8	35.5	8	4.87	44.3
77	24										
78	27	M1	-3.9	6.7	59.5	46.8	10.6	12.7	8	5.55	18.1
79	29	M3	-3.9	12.8	60	37.84	16.7	22.16	14	7.58	43.1
80	30	M4	-2.2	15	59.5	36	17.2	23.5	4	5.6	33.8
81	31	M9	-2.2	10.6	60	41.6	12.8	18.4	7	6.53	30.9

* Average temperature during test period.

TABLE 2 (continued).

Measurements Obtained During Tests to Determine Energy Consumption

Btu/Hr.

Chart No.	Date 1980	Configu-ration	Outside Amb. °C *	Gr. Hse. Amb. °C	Inflow Water Temp. °C	Outflow Water Temp. °C	Δ Ta (ambient) °C	Δ Tw (water) °C	Wind ~ mph	Gal./ Min.	Btu Per Hr. Per Sq. Ft. of G.H.
82	Apr. 1	M7	-2.8	18.1	75	48.96	20.8	26	3.5	8.01	53.5
83	3	M14	-1.1	12.8	79	60.8	13.9	18.2	4	10.64	49.7
84	4	M12	1.7	11.4	78	60.2	9.7	17.8	10	10.99	50.2
85	7	M1	-1.7	15.6	59	41.6	17.2	17.4	5	6.70	29.9
86	11	M3	3.6	19.4	52	41.5	15.8	10.5		19.48	52.5
87	12										
88	14	M3	1	15.3	53	42.5	14.3	10.5		13.13	35.4
88.5	15	M9	-1.1	15.6	50.5	38.3	16.7	12.2		8.31	26
89	16	M11	-0.6	12.2	55.5	40.56	12.8	14.97	7	10.44	40
90	17	M3									
91	22	M3	6.1	18.3	50.7	38.7	12.2	12	4	10.44	32.2
92	23										
93	24	M3	2.7	18.3	53.5	38.6	15.6	14	1	10.68	38.4

*Average tempurature during test period.

TABLE 2 (continued).

Measurements Obtained During Tests to Determine Energy Consumption

Btu/Hr.

Chart No.	Date 1980	Configu-ration	Outside Amb. °C *	Gr. Hse. Amb. °C	Inflow Water Temp. °C	Outflow Water Temp. °C	Δ Ta (ambient) °C	Δ Tw (water) °C	Wind ~ mph	Gal./ Min.	Btu Per Hr. Per Sq. Ft. of G.H.
94	Apr. 25										
95	27	M3	10.6	23.3	52	43	12.8	9		11.14	25.7
96	28	M3	6.1	18.1	51	38.4	12	12.6		10.03	32.4
97	29	M3	0.6	15.1	52	35	14.6	17	3	7.54	32.9
98	30	M3									
99	May 4	M3	12.8	21.1	56	34.5	8.3	21.5		4.2	23.2
100	6	M3	3.9	18.3	59	39.5	14.4	19.5		6.58	32.9
101	7	M3	4.4	20	60	39.3	15.6	20.7		2.47	13.1
102	8	M3	3	19.4	60.5	41.8	16.4	18.7	4+ rain	7.24	34.8

* Average temperature during test period.

GREENHOUSE DESIGN

Calculations for Heat Exchanger Requirements

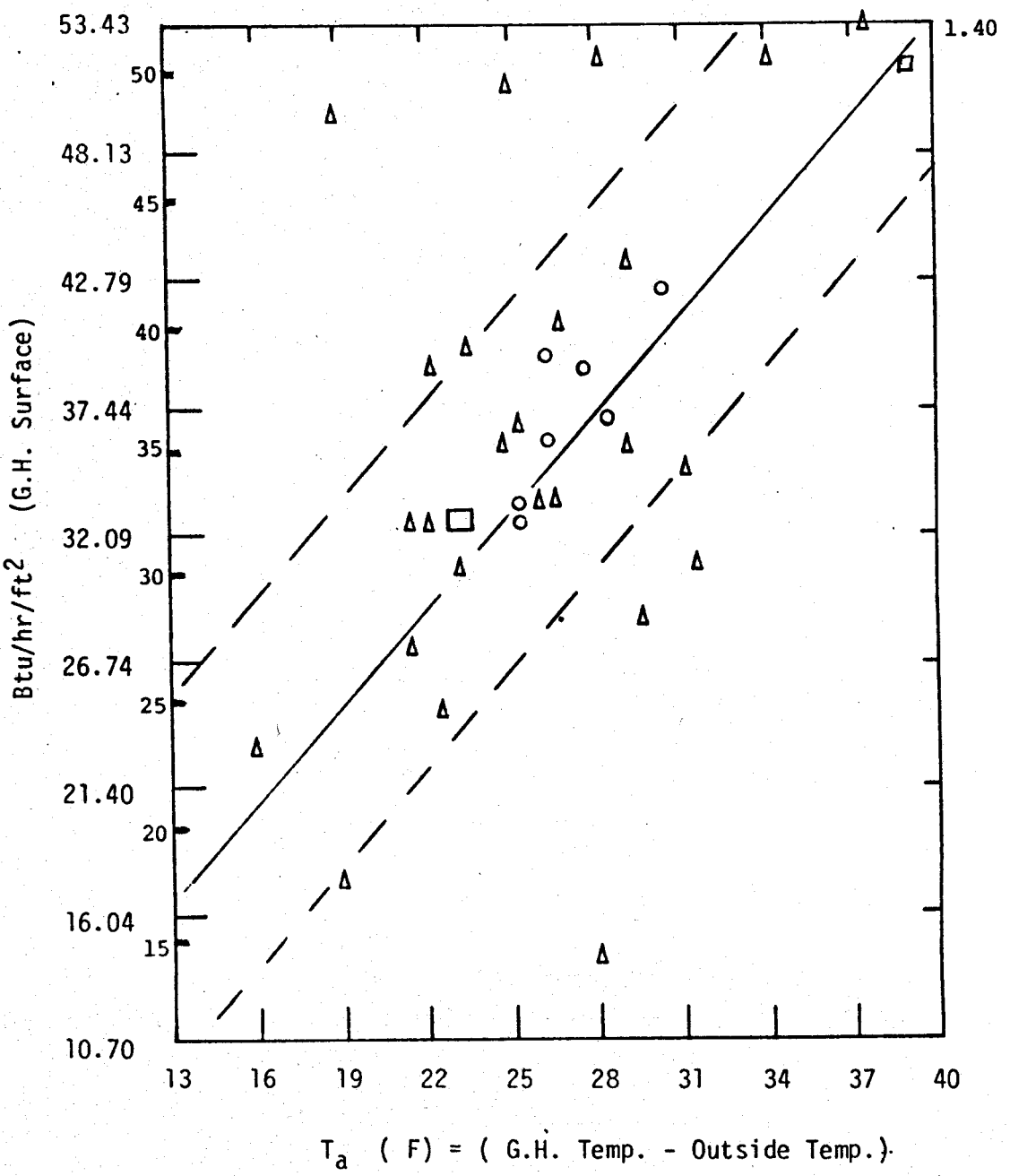
This method provides for determining the amount of heat and size of heat exchanger required when the amount and temperature of available water is known, as well as desired greenhouse size and temperature.

1. Calculate: Greenhouse area (G.H.Ar.) = N sq ft. Appendix A.
2. Multiply: N (sq ft) x 1.4 x [Btu per hr per sq ft of G.H.Ar. per $°F(\Delta T_a)] = \frac{1.4 \times N \times Btu}{hr \times °F}$

   Graph 1 for 1.4 factor origin.
3. Determine: $\Delta T_a(°F)$ = (desired G.H. night temp. °F) - (minimum local night temp. °F) = $\Delta T_a(°F)$

   Multiply: Step 2 x $\Delta T_a(°F)$ = Btu/hr
4. Divide: Step 3 by 0.70 = $\frac{Btu}{hr} \times \frac{1}{.70} = \frac{Btu}{hr}_e$ @ 70% efficiency, Table 3 (origin).
5. To determine <u>minimum</u> size heat exchanger required, see Steps 6 through 10.
6. Determine your minimum (dependable) flow rate = $(gpm)_m$.
7. Determine your minimum (dependable) water temp. = $(E.W.T.)_m$.
8. Using the desired G.H. night temp. and the $(E.W.T.)_m$, enter Graph 2 and determine the proper factor f_m.
9. Divide: $\frac{(Btu/hr)_e \text{ (from Step 4)}}{f_m \text{ (from Step 8)}} = \frac{Btu}{hr}_m$
10. The required (single) heat exchanger would be one which would be rated to supply the $(Btu/hr)_m$ from Step 9 at your $(gpm)_m$ at standard conditions of 200°F entering water temperature and 60°F greenhouse temperature.

Graph No. 1



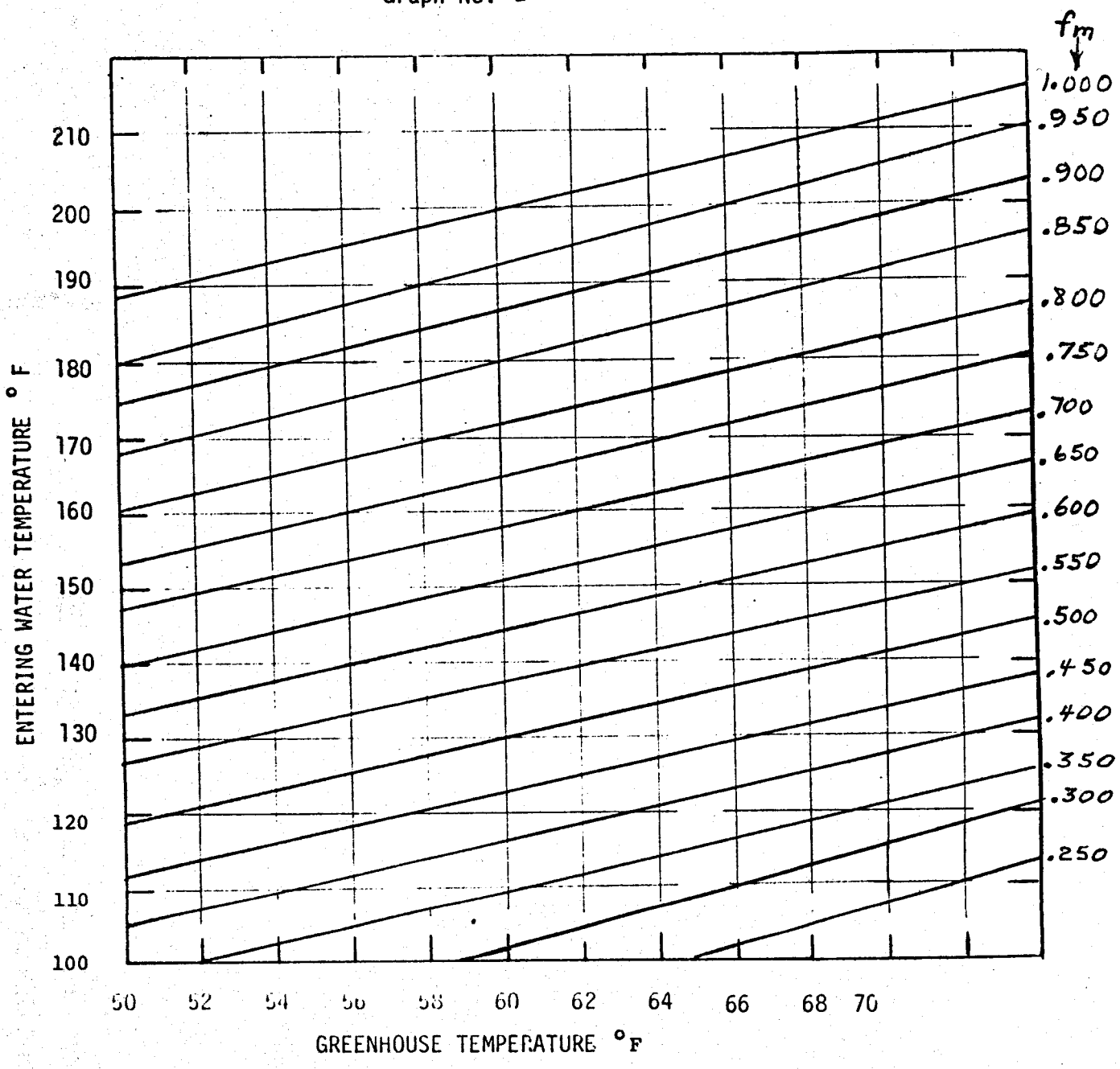
M2 = o

M3 = Δ

M6 = □

M? =

Graph No. 2 *



* Data from Modine Catalog 1-150.1
Racine, Wis.

Discussion of Calculations for Heat Exchanger Requirements

1. Larger heaters will supply more Btu to your greenhouse with the same temperature and gpm of water. For example, the company supplying horizontal heaters can supply heaters which will deliver all the way from 14,000 Btu/hr to 200,000 from the same 5 gpm of 200°F water at a greenhouse temperature of 60°F. On the other hand increasing the flow of water through an existing heater to increase the Btu output soon reaches a point of diminishing returns, Graphs 3 and 4, and Table 4.
2. If the extended outlook is for many greenhouses but your supply of geothermal heat is limited, the available water must be distributed to heat exchangers whose size has been calculated for the limited geothermal water supply.
3. When a minimal amount of capital investment is available, it would be best to use a larger amount of water through a smaller (lower-cost) heater. As greenhouses are added and flow to each greenhouse must be reduced, extra heaters would be required to supplement the original heater capacities.
4. These calculations relate to corrugated-fiberglass-covered greenhouses with metal frames. For glass houses, add 10 percent heat requirement (except for old wood frames with loose glass, add 25 percent), and for double-layered plastic with metal frames, deduct 30 percent.
5. This discussion does not cover distribution of the heat which may be by convection, radiator fans, or Fan-Jet, Figure 1.

TABLE 3.

Check on Operation of Radiator Modine Heaters Versus Factory Specifications

M9 and M12 tests were with heaters only (see Table).

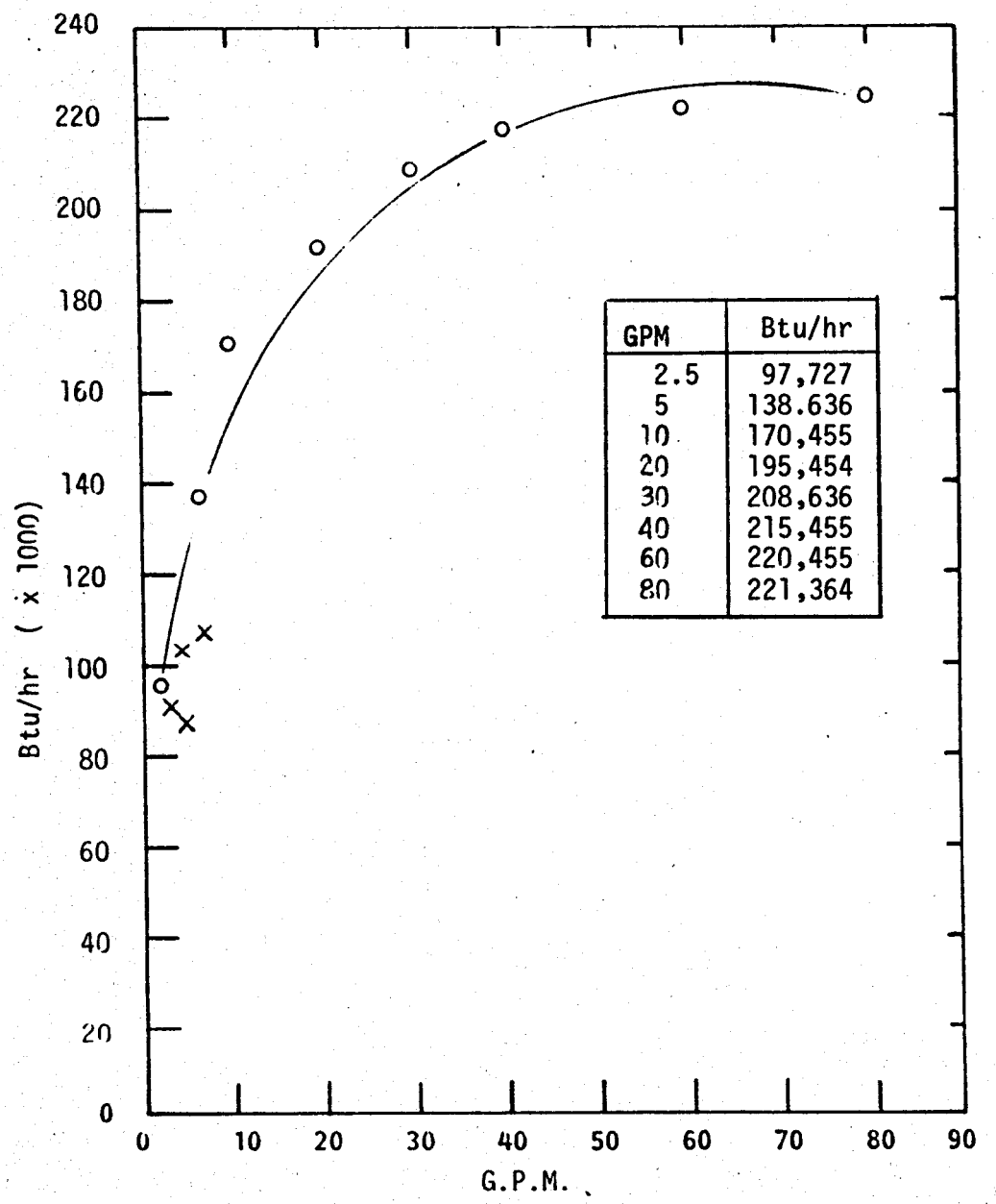
Configu-ration	Chart No.	Temp. of Incoming Water	Temp. of Incoming Air (G.H. Amb.)	G.p.m.	Btu/hr Factory Specs.	Btu/hr in Test	% of Factory Rating
M9	71	136.8	63.6	2.65	53,142 *1	46,742	87.4
M9	81	140	51	3.265	73,302 *2	54,111	73.3
M9	88-1/2	122.9	60	4.15	60,694 *3	45,649	75.2
M12	84	172.4	52.5	5.495	125,425 *4	88,127	70.3

Calcs: Btu/hr Factory Specs.:

	Factor for Entering Air °F vs. Entering Water °F	Factor Times Btu from Table
*1	.521	.521 x 102,000 = 53,142
*2	.643	.643 x 114,500 = 73,300
*3	.450	.450 x 135,000 = 60,694
*4	.865	.865 x 145,000 = 125,425

Btu/hr in Test: $(Gal/hr) \times 8.34 \times (\Delta T_W) = Btu/hr$

Graph No. 3



GPM	Btu/hr
2.5	97,727
5	138.636
10	170,455
20	195,454
30	208,636
40	215,455
60	220,455
80	221,364

Graph based on 200° F entering water temperature and 60° F greenhouse temperature. Individual points are test data factored to these conditions. Curve and individual points are for one Modine HS258 heater.

o = Factory Data Tables, one HS258 Unit

X = Test Data, one Equiv. Unit (M9 & M12)

TABLE 4.

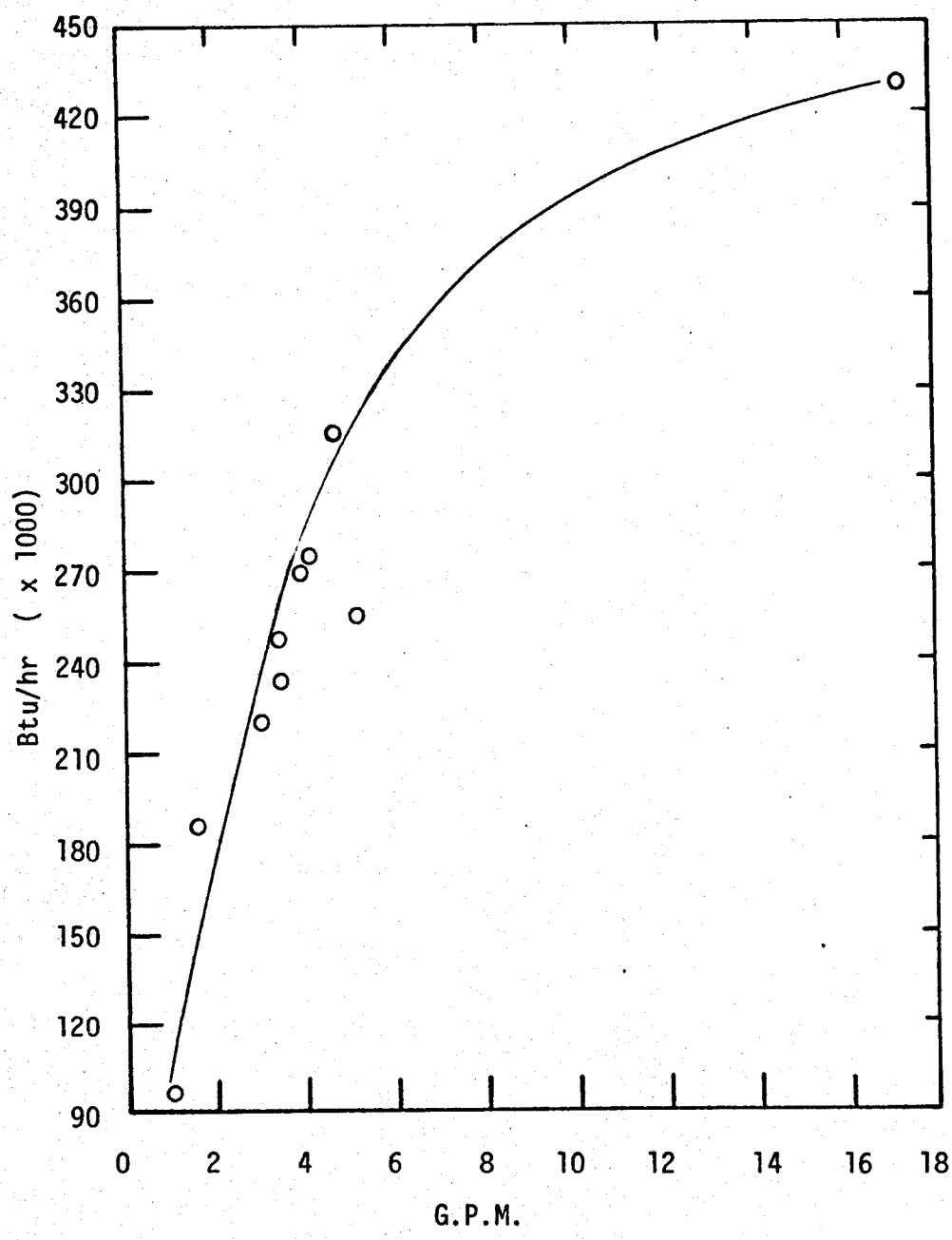
Calculations for Graph 3
(For Test Points "X")

Chart No.	Config.	EWT	EAT	GPM	Actual Btu/hr	Factor	Btu/hr Factor
71	M9	136.8	63.6	2.65	46,742	.521	89,716
81	M9	140	51	3.265	54,111	.643	84,154
88-1/2	M9	122.9	60	4.15	45,649	.450	101,442
84	M12	172.4	52.5	5.495	88,127	.864	101,999

Calculations for Graph 4

86	M3	125.6	67	19.48	184,264	.416	442,942
91	M3	123.3	65	5.215	112,878	.4144	272,388
93	M3	128.3	65	5.34	143,351	.4499	318,628
95	M3	125.6	74	5.57	90,279	.3558	253,735
96	M3	123.8	64.6	5.015	113,831	.4210	270,382
97	M3	125.6	59.2	3.77	115,480	.4750	243,116
99	M3	132.8	70.6	1.685	81,335	.4391	185,231
100	M3	138.2	65	3.29	115,433	.5192	222,328
101	M3	140	68	1.24	46,239	.5094	90,771
102	M3	140.9	67	3.62	121,975	.5232	233,132

Graph No. 4



Graph of (factored) tests of M3 configuration showing same trend as graph No. but higher values due to more heat exchange capacity.

6. Wind is of negligible effect in calculating heat requirements until the velocity reaches 15 mph, but for possible steady wind velocities of 35 mph, about 15 percent more heat will be needed. During these tests, average wind velocities did not exceed 15 mph and no correlation for wind is apparent.
7. Having the hot water flow through several heaters in series is more efficient than in parallel, Table 5; however, it may be more convenient to place them in parallel (as in this greenhouse). Generally, they could be plumbed either way.
8. Calculations using the above method for determining heat exchanger requirements were made on test data, Table 6.
9. There are safety aspects tending to decrease the possibility of plant damage due to insufficient capacity of the heat system. The colder the greenhouse temperature gets as the outside temperatures drops, the more effective the available heat is, Graph 5, to keep the greenhouse temperature from freezing plants when conditions are more severe than anticipated. Design for 50°F night greenhouse temperatures provides a "cushion" of 18°F before freezing. An additional safety factor is that the Btu extracted per gallon goes up rapidly as flow decreases, Graph 6 and Table 7.
10. From available test data, the three perimeter heaters combined were equivalent to 75 percent of one of our radiator/fan units, Table 8.

TABLE 5.

Parallel Versus Series Operation

Calculations based on tables for four radiator (HS 258) heaters using 20 gpm at 200°F, 60°F greenhouse temperature:

	Temp. Drop	Btu/hr	% Efficiency
Four heaters all in parallel	56	560,000	87
Two heaters in parallel and two pair in series	59.8	598,976	94
Four heaters all in series	63.3	633,897	100

Calculations based on tests involving two (equivalent) radiator (HS 258) heaters (always in parallel) and three perimeter heaters (always in series):

Configurations M2 and M6 have heaters and perimeters in parallel; M4 and M8 are in series.

M2 and M6 (averages)	223,044	90.4
M4 and M8 (averages)	244,406	100

See tables of calculations below.

TABLE 5 (Continued).

Examples Parallel Versus Series
(Total Btu Extracted)

Arranging four radiator (HS 258) heaters either in parallel or in series at 20 gpm total flow available 200°F and greenhouse at 60°F:*

Four in Parallel

Each unit = 5 gpm = 140,000 Btu/hr each; 4 x 140,000 = 560,000 total Btu/hr

Temp. drop = $\frac{140,000}{5 \times 500}$ = 56°F 87% efficiency

Two in Parallel, and Two Sets of These in Series

Each unit has 10 gpm.
Each of first pair = 170,454 Btu/hr; 2 x 170,454 = 340,909 total Btu/hr (first pair)

Temp. drop = $\frac{170,454}{10 \times 500}$ = 34°F

Entering water temperature = 166°

(Each of second pair, factor = .757) = 170,454 x .757 = 129,033 Btu/hr each,

= 129,033 x 2 = 258,067 (second pair)

Temp. drop = 25.8°F

Total Btu/hr = 340,909 + 258,067 = 598,976 total Btu/hr

Total Temp. drop = 34° + 25.8°F = 59.8°F 94% efficiency

Four in Series

Each unit has 20 gpm.
First unit = 195,909 Btu/hr

Temp. drop = 19.6°F

Second unit has EWT = (200 - 19.6) = 180.4°F

Factor = .860; 195,909 x .860 = 168,458 Btu/hr
Temp. drop = 16.85°F

* Modine catalog, 1980.

TABLE 5 (Continued).

Third unit has EWT = 180.4 - 16.85 = 163.55

Factor = .740; 195,909 x .740 = 144,886 Btu/hr
Temp. drop = 14.44°F

Fourth unit has EWT = 163.55 - 14.44 = 149.06

Factor = .636; 195,909 x .636 = 124,644 Btu/hr
Temp. drop = 12.45°F

Total Btu/hr = 633,897

Temp. drop = 63.3°F

Efficiency = 100%

TABLE 5 (Continued).

Test Parallel Versus Series Operation
Factored for Comparison

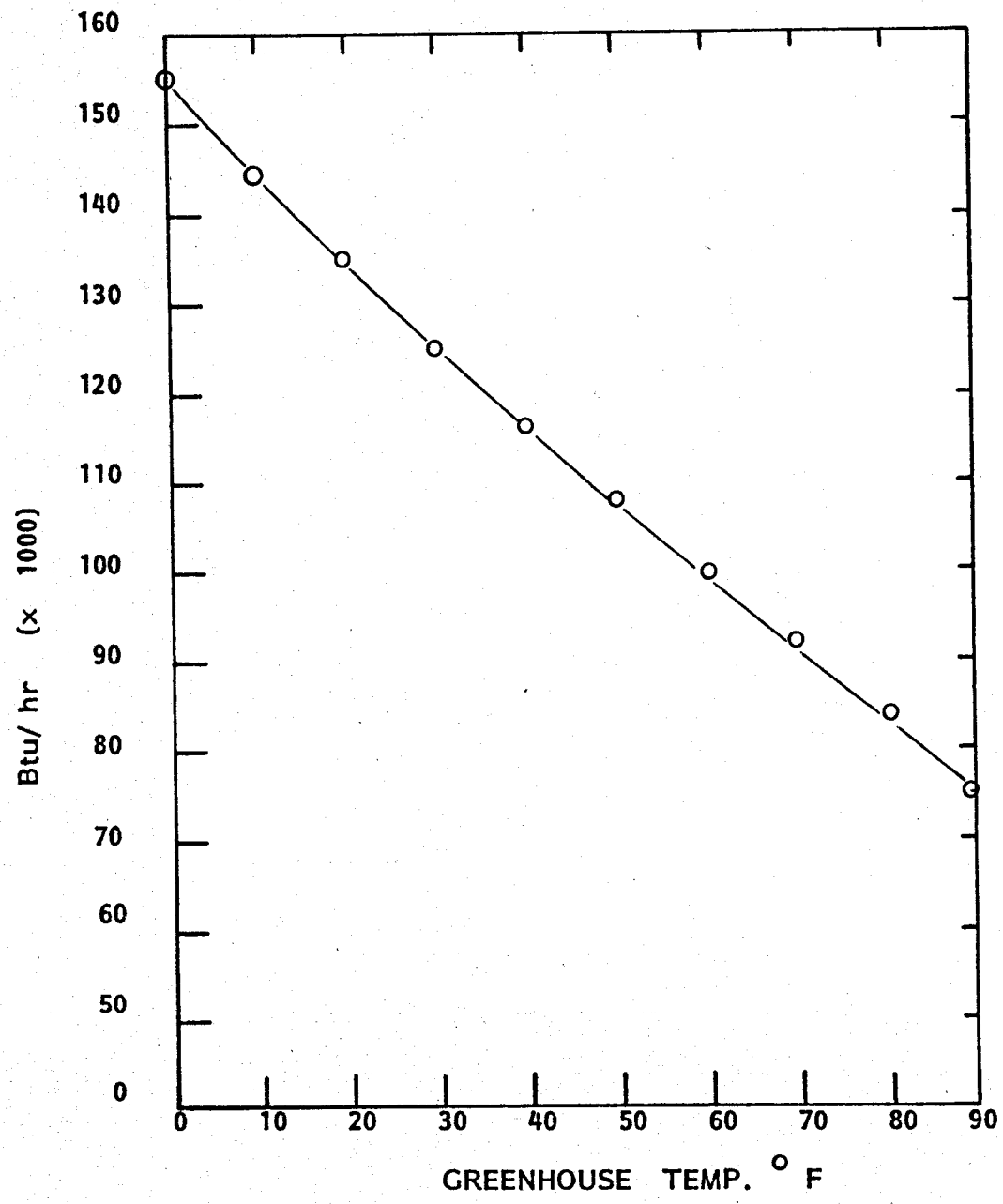
Config.	Chart No.	EWT	EAT	GPM	Actual Btu/hr	EWT-EAT Factor	Act. Btu / Factor	GPM Factor	Adjusted Btu	% Eff.
M2	57	153.50	58	4.80	122,353	.6839	178,905	$\frac{161,589}{135,870} = 1.1893$	212,772	
M2	58	154.94	64	5.86	125,643	.6469	194,223	$\frac{161,589}{147,392} = 1.09$	211,703	
M2	62	155.30	66	8.31	148,152	.6338	233,752	$\frac{161,589}{161,589} = 1.0$	233,752	
M6	66	178.34	70	5.58	159,923	.7652	208,995	$\frac{161,589}{144,349} = 1.1194$	233,949	
								Average	223,044	90.4
M4	80	139.10	59	5.60	118,534	.5726	207,010	$\frac{161,589}{144,566} = 1.1178$	231,395	
M8	68	181.40	70	3.57	135,667	.7869	172,406	$\frac{161,589}{120,208} = 1.3442$	231,748	
M8	69	182.84	67	4.83	186,987	.8214	227,644	$\frac{161,589}{136,196} = 1.1864$	270,076	
								Average	244,406	100

TABLE 6.
Example Calculations for Heater Requirements

Chart No.	ΔT_a	C*	EWT(°F)/ GHT(°F) See Table 1	f_m See Graph 8	$\frac{C}{f_m} = \left(\frac{Btu}{hr}\right)_m$ $\times \frac{1}{2}$ = Btu/hr Asking for Per Modine	GPH $\times \frac{1}{2}$ Two Modine Heaters in Par.	8.34 $\times \Delta T_W$ = Btu/hr Used	Our Modine Rating @ $\frac{1}{2}$ GPM $\times f_m$	Our Modine (Plus Perim.) % Eff.	Cal. Reqd. Btu/hr (x .7 x f_m) is % of Btu/hr actually Used
88-1/2 (M9)	30	210,480	$\frac{122.3}{60}$	.450	233,866	249.25	45,649	58,500	78	161
81 (M9)	23	161,368	$\frac{140}{51}$	.650	124,129	195.9	55,111	74,750	74	103
84 (M12)	17.5	122,730	$\frac{172}{52.5}$	.860	71,413	329.8	88,127	124,700	70	49
89 (M11)	23	161,368	$\frac{132}{54}$	.560	144,079	313	70,194	78,400	90	81
64 (M6)	39	273,624	$\frac{174.7}{67.8}$	.750	182,416	204.6	93,369	90,600	103	103
76 (M5)	33.8	237,141	$\frac{175.5}{64.8}$	.775	152,994	146	77,807	76,725	101	107
66 (M6)	27	189,432	$\frac{178.34}{70}$	.765	123,811	$\frac{167.5}{2.79}$	79,961	84,150	95	83
67 (M6)	23	161,368	$\frac{181.4}{67}$	.812	99,365	105	56,395			101
79 (M3)	30	210,480	$\frac{140}{55}$	.609	172,808	$\frac{227.4}{3.79}$	75,648	76,125	99	98
99 (M3)	15.8	110,853	$\frac{132.8}{70.6}$	.448	123,720	$\frac{126}{2.10}$	40,668	38,080	107	95
88 (M3)	25.7	180,311	$\frac{127.4}{59.5}$	.485	185,888	394.0	62,104			102
									Average	98.5

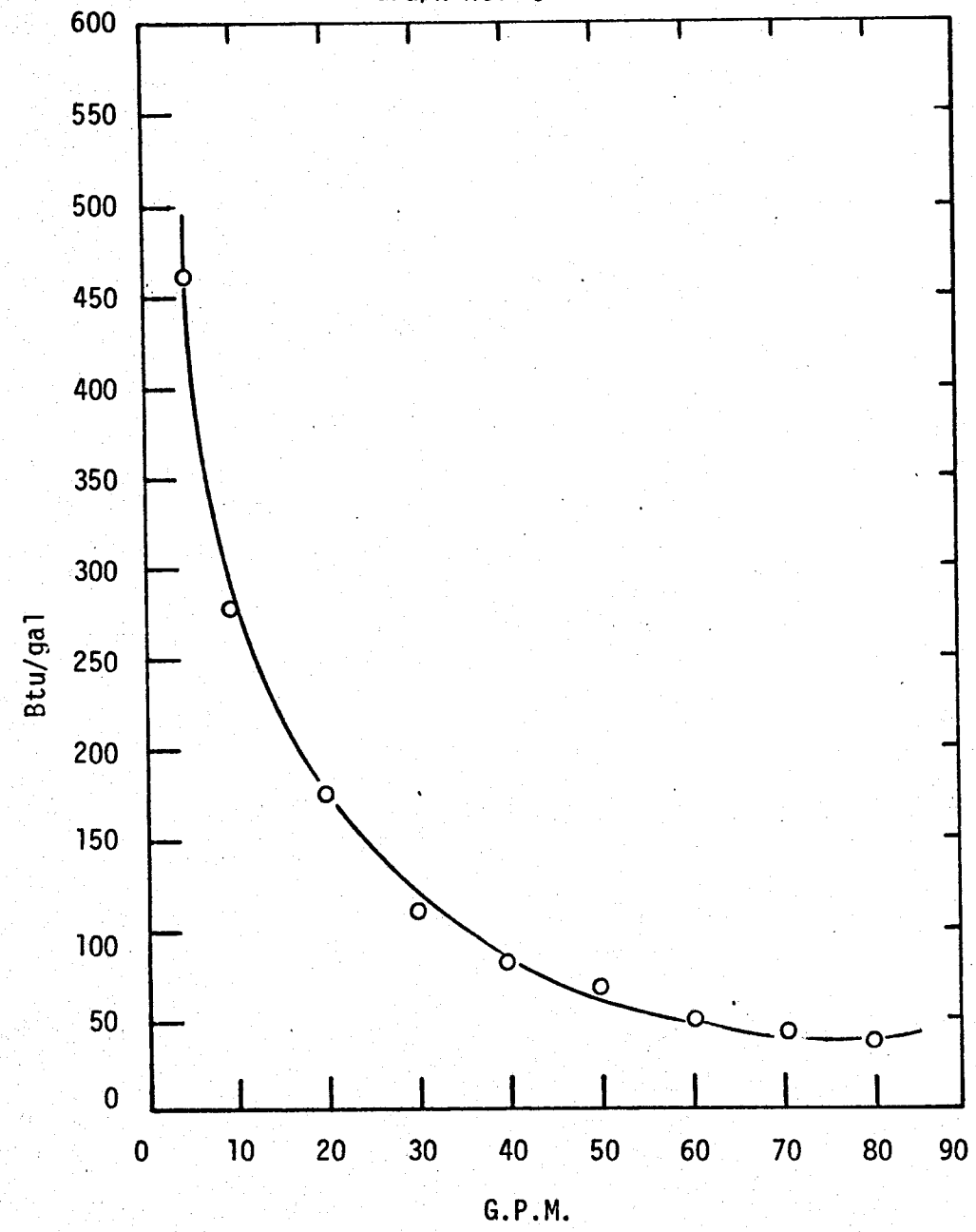
* (Greenhouse Surface Area) x 1.40 ÷ 70 x ΔT_a (difference between G.H. and outside temperatures) = 7,016 x ΔT_a.

Graph No. 5



The effect of dropping temperatures in the greenhouse on the Btu extracted from a constant temp. and amount of water. (200°F entering water temp. @ 2.6 gpm)

Graph No. 6



Graph based on 200° F entering water temperature and 60° F entering air temperature for Modine heater.
Note: @ 600 Btu/gal the exit water temperature is 128° F.

TABLE 7.

Calculations for Graph 6

*80 gpm = 221,364 Btu/hr

70 gpm $\frac{221,364}{4,200} = 52.7$

60 gpm $\frac{220,455}{3,600} = 61.2$

50 gpm $\frac{218,182}{3,000} = 72.7$

40 gpm $\frac{215,455}{2,400} = 89.8$

30 gpm $\frac{208,636}{1,800} = 115.9$

20 gpm $\frac{195,454}{1,200} = 162.9$

10 gpm $\frac{170,455}{600} = 284.1$

5 gpm $\frac{138,636}{300} = 462.1$

2.5 gpm $\frac{97,727}{150} = 651.5$

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* $\frac{\text{221,364 Btu/hr (@ 200°F water, 60° G.H. Temp.)}}{\text{80 gal/min x 60 min/hr}} = 46.12$ Btu/gal

TABLE 8.

Calculations of Equivalency--Perimeter/Modine Radiator Heaters

Config. (Modine Only)	Chart No.	EWT	EAT	GPM	Observed Btu/hr	Factor @ Test Condx.	Obs. Btu ÷ Factor	Calc. Btu for Modine	Eff.
M9	71	136.8	63.6	1/2 = 2.65	1/2 = 46,742	.521	89,716	101,041	.888
M9	81	140.0	51.0	1/2 = 3.265	1/2 = 54,111	.643	84,154	113,864	.733
M9	88-1/2	122.9	60.0	1/2 = 4.15	1/2 = 45,649	.450	101,442	128,805	.788
M12	84	172.4	52.5	1/2 = 5.495	1/2 = 88,127	.864	102,026	143,425	.783
								Average:	.8
Perim. Only									
M10 (Ser.)	72	134.6	44.5	Tot. = 3.644	41,028	.656	62,542	121,750	.514
M11 (Par.)	89	131.9	54.0	1/3 = 3.48	1/3 = 46,826	.561	83,469	118,333	.705
M14 (Par.)	83	174.2	55.0	1/3 = 3.547	1/3 = 58,141	.857	67,842	119,729	.567
								Average:	.6

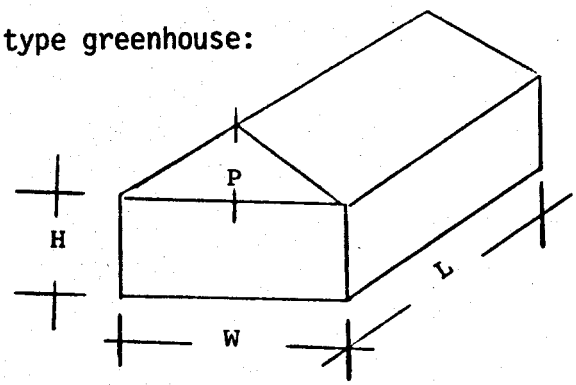
$$\frac{\text{Efficiency of Our Perimeter Heaters (Per Modine)}}{\text{Efficiency of Our Modine Heaters}} = \frac{.6}{.8} = .75$$

Thus, our perimeter heaters were approximately = 75% of one Modine HS 258 heater.

APPENDIX A

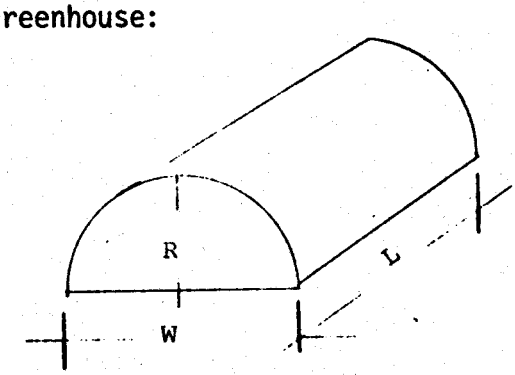
Surface Area Calculations

A. Standard gable-type greenhouse:



$$\text{Surface Area} = 2H(W + L) + W \cdot P + 2L \cdot \sqrt{P^2 + (1/2\ W)^2}$$

B. Quanset-type greenhouse:



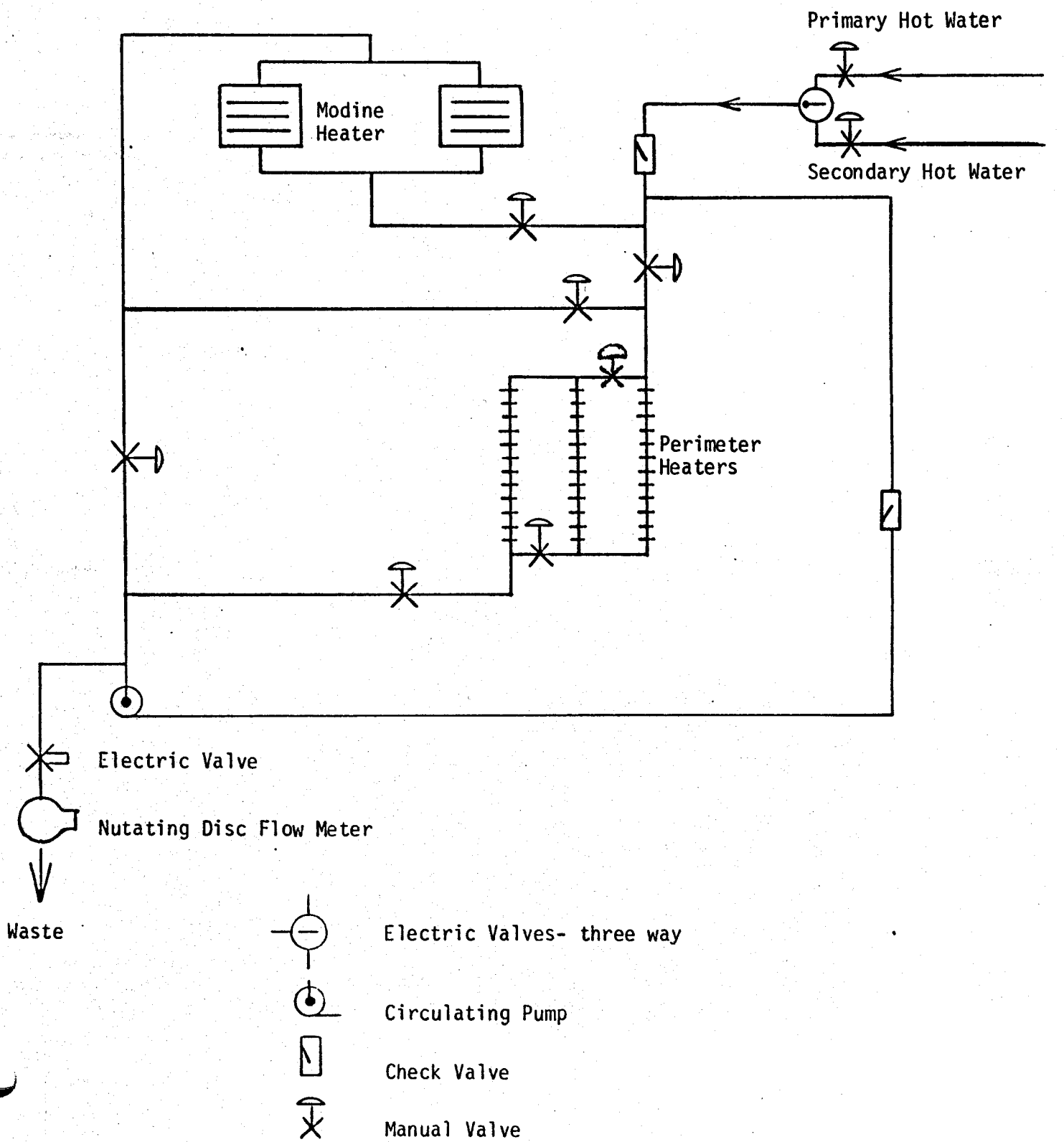
$$\text{Surface area} \approx \frac{\pi \cdot W^2}{4} + \frac{\pi \cdot W \cdot L}{2}$$

This formula assumes that R = 1/2 W; if this is not true, then average R and W for an approximate value of W. If the half-round part has vertical walls below it, then use the above formula for the half-round portion and add to this: 2H(W + L), where H is the height of the vertical side-wall portion.

C. Calculations of surface area for this report included all doors and windows in the surface area with no factors for difference in heat transmission. Most greenhouses will have roughly proportionate share of such openings.

APPENDIX B

SCHEMATIC OF GREENHOUSE HEATING SYSTEM



APPENDIX C

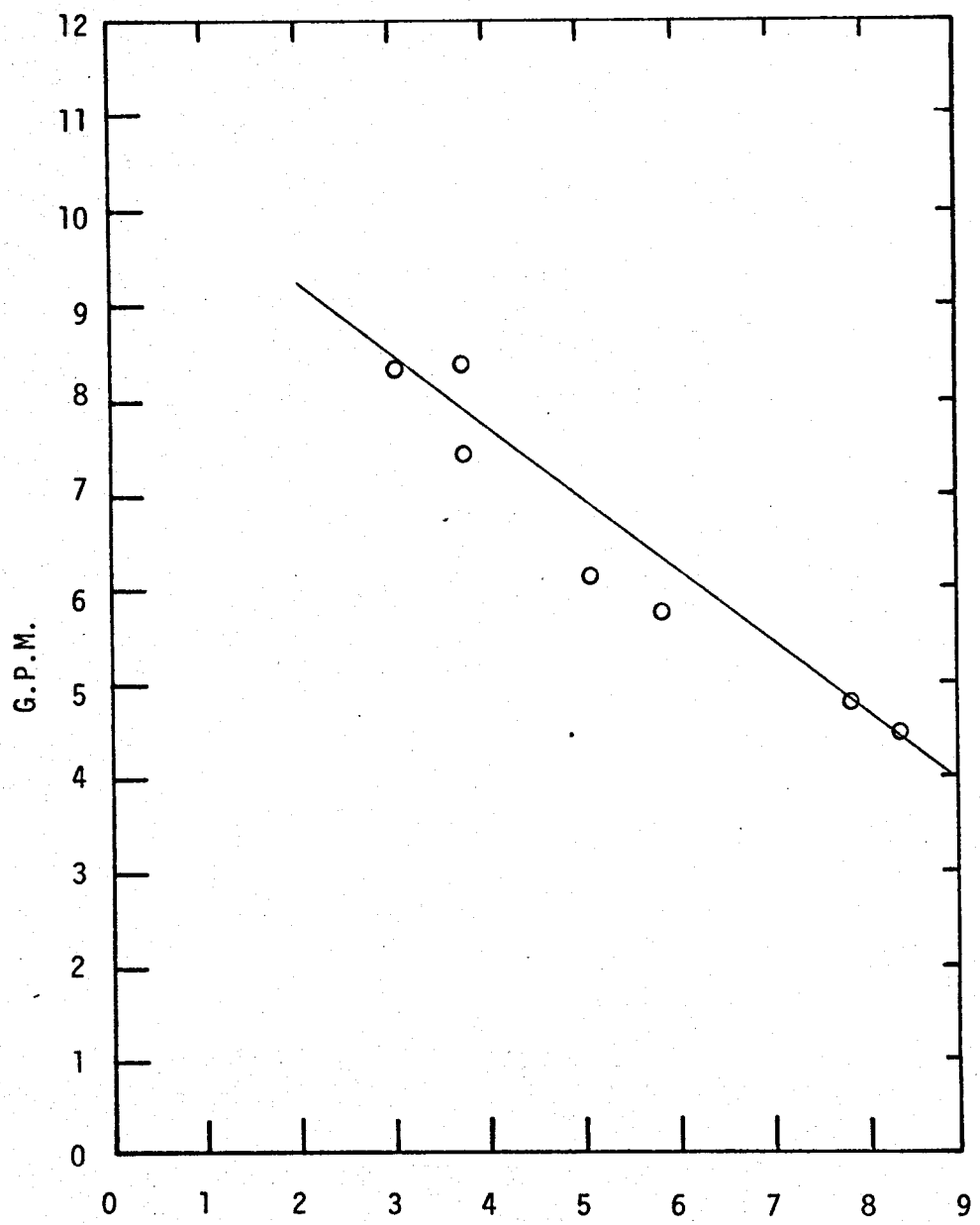
Graphs 7 and 8, correlation of data with Graphs 3 and 4.

Table 9, data for Graph 7.

Table 10, data for Graph 8.

Chart 4, Inflow Water Chart.

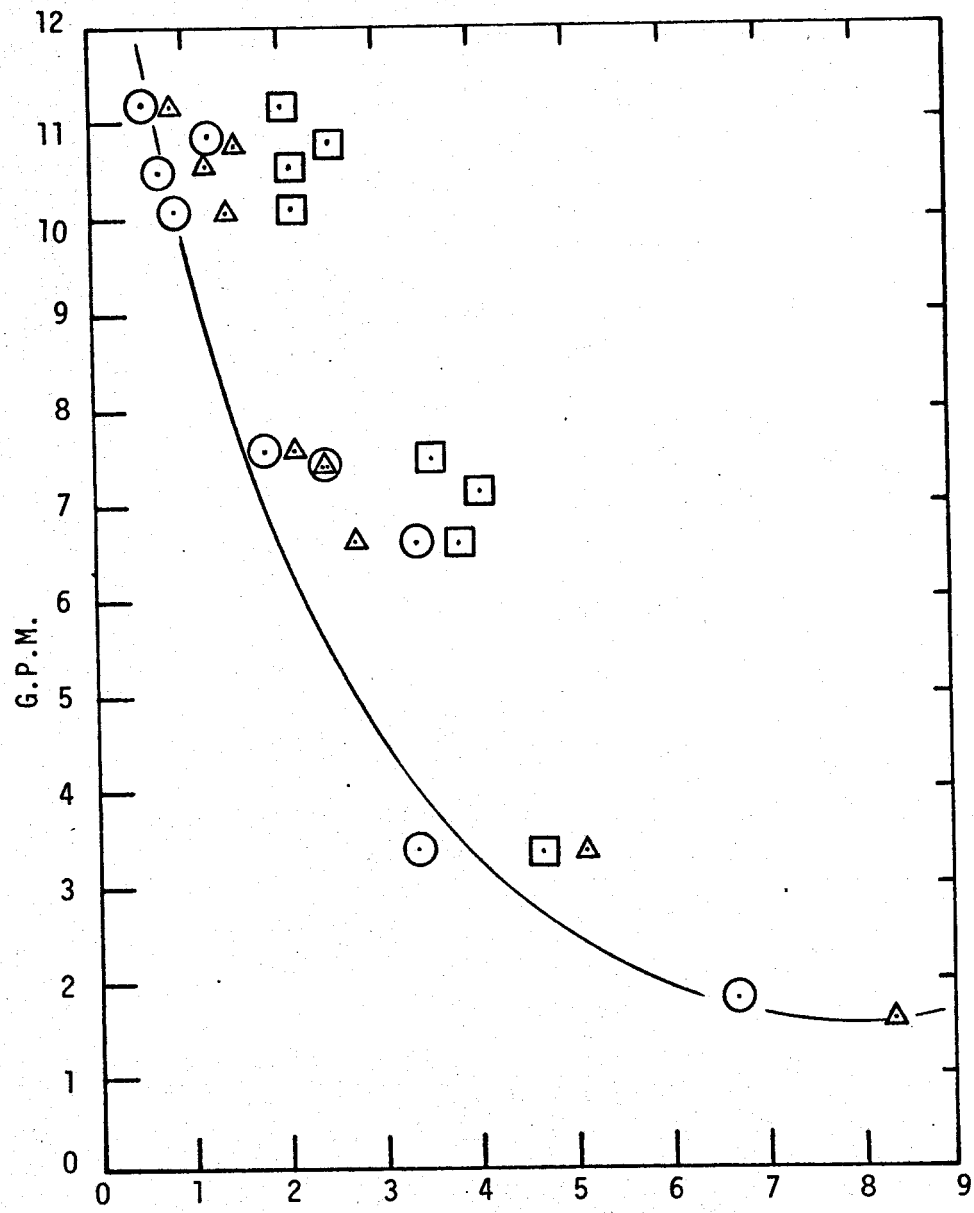
Graph No. 7



$$o = \left[\frac{\Delta T_w (°C) \times \Delta T_a (°F)}{G.P.M.}\right] \times 3$$

The heating effect of water decreases as the G.P.M. increases. These points were all for M2 configuration tests. This datd was not factored but shows the same trends as graphs 3 and 4.

Graph No. 8



△ = $\frac{\Delta T \text{ (Water } ^\circ C)}{GPM}$

⊡ = $\frac{\Delta T \text{ (Amb. } ^\circ F)}{GPM}$

⊙ = $\frac{\Delta T_W \times \Delta T_a}{GPM \times 30}$

TABLE 9.

Data for Graph 7
Configuration = M2

Chart No.	GPM	$\frac{\Delta T_a \times \Delta T_w}{GPH}$	X3
56	4.32	2.794	8.382
57	4.80	2.65	7.95
58	5.87	1.96	5.88
59	5.15	2.015	6.045
61	8.27	1.013	3.039
62	8.30	1.271	3.813
63	7.42	1.27	3.81

TABLE 10.

Data for Graph 8

Chart No.	GPH	GPM	W $\frac{\Delta T_W}{GPM}$	V $\frac{\Delta T_A}{GPM}$	X $\frac{\Delta T_A \quad \Delta T_W}{(GPM)30}$
91	626.6	10.43	1.15	2.11	.84
93	640.79	10.68	1.40	2.62	1.30
95	668.2	11.14	.81	2.06	.62
96	601.8	10.03	1.25	2.10	.90
97	452.5	7.54	2.256	3.47	1.97
99	202	3.37	5.12	4.69	3.36
100	394.5	6.58	2.96	3.95	3.42
101	148	2.46	8.41	10.57	6.87
102	434.5	7.25	2.59	4.07	2.54