



144
670
THS

EFFECT OF ULTRASONICS ON HEAT TRANSFER

Thesis for the Degree of M. Sc.
MICHIGAN STATE UNIVERSITY
Anandrao Pandurang Deshmukh
1956

مكتبة

ع.ع.



3 1293 20077 9795



OVERDUE FINES:

25¢ per day per item

RETURNING LIBRARY MATERIALS:

Place in book return to remove
charge from circulation records

R
JUL 18 1978

EFFECT OF ULTRASONICS ON HEAT TRANSFER

By

Anandrao Pandurang Deshmukh

A THESIS

**Submitted to the School of Agriculture of Michigan State
University of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

Department of Agricultural Engineering

1956

11/11/11

11/11/11

11/11/11

EFFECT OF ULTRASONICS ON HEAT TRANSFER

By

Anandrao Pandurang Deshmukh

AN ABSTRACT

Submitted to the School of Agriculture of Michigan State
University of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1956

Approved by Carl W. Hall, 11/26/56

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to his major professor, Dr. Carl W. Hall of the Agricultural Engineering Department, under whose assistance and supervision the research work was conducted.

The author is grateful to Dr. Arthur W. Farrall and his staff for making materials, equipment and facilities available for this study.

The writer also appreciates the valuable assistance rendered by Mr. Leon J. Newcomer for acquainting the author with the ultrasonic generator.

Thanks are due to Dr. Egon A. Hiedeman and Mr. Mack A. Breazeale of the Department of Physics for their valuable suggestions.

Thanks is expressed to Mr. James Cawood, foreman of the Agricultural Engineering Research Laboratory, and laboratory workmen for their valuable assistance.

The ultimate goal was to study the effect of an ultrasonic field on the rate of heat transfer. The specific topics investigated were the application of ultrasonic waves parallel to and perpendicular to heat transfer surfaces.

A commercially constructed ultrasonic generator was used to generate ultrasonic waves. An electric immersion pyrex glass sheathed cylindrical water heater was used to heat the water. Temperatures at various positions were measured by thermocouples. Ceramic discs and tube transducers were used to produce ultrasonic waves. The amount of heat input by ultrasonics was measured by the calorimetric method.

With the disc transducer at a frequency of 400 kilocycles, there was no appreciable effect on the rate of heat transfer. At this frequency ultrasonic energy is low and has no advantage on the rate of heat transfer. With the transducer at a frequency of 1000 kilocycles there was a definite increase in the rate of heat transfer as compared to the results without ultrasonic energy. The rate of heat transfer was proportionately increased with an increase in ultrasonic power up to 50 ma ultrasonic generator output, and decreased above 50 ma. In an ultrasonic field the system came to steady state in 8 to 10 percent less time as compared to the time required to come to steady state without the ultrasonic field. The rate of heat transfer observed was 18.6 percent more with the heater output of 4 watts and 50 ma ultrasonic energy than the sum of the individual effects. This percentage was decreased with

increased heater watts and increased ultrasonic energy. Low ultrasonic energy of 15 ma had no effect on the rate of heat transfer.

When the tube transducer with 640 kilocycle resonance frequency was used for a series of tests the temperature drop was 2-3 degrees F. higher on the heater surface in trials with heater only as compared to 50 ma ultrasonic field and 4 watts heater power. This indicates reduction in fluid film resistance.

The ultrasonic energy input per unit surface area was much smaller with the tube transducer as compared to the disc transducer. With the tube transducer at 25, 50, and 75 ma, water became heated in 25 percent less time than without ultrasonics with 4, 6, and 8 watts heater power. There was no measurable variation in temperature at various distances from the transducer in liquids, which indicates uniform heating in ultrasonic field with the tube transducer.

TABLE OF CONTENTS

	PAGE
INTRODUCTION	1
OBJECTIVES	3
REVIEW OF LITERATURE	5
Loss of Energy in Ultrasonics	6
Ultrasonic Output	7
Ultrasonic Velocities in Liquids and Gases	7
THEORETICAL PRINCIPLES	9
TEST I	10
Procedure	10
Apparatus	11
Results	28
Conclusions	29
TEST II	31
Procedure	31
Results	31
Conclusion	32
TEST III	37
Procedure	37
Results	37
Conclusions	39
SUMMARY AND CONCLUSIONS	43
Summary	43
Conclusions	45
BIBLIOGRAPHY	46
APPENDIX A	49
APPENDIX B	57

LIST OF FIGURES

FIGURE	PAGE
1. Principal apparatus used for procedure I and II.....	16
2. Transducer assembly for procedure I and II.....	16
3. Section through transducer and tube showing agitation arrangement for procedure I and II.....	17
4. Oscillator circuit.....	19
5. Time temperature curves for different watts of heater element.....	20
6. Time temperature curves for ultrasonic energy only...	21
7. Time temperature curves for 4 heater watts and 0-75 ma ultrasonic energy.....	22
8. Rate of heat transfer by ultrasonic energy only.....	25
9. Rate of heat transfer at 4 heater watts plus ultrasonic energy, 0-75 ma.....	27
10. Time temperature curves for ultrasonic energy.....	35
11. Time temperature curves for disc transducer.....	36
12. Principal apparatus used for procedure III.....	40
13. Time temperature curves for tube transducer (t2).....	41
14. Time temperature curves for tube transducer.....	42

LIST OF TABLES

TABLE	PAGE
I. Heater element performance.....	18
II. Ultrasonic wave length in water.....	18
III. Mean temperature difference at the outside surface of the tube.....	23
IV. Rate of heat transfer at 1000 kilocycles.....	24
V. Saving of heat energy by ultrasonics.....	26
VI. Mean temperature difference per hour at the tube surface.....	33
VII. Amount of heat transferred per hour by the tube....	34

INTRODUCTION

The field of ultrasonics is relatively new yet it has been found to have wide scientific technical applications. Over 1500 papers have been presented on different aspects of ultrasonics. Ultrasonic waves are sound waves of a frequency above the audible range. In early literature concerning this subject the term "supersonics" and occasionally "suprasonics" was used by some authors instead of "ultrasonics."

There is no fundamental physical difference between ultrasonics and audible sound waves. The human ear hears sounds up to 20,000 cycles per sec. Ultrasonic waves are compressional waves with frequencies ranging from 20 to 500,000 kilocycles per sec. It is apparent that the term defines a tremendous range in both frequency and wave length.

In the minimum frequency range the length of ultrasonic waves in solids is about 8 in.; in liquids, about 2.4 in.; in gases, about .63 in. In maximum frequency range the wave length approached a value in solids of 3.2×10^{-4} in.; in liquids, 1×10^{-4} in.; in gases, 24×10^{-4} in. The higher the frequency the shorter is the wave length.

Though there is no fundamental physical difference between sound waves of low, medium and high frequencies, great differences exist in the ease with which high intensities may be

produced and the ease with which the sonic energy may be transmitted to the system under investigation.

Absorption of high frequencies is much faster than or stronger than that of lower frequency waves. At extremely high frequencies the energy losses due to absorption become excessive. The amplitude necessary to transmit a given quantity of energy at low frequency is greater than those at higher frequency. Sound waves of great intensity may bring about many kinds of phenomena such as emulsification of two bulk liquid phases, peptization, destruction of bacteria, disintegration of certain solids, coagulation, production of chemical reactions, production of heating effects, agitation, stimulation of plant growth, submarine signaling, and communications. All frequencies are suitable for the investigation of the physical properties of matter.

There is a great concentration of energy in these waves. Bergman (21) shows intensity of 10 watts/sq. cm. is usual, as compared to 10^{-10} watts/sq. cm. with audible sound waves. The shorter ultrasonic waves are of the same order of magnitude as light waves.

Ultrasonics is mostly used for agitation in this work. The writer's attention was directed to investigate the effects which ultrasonics might have upon heat transfer in liquids. Previous work (26) has shown that ultrasonics used in quenching oil bath has a good effect on the quality of metal and that the time of cooling is decreased as ultrasonics breaks down the gaseous layers along the metal surfaces.

OBJECTIVES

Numerous investigations have shown that the problem involving gases and liquids in contact with heat transfer surface the overall heat conductivity of wall is greatly affected by the conductivity of surface film of the fluid to be heated. Thus the conductivity of the metal is less important than the conductivity of the surface film.

The uniform heating is not always easy with conventional methods of heating, whether the heating may be water, oil or milk. The major difficulty lies in formation of layer of insulating liquid at the heater surface, the instant it is immersed, and as the layer may remain longer on some sections of a part than others, chances for uneven heating are increased.

Experience has shown that the resistance can be reduced by any treatment which reduces the film thickness. Agitation helped to break down liquid film and increases heating effectiveness. Any method of further increasing turbulence and reducing the film layer more quickly and uniformly would be an improvement. Liquid particles are in violent motion under ultrasonic vibration and should give rapid heating. More energy can be put into the liquid by ultrasonics than by agitation while keeping the solution in the vat.

In consideration of these factors, a hypothesis is developed wherein it is proposed that there will be 1) a decrease in the time of heating, 2) a uniform heating by ultrasonics, or 3) an increase in the rate of heat transfer.

REVIEW OF LITERATURE

Agitation by ultrasonic means is well known in certain fields, especially in the chemical field. High frequencies are more readily absorbed in the agitated systems (22). The field of ultrasonic agitation is one of the most promising.

Ultrasonic waves have been found to cause pressure so large that the resulting mechanical stresses may be as much as 15,000 times the hydrostatic pressure. In agitation there is very little liquid to penetrate and therefore little absorption. At the inter-face between the liquid and air the waves fly the liquid up into the air in the form of fine drops.

Emulsification by ultrasonic waves was first described by Wood and Loomis (21). However they dealt principally with qualitative observations of the phenomena and reported little concerning qualitative values of optimum frequency, minimum energy requirements, physical conditions for efficient irradiation. W. T. Richards (21) has investigated such actions and it has been shown that the mixing is strongest at the boundaries of the system, i.e., between the walls of the container and liquid and also between the liquid and vibrating system.

Paulsen (24) noticed heating as well as cavitation by ultrasonics. Lord Rayleigh originally pointed out that when a liquid is undergoing ultrasonic irradiation, a strong hissing noise should be heard. W. R. Wood and Loomis (23) showed the

amount of power being impressed on a liquid bath can be measured calorimetrically or electrically by noting the power dissipated in the driving oscillator. The amount of energy needed to give the measured rise in temperature is the actual ultrasonic wattage. The larger the body of liquid the greater the amount of total heat absorbed in it, although the temperature rise may be greater in smaller amounts of material.

Methods of measuring ultrasonic energy are

1. Calorimetric method - mostly used in oil bath
2. Electric method
3. Glass disc method
4. Suspending balance method
5. Echo method - pulse system

According to Wood the increase in temperature may reach a point where it increases a degree every few seconds. Ordinarily, the center of oil exhibits the greatest amount of heat, and small bubbles of gas form this point.

Loss of Energy in Ultrasonics

The dissipation of energy in an ultrasonic system is primarily due to the viscosity and damping of the liquid. The greatest amount of energy is commonly produced in ultrasonics by the systems which are designed for agitation. Freundlich H. K. Saller (21), obtained about 300 watts in such a system, using transducer 60-70 cm. across their faces.

Most of the ultrasonic energy measurements are made by noting the rise in temperature in the medium. A number of investigators have reported obtaining energy of 10 watts per sq. cm. (22, 26).

Ultrasonic Output

Sokolove (24) stated that the ultrasonic output is proportional to the square of amplitude of oscillation and to the cross-sectional area of the crystal. The larger the plate the more easily it is destroyed by excessive vibration because of its more homogeneous nature. Limitation to the output is set by the point at which the crystal ruptures. Polished faces and square edges give maximum output of ultrasonic energy.

Almost instantaneous film elimination with marked improvement in quenching effectiveness, was the claim of Richard F. Harvey (26), Massachusetts metallurgist, who had used high frequency sound at high intensity for agitation. This method resulted in a greater uniform cooling. The range of vibration frequencies was wide from 100 kilocycles to 5 megacycles per second. Minimum power requirement was about 25 watts per square inch of metal surface being quenched.

Ultrasonic Velocities in Liquids and Gases

Only longitudinal waves can be transmitted in liquids and gases. In such cases it is usually assumed that the

vibrations take place too rapidly for heat to exchange. The velocity either in liquids or gases is then

$$C = \sqrt{\frac{K}{\rho B_{is}}} = \sqrt{\frac{1}{\rho B_{ad}}}$$

$K = \text{ratio of specific heats,} \quad \rho = \text{lb/cu. ft.}$

B_{is} = compressibility at constant temperature

B_{ad} = adiabatic compressibility

Measurement of velocities is made in liquids in order to get an idea of their chemical and physical characteristics.

Ultrasonic velocity in liquids is the function of temperature and pressure, and some methods of measuring ultrasonic velocities are as follows:

- 1) Interferometer is used for both liquids and gases, and
- 2) Pulse method has been more recently applied, and the time of travel of a pulse is measured.

Frequency and Wave Length

The usual relation among frequency, velocity, and wavelength holds for ultrasonic waves. They are related as

$$\lambda = \frac{c}{f}$$

λ = wavelength, meter

c = velocity, meter/sec.

f = frequency, cycles/sec.

THEORETICAL PRINCIPLES

The basic principles upon which this study is based is the rapid removal of surface film which normally acts as a resistance to heat transfer. The overall conductivity of the heat-transfer wall is greatly affected by the conductivity of the surface film of the heating fluids. In a tin-walled apparatus such as pastuerizer, the actual heat transfer of stainless-steel vat is almost equal to that of tinned copper vat, even though the conductivity of copper is 9 to 10 times that of stainless steel. The conductivity can be greatly increased if the liquid film is removed rapidly. Viscous products heat or cool much slower in heating or cooling tank.

In studying these problems it has been shown that when a liquid is in contact with a solid wall, there is a relatively stationery film or fluid adhering on the surface of the solid. The film thickness is decreased as the liquid is agitated and moved away from the solid wall. Heat is transmitted only by conduction through this film, although as soon as heat penetrates the film, the heated portion is picked up and moved into the main body of the fluid.

TEST I

Procedure

The apparatus was set up as shown in Figure 1. The transducer used was 1000 kilocycle frequency and was fixed in a steel holder. Coaxial wire was connected to the transducer as shown in Figure 1. A tinned copper tube which served as a water container, was fixed on the steel holder.

In the beginning a few tests were made to determine the resonant frequency of the transducer. Then water heater was calibrated for $\frac{1}{4}$ to 12 watts of power. The heater was immersed in water to $\frac{1}{4}$ inch from the transducer. Four thermocouples were placed at various depths to measure the temperature of water. One thermocouple (t1) was on the heater surface, the second (t2) was in between the heater surface and inside surface of the tube, (t3) was on the inside surface of the tube, and (t4) was on the outside surface of the tube. All these thermocouples were at a distance of $\frac{1}{4}$ in. above the transducer. The temperatures at various depths were recorded by means of a previously calibrated potentiometer.

The input power of the heater was adjusted by means of variac and input ultrasonic energy was adjusted by means of variac which was on the generator. Tests were made to determine the rate of heat gain and transfer by ultrasonics only by

noting the rise in temperature of water at regular intervals. Ultrasonic energy was used with a 15 to 100 ma of generator input. Output ultrasonic energy was measured by calorimetric and electric methods. The combination of heater and ultrasonic energy was used to determine the rate of heat transfer.

In all of these trials the initial temperature of water was 84° F. and the amount of water was the same for procedure Tests I and II. Tests were run until steady state was reached. The maximum temperature of water was below 172° F. Room temperature was between 80-85° F. Variables studied in these trials were output of ultrasonic energy, power of heater watts, and temperature of water.

Apparatus

The apparatus shown in Figure 1 was used for Tests I and II. It consisted of ultrasonic generator (B), transducer assembly (A), in which the liquid was agitated with 400 and 1000 kilocycles/sec. The actual amount of ultrasonic energy was measured by calorimetric method. Thermocouples t1, t2, t3, and t4 were placed to measure the temperatures at various positions. Electric immersion pyrex brand glass sheath water heater (C) was used to heat the liquid; tinned copper tube was used as a water container; potentiometer (D) was used to measure the temperature of thermocouples. Variac (E) was used to change the voltage from 110 volts to desired voltage, i.e.

10-20 volts. Ammeter (F) was used to measure the current passing through the water heater. From knowing the current and the applied voltage to the water heater power input by the heater was calculated. Milliammeter on the generator indicates the current strength of the ultrasonic energy to the transducer. Since the physical dimensions of the barium titanate transducer element determines the ultrasonic frequency it is necessary to tune the generator output frequency to match the natural frequency of the transducer. This was done with dial (G). The output current of the generator was adjusted with the dial (I). The ultrasonic energy was transmitted from the generator to the transducer through the coaxial cable (J). The output of the generator through the water sample was also reported through milliammeters. The output current of the generator was reported here in milliamperes. Milliammeter is provided from 0 to 300 ma. This reads the cathode current of the oscillator. In Figure 2 a more detailed view of the transducer assembly is shown. Barium titanate, (A), crystal holder, steel base (B), leads connecting to the coaxial cable (C), insulation which is around the crystal (D).

The generator and the transducers have the following specifications:

Generator:

Model - Bu 204

Mfg. by Brush Electronic Company, Cleveland, Ohio

Power input = 115 volts, 6.5 amps., 660 watts, 60
cycles, single phase, A.C.

Output frequency = tuning drawer (B), 300 to 1000 kc.

Generator circuit = self-excited Hartley oscillator.

Transducers (disc):

Model = 55304B and 55305B

Mfg. by Brush Electronics Company, Cleveland, Ohio

Type of element - barium titanate ceramic B, elements
disc type.

Resonance frequency = 998 kc and 400 kc.

Element thickness = .10 in. and .27 in.

2.5 mm. 6.75 mm.

Area of transducer = .785 sq. in. and .785 sq. in.

including insulation.

.628 sq. in. without insulation.

Wave length at resonance frequency =

water = 100 kc 400 kc

.06 in. .15 in.

gas = .0014 in. .068 in.

steel = .234 in. .58 in.

Transducer (tube):

Model - 55347B

Mfg. by Brush Electronics Company

Type of element - barium titanate ceramic B

Resonance frequency = 630 kc.

Thickness = .125 in. or 3.125 mm.

Inside area = 5.88 sq. cm.

Wave length at 640 kilocycles - 1.0 in.

Tube specifications:

Material - tinned copper

Weight of tube: 387.6 gm.

Specific heat of tube: .093 BTU/deg. F. per lb.

Emmissivity of tube: .28

Outside diameter = 1.5 in.

Inside diameter = 1.37 in.

Length of tube = 7 in.

Outside area of tube = 33 sq. in.

Inside area of tube = 30.1 sq. in.

The following equation is used to find the amount of heat transferred to water:

$$Q = (\Delta t) (wt.) (Sp. H)$$

Q = heat transferred BTU/hr.

Δt = mean temperature difference, deg. F.

wt = weight of water in pounds

Sp. H. = specific heat of material, BTU/lb. deg. F.

$$Q = (15) \frac{(118.4)}{453.6} (.998)$$

$$= 3.9 \text{ BTU/hr.}$$

Amount of heat energy input by heater was measured by watt-meter.

$$\text{watts} = E I \cos \theta$$

E = applied volts

I = current amps

Θ = phase angle

Ultrasonic energy was measured by calorimetric method and electric method.

Calorimetric method:

Heat given out by ultrasonic was used to raise the temperature of water and the container.

Heat lost = (heat gained by water + heat gained by container)

Heat gained by water

$$\begin{aligned} Q &= \Delta t \text{ (wt) (Sp. H.)} \\ &= 10 \times \frac{134.4}{453.6} \times \frac{.998}{1} \times \frac{60}{15} \\ &= 11.8 \text{ BTU/hr.} \end{aligned}$$

Heat gained by the tube

$$\begin{aligned} Q &= \Delta t \text{ (wt.) (Sp. H.)} \\ &= 10 \times \frac{389.6}{453.6} \times .093 \times \frac{60}{15} \\ &= .31 \text{ BTU/hr.} \end{aligned}$$

Electric method:

$$\begin{aligned} \text{watts} &= \text{volts} \times \text{amps} \times \cos \Theta \\ &= 38 \times .078 \times .9 \times 4.316 \\ &= 10.08 \text{ BTU/hr.} \end{aligned}$$

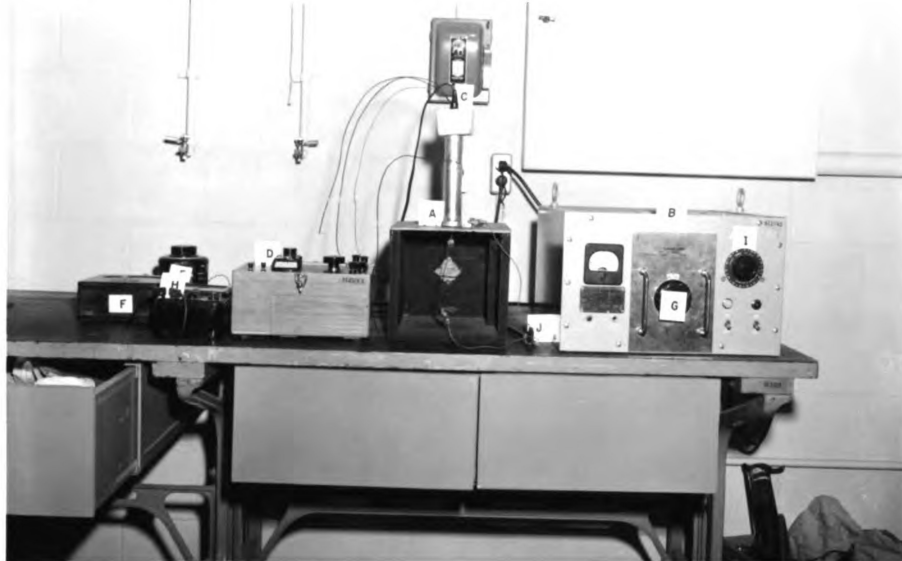


Fig. 1. Principal apparatus used for procedure I and II.



Fig. 2. Transducer assembly for procedure I and II.

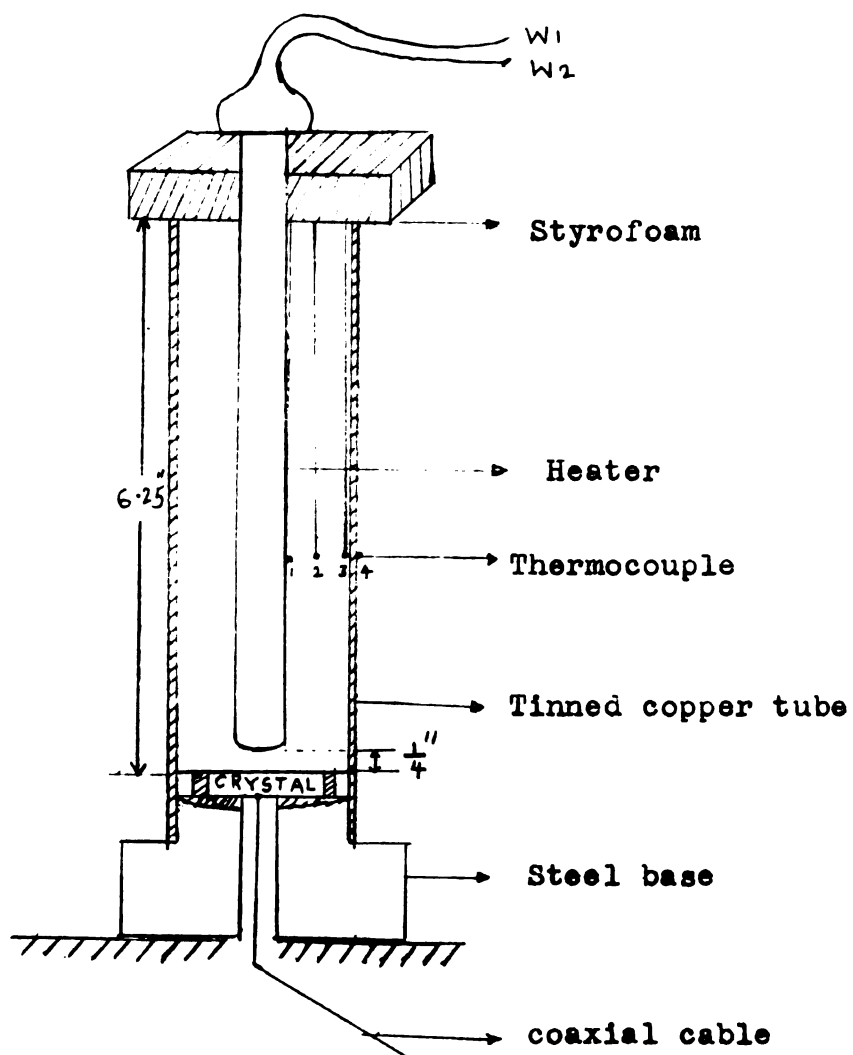


Fig. 3. Section through transducer and tube showing agitation arrangement for procedure I and II.

TABLE I
HEATER ELEMENT PERFORMANCE

Watts	Maximum Temperature (°F)	Time to Reach Maximum Temperature (minutes)
4	106.5	120
5	110.5	110
6	115.5	120
7	121.0	110
8	126.0	130
9	130.0	120
10	133.0	130
11	137.0	120
12	140.0	120

TABLE II
ULTRASONIC WAVE LENGTH IN WATER

Frequency	Wave Length
100 kilocycles	1.43 cm
200 "	.725 "
500 "	.286 "
600 "	.241 "
700 "	.204 "
1000 "	.143

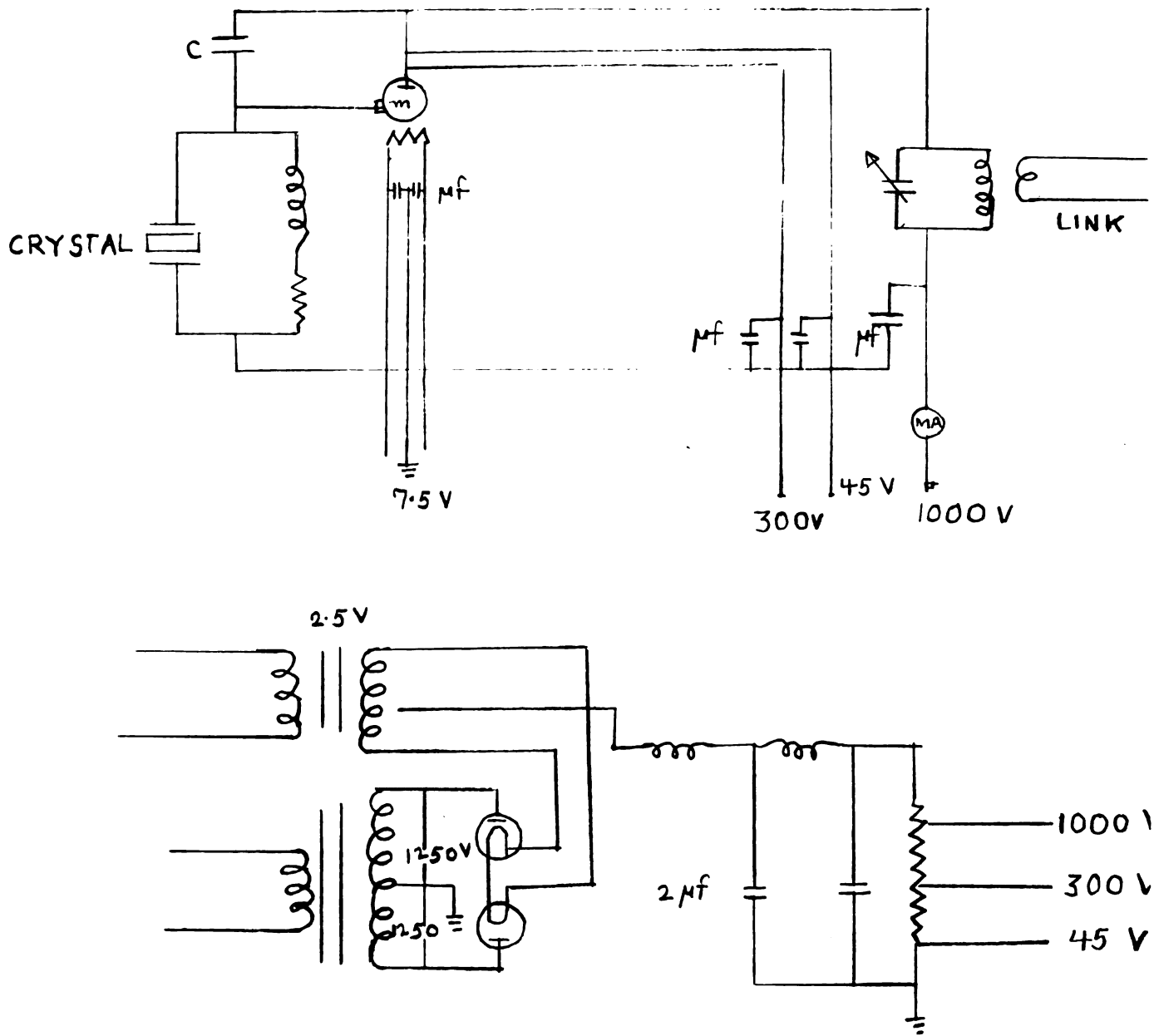


Fig. 4. Oscillator circuit.

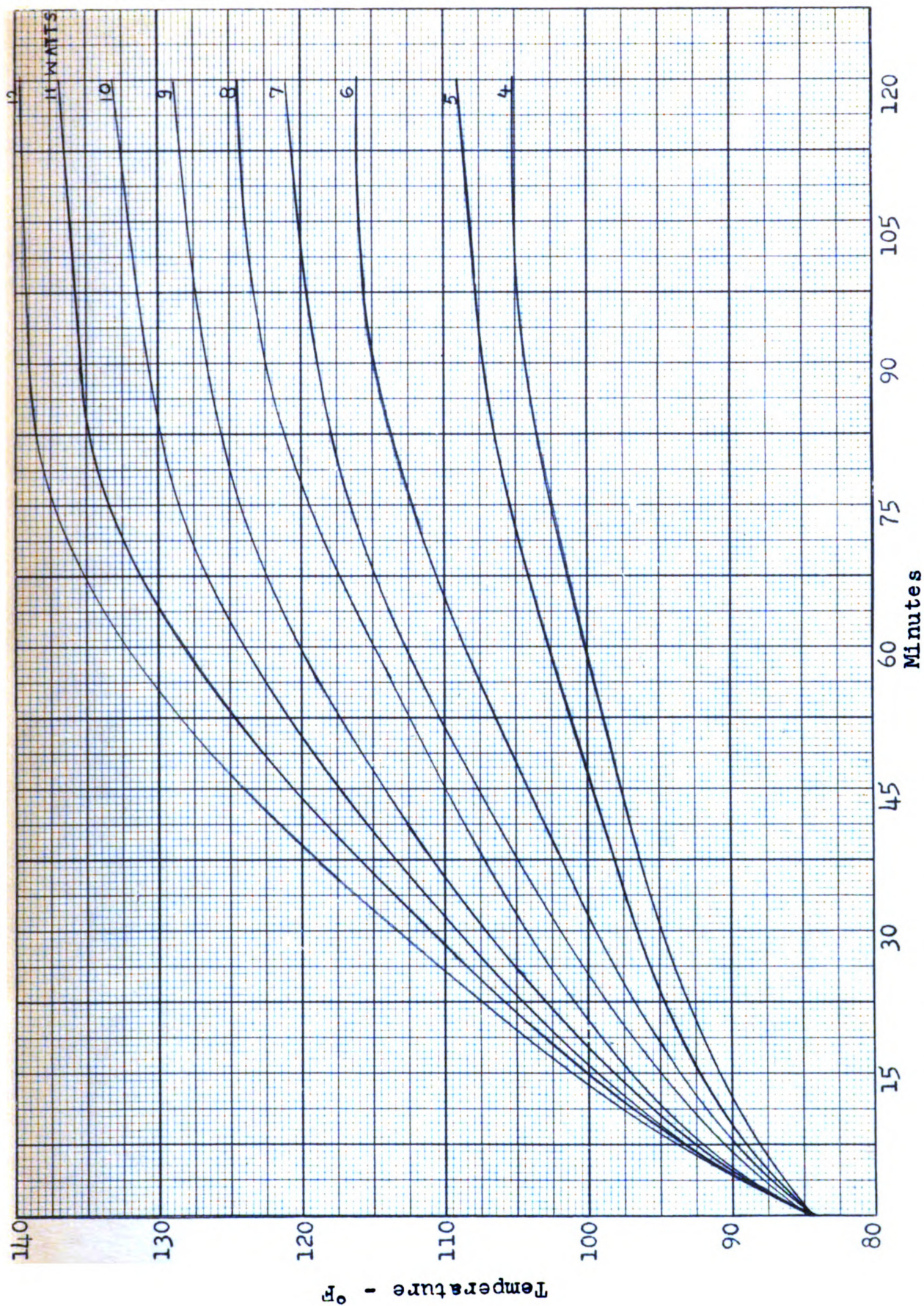


Fig. 5. Time temperature curves for different watts of heater element.

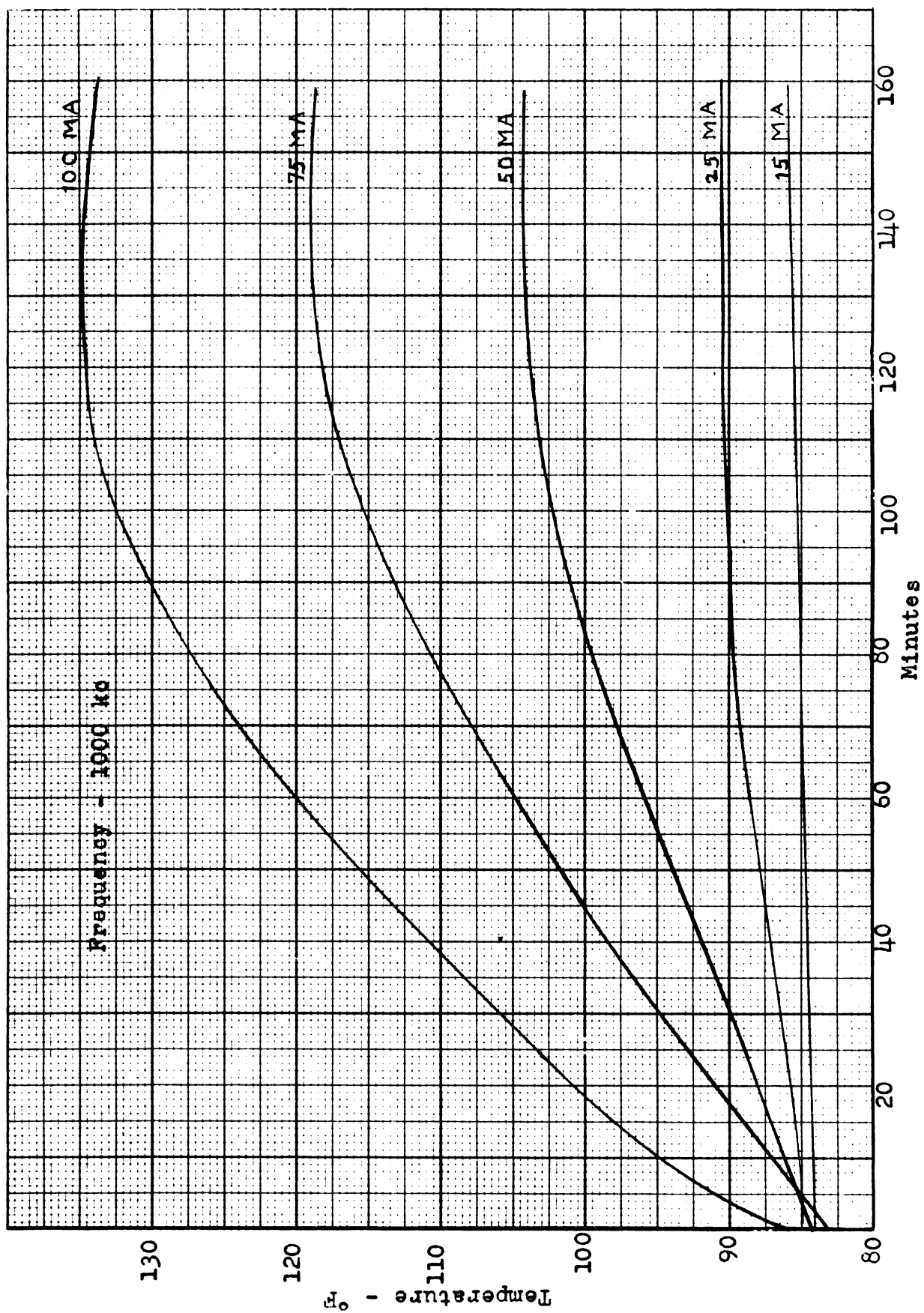


Fig. 6. Time temperature curves for ultrasonic energy only.

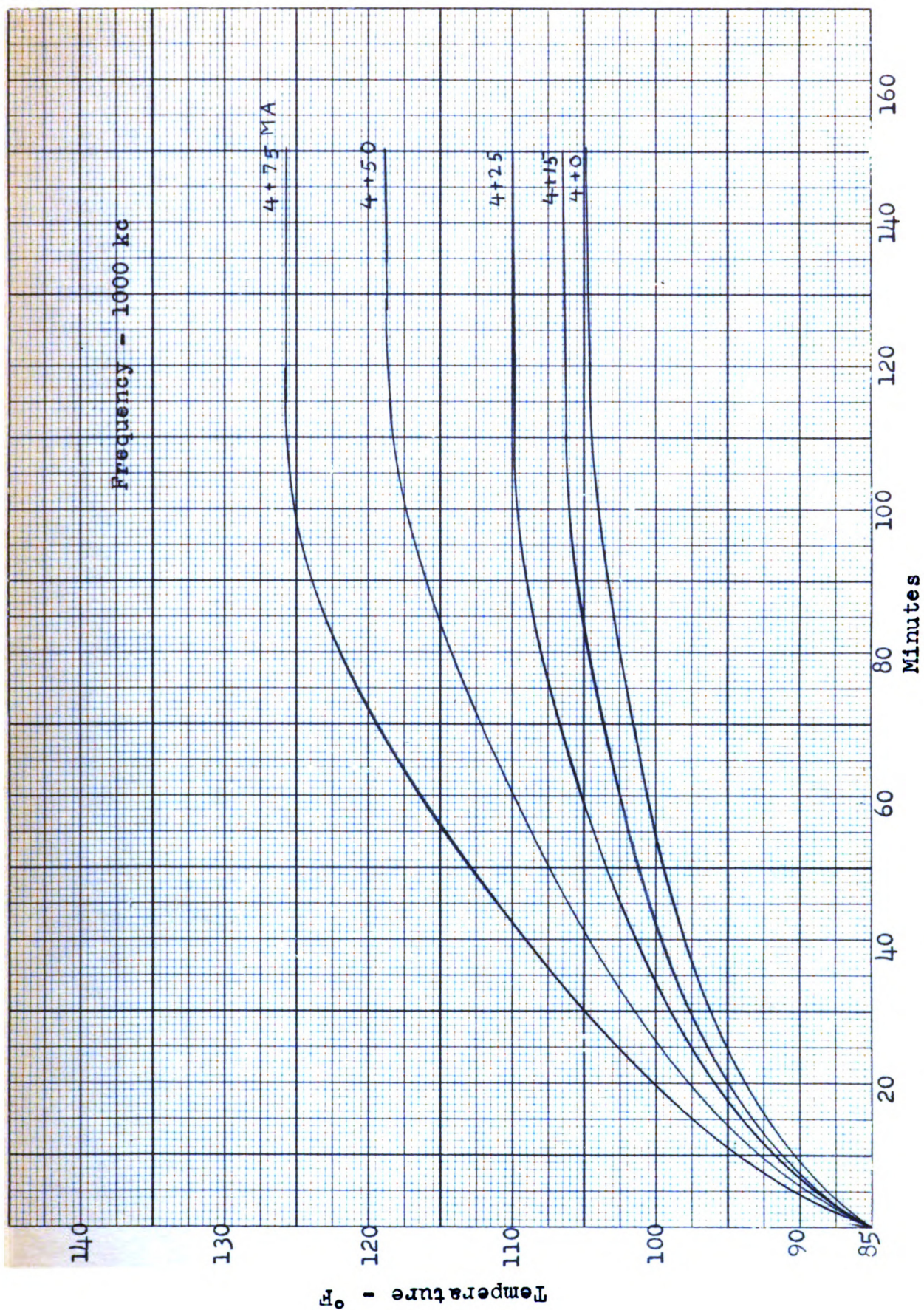


Fig. 7. Time temperature curves for 4 heater watts and 0-75 ma ultrasonic energy.

TABLE III
MEAN TEMPERATURE DIFFERENCE AT THE OUTSIDE
SURFACE OF THE TUBE

Time (min.)	Heater (watts)	0 ma*	15 ma	25 ma	50 ma	75 ma	100 ma
20	0	0	1	4	11.0	20.0	34
80	0	0	0.75	2.5	10.0	16.0	19
120	0	0	0.5	1.0	5.5	6.5	2.0
20	4	17.0	19.0	20.0	25.0	39.0	--
80	4	5.0	6.0	7.0	11.0	19.0	--
120	4	1.5	1.5	0.5	2.0	.5	
20	6	26.0	32.0	35.0	37.0	40.0	--
80	6	8.0	8.0	9.0	17.0	--	--
120	6	2.0	1.0	1.0	1.0	--	--
20	8	33.0	34.0	36.0	37.0	45.0	--
80	8	11.0	13.0	13.0	15.0	28.0	--
120	8	3.5	1.0	.50	1.5	.75	--
20	10	36.0	--	43.0	45.0	--	--
80	10	15.0	--	16.0	26.0	--	--
120	10	5.0	5.0	6.0	11.5	.75	--

* ma - milliamps

TABLE IV
RATE OF HEAT TRANSFER AT 1000 KILOCYCLES
BTU/hr

Time (min.)	Heater (watts)	0 ma	15 ma	25 ma	50 ma	75 ma	100 ma
20	0	0	0.261	1.04	2.87	5.00	6.82
80	0	0	0.196	0.65	2.61	4.16	4.95
120	0	0	0.131	0.261	1.44	1.70	0.52
20	4	4.4	4.95	5.21	6.52	7.4	--
80	4	1.31	1.57	1.86	2.87	4.95	--
120	4	0.39	0.39	.139	.531	.131	--
20	6	6.8	8.35	9.14	9.65	10.4	--
80	6	2.4	2.4	2.34	4.44	--	--
120	6	0.522	.261	.261	.261	--	--
20	8	8.6	8.86	9.4	9.65	11.72	--
80	8	2.862	3.39	3.39	3.91	7.30	--
120	8	.915	.261	.131	0.39	.21	--
20	10	9.4	10.2	11.2	11.7	--	--
80	10	3.9	4.16	6.80	--	--	--
120	10	1.31	1.31	1.56	3.0	--	--

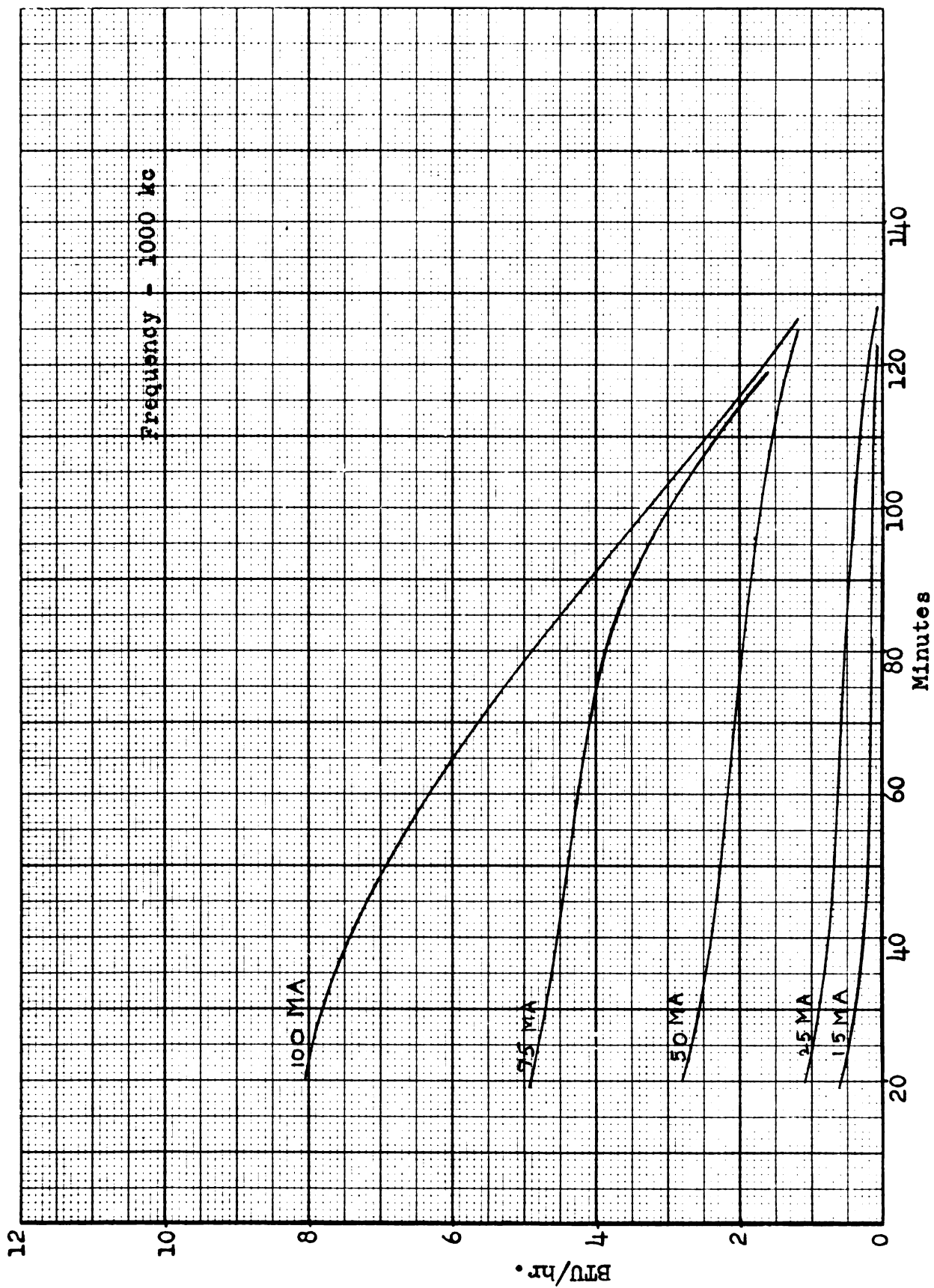


Fig. 8. Rate of heat transfer by ultrasonic energy only.

TABLE V
SAVING OF HEAT ENERGY BY ULTRASONICS

Ultrasonic Energy (milliamps)	Heater Energy (watts)	Maximum Temperature Reached by Heater + Ultrasonics (°F.)	Time to Reach Max. Temperature by Heater + Ultrasonics (minutes)	Watts Required To Reach Temperature in Column 3	Time to Reach Temperature in Column 5 (minutes)	Ultrasonic Energy (watts)	Saving of Energy (watts) 5-(2+7)
1	2	3	4	5	6	7	8
0	4	106.0	120	4.0	120	0.0	0.0
15	"	107.5	110	4.4	120	0.07	0.33
25	"	109	110	5.0	110	0.15	0.85
50	"	121.5	110	7.05	120	1.65	1.35
75	"	126	120	8.0	120	3.18	0.82
0	6	112.5	110	6.0	100	0.0	0.0
15	"	115.0	90	6.25	120	0.07	0.18
25	"	120.0	120	7.0	110	0.15	0.85
50	"	129.0	120	8.0	110	1.65	0.35
75	"	150.0	120	10.0	130	3.18	0.82
0	8	124	110	180.0	120	0.0	0.0
15	"	127.5	110	8.44	120	0.07	0.37
25	"	130	110	8.75	150	0.15	0.60
50	"	138	100	9.75	150	1.65	0.30
75	"	152	110	12.0	150	3.18	0.82
0	10	134	135	10	135	0.0	0.0
15	"	135.5	130	10.25	140	0.07	0.18
25	"	137.5	120	10.50	110	0.15	0.35
50	"	155	130	12.5	130	1.65	0.85

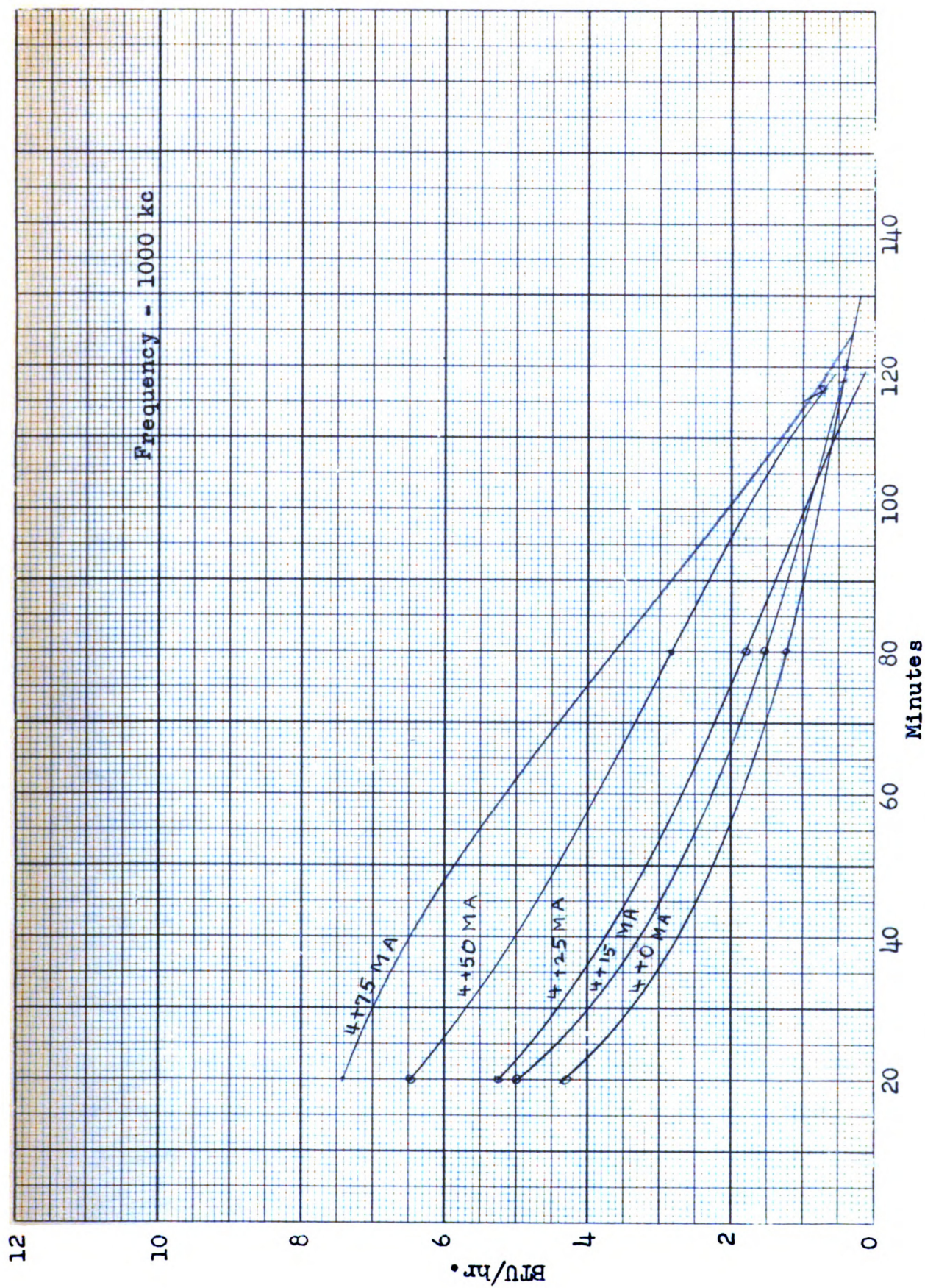


Fig. 9. Rate of heat transfer at 4 heater watts plus ultrasonic energy, 0-75 ma.

Results

It appears from Figure 5 that the increase in temperature is proportional to the input power of the water heater. The rate of increase in temperature is higher in the beginning of the trial and gradually decreases with the increase in time of the trial. The tube comes to steady state after 110 to 120 minutes. At higher heater power the time for rapid increase in temperature is longer as compared to low power of the heater. Figure 6 shows ultrasonic energy increases the temperature of the tank. The increase in temperature at 15 milliamp output is negligible. As the output of ultrasonic energy was increased, the increase in temperature was increased. The rate of increase in temperature was much faster at higher output of ultrasonic energy. The proportion of increase in temperature is proportionately higher at higher output of ultrasonic energy. The time to come to steady state was less for 50 ma of ultrasonic energy than 25 and 100 ma. The time for the tube to come to steady state was slightly less with the trial of ultrasonic energy than with the trial without ultrasonic energy. The rate of heat transfer was higher at 20 minutes time than 80 and 120 minutes. This rate was decreased with increased time length of the trial. The rate of heat transfer increased with increased ultrasonic energy and with the increased power of the heater up to a certain limit. The combination of ultrasonics and heater has shown

higher rate of heat transfer than the sum of the individuals. Figure 7 shows the combination of heater and ultrasonic energy appears more effective at 50 ma ultrasonic energy output. It is clear that the change in temperature at 4 watts plus 50 ma was much more than higher watts plus 50 ma. The temperature difference was 22° F as compared with 16° F in ultrasonic energy only for the same heater power, though the more heat was given out by convection at higher temperature.

Table V shows the amount of heat transferred in various trials. From column six it appears that more heat energy was transferred in the combination of 4 watts and 50 ma. It appeared 50 ma might be critical ultrasonic energy for 1000 kilocycle frequency.

Conclusions

In conclusion it is believed that

- 1) Most of the tests required 110 to 120 minutes to come to the steady state. Tests with ultrasonic energy came to steady state 8 to 10 percent earlier than only heater watts. Output ultrasonic energy was not proportional to the input power of the generator.

- 2) Lower heater watts and 50 ma ultrasonic energy gave best advantage. The wattage combination of heater and ultrasonic 5.65 watts, which gave the same heating effect of 7 watts of heater alone. The above combination of heater and ultrasonics was for 118.4 gm. cc's of water. The optimum combination for

this quantity of water was obtained with ultrasonics of 72 cc per watt and for heater, 30 cc per watt.

3) Lower heater watts of 4 and 50 ma ultrasonic energy gave best advantage. Low ultrasonic energy of 15 ma had negligible effect on the rate of heat transfer. In ultrasonic field, uniform heating was observed. Temperature drop on the heater surface was 15 degrees F higher in heater tests than with ultrasonic tests for 4 watts and 50 ma.

TEST II

Procedure

The apparatus used was the same as was used in procedure I except a transducer with a frequency of 400 kilocycles having .27 in. thickness. The outside diameter of transducer was 1.5 in. and made of barium titanate. The transducer was mounted as shown in Figure 2. Tests were run to find the effect of ultrasonic energy on the change in temperature of water. It has shown that low ultrasonic energy of below 50 ma has no effect on the temperature rise of water more than two degrees F. Tests were run to find the effect of 50, 75, and 100 ma. ultrasonic energy and they were used in combination with low heater energy.

Results

In these trials 25 and 50 ma of generator output did not show appreciable change in temperature of water. At this frequency ultrasonic energy was not enough to cause rapid agitation. Ultrasonic energy is less concentrated as compared to 1000 kilocycle frequency. In trial of 4 watts of resistance heater and 25 and 50 ma ultrasonic had no advantage over only 4 watts of heater.

The change in temperature by ultrasonic energy was not more than 8 degrees F. at 100 ma generator output. The increase in temperature was 2.5 degrees F. per additional 25 ma ultrasonic energy. The combination of heater watts and ultrasonic energy did not show any better results at 400 kilocycle frequency on the rate of heat transfer. Mean temperature difference was higher at 20 minutes time and gradually decreased with increased length of time. The mean temperature difference at 20 minutes time was almost the same for 50, 75 and 100 ma ultrasonic energy. All of the tests came to steady state after 110 to 120 minutes. Below 50 ma ultrasonic energy had no effect on the rise in temperature of water. The rate of heat transfer was the same in tests of heater, and combination of heater and ultrasonics.

Conclusion

For frequency of 400 kilocycles there was no increase in the rate of heat transfer for using electric resistance heater. Heater power was from 0-10 watts and ultrasonic power for 0 to 100 ma.

At 400 kilocycles the ultrasonic energy may not be enough to cause rapid agitation and to break down the fluid film. Ultrasonic energy raised the temperature of water by 7.8° at 100 ma generator output.

TABLE VI

MEAN TEMPERATURE DIFFERENCE PER HOUR AT THE TUBE SURFACE

Frequency - 400 kc.

Disc transducer

Combination of heater watts and ultrasonic energy

Time (min.)	Heater (watts)	0 ma (°F)	50 ma (°F)	75 ma (°F)	100 ma (°F)
20	0	0	3.5	3.5	3.5
80	0	0	2.5	2	2.5
120	0	0	0.5	1	1
20	4	21	24	24	24
80	4	7.5	5.5	7	12
120	4	1	1	1	3
20	6	25	30	38	36
80	6	15	14.5	13	12
120	6	1.5	2.0	2.5	2.8
20	8	39	39	39	39
80	8	10	10	13	13
120	8	1.5	1.5	2.5	2.5

TABLE VII
RATE OF HEAT TRANSFERRED PER HOUR BY THE TUBE

Time (min.)	Heater (watts)	BTU/hr.			
		0 ma	50 ma	75 ma	100 ma
20	0	0	.91	0.92	.92
80	0	0	.65	.522	.65
120	0	0	.13	.261	.261
20	4	5.45	6.25	6.25	6.25
80	4	1.95	1.43	1.82	3.12
120	4	.261	.261	.261	.783
20	6	6.5	7.8	9.9	9.35
80	6	3.9	3.77	3.38	3.12
120	6	.39	.52	.65	.775
20	8	10.15	10.15	10.15	10.15
80	8	2.61	2.61	3.38	3.38
120	8	.39	.39	.65	.65

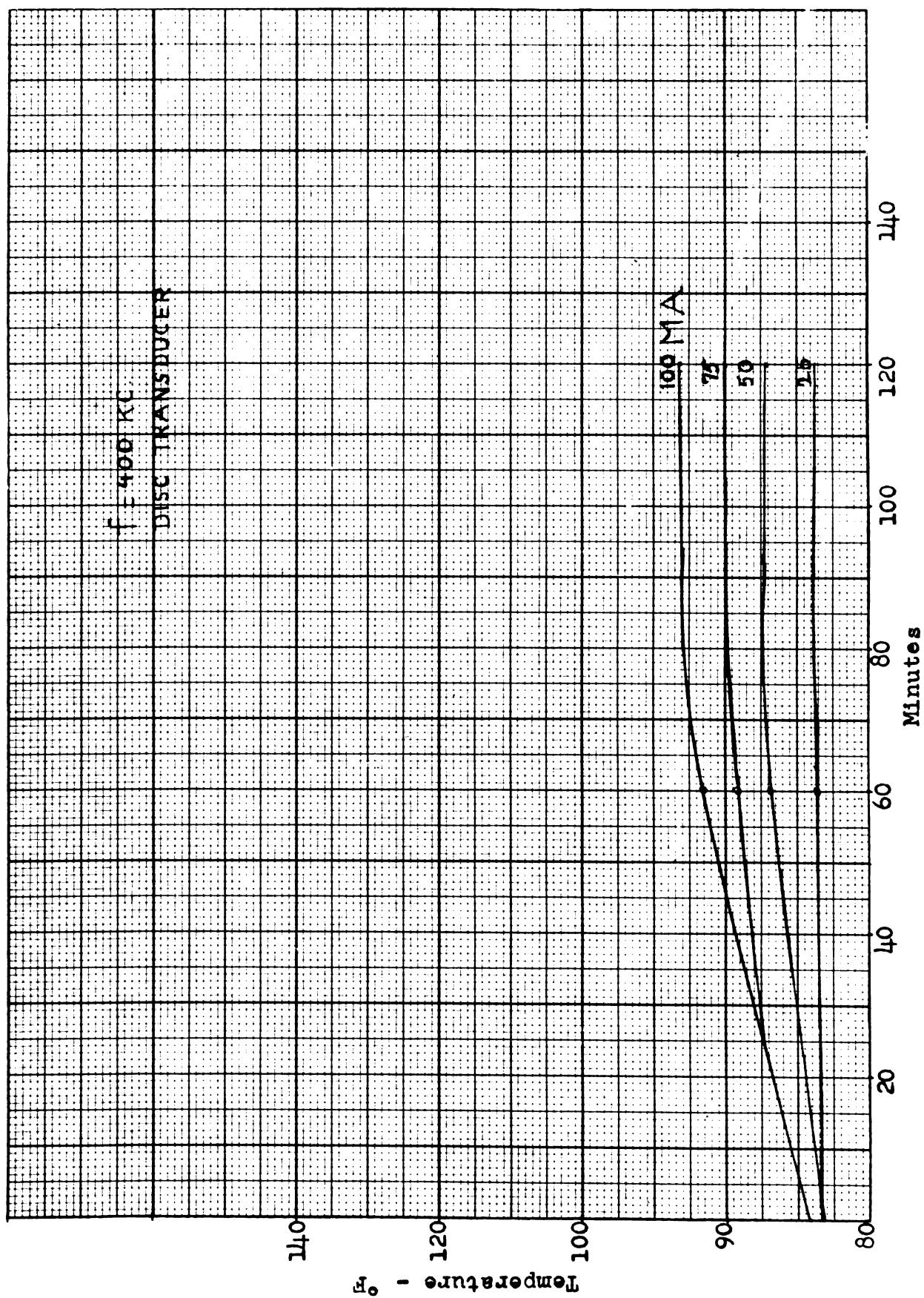


Fig. 10. Time temperature curves for ultrasonic energy.

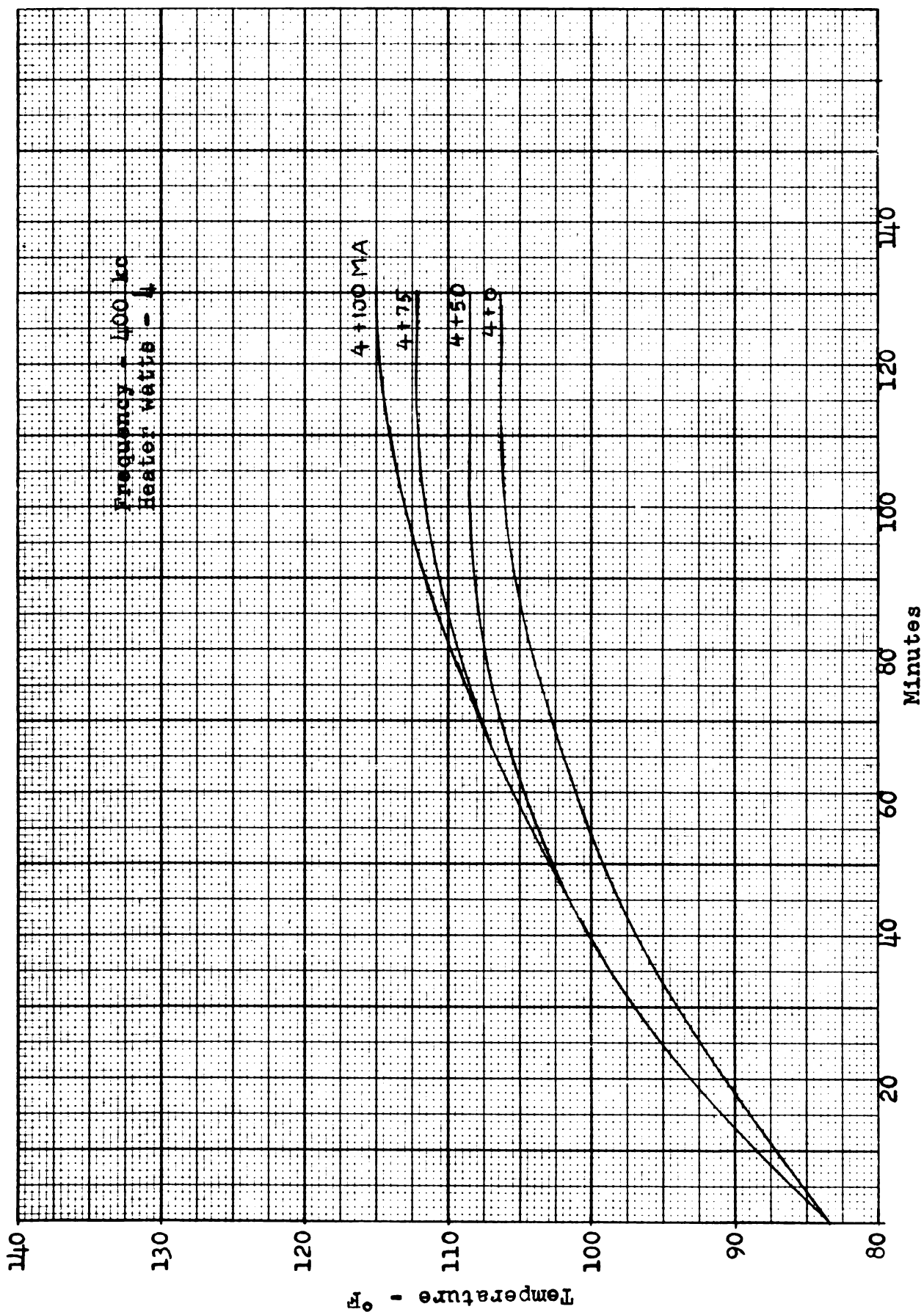


Fig. 11. Time temperature curves for disc transducer.

TEST III

Procedure

From the previous trials it has been shown that lower heater energy had better results from the standpoint of heat transfer so only low heater watts were tried. In these trials the tube transducer was used with a frequency of 630 kilocycles. The basic apparatus was the same as procedure I and II. The apparatus is shown in Figure 12. Amount of water was one-seventh times as compared to the procedure I and II. Thermocouples t1, t2, t3, and t4 were placed at various locations. Thermocouple t1 was on the surface of the heater, t2 was in between the heater surface and the inside surface of tube transducer, t3 was on the inside surface of the transducer, and t4 was on the outside surface of the transducer. The transducer itself was used as a water container and was sealed with waterproof cement on a plastic sheet. Trials were run until they came to steady state. Most of the trials were run from 60 to 80 minutes.

Results

It has been found that all tests came to steady state with cylindrical transducer in less time than with the disc transducers. Tests of ultrasonic energy only came to steady

state earlier than with heater only, or combination of heater and ultrasonics. In this transducer, the output ultrasonic energy was less per unit surface area than the disc transducers. This means the transducer produces low concentrated ultrasonic waves. The energy output by 75 ma was much higher as compared to 50 and 25 ma generator input.

As ultrasonic energy was increased, the time to come to steady state was 5 percent decreased. The temperature difference between t_1 and t_2 was small in trials of ultrasonic energy only, and in combination of heater and ultrasonic energy as compared to heater only trials. This means the temperature drop on the heater surface is more in trials of heater only and less in trials of ultrasonics only and combination trials. The temperature drop between t_3 and t_4 decreased with increased ultrasonic energy only. This temperature difference was much smaller in ultrasonic energy only, as compared to heater and combination trials.

Heat transfer was higher in trials of 75 ma and 4 watts combination. Below this ultrasonic energy was not advantageous. The temperature drop between t_2 and t_3 was negligible with ultrasonic trials and in combination trials. On the other hand the difference was much higher in trials with heater only which indicates uniform heating by ultrasonic waves.

Conclusions

1. The temperature drop on the heater surface was 1.5 degrees F. higher in trials with heater only. This drop decreased as ultrasonic energy increased. Ultrasonic energy was less concentrated with tube transducer as compared to disc transducer energy.

2. Rate of heat transfer was slightly higher at 75 ma generator input than lower inputs. Heating was uniform in trials with ultrasonics only and in combination of heater and ultrasonic trials.

3. The time to come to steady state was 8 to 10 percent less in ultrasonic trials and combination trials, as compared to heater trials. This time was 25 percent less as compared to disc transducer for 4 watts of heater and 50 ma.

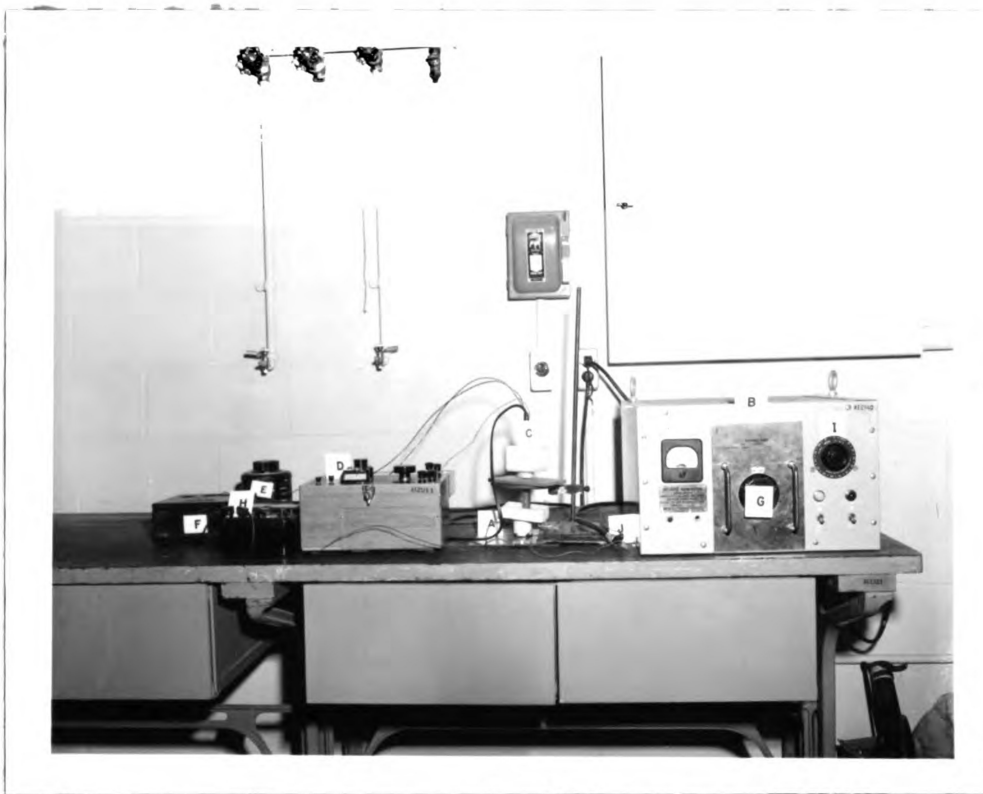


Fig. 12. Principal apparatus used for procedure III.

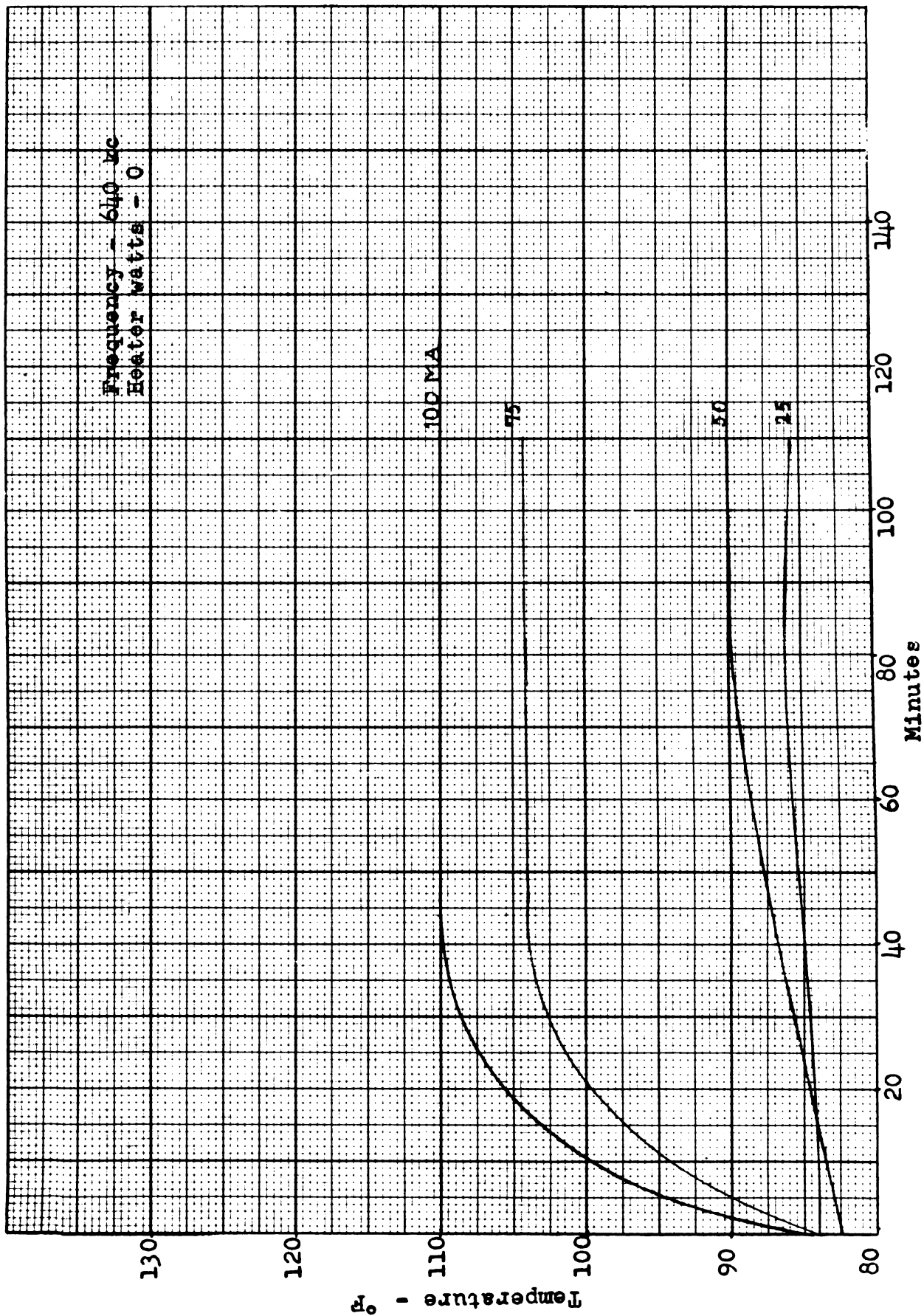


Fig. 13. Time temperature curves for tube transducer (t2).

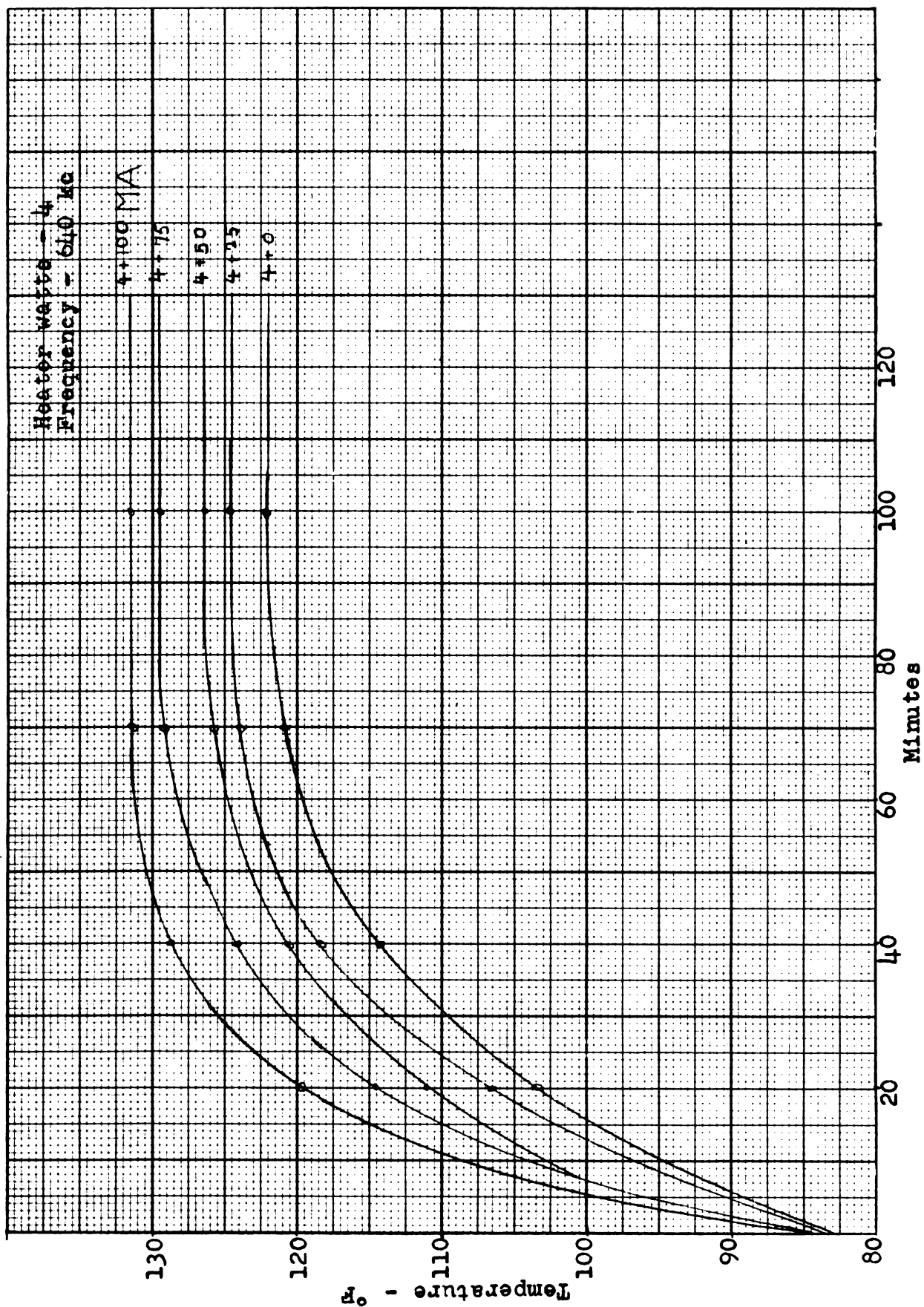


Fig. 14. Time temperature curves for tube transducer.

SUMMARY AND CONCLUSIONS

Summary

The effect of ultrasonics on the rate of heat transfer was studied. The approach consisted of passing ultrasonic energy through water parallel and perpendicular to the liquid film on a heater element. The variables studied were heater power, ultrasonic energy and temperature of water.

A commercially available standard generator was used to obtain the ultrasonic waves. An immersion pyrex glass sheath cylindrical resistance heater was used to heat water. For longitudinal waves, parallel to the film, a disc transducer were used with frequencies of 400 and 1000 kilocycles. For transverse waves perpendicular to the film, a tube transducer having a frequency of 640 kilocycles was used. The amount of heat input by ultrasonics alone was measured by the calorimetric method and the amount of heat produced from the container was calculated. The amount of heat input by the heater was measured by a wattmeter. Several tests were run to calibrate the heater to determine wattage output.

The study was divided into three groups. The first consisted of work done with 1000 kilocycles disc transducer; the second, of work done with 400 kilocycles disc transducer; and the third, of work done with 640 kilocycles tube transducer.

The disc transducer with a frequency of 400 kilocycles had no appreciable effect on the rate of heat transfer. At this frequency ultrasonic energy is low and had no advantage for the transfer of heat.

A disc transducer with a frequency of 1000 kilocycles showed a definite increase on the rate of heat transfer over the tests without ultrasonic energy. The rate of heat transfer is proportionately increased up to a certain limit above which it has no additional advantage. In an ultrasonic field of 50 ma and 4 heater watts, the system comes to a steady state of 120 degrees F. in 8 to 10 percent less time than without the ultrasonic field. The rate of heat transfer was 18.6 percent higher at four heater watts and 50 ma ultrasonic energy, than the sum of the individual effects.

The rate of heat transfer was decreased with increased heater watts and increased ultrasonic energy beyond the above range. Low ultrasonic energy of 15 ma had negligible effect on the rate of heat transfer at all heater wattage from 0 to 10 watts. Low heater power of 4 watts and 50 ma ultrasonic energy was most effective. The ultrasonic energy was 72 cc/watt at 50 ma and 30 cc/watt, at 4 heater watts. The ratio of ultrasonic to heater power for optimum rate of heating at this level was 1 to 2.4.

A tube transducer with a frequency of 640 kilocycles was used for a series of tests such that the ultrasonic energy input per unit surface area of transducer was one-

eighth that of disc transducer. In these tests the time required to come to steady state of 120 degrees F was 20 to 25 percent less than that of the disc transducer. The heat transfer was not appreciably higher at 4 watts and 0 to 100 ma ultrasonic energy.

Conclusions

1. The rate of heat transfer is higher with increased ultrasonic frequency. A heater wattage of 4 and ultrasonic energy of 50 ma has maximum advantage. Above 50 ma ultrasonic energy it has no additional advantage in 118 cc water.

2. Due to agitation of liquid by ultrasonic energy there is uniform heating of liquid. With ultrasonics the maximum temperature difference in the water container was 1 to 2 degrees F. as compared to 3 to 4 degrees F. without ultrasonics.

3. Temperature drop in between heater surface and liquid is 2 degrees F. less in ultrasonic field which indicates the reduction in film resistance to heat transfer.

4. With the tube transducer at a frequency of 640 kc, at 25, 50 and 75 ma, the water became heated in 25 percent less time than without ultrasonics with 4, 6 and 8 watt heater power.

SUGGESTIONS FOR FUTURE WORK

From the experience gained in this work, further studies should be undertaken to further develop the relationship between ultrasonic energy and heat transfer.

1. More study is needed with the frequencies above 1000 kc. It was shown that with increased frequency of ultrasonic energy, the rate of heat transfer increases. This work was limited to a maximum frequency of 1000 kc.

2. Determine the effect of applying ultrasonic energy for improving heat transfer for continuous flow of fluid over heater surface.

3. Analyze the relationship of wave length of ultrasonic energy and film thickness of fluid.

4. Additional studies are needed to evaluate the performance of the tube transducer at different frequencies.

5. Further efforts should be directed toward development of devices for measurement of ultrasonic energy.

6. Further consideration should be given to development of the theory involved in using ultrasonic energy to change the film thickness or to change the heat transfer characteristics.

7. After getting sufficient basic data and minimum frequency at which ultrasonic energy will be most advantageous, this principle should be applied to grain drying, seed treatment, and other agricultural processes.

BIBLIOGRAPHY

1. American Institution of Physics. Proceeding as of the Symposium on Temperature, its Measurement and Control in Science. 1939. 13 pp.
2. Bates, O. K., G. Hazzard and G. Palmer. Thermal Conductivity of Liquids, Industrial and Engineering Chemistry. 33 (1941) pp. 375-376.
3. Birth, G., and C. W. Hall. Ultrasonics in Quality Control. Unpublished M. S. special research problem, Michigan State University, 1955, 26 pp.
4. Brown, A. I. Introduction to Heat Transfer. Ed. New York: McGraw-Hill Book Company, 1942, 232 pp.
5. Cardinell, H. A. Refrigerator cans as farm storage. Michigan State College Agricultural Research Experiment Station, Bull. 308, 1941, 11 pp.
6. Corlin, B. Ultrasonics. Ed. New York: McGraw-Hill Book Company, 1949, 270 pp.
7. Clarke, L. N. Methods of Measuring Thermal Conductivity of Poor Conductors. Australian Journal of Applied Sciences. 5 (June, 1954), pp. 178-82.
8. Davis, A. H. Thermal Conductivity of Liquids. Philosophical Magazine and Journal of Science. 47 (1924), pp. 972-76.
9. Farrall, A. W. Dairy Engineering. Ed. 2, New York: John Wiley and Sons, 1952, 405 pp.
10. General Electric Supply Corporation. Wiring Materials and Power Apparatus. Grand Rapids: The Jaqua Company, 1951, pp. 635-36.
11. Harvalik, Z. V. Modified Pitch Thermal Conductivity Apparatus. Research Science Institution. 18 (September, 1947), pp. 1815-17.
12. Hawkins, J. A. Element of Heat Transfer. New York: John Wiley and Sons, 1948, 960 pp.

13. Henderson, S. M., and R. L. Perry. Agricultural Process Engineering. New York: John Wiley and Sons, 1955, pp. 212-17.
14. Jespersen, H. B. Thermal Conductivity of Moist Materials and its Measurements. Industrial Heating and Ventilating Engineers. 21 (August 1953), 8 pp.
15. Kannuluik, W. G., and E. H. Carman. Temperature depends on Thermal Conductivity of Air. Australian Journal of Science Research Series. 4 (September 1951), pp. 304-15.
16. Keyes, F. G. Thermal Conductivity of Gases. American Society of Mechanical Engineers, paper 53 for meeting November 29-December 3, 1953, 8 pp.
17. McAdams, W. H. Heat Transmission. New York: McGraw-Hill Book Company, 1942, pp. 60-87.
18. McLearn, M. G. Rapid Determination of Relative Thermal Conductivity. American Society of Mechanical Engineers. 29 (July 1950), pp. 250-53.
19. Manson, H. L. Thermal Conductivity of Industrial Fluids. American Society of Mechanical Engineers. 76 (July 1954), pp. 817-20.
20. Mischke, C. R., and F. A. Farber. Film Coefficient of Liquids. American Society of Mechanical Engineers. 29 (December 1953), pp. 713-18.
21. Newcomer, J. L. Effects of ultrasonics on milk. Unpublished M. S. thesis, Michigan State University, 1953, 63 pp.
22. Perry, J. H. Chemical Engineering Handbook. Ed. 3, New York: McGraw-Hill Book Company, 1950, pp. 417-18.
23. Richardson, E. G. Ultrasonic Physics. Ed. 1, New York: Elsevier Publishing Company, 1952, 283 pp.
24. Sakiadis, B. C. and J. Coates. Studies of Thermal Conductivity of Liquids. Louisiana University and Agricultural and Mechanical College Engineering Experiment Station Bull. 45 (1954), 13 pp.
25. Sherratt, G. G. A Hot Wire Method for Thermal Conductivities of Gases. Philosophical Magazine and Journal of Science Series. 27 (May 1939), pp. 68-75.

26. Industrial Engineering Chemistry. Technical and Commercial Development, pp. 73A. October 1954.

APPENDIX A

- t1 - temperature of heater surface, degrees F.
- t2 - temperature of water in between heater surface
and inside surface of the tube, degrees F.
- t3 - temperature of inside surface tube, degrees F.
- t4 - temperature of outside surface of tube, degrees F.

Disc Transducer
Frequency - 1000kc

Time (min.)	t1	t2	t3	t4	Time (min.)	t1	t2	t3	t4
<u>4 watts + 0 ma</u>					<u>4 watts + 50 ma</u>				
0	84	84	84	84	0	84.5	84.5	84.5	84.5
15	96	93.2	92.0	80.8	10	96.5	94	93	92
30	102	106	99	95.5	20	103	102	101	97
40	105	103	102	97	30	108.5	106	105	101
50	108	105	104	99	40	112	110	109	105
60	109	107	105	100.4	50	116	115	114	108
70	110	108.5	107.5	102	60	119	117.5	116.5	110.5
80	111.5	109.5	108.5	103	70	121.5	120	119	113
90	112	110	109	104	80	123	121.5	121.8	114.5
100	113	111.2	110	104.8	90	125	124	123	115
110	113.5	112.5	111.5	105	100	126	125	124	116.1
120	114.5	112.5	111.5	105.8	110	127	126	125	117.5
					120	128	127	126	119

<u>4 watts + 15 ma</u>					<u>4 watts + 25 ma</u>				
0	84	84	84	84	0	84	84	84	84
10	91.5	88.5	88.5	87	10	95	93	92	90
20	99	96	95	92.25	20	100.5	99	98	95
30	102	99	98	95	30	104	103	102	97.5
40	104.5	102	100.5	97.5	40	107.6	105.5	104.5	100
50	107	106	105	100	50	110	108	107	102.5
60	109	107	106	101	60	113	111	110	105
70	110	108	107.5	103	70	114	112.4	110.4	106.4
80	111	109	108	104.5	80	116	114	113	107.5
90	"	"	"	"	90	117	115	114	108.4
100	112	110	109	105.5	100	118.0	116	115	108.5
110	112.5	110	109	106	110	119	117	116	109.5
120	113	111	110	107.0	120	119.5	118	117.2	110

<u>4 watts + 75 ma</u>									
0	84.5	84.5	84.5	84.5	60	137.5	136.5	136	125
10	100.5	99	98	96	70	143	142	141	131
20	112	110	109	105.8	80	148	146	145	132
30	121	119	118	112	90	151	149	148	135
40	130	127.5	126.5	120	100	156	154	153	140
50	133.5	132	131	122	110	159	155	154	141

Disc Transducer

Frequency - 400 kc

Time (min.)	t1 F°	t2	t3	t4	Time (min.)	t1 F°	t2	t3	t4
<u>4 watts + 0 ma</u>					<u>4 watts + 50 ma</u>				
0	83	83	83	83	0	83	83	83	83
10	93.0	91.5	90.5	87	10	96	94	92	90
20	97	95	94	90.3	20	99.5	98	97	93
40	104	102	101	96	40	107.5	105.5	104.8	100
60	110	108	107	101	60	113	111.5	111.0	103.0
80	113	111	110	104	80	117	116	115	107
100	115	114.3	113.5	106.5	100	118.5	116.5	107	108
- - - - -									
<u>4 watts + 75 ma</u>					<u>4 watts + 100 ma</u>				
0	83	83	83	83	0	83	83	83	83
10					10	95	93	91.5	89
20	98.5	96.5	95.5	92	20	101	99	98	93.5
40	108	106	105	100.5	40	110	109	108	101
60	114	112	101	105	60	118.5	114	113	105.5
80	118.3	116.3	115.5	109.5	80	121	119.0	118.0	109
100	121	119	118	111.5	100	124	122	121	112
110	122.5	120	119	112.2	120	126	124	123	115
120	122.5	120	119	112.5					

Tube Transducer
Frequency - 640 kc

Time (min.)	t1 F°	t2	t3	t4	Time (min.)	t1 F°	t2	t3	t4
<u>4 watts + 0 ma</u>					<u>4 watts + 25 ma</u>				
0	81	81	81	80	0	84	84	84	81
10	96	95	93.5	86.2	10	100	97.5	99	86.5
20	106.5	105	103.5	94	20	110	107.5	108	95.0
30	114	111.5	110	98.5	35	118	117.5	117	102
40	117	115	113	101	40	120	119	119	105
50	120	118	116.5	103	50	123	120	122	106
60	122	120	119	104	80	126	125	125	109
80	124	122	121	107	90	126	125	125	109

<u>4 watts + 50 ma</u>					<u>4 watts + 75 ma</u>				
0	84	84	84	84	0	83	83	83	83
10	102	104	105	94	10	100	100	100	91
20	110	112	114	100	20	111	108	109	98
40	113	120	122	106	40	118	118	117.5	107
60	120	122	123	108.5	60	123	126.5	123	110
70	122.5	123	124.5	109	75	125	125	125	111.5
80	123	125	125.5	109.5	80	127	128.5	126	113
90	125	127	127.5	110	90	129	129	126.5	114

<u>4 watts + 100 ma</u>									
0	84	84	84	84					
10	110	109	109	103					
20	121	120	120	112					
30	127	126	126	117					
40	131	130	130	120					
50	132	131	131	121					
60	132	132	132	122					

Temperature Difference between t1, t2, t3, t4 and t5
4, 6, 8 and 10 watts heater energy, 0-75 ma, frequency - 1 mc

Time (min.)	t1-t2 I	t2-t3 II	t3-t4 III	Time (min.)	t1-t2 I	t2-t3 II	t3-t4 III
<u>25 ma only</u>				<u>50 ma only</u>			
10	0	0	0	10	0	0	0
20	0	0	0	20	0	0	1
40	0	0	0.5	40	0	0	3
80	0	0	0.5	80	0	0	6
120	0	0.5	0.0	120	0.0	0	4
<u>75 ma only</u>				<u>100 ma only</u>			
10	0	0	.5	10	0	0	3
20	0	0	2.5	20	0	0	8
40	0	0	5.5	40	0	0	7
80	0	0	7.0	80	0	0	11
120	0	0	7.0	120	0	0	9
<u>4 watts only</u>				<u>4 watts + 15 ma</u>			
10	2	2	2	10	2	.5	2
20	3	1.5	3	20	1	1	3.5
40	3	1.5	6	40	2	1	5
80	3	.5	5.5	80	1	1	8
120	3	1	5	120	1	1	8
<u>4 watts + 25 ma</u>				<u>4 watts + 50 ma</u>			
10	2	1	2	10	2	1	4
20	1.5	1	3	20	2	1	3
40	2	1	5.5	40	2	1	4
80	2	1	5	80	2	1	4
120	1.5	1	7	120	2	1	5.2
<u>4 watts + 75 ma</u>				<u>6 watts only</u>			
10	0.5	1	2	10	4	0	2
20	2	1	4.2	20	3.5	1	2.5
40	2.5	1	6.5	40	3.5	1	4.5
80	2	1	12	80	3.5	1.5	6
120	4	1	13	120	3	1	6

Time (min.)	t1-t2 I	t2-t3 II	t3-t4 III	Time (min.)	t1-t2 I	t2-t3 II	t3-t4 III
<u>6 watts + 15 ma</u>				<u>6 watts + 25 ma</u>			
10	3	1	4	10	2	1	3.5
20	3	1	5	20	2	1	4.5
40	3	1	6	40	2	1	6
80	3	1	7.5	80	2.5	1	6.5
120	2	1	7	120	2.5	1/2	8
<u>6 watts + 50 ma</u>				<u>6 watts + 75 ma</u>			
10	2	1	5	10	3	1	2
20	3	1	7	20	2	1/2	3.5
40	3	1	7.5	40	2	1	5
80	3	1	9	80	2	1	4.5
120	2	1	11	120	2	1	15
<u>8 watts only</u>				<u>8 watts + 15 ma</u>			
20	3	1	7	10	3.5	0	7
40	3	1	8	20	3.5	1/2	6.5
80	3	1	10	40	3.5	1/2	7.5
100	4	1	10	80	4	1	8
120	3	1	10	120	3	1	12
<u>8 watts + 25 ma</u>				<u>8 watts + 50 ma</u>			
10	4	1	5	10	4	1	4
20	4	1	9	20	3	1	3
40	4	1	6	40	4	1	7
80	3	1	9	80	3.5	1/2	12
120	3	1	10	120	3.5	1/2	11
<u>10 watts only</u>				<u>10 watts + 25 ma</u>			
10	4	1	10	10	3	1	8
20	4	3	4	20	3	1	7
40	4	1	7	40	3	1	15
80	4	1	7	80	2	1	19
120	3	1	11	120	2	1	20

Time (min.)	t1-t2 I	t2-t3 II	t3-t4 III
----------------	------------	-------------	--------------

10 watts + 50 ma

10	2	1	6
20	2	1	10
40	2	1	9
80	2	1	14.5
120	2	1/2	12.5

Specific Heat of Water at Various Temperatures

°F	Sp. Heat in BTU/lb-°F
50	1.002
60	1.000
70	.998
80	.998
90	.998
100	.997
110	.997
120	.997
130	.980
140	.980
150	.999
160	1.000
170	1.001
180	1.002
190	1.003
200	1.004

APPENDIX B

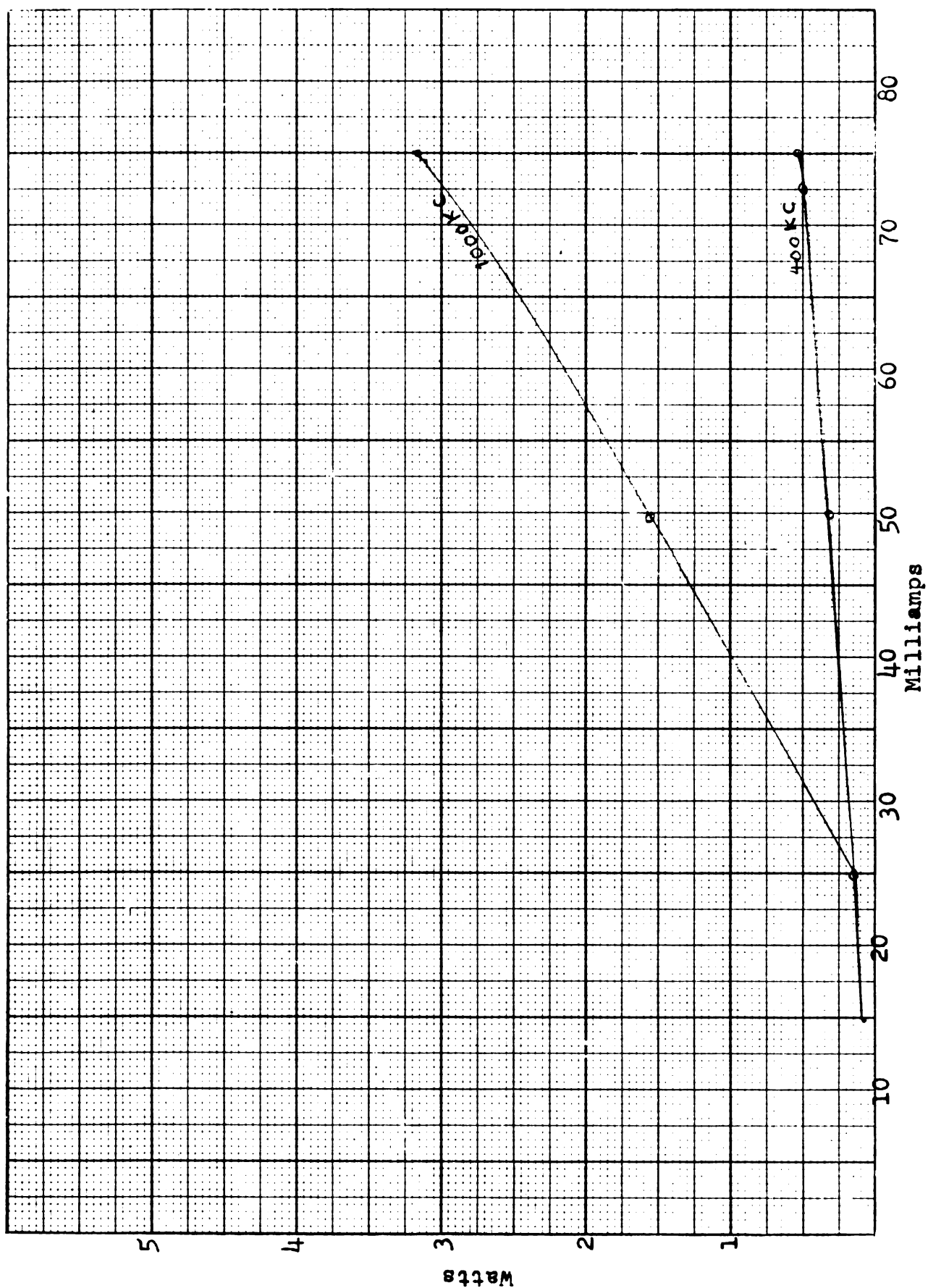


Fig. B-1. Ultrasonic energy at different milliamperes.

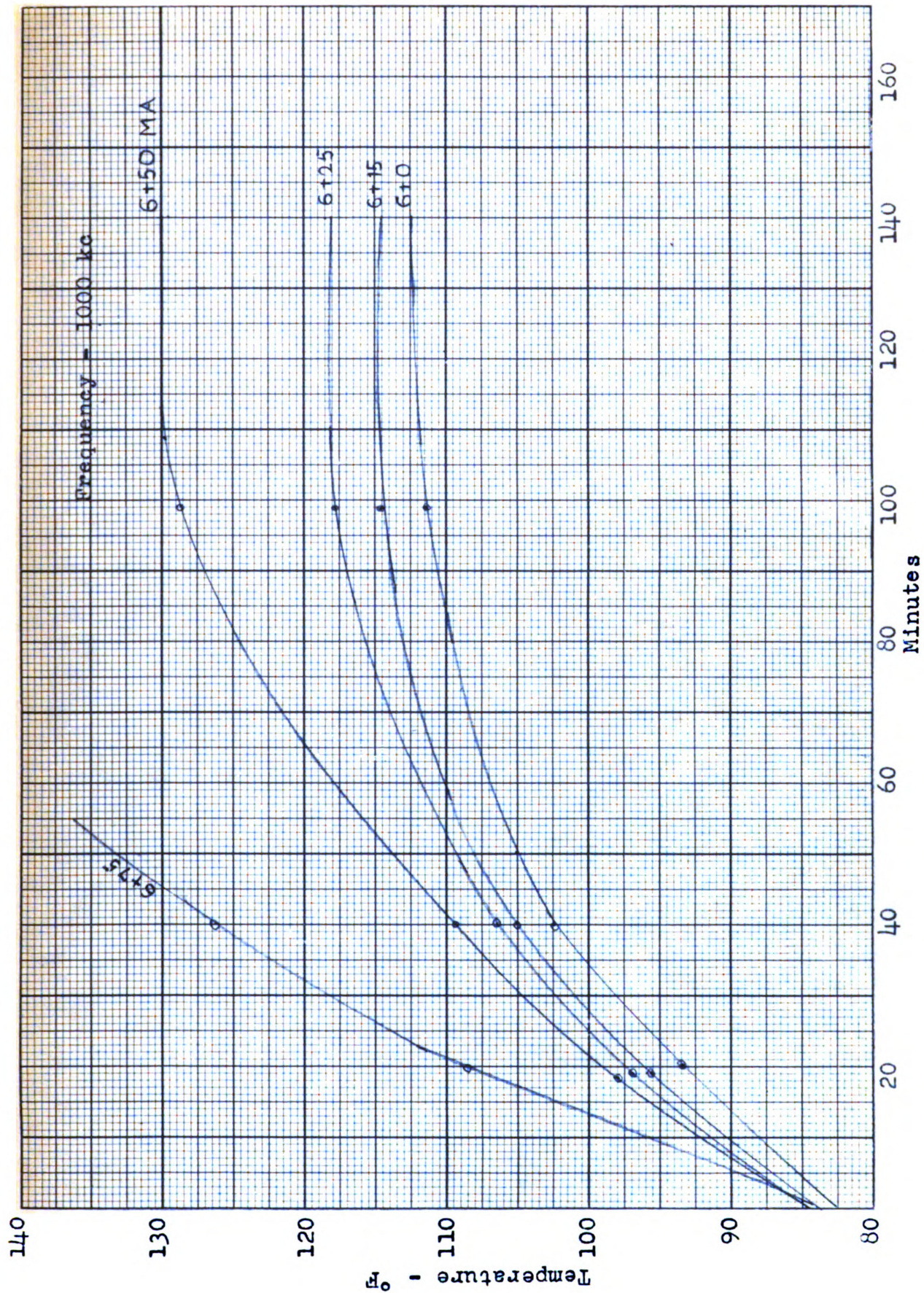


Fig. B-2. Time temperature curves for 6 watts and 0.75 ma ultrasonic energy.

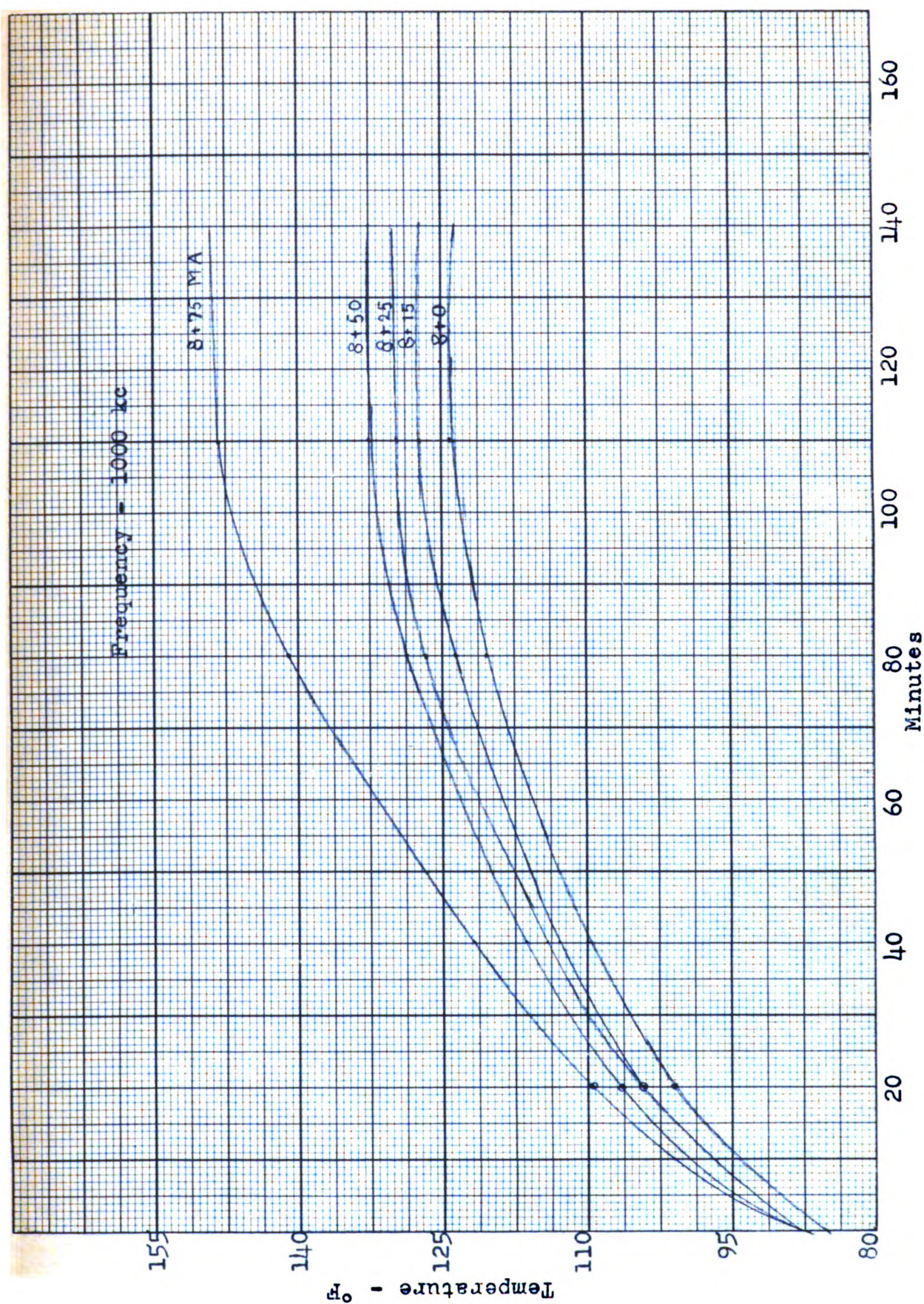


Fig. B-3. Time temperature curves for 8 watts and 0-75 ma ultrasonic energy.

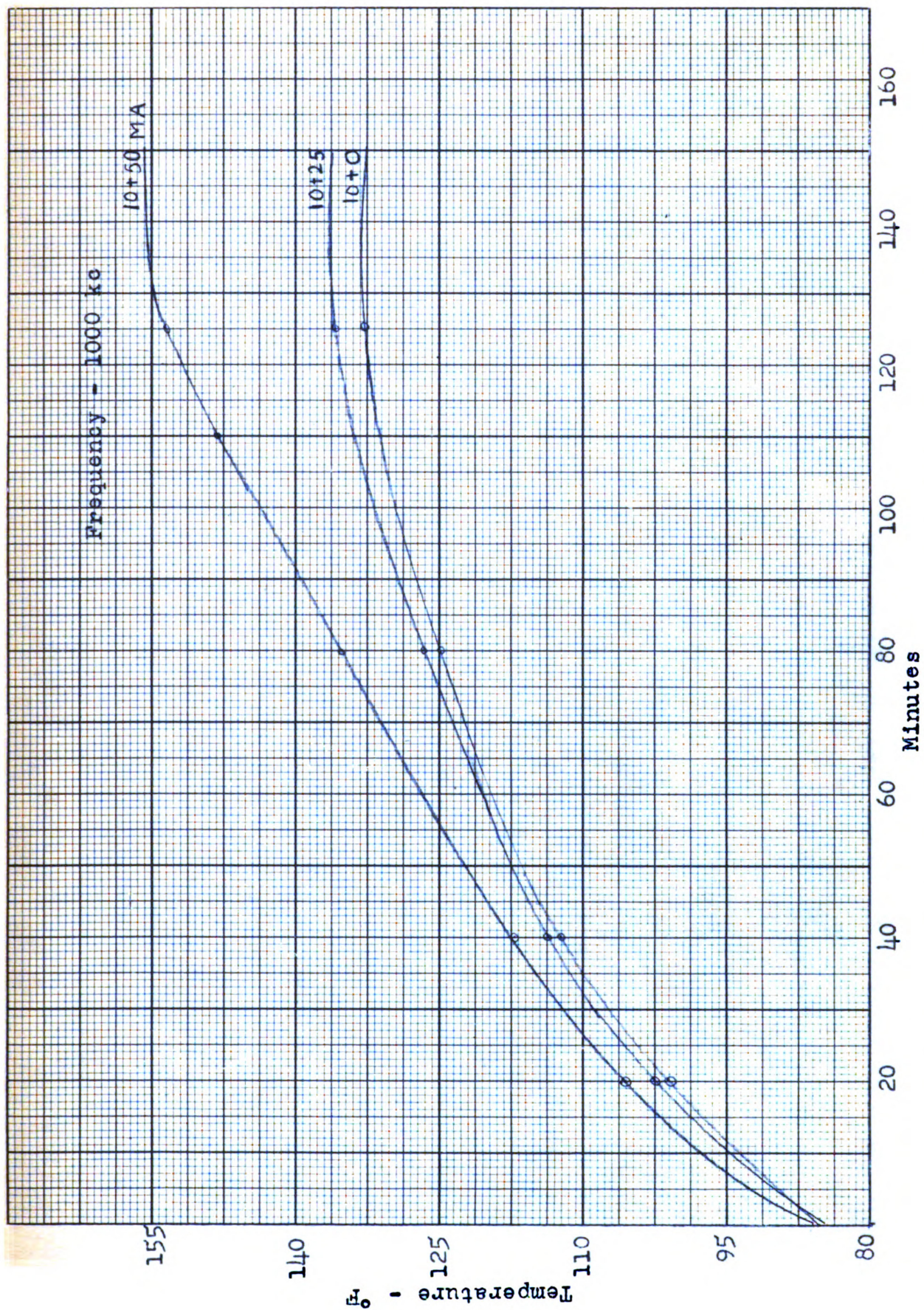


Fig. B-4. Time temperature curves for 10 watts and 0-50 ma ultrasonic energy.

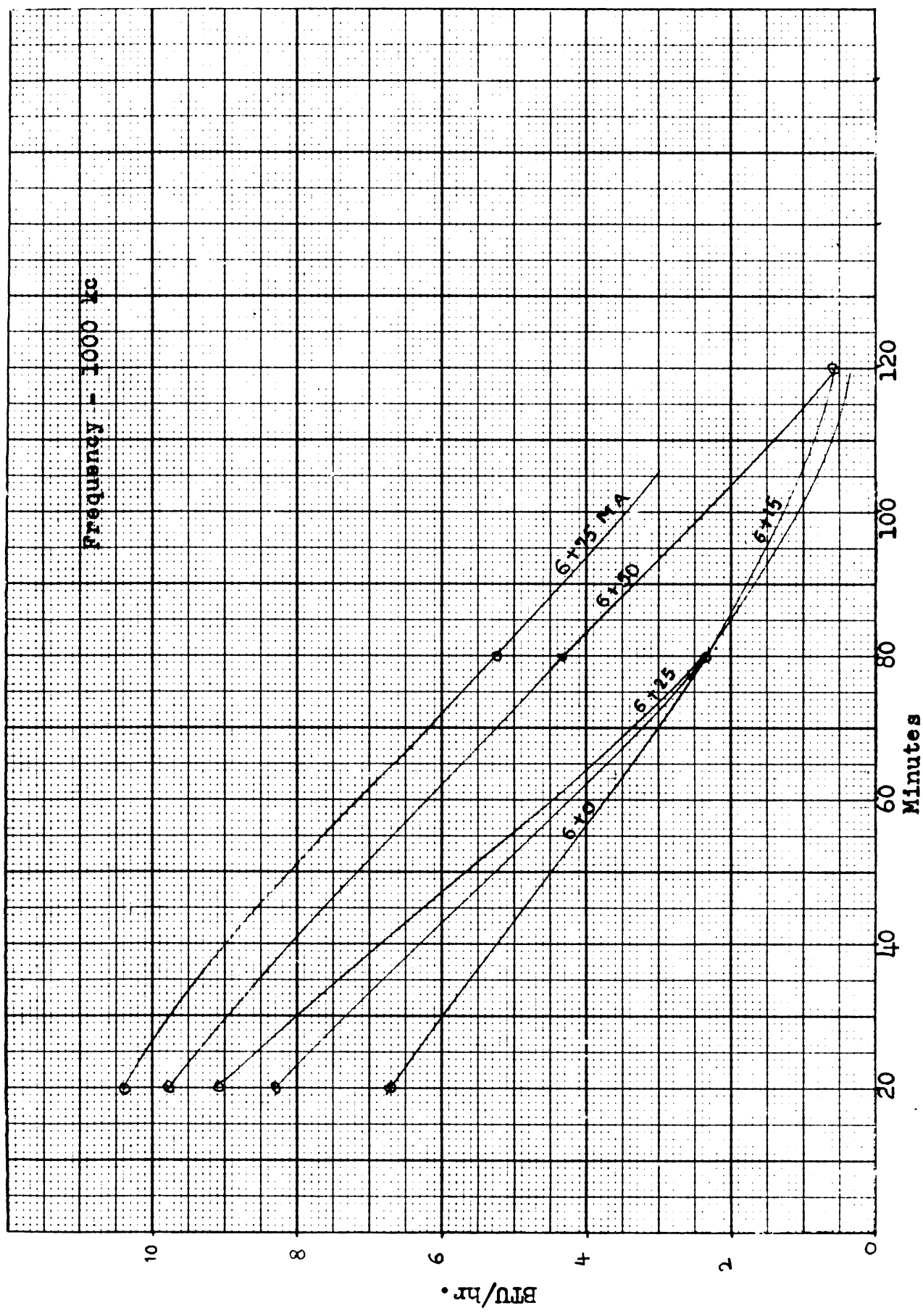


Fig. B-5. Rate of heat transfer of 6 watts and 0-75 ma ultrasonic energy.

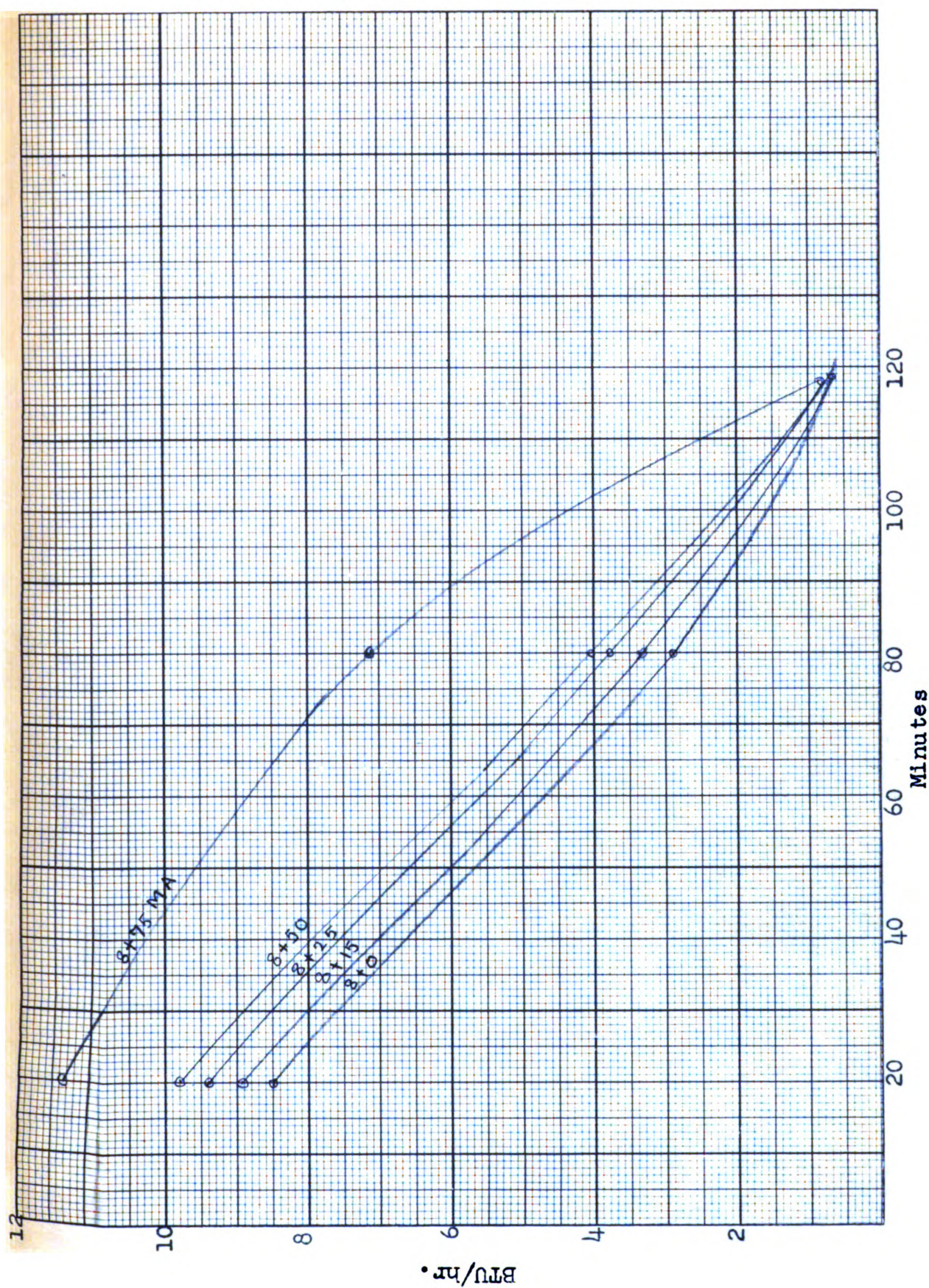


Fig. B-6. Rate of heat transfer at 8 heater watts and 0-75 ma ultrasonic energy.

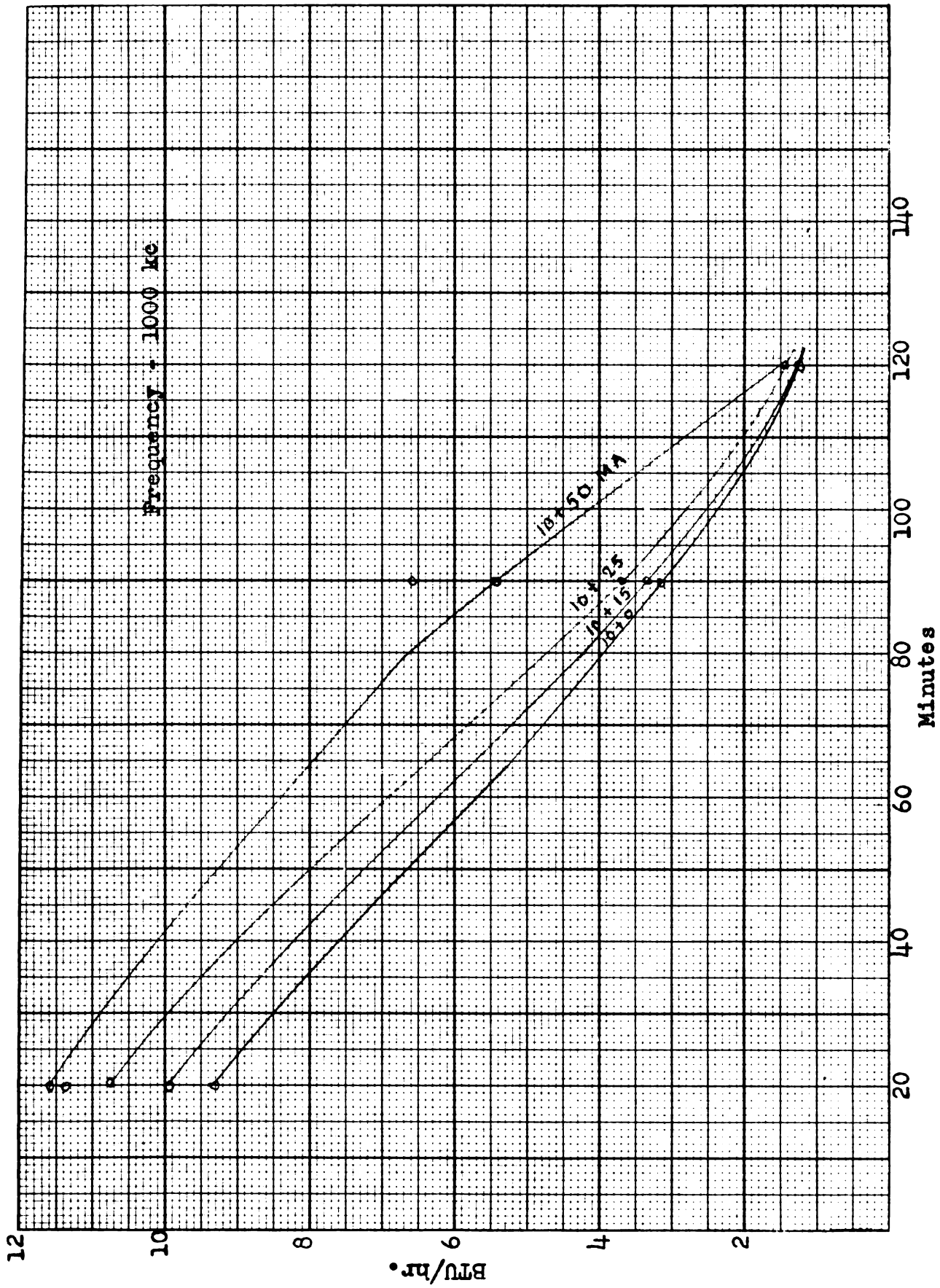


Fig. B-7. Rate of heat transfer at 10 heater watts and 0-50 ma ultrasonic energy.

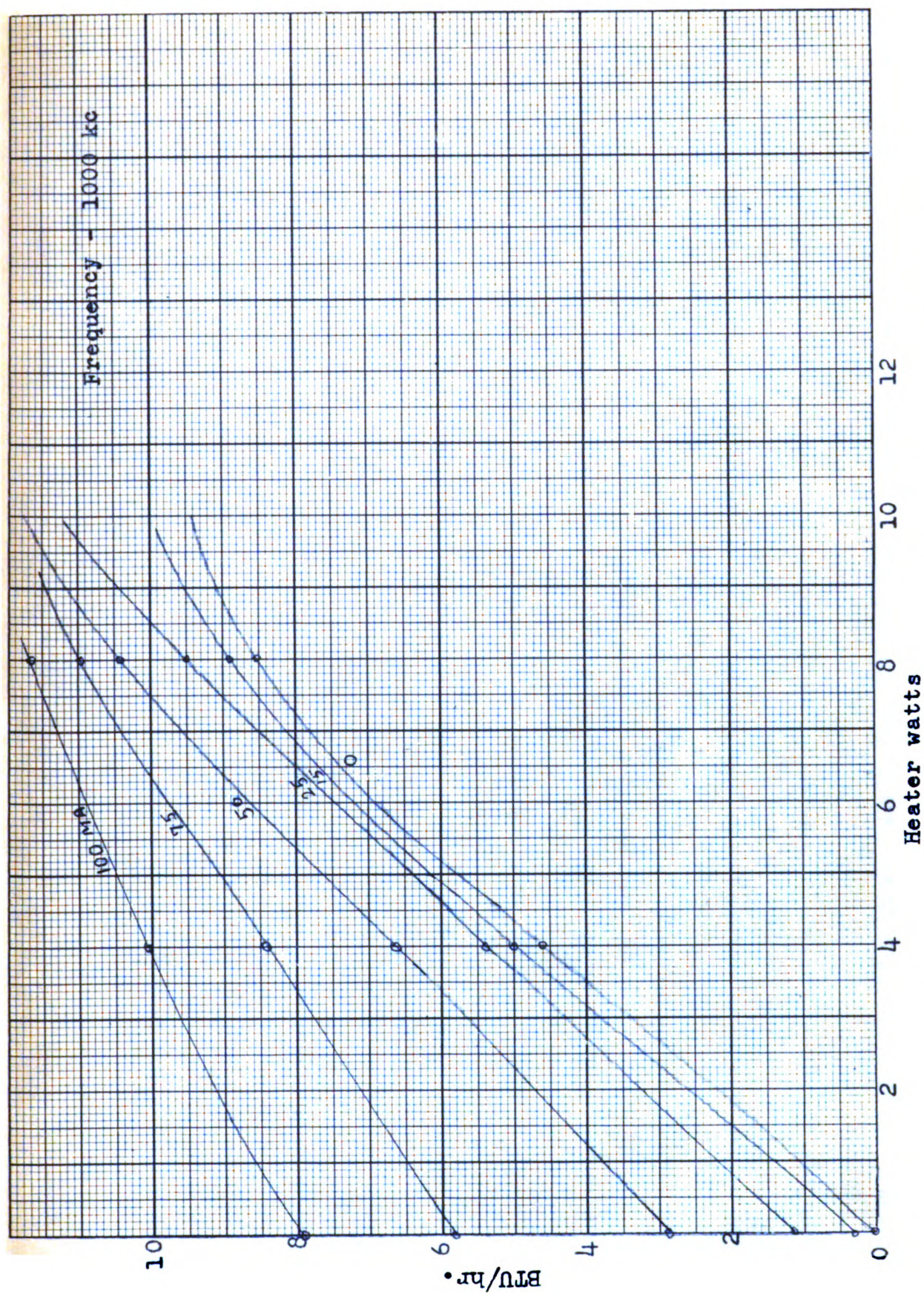


Fig. B-8. Rate of heat transfer by ultrasonic energy at 20 minutes time.

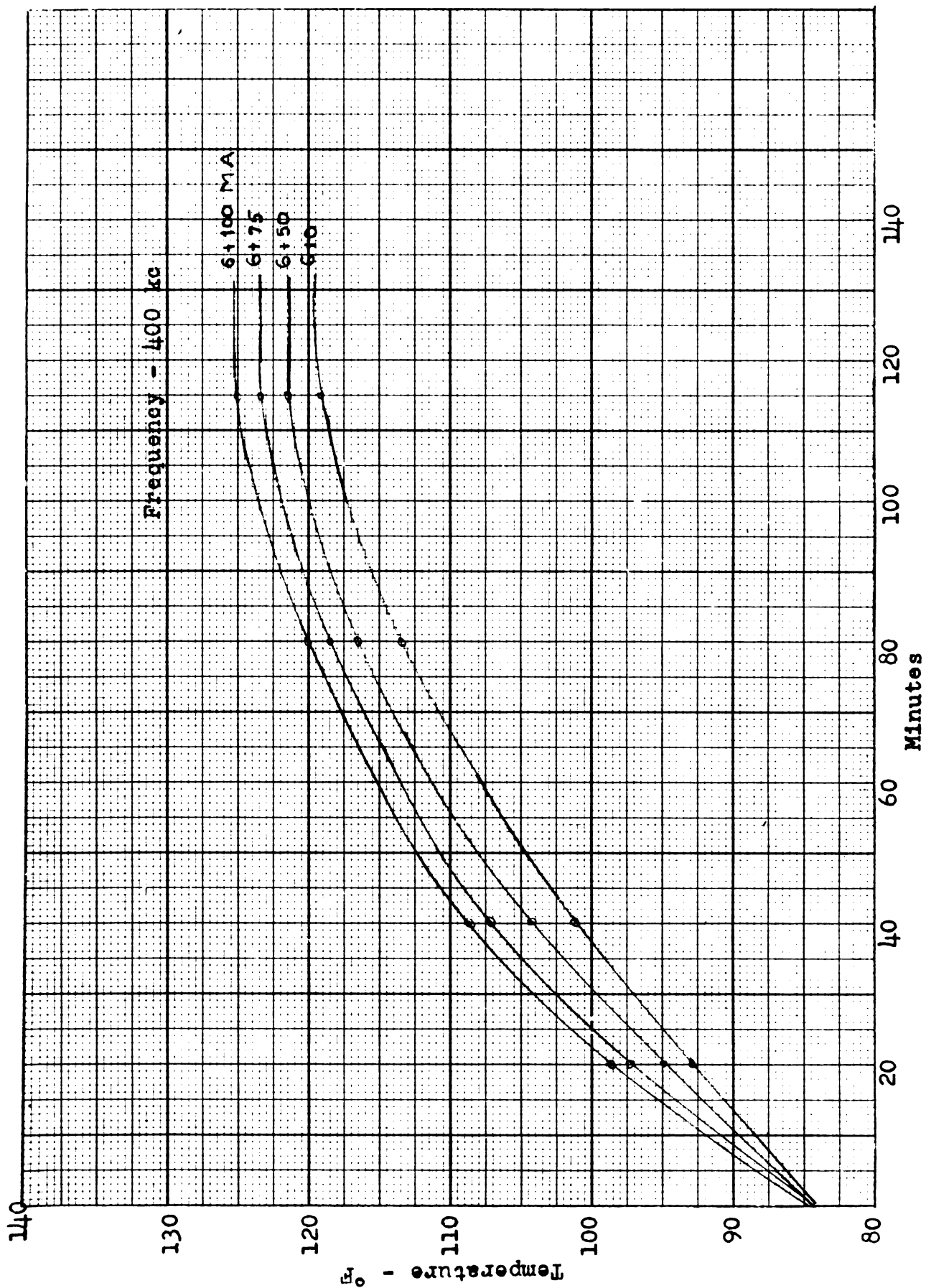


Fig. B-9. Time temperature curves for 6 heater watts and ultrasonics
0-100 ma.

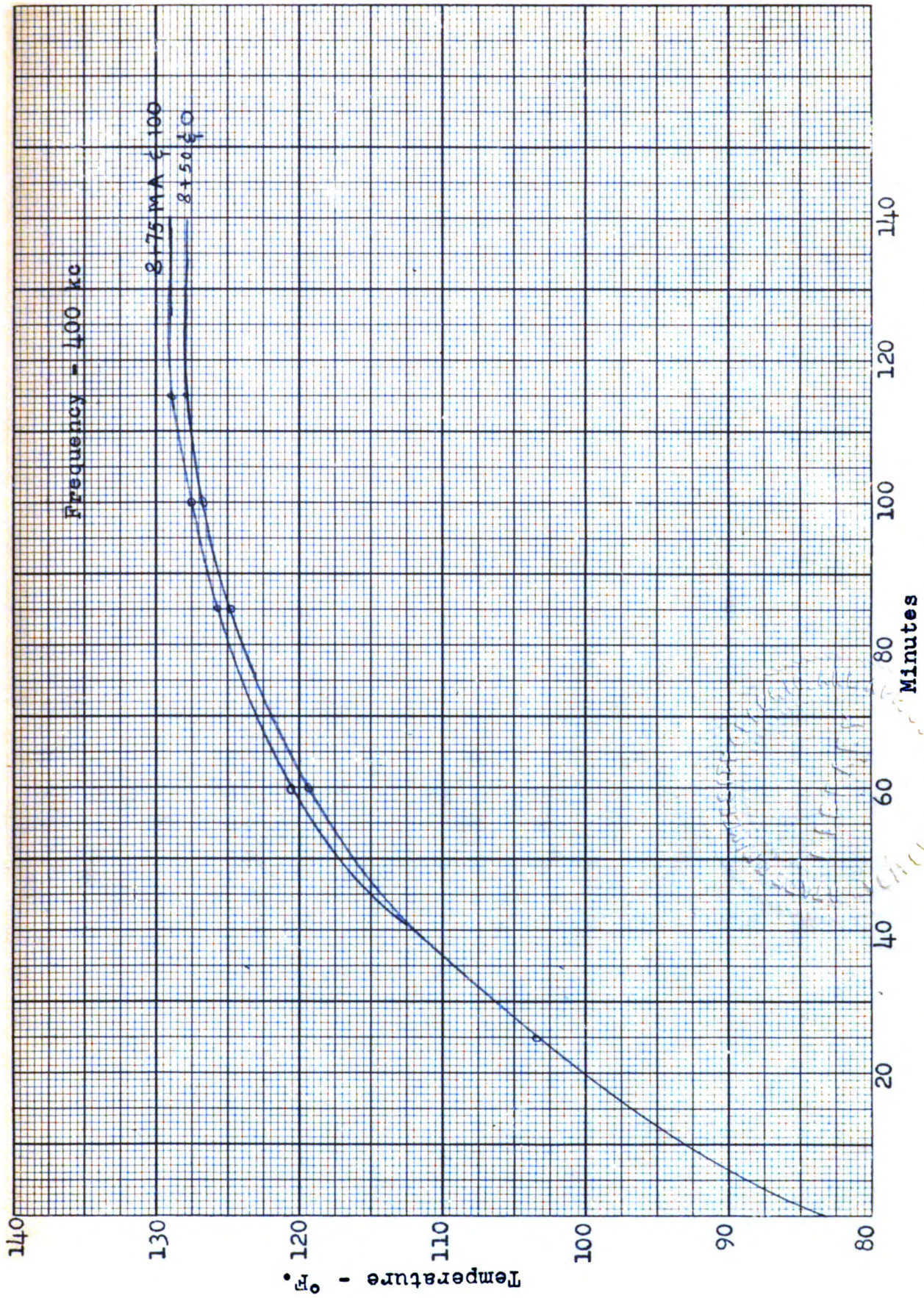


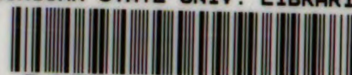
Fig. B-10. Time temperature curves for 8 heater watts and 0-100 ma ultrasonic energy.

ROOM USE ONLY

Date Due[illegible]

Demco-293

MICHIGAN STATE UNIV. LIBRARIES



31293200779795