THE CONSTRUCTION AND TESTING OF A HARTLEY OSCILLATOR FOR MEASURING TEMPERATURES IN FREE-FLOATING OBJECTS

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ABSTRACT

Several modified Hartley oscillators were constructed from inexpensive, easily obtained materials and were calibrated for use as wireless temperature probes. Three classical experiments involving heat conduction inside solid spheres were performed to test the oscillators' accuracy. Excellent agreement was found between theoretical and oscillator-measured temperature profiles. Further experiments were made in which the oscillator was embedded in a neutrally-buoyant, free-floating solid in order to gain insight into the thermal history and motion of an object in a confined, heated liquid. These experiments demonstrated the device's usefulness as a free-floating temperature probe with potential applications in studies of natural convection and sterilization of enclosed foodstuffs.

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INTRODUCTION

The recent deaths in California linked to inadequately sterilized processed cheese underscore the importance to the food industry of bacteriological destruction. Various ways are known to accomplish sterilization, including heat treatment, addition of chemicals, irradiation, freezing, fluid shear, and sonic shock. In almost every branch of the food industry which produces canned and bottled foodstuffs, however, the most common sterilization method is heat treatment.

Thermal sterilization is a delicate process since foods must be heated until the desired lethality of bacteria is achieved, but not so long that significant degradation of nutrients and flavor occurs. Currently, the food industry employs high-temperature short-time processes in an attempt to balance these effects. To make improvements in canned food sterilization processes, it is essential to gain a thorough understanding of the temperature histories and induced flows (in the case of liquid foods) as a function of position inside enclosed containers. Position-dependent temperature histories now can be predicted only for conduction-heated (solid) materials. With respect to convection heating of liquid materials, Stumbo [12] wrote in 1953, "It would appear to be too complicated for any generally applicable mathematical description."

Some progress, most notably by Hiddink [6], has been made since then, but natural convection heating of an enclosed liquid is still not well understood.

Even less is known of the thermal history observed by a neutrally buoyant* solid in an enclosed, heated liquid. This information is needed, for example, to estimate bacterial survival in the vegetables contained in a can of soup placed in a steam retort.

THE PROBLEM There does not exist now a way to rigorously and accurately predict the temperature history of a free-floating solid inside a heated container. This much is clear: the heated vessel walls will generate natural convection currents and density variations inside the liquid. These in turn will influence (and may be influenced by) the motion and temperature of enclosed solid particles. The temperature on the surface and in the interior of these particles, as a function of time, will depend upon initial temperature, heating medium temperature, particle solid properties (e.g., thermal conductivity, density, heat capacity), fluid properties (e.g., thermal conductivity, density, heat capacity, viscosity, volume expansivity), the dimensions and geometry of the container and enclosed solids, and the concentration (in number per unit volume) of solid particles.

This report describes a small temperature-sensitive Hartley oscillator and the rest of a real-time temperature monitoring system. This equipment allows an investigator to measure and record immersed objects' thermal histories.

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*In this writing the terms neutrally buoyant and free-floating are used to describe objects which neither float at the top of a liquid nor rest on a vessel's bottom. Rather, these objects move in the fluid bulk, under the influence of gravity, buoyancy, and fluid drag.

PREVIOUS RELATED WORK

FLUID PHYSICS The governing equations and boundary conditions describing a liquid heated in a closed container have not been solved analytically to yield time-dependent temperature and velocity fields. Okada [9] has shown that, in dimensionless terms, the temperature field can be related to other problem parameters with a representation of the form

$$\frac{T_a - T}{T_a - T_0} = f\left(\frac{x}{l}, \frac{y}{l}, \frac{z}{l}, \frac{\alpha t}{l^2}, Bi, Gr, Pr\right)$$

where

T_a = Temperature of external heating medium

T_0 = Initial temperature of container contents

x,y,z, = Spatial coordinates

l = Characteristic container dimension

t = Time

α = Fluid thermal diffusivity

Bi = Biot modulus = $h_{out}\, l/k$. Relates the conductive resistance of the contained liquid to the thermal resistance of the external heating medium.

Gr = Grashof number = $l^3 g\beta(T_a - T_0)/\nu^2$. Gives the importance of inertial and buoyant effects relative to viscous effects.

Pr = Prandtl number = ν/α. Gives the inside fluid's ratio of momentum diffusivity to thermal diffusivity.

β = Fluid volume expansivity = $(1/V)(\partial V/\partial T)_p$

ν = Fluid kinematic viscosity

k = Fluid thermal conductivity

h_{out} = Heat transfer coefficient between heating medium and container wall

This representation can be expected to be valid only if the temperature sensitivity of the fluid properties--other than density--can be neglected.

FOOD TECHNOLOGY For application in natural convection heating inside a cylinder, Charm [3] presents a correlation of the form

$$\frac{hD}{k} = c(GrPr)^n$$

where

h = Individual heat transfer coefficient between the cylinder's inside wall and the bulk fluid

Gr = Grashof number = $D^3\beta g(T_{wall}-T_{fluid})/\nu^2$

Although this correlation helps in the calculation of total heat transfer rate, it gives no information on the temperature differences from point to point inside the container, and it says nothing about the temperature histories of any particles traveling with the fluid.

Hiddink made great strides in describing the heating of a liquid in a cylindrical container which is steam-heated on the bottom and sides. He presented measured temperature and velocity fields and a dimensionless

correlation involving the overall heat transfer coefficient between outside steam and inside liquid. This correlation is a conceptual improvement over the one recommended by Charm, as Hiddink's was developed from tests on an enclosed fluid. Hiddink even looked at the influence of solid particles, packed in beds inside the container, on the overall heat transfer coefficient. He did not, however, measure the temperature of a solid free to move with the fluid.

Pfeifer and Vojnovich [10] indirectly reported on the effect of solid particle size on the temperature history of the solid's interior. They found in experiments with pilot plant continuous sterilization equipment that, "If the solids were not uniformly and finely ground, much higher temperatures were required to effect sterilization of the medium." This result is to be expected, as smaller particles have lower resistance to heat conduction.

WIRELESS TEMPERATURE PROBES The food industry used wireless temperature probes and transmitters in process evaluation as early as 1960. Elsken [4] described a thermistor-cum-radio transmitter which was used to obtain temperature distribution information on batches of frozen strawberries. A similar device was used to measure product temperature in a can as it passed through the heating and cooling phases of a sterilization process [11], and in a pouch as it passed through a continuous cooker [5]. Unlike the temperature probe described in this report, however, the devices described in these references were large, with transmitters approaching the size of the food containers. Moreover, thermistors were used with these devices to obtain temperature histories at fixed locations in the containers. No free-floating

measurements were possible.

A Hartley oscillator has been used [8] as a temperature telemeter to measure the temperature of incubating penguin eggs and to evaluate the insulating characteristics of sea rescue clothing. This device showed greater transmission range but was larger in size than the oscillator described in this report.

PURPOSE

The purpose of the research effort described in this report is fourfold:

1. To construct an inexpensive, accurate, precise, wireless temperature probe which could be embedded in small, free-floating objects, and to integrate the probe in a personal computer-driven system which would permit real-time measurement and recording of temperature histories.
2. To test the device in classical experiments in which the oscillator's temperature history can be predicted beforehand. For this purpose three experiments involving transient conduction in a solid sphere were chosen.
3. To conduct some "survey" or exploratory experiments, whose results cannot be predicted in advance. In these experiments the temperature histories experienced by neutrally buoyant objects in confined, heated/cooled liquids were recorded.

4. To formulate, in light of knowledge gained from the exploratory runs, a set of questions aimed at better understanding the physical processes involved in food sterilization and heat transfer to free-floating particles.

SUMMARY OF EXPERIMENTS

A. HEAT CONDUCTION EXPERIMENTS

	Sphere Material		Sphere Surface Temperature		
Expt.	Polyurethane	Polyur. + 11% Al	Const.	Linear	Exponential
I	X	X	X		
II		X		X	
III		X			X

B. FREE-FLOATING EXPERIMENTS

	Jacketed Vessel Size		Initial Oil	Jacket Water	
Expt.	178mm OD	315mm OD	Temp	Temp.	Remarks
IV					(1)
Va,Vb,Vc	X		Room temp	Hot	(2)
VI	X		Room temp	Hot	(3)
VIIi,VIIj,VIIk,VIIl	X		Room temp	Warm	(4)
VIIn,VIIo,VIIp,VIq	X		Room temp	Hot	(4)
VIII	X		Room temp	Hot	(4,5)
IX		X	Room temp	Hot	(4)
X	X		Hot	Cold	(4)

Key to Remarks

(1) In Expt. IV the ball was placed in a beaker of silicone oil with an ice bath at the upper solid surface, and a hot plate at the lower solid surface.

(2) At the start of Expts. Va, Vb, and Vc, hot water was already circulating through the jacket. The experiments began by pouring silicone oil into the vessel.

(3) Magnetic stirrer used to stir oil at about 100 rpm.

(4) In Expts. VII-X the experiments began with quiescent oil already in the vessel, and with the jacket empty. The runs started when water filled the jacket.

(5) No oscillator temperature measurements were made in Expt. VIII. The ball's motion was observed very near the vessel wall.

EXPERIMENTAL APPARATUS AND FABRICATION OF THE OSCILLATOR

OSCILLATOR COMPONENTS Only the five electrical components shown in Figure 1 were required to build the Hartley oscillator. These are:

1. A germanium transistor, Texas Instruments model number 2N1305 TI. Germanium transistors were chosen over silicon transistors because of germanium's greater temperature sensitivity.
2. A three volt camera battery. Figure 1 shows a Duracell model DL1/3N.
3. One 1μF capacitor.
4. One 100 pF capacitor.
5. One handmade, center-tapped inductance coil. The coil is described further below.

These five components were connected according to the circuit diagram of Figure 2.

It should be noted that the circuit of Figure 2 does not contain a thermistor. The germanium transistor is the temperature-sensitive circuit component in this Hartley oscillator. This feature, along with the small size of the circuit's other components, permits the construction of a finished device which can be used to measure temperatures of small, free-floating objects.

STEP-BY-STEP FABRICATION OF THE OSCILLATOR

1. Fabrication was begun by hand-winding the inductance coil, using 34 AWG

magnet wire and a wooden toothpick as a core. On one side of the center tap were wrapped five layers of 45 turns (225 turns total); five layers of 15 turns (75 turns total) were wrapped on the other side. The wire was anchored to the wood core with epoxy and the leads were sanded to remove insulation.

2. The use of bulky battery clips was avoided by attaching brass plates to the battery's positive and negative terminals with Duro brand Liquid Solder. Wire leads were then easily soldered to the brass plates.
3. Before permanent connections were made, the complete set of components was tested using a circuit board. It was discovered that testing the integrity of the components individually was inadequate; for example, certain combinations of transistor and coil were found to be inactive, while other combinations, using some of the same components, would pulse at elevated temperature.
4. To build a compact oscillator from a tested group of components, a thin coating of epoxy was first applied to the battery's outer surface. This prevented short-circuiting of components in contact with the battery housing.
5. The 1 μF and 100 pF capacitors were glued to the bottom of the battery, their leads splayed out for later connection.
6. The inductor coil was glued to the side of the battery, parallel to the battery's cylindrical axis, with the 225-turn end nearest the capacitors.
7. The coil's 225-turn lead was soldered to one lead from each capacitor according to Figure 2. This connection was made at the bottom of the battery.

8. The 75-turn lead was next soldered to the battery's positive terminal and to the remaining lead from the 100 pF capacitor. This connection was also made on the underside of the battery.
9. Its three leads arranged radially in a plane beneath it, the transistor was glued to the top of the battery. When the epoxy dried, the transistor's base lead was led down the side of the battery and soldered to the free terminal of the 1 μF capacitor.
10. The negative battery terminal was next soldered to the transistor's collector on top of the battery. Also, at the top of the battery, the emitter was soldered to the coil's center tap. This was the final electrical connection.
11. The oscillator was tested for thermal activity by heating the transistor with a cigaret lighter or hair dryer and setting the device a few inches from an AM radio tuned to approximately 1400 kHz. After a successful test, excess wires were trimmed from the oscillator to minimize bulk.
12. The finished oscillator was coated almost completely in RTV silicone rubber adhesive sealant. As the transistor is effectively the circuit's temperature sensor, its surface was left exposed.

It should be noted that Step 11 most often resulted in failure. Roughly one transistor in ten, it was found, had the necessary temperature sensitivity, regardless of how many combinations of batteries, capacitors, and coils were tried in the same circuit.

Figure 3 is a photograph of a finished oscillator. The device measures 2.5 cm by 1.5 cm by 1.8 cm. Each completed oscillator was active (i.e., would

emit an AM radio signal whose frequency depended upon the transistor's junction temperature) only over a narrow temperature range. No oscillator was active below about 30 deg C or above about 80 deg C. The active temperature range (high temperature cutoff minus low temperature cutoff) varied by device from about 20 deg C to 45 deg C. The thermal time constant of one oscillator was found to be roughly nine seconds. The maximum transmission range from oscillator to AM radio was typically one foot to 18 inches.

OSCILLATOR CALIBRATION The modified Hartley oscillator pulse period was observed to increase with decreasing transistor junction temperature. The devices were calibrated in dielectric vegetable oil, as it was feared that water would cause short-circuiting or would otherwise damage the oscillator components. A plot of temperature against the logarithm of pulse period was found to give, in each case, an excellent linear fit of the form

$$T = A + B \ln (PP)$$

where
- T = junction temperature, deg C
- PP = pulse period of oscillator, msec
- A = least-squares fit parameter, typically 95 to 125
- B = least-squares fit parameter, typically 11.5 to 14.

The standard deviations from the least-squares linear fits varied by oscillator from 0.3 deg C to 0.9 deg C. These figures give an indication of the oscillator's accuracy as temperature probes when measurements are made at

steady-state, that is, when time lag is eliminated from the measurements.

Battery life was observed to affect the calibration. One oscillator containing a battery with low charge was found to lose its linear relation between temperature and the logarithm of pulse period.

ASSOCIATED EQUIPMENT The Hartley oscillator was one component of an integrated system for temperature measurement. Other components included an AM radio, used to receive the oscillator's signal, "clean" and amplify it, and relay it through a cable from the earplug jack to a pulse counter. This device, a Hewlett Packard model 5316A Universal Counter, was in turn controlled by an IBM PC-XT personal computer with installed GPID IEEE488 interface card. Once the calibration parameters had been determined for a given oscillator, the entire system permitted an investigator to choose a sampling frequency for temperature measurements and, afterward, to save a temperature history in a labeled data file for later use. The computer program governing these operations is included in Appendix 3 of this report.

Other equipment used in heat transfer experiments included:

Vessels

3000 ml and 4000 ml Pyrex beakers

One Pyrex bell jar, measuring 11.5 in. ID by 12 in. high

One cylindrical jacketed glass vessel, measuring 143 mm inside by 8.5 in. high. The jacket outer diameter was 178 mm.

Another cylindrical jacketed glass vessel, larger than the first,

measuring 260 mm inside by 9.25 in. high. The jacket outer diameter was 315 mm.

NOTE: All vessels used were glass, as the oscillator's radio signal could not penetrate metal.

Fluids

Vegetable oil for calibration of oscillators

Water

Dow Corning 200 fluid 20 cS silicone oil.

Properties of this fluid are listed in Appendix 4.

Heaters and Temperature Controllers

Neslab brand thermostatic bath and liquid circulator, model TEZ-3

Various hot plates and magnetic stirrers.

Miscellaneous

One polyurethane sphere, radius 3.85 cm, used in heat conduction experiments

Another sphere of radius 3.85 cm, composed of polyurethane with 11 wt% aluminum powder (added to enhance thermal conductivity). Also used in heat conduction experiments.

Copper-constantan thermocouples and voltmeter with stripchart, used to monitor temperature of water in the jackets of

glass vessels described above.

Table tennis balls, used to encase Hartley oscillator for experiments on free-floating objects.

THEORETICAL PREDICTIONS OF CLASSICAL EXPERIMENTS

As a test of the oscillator's accuracy, three "classical" experiments concerning heat conduction inside solids were performed. In each, the oscillator was placed at the center of a sphere, and the theoretically predicted temperature history at this location was compared to the oscillator's measurements. The three experiments shared a common format. In each a sphere of radius R and thermal diffusivity α, with initial temperature T_0, was subjected to a change in its surface temperature from T_0 for $t \leq 0$ to $F(t)$ for $t > 0$. Only the function $F(t)$ varied from experiment to experiment. The three experiments were thus boundary value problems satisfying [1]:

Heat Conduction Equation

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r}\right)\right] \tag{1}$$

Initial Condition

$$\text{At } t = 0, \quad T(r,0) = T_0 \tag{2}$$

Boundary Condition 1: Sphere Surface Temperature

$$\text{At } r = R, \quad T(R,t) = F(t), \text{ an arbitrary function of time} \tag{3}$$

Boundary Condition 2: Spherical Symmetry

$$\text{At } r = 0, \quad \frac{\partial T}{\partial r} = 0 \tag{4}$$

EXPERIMENT I In the first experiment the sphere's surface temperature was maintained constant for t>0 at $F(t)=T_S$ ($\neq T_0$). This was accomplished physically by immersing the sphere in a well-mixed thermostatic water bath.

The dimensionless solution to the problem defined by Equations (1)-(4), with $F(t) = T_S$, is [2]

$$\Theta = 1 + \frac{2}{\pi\zeta} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin(n\pi\zeta) \exp(-n^2\pi^2\tau) \tag{5}$$

where

Dimensionless temperature $\Theta = \dfrac{T-T_0}{F(0)-T_0}$

Dimensionless time $\tau = \dfrac{\alpha t}{R^2}$, and

Dimensionless distance $\zeta = r/R$

At the sphere's center ($\zeta = 0$) the solution becomes

$$\Theta(0,\tau) \equiv \theta(\tau) = 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp(-n^2\pi^2\tau) \tag{6}$$

This solution was to be compared to the temperature history measured by the embedded oscillator.

EXPERIMENT II In the second experiment the surface temperature of the sphere was changed linearly according to the form

$$T(R,t) = F(t) = a + bt \tag{7}$$

This temperature change was accomplished by immersing the sphere in a well-mixed water bath, and changing the set point on the thermostatic circulator which controlled the bath temperature. The circulator's heat input, beginning at t=0, created an approximately linear bath temperature history.

The solution to the heat conduction problem with boundary condition (7) was found using Duhamel's Theorem (see Appendix 1 for details). In dimensionless form it is

$$\Theta = 1 + \beta\tau + \frac{2}{\pi\zeta} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} [e^{-n^2\pi^2\tau} +$$

$$\frac{\beta}{n^2\pi^2} (1-e^{-n^2\pi^2\tau})]\sin n\pi\zeta \tag{8}$$

where $\beta = bR^2/\alpha(a-T_0)$

and Θ, τ, and ζ are as before.

At the center of the sphere, the temperature profile is

$$\Theta(0,\tau) \equiv \theta(\tau) = 1 + \beta\tau + 2 \sum_{n=1}^{\infty} (-1)^n [e^{-n^2\pi^2\tau} +$$

$$\frac{\beta}{n^2\pi^2}\,(1 - e^{-n^2\pi^2\tau})] \tag{9}$$

EXPERIMENT III In the third experiment the temperature of the sphere's surface was changed exponentially according to

$$T(R,t) = T_i + (T_f - T_i)(1 - e^{-\kappa t}) \tag{10}$$

This profile was generated by immersing the sphere in a well-mixed water bath of initial temperature T_i, and by charging the bath at constant rate with water at temperature T_f. Water was removed from the bath at the same rate.

Using Duhamel's Theorem (see Appendix 1) the solution to the conduction problem with surface boundary condition (10) was found to be

$$\Theta = 1 + \Gamma(1-e^{-c\tau}) + \frac{2}{\pi\zeta}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\,(\sin n\pi\zeta)\,\left\{e^{-n^2\pi^2\tau} + \right.$$

$$\left.\frac{c\Gamma}{n^2\pi^2-c}\,[e^{-c\tau} - e^{-n^2\pi^2\tau}]\right\} \tag{11}$$

where $$\Gamma = \frac{T_f-T_i}{T_i-T_0} \quad \text{and} \quad c = \frac{R^2\kappa}{\alpha}$$

The dimensionless temperature at the sphere's center is

$$\theta(0,\tau) \equiv \theta(\tau) = 1 + \Gamma(1-e^{-c\tau}) + 2 \sum_{n=1}^{\infty} (-1)^n \left\{ e^{-n^2\pi^2\tau} + \frac{c\Gamma}{n^2\pi^2-c} [e^{-c\tau} - e^{-n^2\pi^2\tau}] \right\} \quad (12)$$

Equation (12) gives the temperature history that was compared to the oscillator's measurements in Experiment III.

CLASSICAL EXPERIMENTS: RESULTS AND DISCUSSION

EXPERIMENT I: CONSTANT SURFACE TEMPERATURE The constant surface temperature experiment was performed once with a pure polyurethane sphere and once with a polyurethane sphere containing 11 wt% aluminum powder. In neither case was the solid's thermal diffusivity α available in a reference book, as this property is, for polyurethane, a strong function of processing conditions and therefore not universal. Consequently, Experiment I became a means to measure α for each sphere.

To determine the α values, a family of curves of θ vs. t, with α as a parameter, was developed from Equation (6). These curves were compared to the experimental θ vs. t plots as measured by the Hartley oscillator. For each sphere the thermal diffusivity was found by identifying the theoretical curve which best fit the experimental data. The goodness of fit between theoretical and experimental curves was determined by averaging the experimental error at $\theta = 0.1, 0.2, 0.3, \ldots, 0.9$. This procedure resulted in:

$$\alpha(\text{Polyurethane sphere}) = 0.00095 \text{ cm}^2/\text{sec}$$

$$\alpha(\text{Polyurethane + 11 wt\% Al}) = 0.0019 \text{ cm}^2/\text{sec}$$

Using these "best" values of thermal diffusivity, the experimental temperature profiles were converted to dimensionless profiles of θ vs. τ. Figure 4 shows the experimental curve for the pure polyurethane sphere, and also plots the theoretical solution, Equation (6). The root-mean-square (rms) error in θ between the experimental and theoretical curves is 0.0098. Figure 5

shows the corresponding pair of curves for the sphere containing aluminum powder. The rms error in θ between these curves is 0.013. The excellent agreement between experimental and theoretical curves in both cases suggests that the oscillator's performance as a temperature probe was good enough to permit a theoretically-based one-parameter (α) fit of the data.

EXPERIMENT II: LINEARLY CHANGING SURFACE TEMPERATURE Because of heat losses to the environment, the temperature history of the water bath in Experiment II showed a slight downward concavity, as shown by the red curve in Figure 6. The least squares linear fit, shown in blue, was in error (rms) by about 0.6 deg C. The parameters for use in Equation (7) were

$$a = 46.7 \text{ deg C} \quad \text{and} \quad b = 0.283 \text{ deg C/min}$$

Equation (9) gives the theoretical dimensionless temperature response of the center of the sphere to a linear change in the surface temperature. The red curve in Figure 7 shows this response for the values of a and b given above. The experimental blue curve of Figure 7 was obtained by non-dimensionalizing the oscillator's temperature readings and converting dimensional time to dimensionless τ using the thermal diffusivity determined from Experiment I. (Only the aluminum-impregnated sphere was used in Experiments II and III.) Figure 7 shows close agreement between theory and experiment. The rms error in θ between curves is 0.031.

EXPERIMENT III: EXPONENTIALLY CHANGING SURFACE TEMPERATURE The actual water bath temperature history, shown as a red curve in Figure 8, deviated slightly from the exponential form of Equation (10). The best-fitting function to these data was

$$T = 57 - 34\,(1 - e^{-0.3075t}) \qquad (13)$$

with T in (deg C) for t in (min). This equation is the blue trajectory in Figure 8. The rms error between real and model temperature profiles is 0.5 deg C.

The dimensionless temperature change at the center of a sphere whose surface temperature is changing exponentially is given by equation (12). From the exponential model of Equation (13) and the value α=0.0019 cm²/sec for the aluminum-impregnated sphere, the red theoretical curve of Figure 9 has been drawn. The dimensionless oscillator temperature measurement is shown in blue. The rms error in θ between curves is 0.057, indicating close agreement. It should be noted from Figure 9, however, that the oscillator response curve (blue) lies entirely above the theoretical response. This might be attributed to one of two causes:

1. Figure 9 might reflect a slow response to the discrepancy between the measured and modeled surface temperatures of Figure 8. For $t \leq 6$ min the measured bath temperature was consistently below the model's prediction. Only for $t > 6$ min is the model's predicted temperature less than that measured. It is very possible that if the experiment were conducted for

a longer period that τ=0.18, the red and blue curves in Figure 9 would cross.

2. Another explanation for the unexpected fast oscillator response of Figure 9 is heat "bypassing". The spheres used in these experiments were not solid, but were cut into hemispherical halves for access to the oscillator. Although care was taken when the spheres were closed to prevent heat or fluid from entering the crack, heat leak by this mechanism cannot be ruled out.

Overall, the agreement between theory and experiment in each of the classical boundary value problems of Experiments I, II, and III was excellent. The modified Hartley oscillator has been shown to be an accurate wireless temperature probe.

FREE-FLOATING PARTICLE EXPERIMENTS

OVERVIEW The conduction trials, Experiments I, II, and III, have demonstrated the oscillator's accuracy and reliability. The next step was to embed the oscillator in a neutrally-buoyant object, place the object in an enclosed liquid, heat or cool the liquid at solid boundaries, and make some temperature measurements. These measurements and observations comprise Experiments IV through X. These experiments were exploratory in nature, designed only to give insight into the object's temperature history under various conditions, not to produce a correlation or other immediately useful quantitative information. It is believed the free-floating measurements given in this report are the first of their kind.

FREE-FLOATING PARTICLE The free-floating particle used in Experiments IV through X was a modified table tennis ball. First, the oscillator was placed inside the ball with only the transistor exposed. Next, the ball was sealed with epoxy and RTV sealant, and lead weights were glued to the ball's outer surface until the ball's density matched that of the silicone oil used in the experiments.

THERMAL TIME CONSTANT The time constant, t^*, for a temperature-measuring device is the time required for the device to register 63% of a temperature change from an initial temperature to a new ambient temperature. If the device is modeled as a mass m with heat capacity Cp, surface area A, and heat transfer coefficient h between surface and ambient fluid, the time constant is

given by $t^*=mCp/hA$. This relationship is derived in Appendix 2.

It was earlier reported that the oscillator's thermal time constant was nine seconds. This corresponds to a bare oscillator. For the oscillator embedded in the table tennis ball, however, the measured t^* was closer to 42 seconds. This was determined by dropping the oscillator-and-ball in a beaker of hot silicone oil and recording the temperature change. The increase in t^* is attributed to the increase in thermal mass and the decrease in exposed surface of the transistor.

The significance of the 42 second time constant is analyzed further in the discussions of Experiments IV and V.

ATTRACTION TO RADIO It was discovered in the midst of the free-floating experiments that the oscillator-and-ball moved not only under the influence of gravity, fluid drag, and buoyancy; the radio exerted a weak magnetic attraction for the metal of the oscillator's transistor housing. As a result, the temperature histories are not those that would be experienced by a particle subject only to gravitational and fluid forces. This is unfortunate. On the other hand, this characteristic did permit the measurement of temperatures very near the jacketed vessels' inner walls. Without the radio to "steer" the ball toward the wall, these measurements would not have been possible.

EXPERIMENT IV

PROCEDURE In the first free-floating experiment a powerful convection cell was generated by placing silicone oil in a 4000 ml Pyrex beaker, setting the beaker on a hot plate, and immersing an ice bath in the top of the oil. Approximately 19 cm separated the ice bath from the hot plate's surface. The ball was allowed to move about in the oil, and temperatures were recorded after the system reached a pseudo-steady state, that is, after the pattern of the ball's motion appeared unchanged.

RESULTS AND DISCUSSION The fluid's motion in the beaker was that of a single convection cell, easily visible to the naked eye. Oil rose in plumes from the beaker's heated bottom, passed across the ice bath's cold stainless steel surface, and fell back toward the bottom. The motion of the ball containing the oscillator was less regular, but was still approximately periodic. The ball would fall from the ice bath, pause briefly at the bottom, rise, pause at the ice bath, and repeat. The period of the motion was about 60 to 90 seconds.

The temperature history transmitted by the oscillator in this experiment is presented in Figure 10. The peak-to-peak period is in rough agreement with the observed period of the ball's motion, but the amplitude--approximately 0.5 to 1 deg. C--seems very low compared to the (unmeasured) actual temperature difference between the top and bottom of the oil. This amplitude attenuation is to be expected for measurement of a periodically changing temperature. As shown in Appendix 2, if an oscillator with thermal time constant t^* is

subjected to a sinusoidal temperature change of frequency ω and amplitude A, the measured temperature history will have amplitude $A[1+(\omega t^*)^2]^{-0.5}$ For the experiment at hand, $\omega \doteq 0.083$ rad/sec (based on the period of the ball's motion) and $t^* \doteq 42$ sec, so the amplitude has been attenuated by approximately 72%. Clearly, if it is desired to measure periodically changing temperatures with frequencies on the order of 1 cycle per minute, a device with a smaller time constant is needed.

EXPERIMENT V

PROCEDURE Experiments Va, Vb, and Vc were conducted in the smaller (143 mm ID) of the two jacketed vessels. In each run hot (65 deg. C) water circulated through the jacket; this temperature was maintained by the Neslab thermostatic circulator. At the start of each experiment, room temperature oil and the weighted ball were poured into the center of the vessel. When the oscillator grew warm enough to start pulsing, the computer recording was begun. There was no difference in procedure among the three experiments.

RESULTS AND DISCUSSION The ball's motion in each case was nonperiodic. At the start, when the oil was still cool, the ball floated at the top of the oil, almost completely submerged. As the oil grew warmer and less dense, the ball slowly sank and moved radially outward, transistor first, in the direction of the radio. The ball then worked its way down the wall and came to rest on the bottom.

Figures 11, 12, and 13 give the temperature histories transmitted by the oscillator during Experiments Va, Vb, and Vc, respectively. In each figure the temperature curve exhibits a slow-heating period followed by a fast-heating period. The slow-heating period corresponds to the time when the ball had not yet reached the wall. The fast-heating period occurred after the transistor came within a couple millimeters of the glass.

The brief cooling period of Experiment Va (between time = 730 sec and time = 800 sec in Figure 11) is believed to be the result of the transistor's passing through a cold zone in the vessel. The glass vessels were designed with about 0.5 in. of unjacketed wall near the bottom of each container. A thin layer of cold silicone oil must have existed at the vessel's bottom, and, in Experiment Va, the oscillator was probably measuring temperatures in this zone after 730 seconds.

An attempt has been made in Figures 11-13 to correct for the thermal lag of the oscillator-and-ball. Appendix 2 shows how this correction was made. Temperature histories in later experiments were not similarly corrected for the following reasons:

1. The two curves in each of Figures 11-13 do not differ by a substantial amount; in other words, the oscillator measurements appear to be quite good.
2. The corrected curves reflect an oscillator-ball time constant of 42 seconds, a value which was determined in quiescent oil and which is therefore conservative. Thus the "true" temperature histories may be even closer to the oscillator histories than they appear in Figures 11-13.

EXPERIMENT VI

PROCEDURE The procedure in this experiment was identical to that in Experiments Va, Vb, and Vc, except a magnetic stir bar, turning at roughly 100 rpm, was placed in the silicone oil.

RESULTS AND DISCUSSION The stirrer's vortex kept the ball at the center of the oil, away from the vessel walls. Again, over the course of the experiment, the ball moved from the top of the oil to the bottom as the oil grew warmer and less dense.

A plot of the logarithm of dimensionless temperature, log $[(T_a-T)/(T_a-T_0)]$, vs. time, is given in Figure 14. (T_a is jacket water temperature.) In addition to the curve for Experiment VI, curves for Experiments Va, Vb, and Vc are also shown. Note that the heating rate for Experiment VI, given by the slope of the curve, is virtually indistinguishable from that of Experiments Va, Vb, and Vc before the ball reached the wall. The surface temperature of the ball changes much more rapidly in a region near the wall than in the bulk fluid, and, apparently, moderate mixing of the bulk fluid does not affect this conclusion.

EXPERIMENT VII

PROCEDURE The runs in Experiment VII, like those of Experiments V and VI, were made with the smaller jacketed glass vessel. In Experiment VII, however,

the runs began with quiescent, room temperature oil already in the vessel. At time zero heated water was allowed to circulate in the jacket. The temperature of the jacket water was held constant by the thermostatic circulator. A thermocouple, connected to a voltmeter with a stripchart, measured the jacket water effluent temperature.

Two groups of runs were made:

1. "Warm" (average temperature 51.3 deg. C) Jacket Water Runs. These included Experiments VIIi, VIIj, VIIk, and VIIl.
2. "Hot" (average temperature 61.7 deg. C) Jacket Water Runs. These included Experiments VIIn, VIIo, VIIp, and VIIq.

RESULTS AND DISCUSSION In each run of Experiment VII, the ball started at the top of the oil, sank slowly as the oil grew warmer, moved toward the glass wall nearest the radio, slipped gradually down the glass (without actually touching it) and came to rest on the vessel's bottom. No difference in the ball's journey could be detected between runs.

The non-dimensionalized temperature profiles recorded during the "warm" jacket water runs are shown in Figure 15. Figure 16 shows a similar set of curves for the runs made with "hot" jacket water. In an attempt to compare the effects of heating medium temperature on the heating rate of the ball, the four curves in each group of runs were combined to give two average heating curves. These curves, one each for hot and warm jacket water, are plotted in Figure 17. Additional curves, indicating the range of measurements in each experiment, are also shown.

It appears, on inspection of Figure 17, that for 600 sec $\lesssim$ t $\lesssim$ 1100 sec the floating sphere was heated faster by "warm" jacket water than by "hot". This is contrary to what would be expected for the oil as a whole. A higher temperature difference between heating material and enclosed liquid (silicone oil in this instance) should produce a greater overall heat transfer coefficient, and therefore a higher heating rate. It is very difficult to give a satisfactory explanation for the effect illustrated in Figure 17. If a greater number of runs were made, in fact, the effect might disappear altogether. Nonetheless, this result should be explored further as it may lead to different thermal sterilization strategies than are currently used for free-floating food particles.

EXPERIMENT VIII

PROCEDURE The purpose of these runs was to determine if the ball could be maintained near the glass wall in the absence of the radio. In each case silicone oil, at room temperature, was poured into the small jacketed vessel. The ball was next dropped into the oil and positioned next to the wall. Finally, hot (65 deg. C) water was allowed to fill the jacket, and the ball's motion was observed. No oscillator temperature data were taken.

RESULTS AND DISCUSSION In every run the ball remained against the glass wall until the hot water filled the jacket. At this point the ball moved abruptly to a position about 1 cm away from the glass. At no time during any

run did the ball return to the glass. The separation distance grew from 1 cm to 2.5 or 3 cm as the ball sank in the heat oil.

It is clear from this result that in previous runs the radio's magnetic attraction was needed to overcome the ball's aversion to the heated vessel walls. This aversion was probably caused by a lubrication force, generated when convection-driven oil flowed through the narrow gap between the sphere and the wall. In runs with the radio placed just outside the glass, the separation distance was determined by the balance between the attractive force of the radio and the repulsive fluid force expected from lubrication theory.

EXPERIMENT IX

PROCEDURE Experiments IXa and IXb were identical to the "hot" jacket water runs of Experiment VII, except for the use of a larger (260 mm ID) vessel.

RESULTS AND DISCUSSION The general path taken by the ball in each run of Experiment IX was the same as in Experiment VII; the ball's motion, however, was slower. The dimensionless temperature profiles in Figure 18 show that the temperature change of the oscillator was slower in the larger vessel as well. By comparison, the curves in Figure 16 are much steeper.

A significant factor in the difference in heating rates between vessels was the difference in ratios of heat transfer area to enclosed fluid volume:

Small Vessel (A/V) = 0.67

Large Vessel (A/V) = 0.37

All else being the same, the vessel with the higher A-to-V ratio will be able to heat its contents more rapidly.

The two curves in Figure 18 differ in shape. In Experiment IXa the ball reached the bottom of the vessel before migrating to the glass wall near the radio. This section of wall includes the unjacketed bottom one half inch of glass. In Experiment IXb, on the other hand, the ball reached the wall 1-2 inches above the vessel bottom. This accounts for the additional slope change or knee in the curve for Experiment IXb.

EXPERIMENT X

PROCEDURE Experiment X examined the effect of using ice water to cool hot oil and the free-floating oscillator. The smaller (143 mm inside ID) jacketed vessel was used in these runs.

In Experiment Xa hot (initial temperature 61 deg. C) silicone oil, containing the oscillator, was cooled by feeding the jacket with ice water and circulating the heated effluent water through an ice bath. A large Pyrex bell jar served to hold the ice. Oscillator temperature measurements were taken throughout the experiment. During this run the radio was placed near enough to the vessel to receive the oscillator's signals, but not so near as to influence the ball's motion.

In Experiment Xb hot (initial temperature 67 deg. C) silicone oil, containing the oscillator, was again cooled in the jacketed vessel with circulating ice water. During this run, however, the radio was placed against the jacket's outer glass wall.

At the start of Experiments Xa and Xb, a pinch of tiny polypropylene beads was dropped into the hot silicone oil. The beads were watched during the runs for signs of fluid motion.

RESULTS AND DISCUSSION Because of the radio's remote location in Experiment Xa, the ball remained in the oil's central core throughout the run. At the start of the run, when the oil was hot and relatively low in density, the ball sat motionless on the vessel's bottom. Later, as the oil cooled and became denser, the ball rose gradually towards the surface. Recording of oscillator temperatures was stopped when the ball reached the surface.

The proximity of the radio in Experiment Xb affected the ball's motion. As in Experiment Xa, the ball-and-oscillator began the run on the bottom of the vessel. When the ball rose, however, it slowly migrated in the direction of the radio. By the time the ball broke the oil's surface (at which time the computer recording was discontinued) the oscillator's transistor was 1-2 mm from the glass.

The tiny polypropylene beads were observed, in both experiments, to move slowly down the cold glass walls and radially inward at the vessel's bottom. This is the expected pattern for such temperature-induced fluid motion. Continuity requires that there be some upward motion, probably in the central core of the oil, but this could not be detected.

The non-dimensionalized temperature histories transmitted by the oscillator during each run are plotted in Figure 19. Note that each curve is concave-up for most of the run time, indicating slower-than-exponential cooling. The abrupt change in cooling rate in Experiment Xb was the result of the transistor's reaching the boundary layer near the vessel wall. This zone was substantially colder than the bulk of the oil.

GENERAL CONCLUSIONS FROM TEMPERATURE MEASUREMENTS OF A FREE-FLOATING OBJECT

1. There is a very significant difference in temperature--and therefore in heat transfer rate to a solid particle moving in the fluid--between the central core of oil and a thin region, or boundary layer, near the wall. This was observed both when cold oil was heated by hot jacket water and when hot oil was cooled by cold jacket water. This result is in agreement with numerical simulations by Hiddink, although his model considered simultaneous bottom and sidewall heating.

   To improve the heat transfer to free-floating solids, some means should be employed to cause the particles to gravitate toward the vessel walls. This might be achieved by spinning the container along its axis. Note, however, that if the container held more than enough solids to completely cover the inside walls, those particles which contacted the walls would act as a layer of thermal insulation, impeding the heat transfer to the others.

2. Temperature histories taken when the ball is perfectly stationary are approximately linear when plotted as log $[(T_a-T) / (T_a-T_0)]$ vs. t. Examine, for example, the curves in Figure 16 for t>1000 sec; these measurements were taken when the ball was resting on the bottom of the vessel. The linearity on this plot implies that the temperature change is approximately exponential, in agreement with the fixed-thermocouple

measurements reported by Hiddink.

3. The surface temperature histories of the ball in motion showed that heating was slower than an exponential approach to the jacket temperature. In this case, the plots of log $[(T_a-T) / (T_a-T_0)]$ vs t are not straight lines, but are curves with upward concavity. This general result held true in both the large and small vessels, and for instances of heating or cooling of the silicone oil. The motion of the ball-and-oscillator explains the upward concavity:

   (i) During heating of the cold oil, fluid drag and density changes forced the ball into colder (lower) regions. The ball's temperature would have risen faster if it had been held in place.

   (ii) During cooling of hot oil, fluid drag and density changes forced the ball into warmer (higher) regions. The ball's temperature would have fallen faster if it had not moved.

In a sterilization process food particles which undergo motions like those of the oscillator in this series of experiments will experience slower heating than can be predicted by an exponential model of the form

$$\frac{T_a-T}{T_a-T_0} = \exp\left[\frac{-UAt}{mCp}\right] \qquad (14)$$

4. On the basis of the averaged curves in Figure 17 for "hot" and "warm" jacket water, there is some indication that the temperature of a free-floating particle will faster approach the heating medium's temperature if the initial temperature difference (T_a-T_0) is lower. An exponential

model, like Equation (14) above, would predict the opposite. A larger temperature difference would mean a larger Grashof number, and this, according to most natural convection correlations, should increase the coefficient U.

5. The Hartley oscillator and associated equipment have been demonstrated to be useful tools for the measurement of temperature histories experienced by free-floating particles.

FUTURE RESEARCH

IMPROVING THE OSCILLATOR The oscillator would be more useful if three improvements could be made:

1. Decrease the size. This would permit the use of smaller scale equipment in future experiments. Also, if the oscillator could be built small enough and embedded in the proper solid, it could be used in very large vessels to measure temperatures along a streamline.
2. Increase the transmission range. It was found in some experiments that the use of magnet wire as an AM antenna extension allowed for greater distances between oscillator and radio. Unfortunately, the increase in electromagnetic noise accompanying the external antenna was significant.
3. Decrease the thermal time constant. If the oscillator is to be used to measure abrupt or periodic changes in temperature, time constants less than measured here (9 sec for a bare oscillator, 42 sec when encased in a table tennis ball) would be desirable.

BUOYANT SOLID PARTICLE RESEARCH A complete understanding of the process of heat transfer to free-floating particles will require answers to questions like those listed below.

1. Suppose that the density of a given particle is ρ_{part}, and the density of an enclosed heated liquid is ρ_{Lo} at initial temperature T_0 and ρ_{La} at the temperature of the external heating medium. (The experiments described

in this report were designed so that $\rho_{La} < \rho_{part} < \rho_{Lo}$. This insured that the solid started each heating experiment at the liquid's surface and finished on the vessel's bottom.) How would the temperature history of a particle of fixed size, in a given fluid, in a given container with given heating pattern, change if its density could be altered and made to approach ρ_{Lo} or ρ_{La}? What if the particle's density is such that $\rho_{part} > \rho_{Lo}$? What if $\rho_{part} < \rho_{La}$?

2. In Experiment IV the ball-and-oscillator underwent an approximately periodic motion, passing from the cold upper solid surface to the hot lower surface and back again. In all of the runs involving the jacketed vessels, however, the ball's journey was unidirectional, either passing from the oil's surface to the bottom of the vessel or vice versa. Why? What combination of temperature gradients and flow patterns permitted periodic (i.e., "up-and-down") particle motion in Experiment IV but did not exist in the other runs?

3. Consider the heating of a fluid and a solid particle, in a container of given geometry. As long as the heating pattern is not one in which the container's upper surface is uniformly heated while the bottom is uniformly cooled, a fluid circulation pattern will appear [13]. If the density of the particle is fixed, is there a critical size, below which the particle will tend to follow the fluid in approximately periodic motion? If so, what is this size, and how does it relate to problem parameters such as fluid properties, particle density, heating pattern, etc.? What dimensionless groups would be significant in correlating the critical particle size to other problem parameters?

From Stokes' Law any spherical solid of density ρ_s and radius a, placed in a fluid of density ρ and viscosity μ, can be vertically entrained as long as the fluid's uniform upward velocity u satisfies

$$u \geq \left(\frac{2}{9}\right) a^2 (\rho_s - \rho) g/\mu$$

This implies that, given a particle density, a fluid, and an upward velocity, a particle size can always be specified which will guarantee entrainment. This is true regardless of the magnitude of the relative density $\rho_s - \rho$. Thus, it is not unreasonable to believe that there may exist a critical particle size for (approximately) periodic motion of a particle in an enclosed liquid.

4. Suppose that such a critical particle size exists, and consider two particles, one slightly larger, and the other slightly smaller, than the critical size. Under the proper conditions, the smaller particle would undergo approximately periodic motion, while the larger particle's movements would be nonperiodic. How would the rates of heat transfer to such particles compare? Which motion would produce the faster temperature rise at the particle's center?

The heat flux at the particle's solid surface is given by

$$\text{Flux} = hA(T_{fl} - T_{surf})$$

where

h = Heat transfer coefficient between particle

surface and fluid surrounding the particle

A = Particle surface area

T_{fl} = Temperature of the fluid immediately surrounding the particle

T_{surf} = Temperature at the particle's surface

The coefficient h is dependent upon the motion of the fluid relative to the particle's surface. The rates of heat transfer to the two particles therefore depend both on the temperature history T_{fl} (t) and on the fluid motion observed in the particle's reference frame. Two more questions arise: does the periodic particle or the nonperiodic particle experience the larger (time-averaged) temperature difference, $T_{fl} - T_{surf}$? Which particle has the larger (time-averaged) heat transfer coefficient, h?

5. If a substantial difference in heat transfer rate exists between periodic and nonperiodic particles, would it be practical, economical, or desirable to take advantage of it? In considering changes in food particle size, for example, consumer tastes must be taken into account.
6. Is it possible for a particle to change its mode of movement, from nonperiodic to periodic or vice versa, over the course of a heating run?
7. What is the influence of particle concentration? Hiddink found that when particles are packed in a bed inside a container, the overall heat transfer coefficient is lower than when no solids are present. He concluded that the particle bed influenced the motion of the heated fluid inside the vessel. What if the container held just a few neutrally

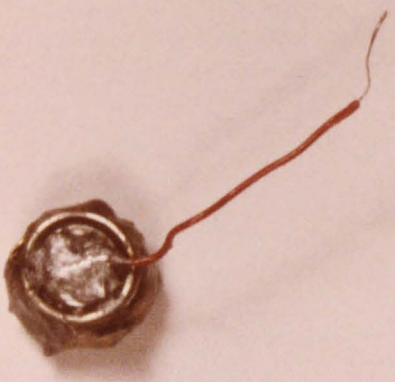
buoyant particles? How would increasing the particle concentration affect the nature of the particle motion (period vs. nonperiodic)? What particle concentration would be required to effectively prevent all particle motion?

To answer the questions posed above requires a deep understanding of the interactions between neutrally buoyant particles and enclosed, heated liquids. When the knowledge exists to answer these questions quantitatively, the food industry will have the tools to better evaluate proposed improvements in the sterilization processes for canned foods. Agitation and rotation of containers, exploring various patterns of heating the container walls, considering alterations of particle size--these and other options may be studied in detail. And, after improvements, small Hartley oscillators may well be used in these studies.

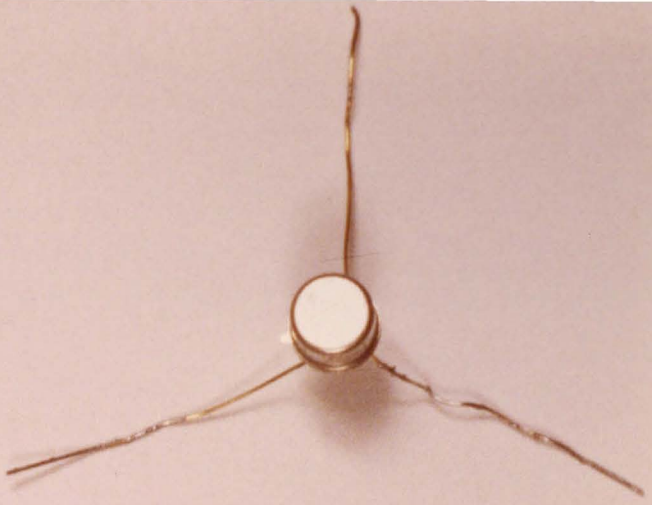
FIGURES

Note: In the graphs in Figures 4-19, the experimental curves connect consecutive data points. The points themselves are not shown, for purposes of clean presentation.

FIGURE 1 (next page): Photograph of Hartley oscillator circuit components



3-VOLT BATTERY



GERANIUM TRANSISTOR

COIL

100 pf CAPACITOR

1 µf CAPACITOR

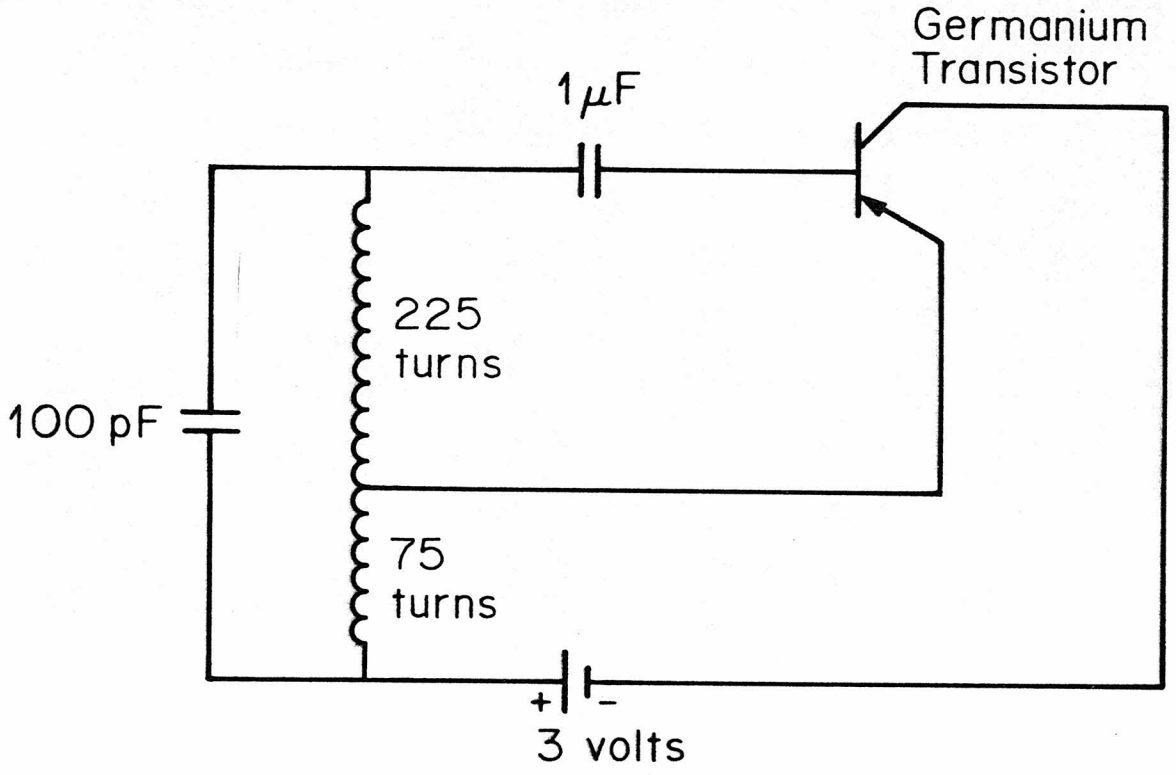


FIGURE 2. Hartley oscillator circuit

FIGURE 3 (next page): Photograph of finished Hartley oscillator

FINISHED OSCILLATOR

FIGURE 4

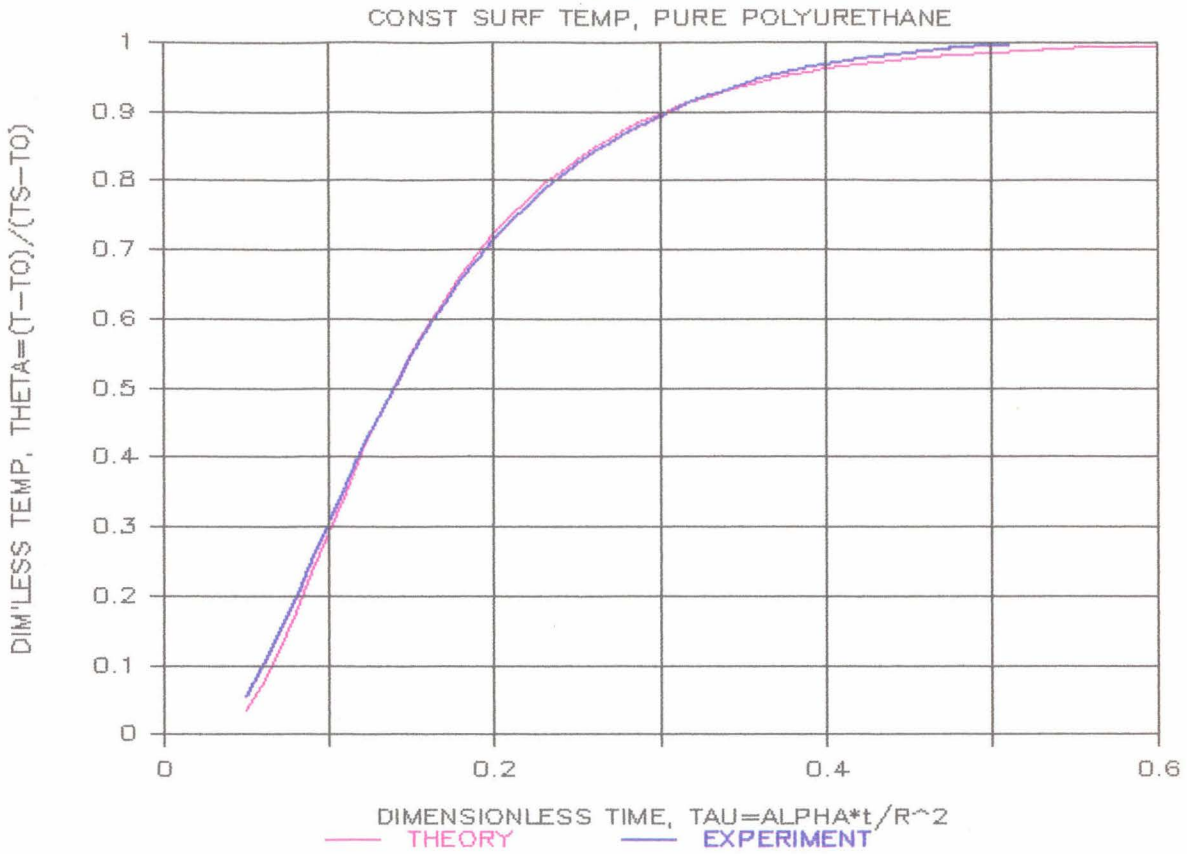

CONST SURF TEMP, PURE POLYURETHANE
DIM'LESS TEMP, THETA=(T-TO)/(TS-TO)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
DIMENSIONLESS TIME, TAU=ALPHA*t/R^2
THEORY
EXPERIMENT

FIGURE 5

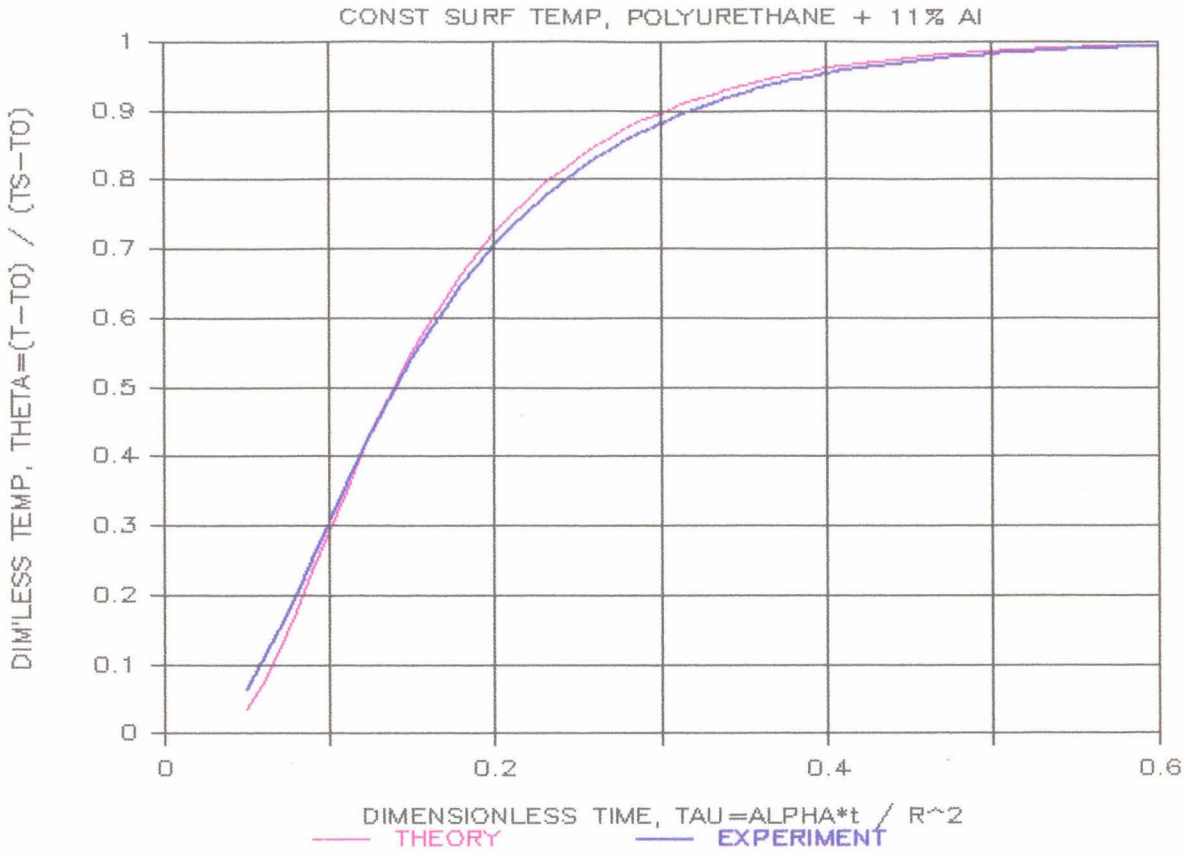

CONST SURF TEMP, POLYURETHANE + 11% Al
DIM'LESS TEMP, THETA=(T-TO) / (TS-TO)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
DIMENSIONLESS TIME, TAU=ALPHA*t / R^2
THEORY
EXPERIMENT

FIGURE 6

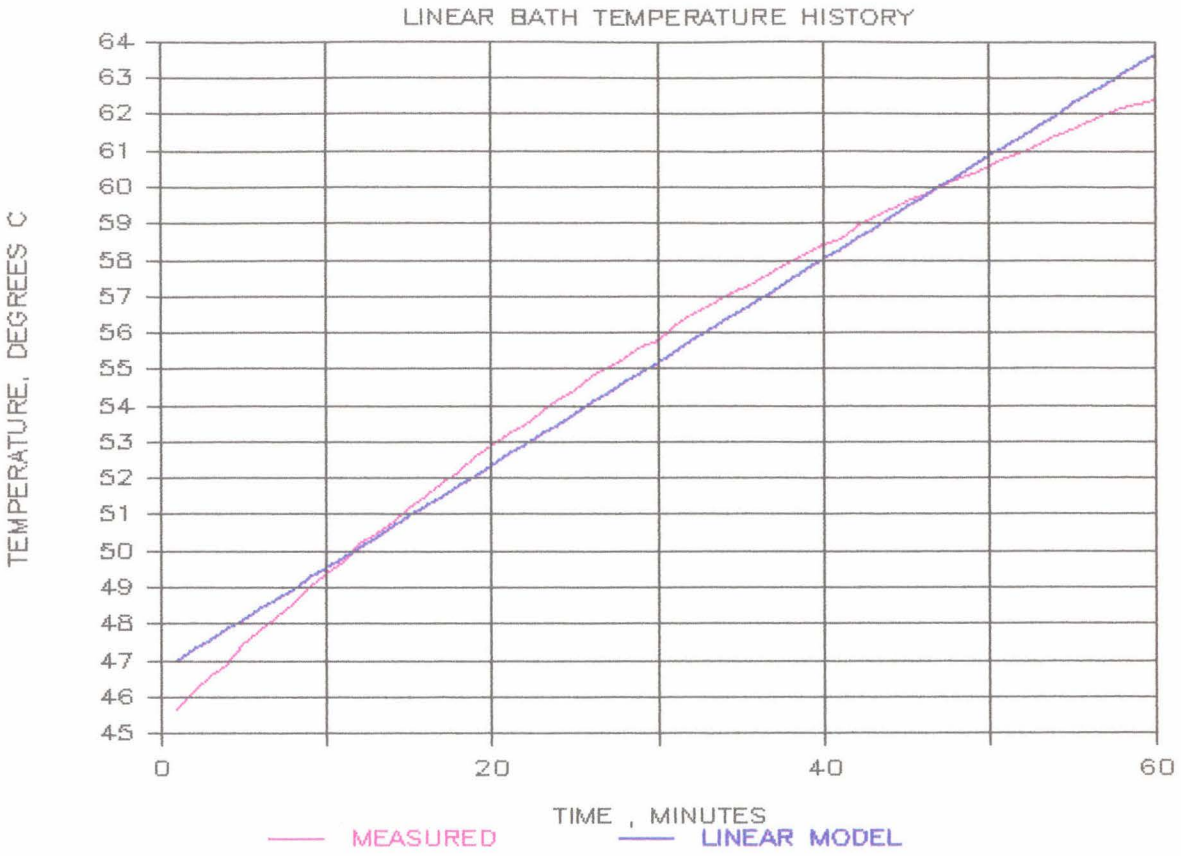
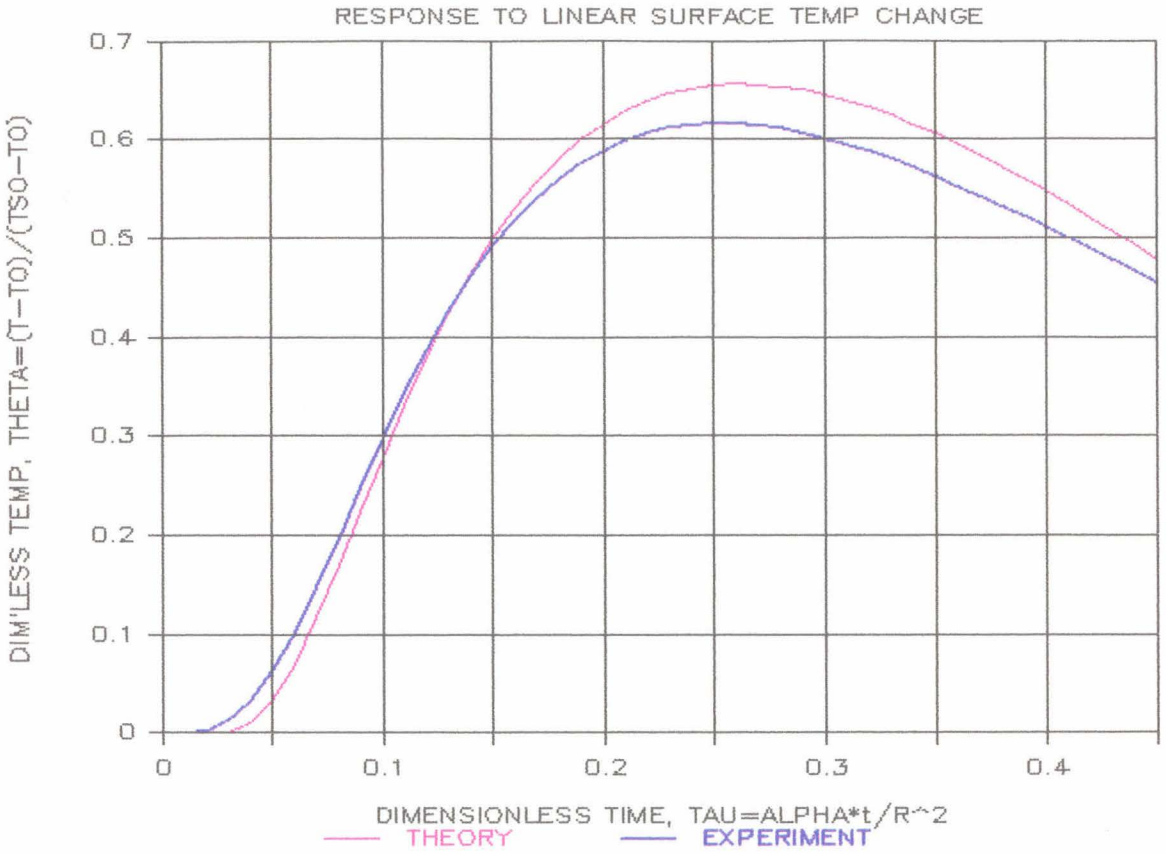

LINEAR BATH TEMPERATURE HISTORY
TEMPERATURE, DEGREES C
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
0
20
40
60
TIME , MINUTES
MEASURED
LINEAR MODEL

FIGURE 7



Initial sphere temperature T0 = 68.4 deg C. Sphere surface temperature changed linearly according to Figure 6. Temperature at center of sphere decreases initially, later increases.

FIGURE 8

EXPONENTIAL BATH TEMPERATURE HISTORY

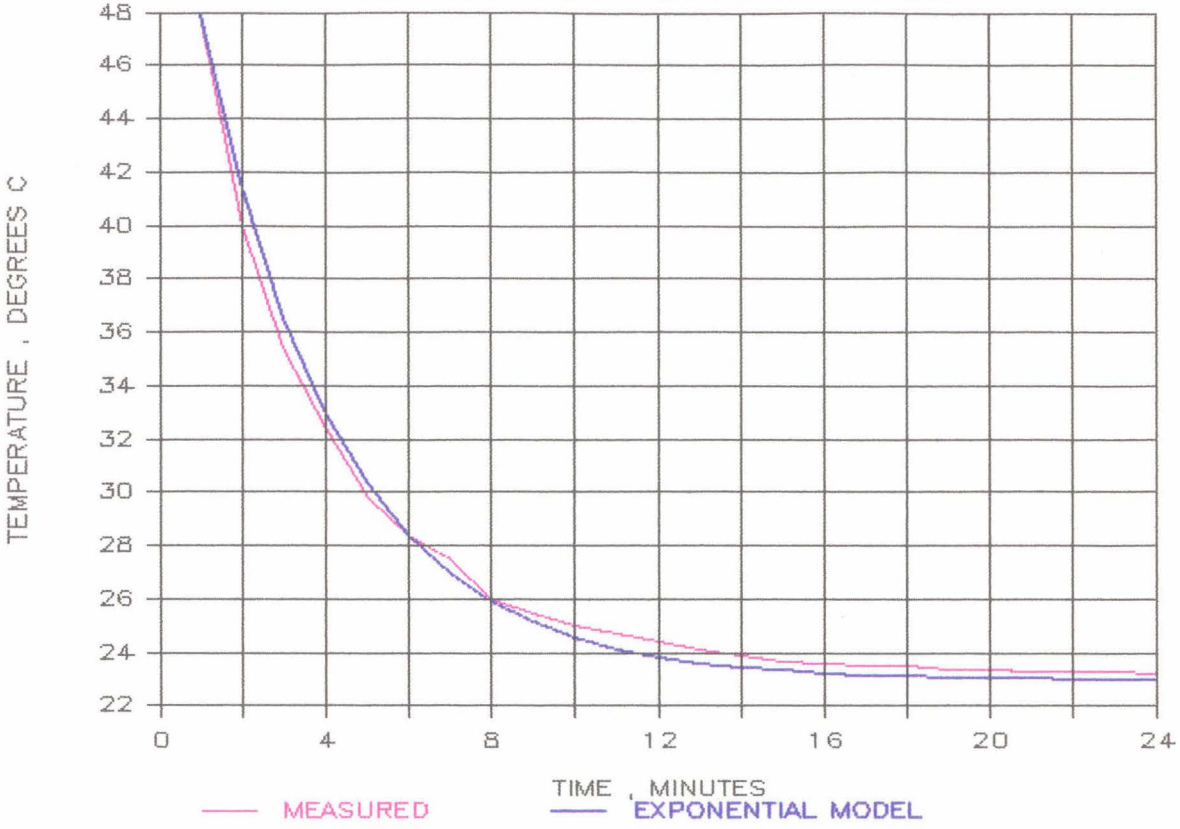


FIGURE 9

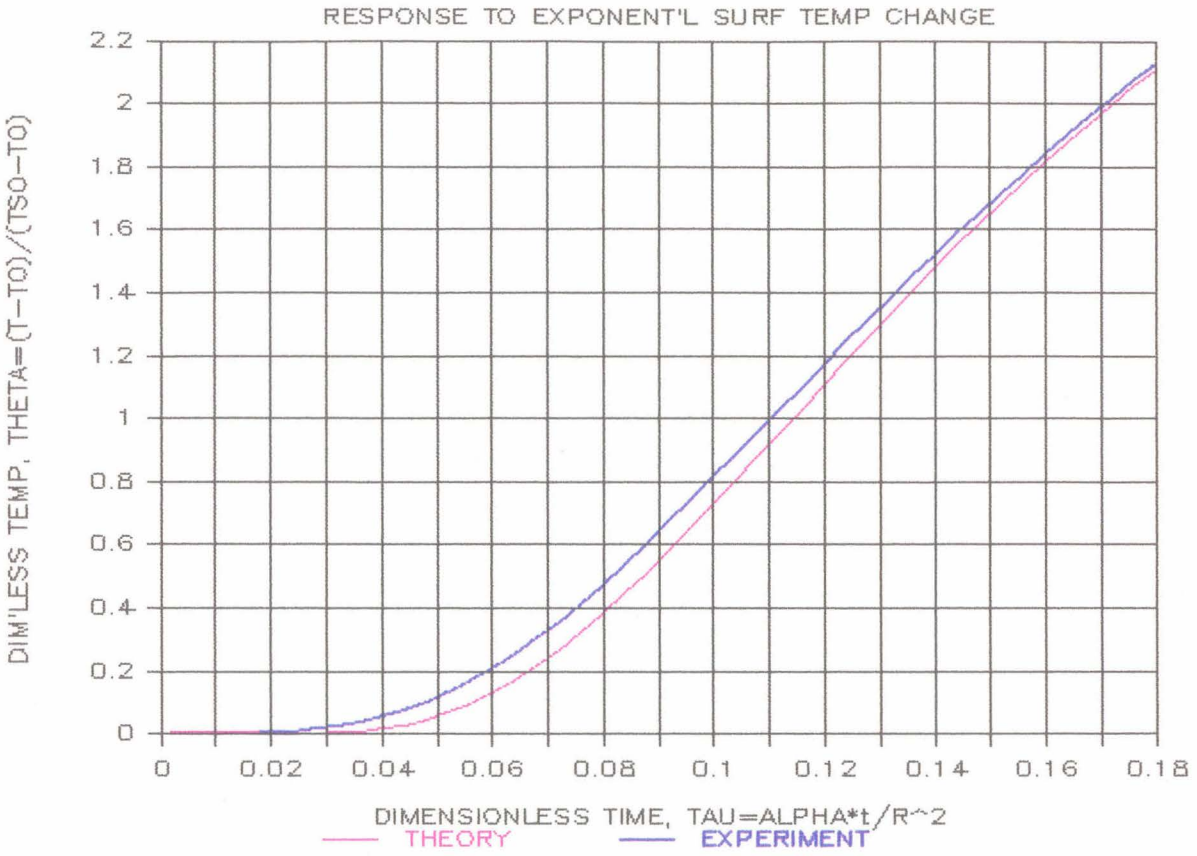

RESPONSE TO EXPONENT'L SURF TEMP CHANGE
DIM'LESS TEMP, THETA=(T-TO)/(TSO-TO)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
DIMENSIONLESS TIME, TAU=ALPHA*t/R^2
THEORY
EXPERIMENT

FIGURE 10

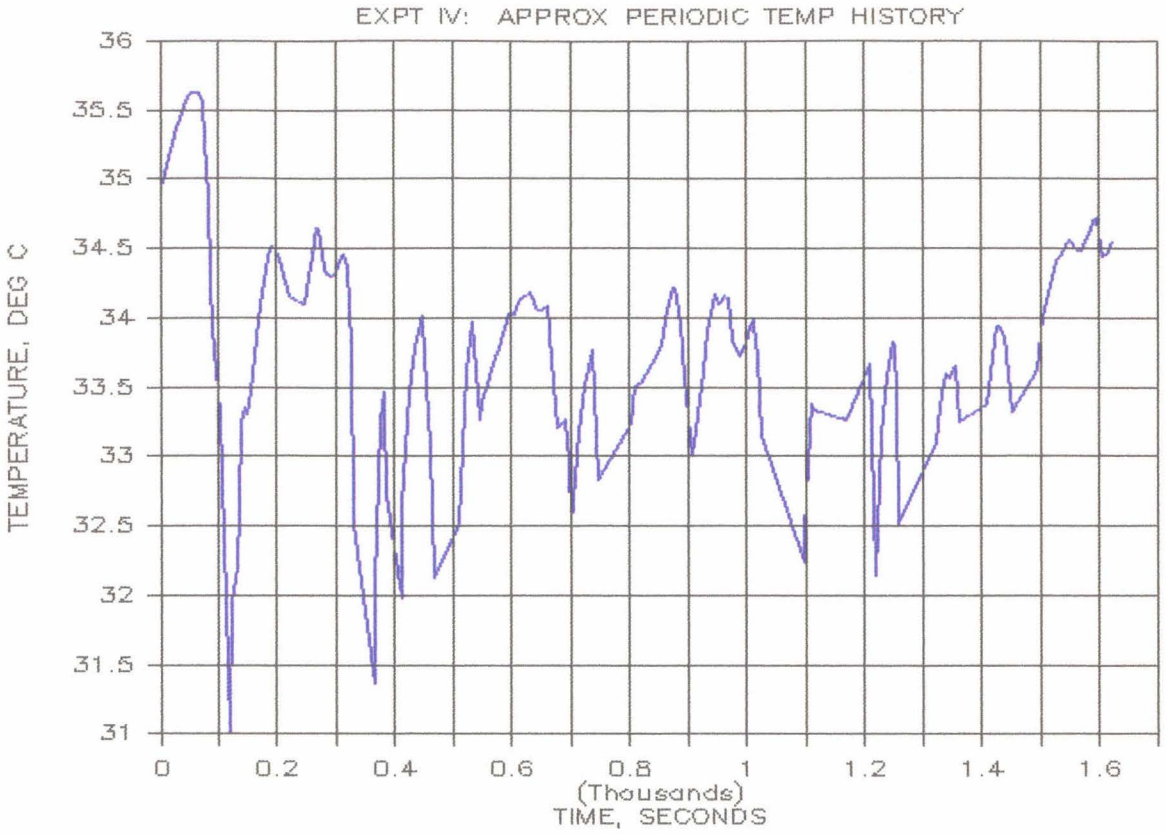

EXPT IV: APPROX PERIODIC TEMP HISTORY
TEMPERATURE, DEG C
36
35.5
35
34.5
34
33.5
33
32.5
32
31.5
31
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
(Thousands)
TIME, SECONDS

FIGURE 11

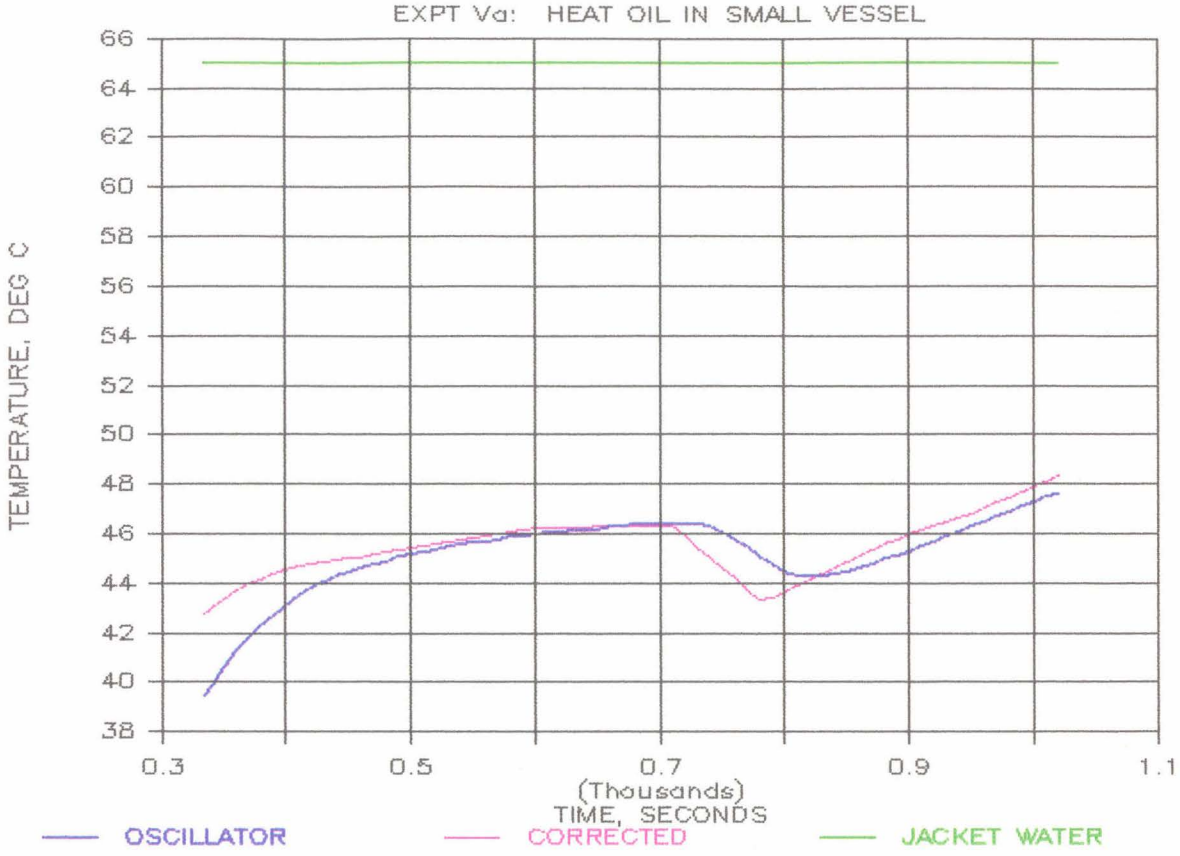

EXPT Va: HEAT OIL IN SMALL VESSEL
TEMPERATURE, DEG C
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
0.3
0.5
0.7
0.9
1.1
(Thousands)
TIME, SECONDS
OSCILLATOR
CORRECTED
JACKET WATER

FIGURE 12

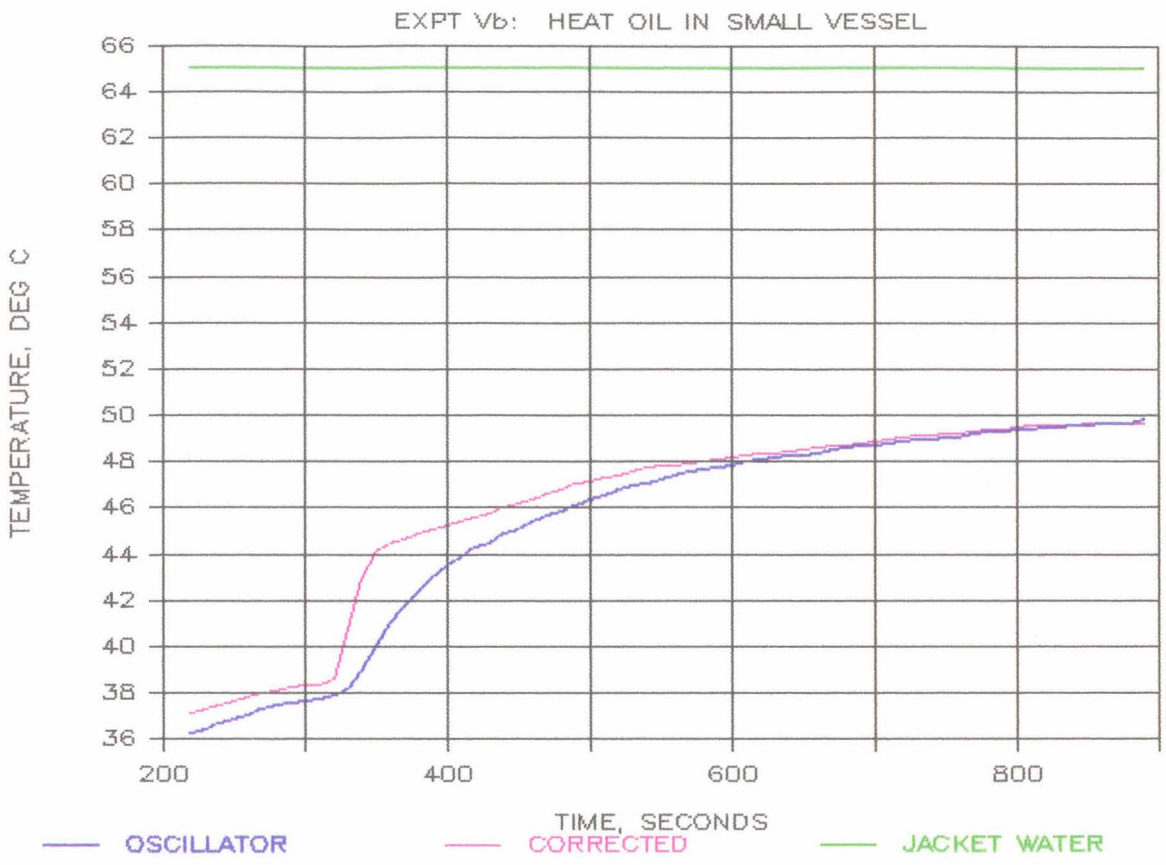

EXPT Vb: HEAT OIL IN SMALL VESSEL
TEMPERATURE, DEG C
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
200
400
600
800
TIME, SECONDS
OSCILLATOR
CORRECTED
JACKET WATER

FIGURE 13

EXPT Vc: HEAT OIL IN SMALL VESSEL

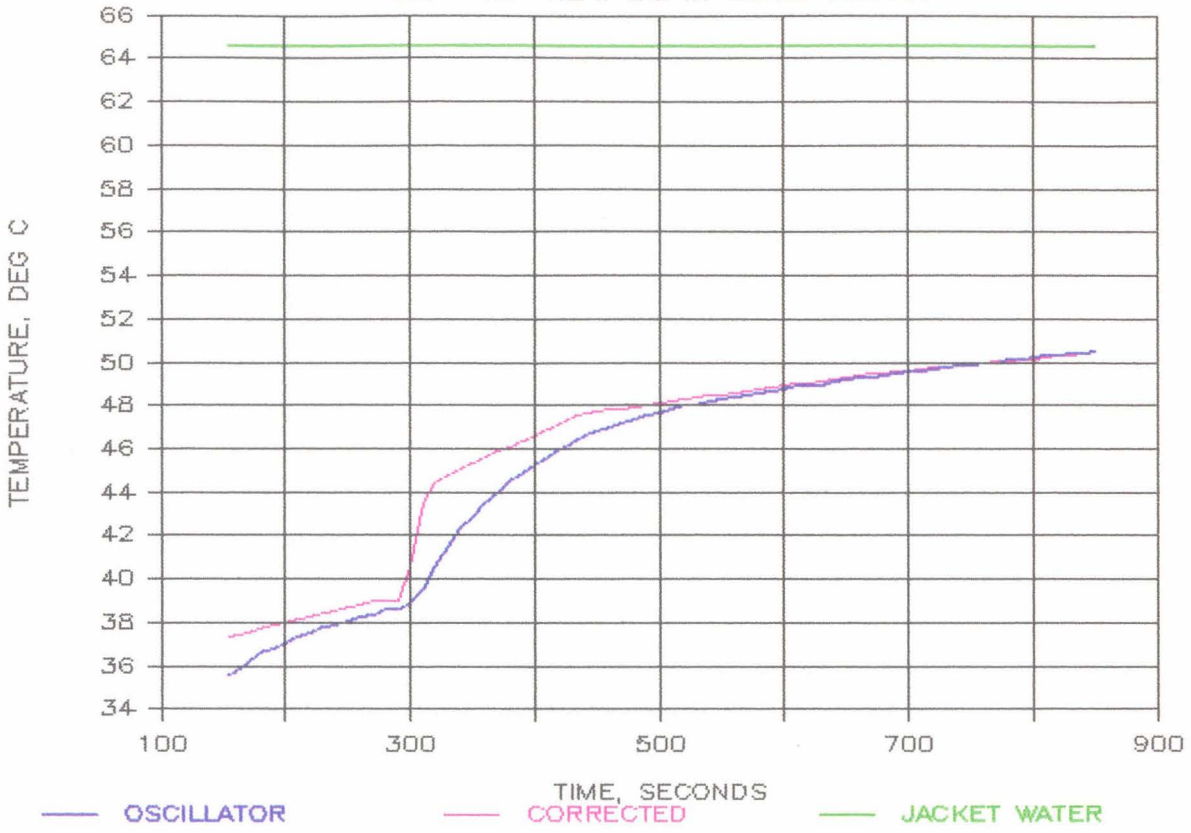
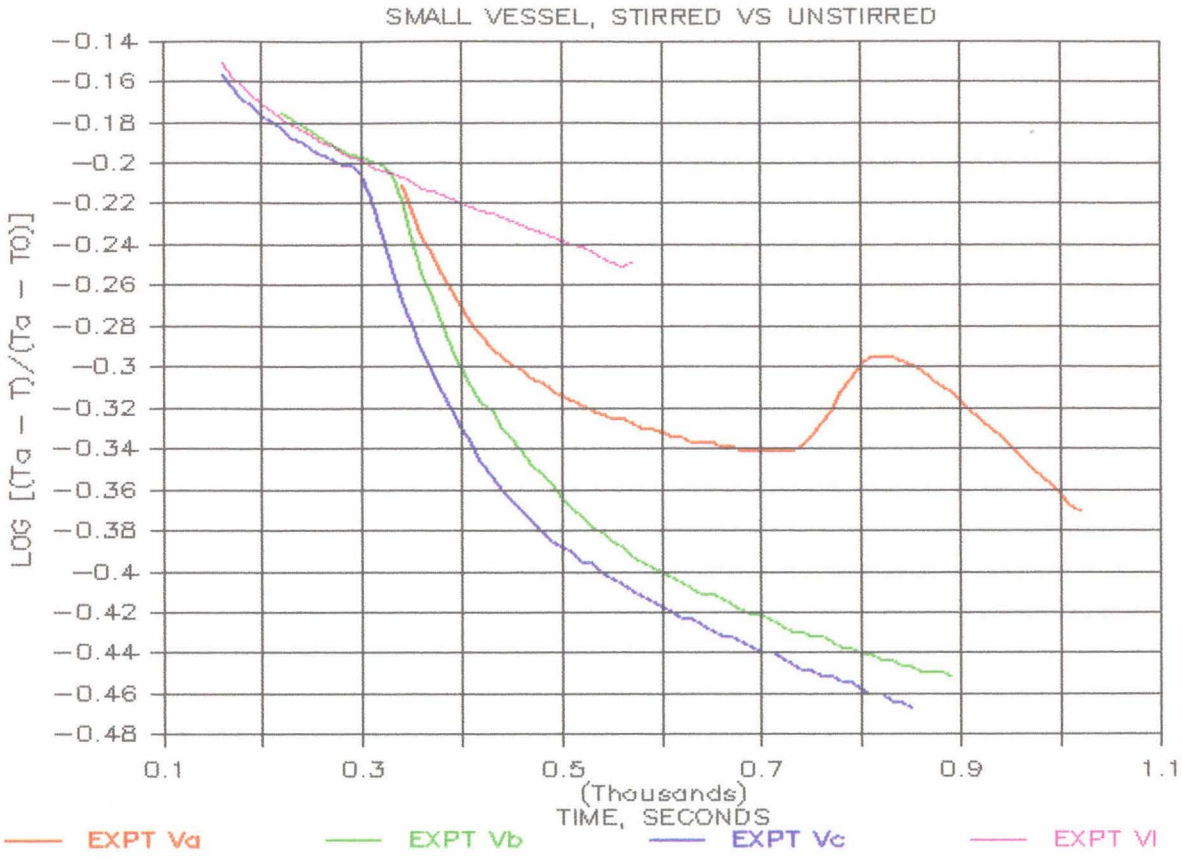


FIGURE 14



Expts Va, Vb, and Vc in unstirred oil
Expt VI in stirred oil

FIGURE 15

WARM JACKET WATER RUNS

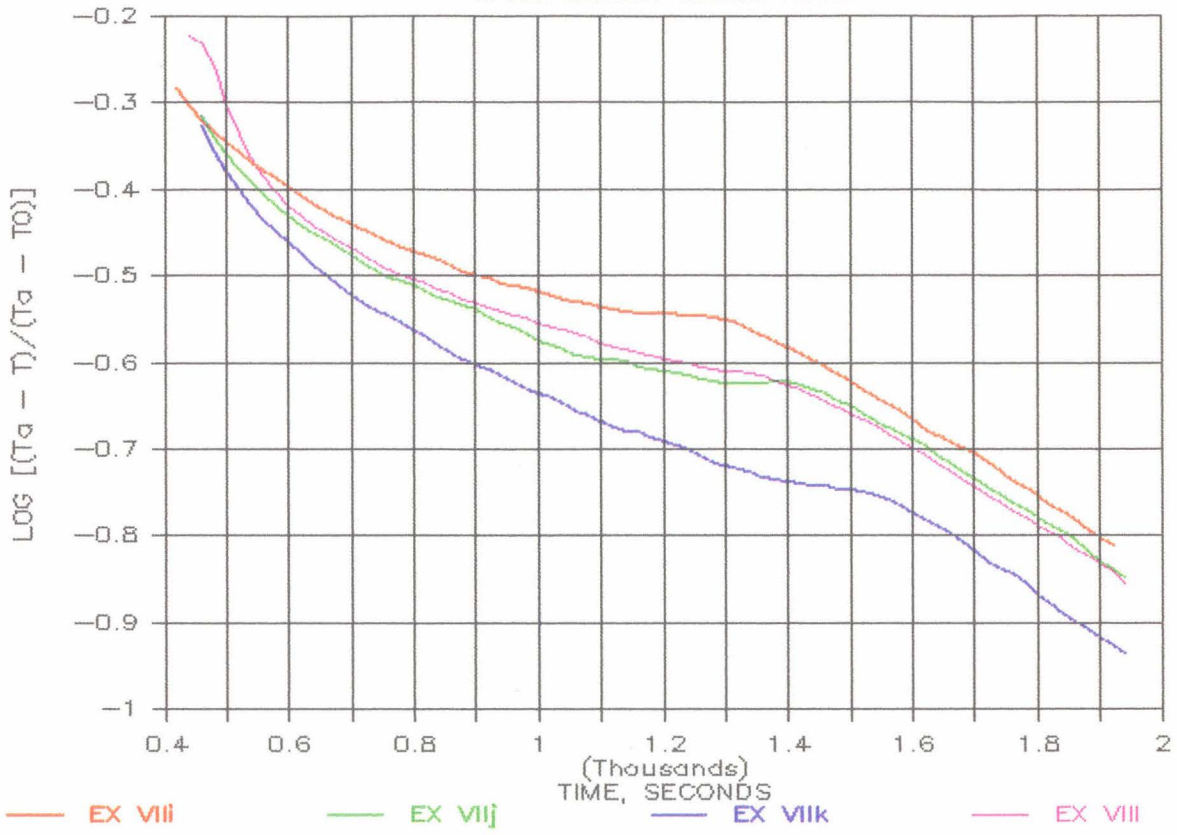


FIGURE 16

HOT JACKET WATER RUNS

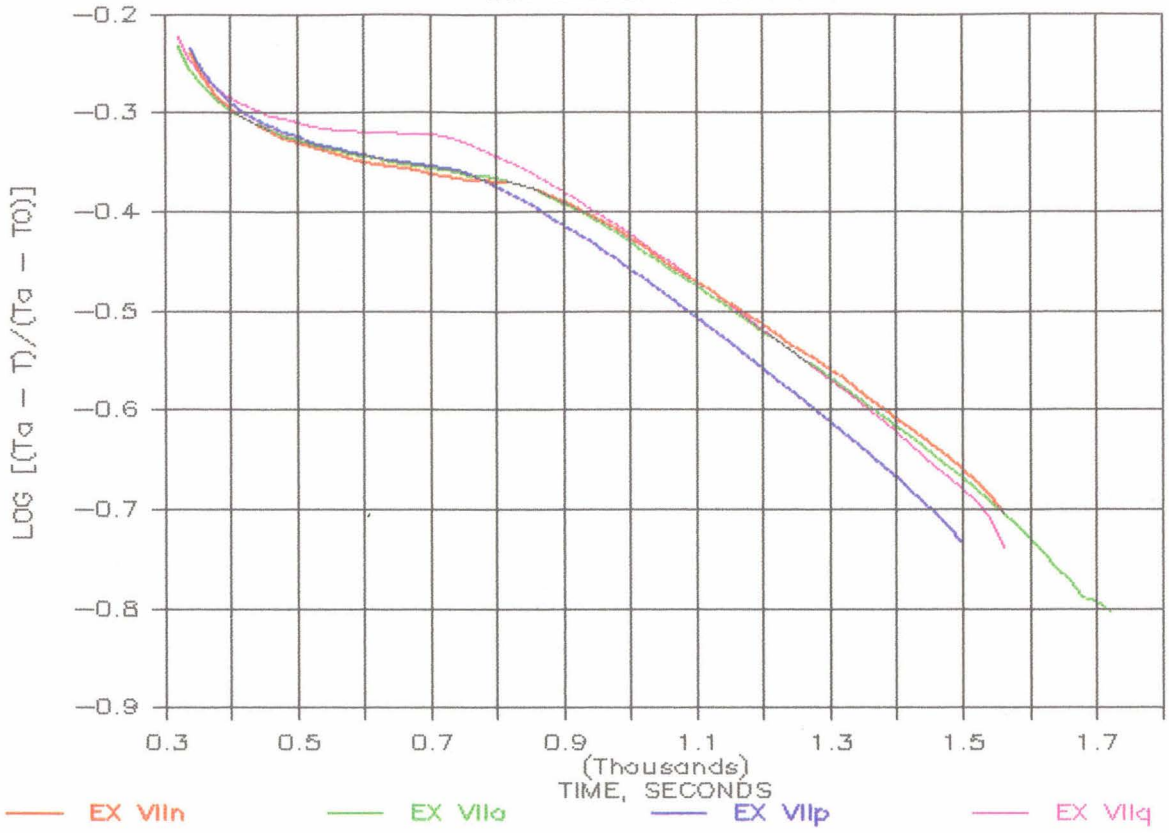
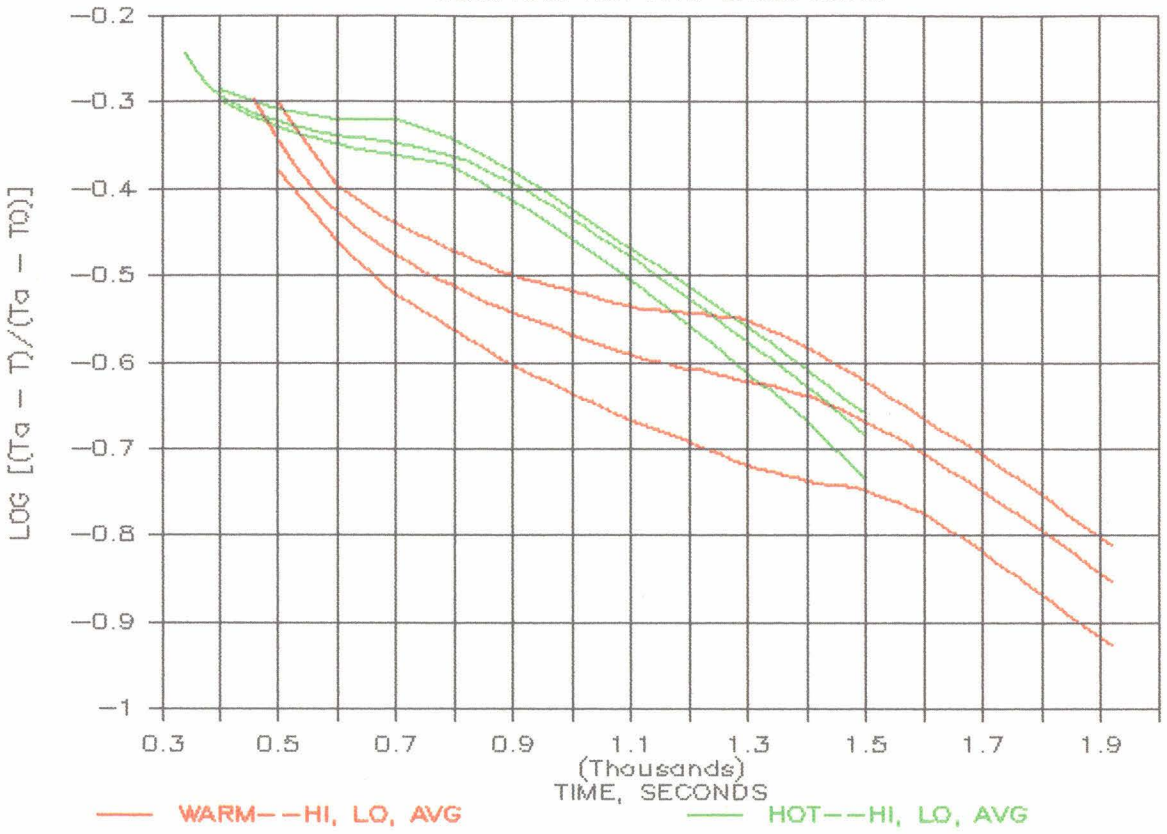


FIGURE 17

COMPARE HOT AND WARM RUNS



In each trio of curves, the center curve is the average of the data set. The upper and lower curves define the range of measurements.

FIGURE 18

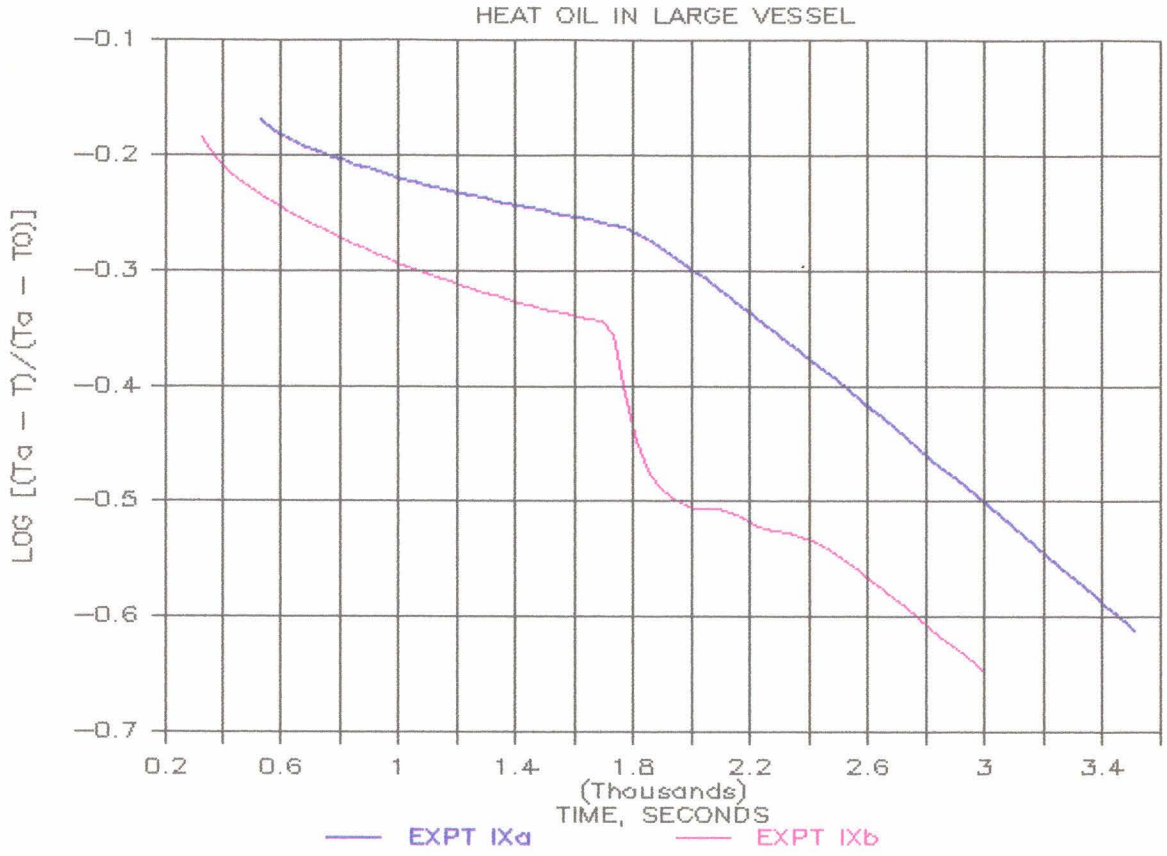
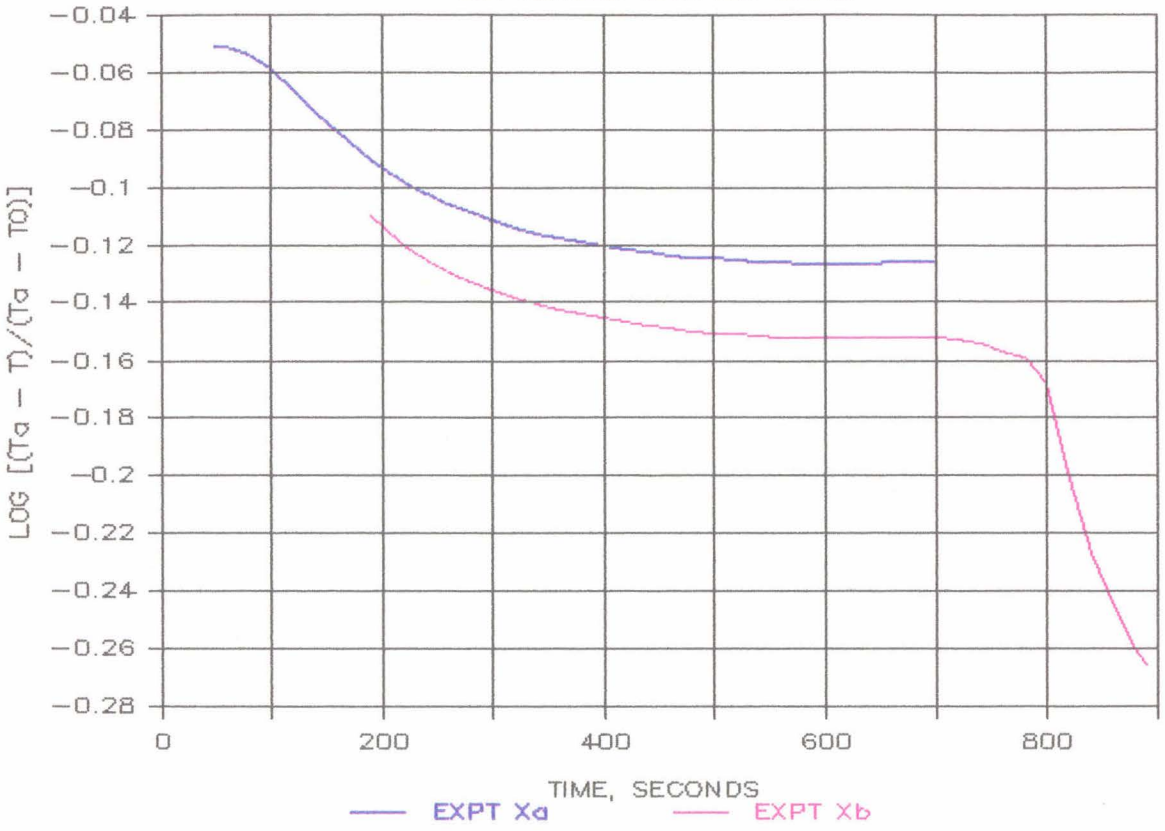

HEAT OIL IN LARGE VESSEL
LOG [(Ta − T)/(Ta − T0)]
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
0.2
0.6
1
1.4
1.8
2.2
2.6
3
3.4
(Thousands)
TIME, SECONDS
EXPT IXa
EXPT IXb

FIGURE 19

OIL COOLED WITH ICE WATER



NOMENCLATURE

Symbol	Definition	Typical Units
A	Heat transfer area, e.g., surface area of a cylinder, heated container, etc.	cm^2
	Surface area of oscillator in mathematical model for time constant	cm^2
a	Radius of spherical solid in Stokes' Law	cm
	Parameter in model for linearly changing surface temperature of a sphere, $T(R,t) = a + bt$	°C
b	Parameter in model for linearly changing surface temperature of a sphere, $T(R,t) = a + bt$	°C/sec
Bi	Biot's modulus, h_{out} l/k	--

Symbol	Definition	Typical Units
c	A constant	--
	Parameter defined in Expt. III as $c = R^2\kappa/\alpha$	--
Cp	Heat capacity	cal/g.^oC
D	Diameter of container or cylinder	cm
g	Acceleration of gravity	cm/sec^2
Gr	Grashof number, $l^3g\beta(\Delta T)/\nu^2$	--
h	Heat transfer coefficient between solid's surface and bulk fluid	cal/sec$\cdot$cm$^2\cdot^oC$
h_{out}	Heat transfer coefficient between outside heating medium and container wall	cal/sec$\cdot$cm$^2\cdot^oC$
k	Thermal conductivity	cal/sec$\cdot$cm$\cdot^oC$

Symbol	Definition	Typical Units
l	Characteristic container dimension	cm
m	Oscillator mass in mathematical model for time constant	g
Pr	Prandtl number, ν/α	--
R	Radius of solid sphere in Expts. I, II, and III	cm
r	Distance from center of sphere	cm
T	Temperature	^{o}C
t	Time	sec
T_a	Temperature of heating or cooling medium, e.g., water temperature in glass vessel's jacket	^{o}C
T_f	Temperature of feed water to water bath in Expt. III	^{o}C

Symbol	Definition	Typical Units
T_{fl}, T_{fluid}	Temperature of fluid outside boundary layer	°C
T_i	Initial temperature of water bath in Expt. III	°C
T_s	Surface temperature of sphere in Expt. I	°C
T_{surf}	Temperature at the surface of a free-floating particle	°C
T_{wall}	Temperature at inside wall of a cylinder	°C
T_0	Initial sphere temperature	°C
	Initial temperature of container contents	°C
t^*	Oscillator time constant	sec
U	Overall heat transfer coefficient between external heating medium and container contents	cal/sec·cm²·°C

Symbol	Definition	Typical Units
u	Stokes' Law Velocity	cm/sec
x	Spatial coordinate inside container	cm
y	Spatial coordinate inside container	cm
z	Spatial coordinate inside container	cm
α	Thermal Diffusivity	cm^2/sec
β	Volume expansivity of fluid	$(^oK)^{-1}$
	Parameter defined in Expt. II as $\beta = bR^2/\alpha(a-T_0)$	---
Γ	Parameter defined in Expt. III as $\Gamma = (T_f-T_i) \Big/ (T_i-T_0)$	---
ζ	Dimensionless distance from center of sphere, $\zeta = r/R$	---
Θ	Dimensionless temperature inside solid sphere, defined $\Theta = (T-T_0) \Big/ [T(R,0)-T_0]$	---

Symbol	Definition	Typical Units
θ	Dimensionless temperature evaluated at sphere's center, $\theta = \theta(0,\tau)$	--
κ	Space-velocity for water bath in Expt. III	sec^{-1}
μ	Viscosity	g/cm·sec
ν	Kinematic viscosity	cm^2/sec
ρ	Fluid density	g/cm^3
ρ_{La}	Liquid density at temperature of heating medium	g/cm^3
ρ_{Lo}	Liquid density at initial temperature	g/cm^3
ρ_{part}	Density of particle	g/cm^3
ρ_S	Solid density	g/cm^3
τ	Dimensionless time, $\tau = \alpha t/R^2$	--
ω	Frequency	rad/sec

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APPENDICES

APPENDIX 1: Derivations of Solutions to the Heat Conduction Problems of Experiments I, II and III

APPENDIX 2: Model for Oscillator Time Constant

APPENDIX 3: Computer Programs

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APPENDIX 1: DERIVATIONS OF SOLUTIONS TO THE HEAT CONDUCTION PROBLEMS OF EXPERIMENTS I, II, AND III

GENERAL PROBLEM Consider a sphere of radius R and thermal diffusivity α with initial uniform temperature T_0. At t=0 the temperature of the sphere's surface is changed so that T(R,t) = F(t), an arbitrary function, for all positive time.

The heat conduction equation is

$$\frac{\partial T}{\partial t} = \alpha\left[\frac{1}{r^2}\ \frac{\partial}{\partial r}\ r^2\ \frac{\partial T}{\partial r}\right] \tag{A1}$$

The initial condition is

$$T(r,0) = T_0 \tag{A2}$$

The two boundary conditons are

$$T(R,t) = F(t) \tag{A3}$$

and

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0 \tag{A4}$$

Define the following new dimensionless variables:

$$\theta = \frac{T-T_0}{F(0)-T_0} \quad , \quad \zeta = \frac{r}{R} \ , \ \text{and} \quad \tau = \frac{\alpha t}{R^2}$$

In terms of these variables, Equation (A1) becomes

$$\frac{\partial \theta}{\partial \tau} = \frac{1}{\zeta^2} \frac{\partial}{\partial \zeta} \left[\zeta^2 \frac{\partial \theta}{\partial \zeta} \right] \tag{A5}$$

The initial condition (A2) becomes

$$\theta(\zeta,0) = 0 \tag{A6}$$

and the boundary conditions, Equations (A3) and (A4), become

$$\theta(1,\tau) = \frac{F(t)-T_0}{F(0)-T_0} \equiv \phi(\tau) \tag{A7}$$

and

$$\left. \frac{\partial \theta}{\partial \zeta} \right|_{\zeta=0} = 0 \tag{A8}$$

CONSTANT SURFACE TEMPERATURE (EXPERIMENT I)

If the sphere's surface temperature is maintained constant at $F(t) = F(0) = T_s$, the temperature field inside the sphere is, from Carslaw and Jaeger [2],

$$T(r,t) = T_S + \frac{2R(T_S-T_0)}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin \frac{n\pi r}{R} \exp \left[\frac{-\alpha n^2\pi^2 t}{R^2}\right] \qquad (A9)$$

Equations (A7) and (A9) are, in terms of dimensionless variables,

$$\phi(\tau) = 1 \quad \text{and}$$

$$\Theta = 1 + \frac{2}{\pi\zeta} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} (\sin n\pi\zeta)\exp(-n^2\pi^2\tau) \qquad (A10)$$

The dimensionless temperature history at the center of the sphere is

$$\Theta(0,\tau) = 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp(-n^2\pi^2\tau) \qquad (A11)$$

The program "CONTHRY.BAS", listed in Appendix 3, uses Equation (A11) to generate dimensionless temperature histories for various values of α and R.

LINEARLY CHANGING SURFACE TEMPERATURE (EXPERIMENT II)

Consider a surface temperature which has the form

$$T(R,t) = F(t) = a + bt \qquad (A12)$$

In dimensionless terms,

$$\Theta(1,\tau) = \phi(\tau) = 1 + \frac{bR^2\tau}{\alpha(a-T_0)} = 1 + \beta\tau \tag{A13}$$

$$\text{where} \qquad \beta = \frac{bR^2}{\alpha(a-T_0)} \tag{A14}$$

The solution to this problem is obtained with the help of Duhamel's Theorem [7], which states

$$\Theta(\zeta,\tau) = \phi(0)\cdot A(\zeta,\tau) + \int_0^\tau A(\zeta,\tau-\tau^*)\ \phi'(\tau^*)d\tau^* \tag{A15}$$

where $\phi(\tau)$ may be arbitrary and $A(\zeta,\tau)$ is the solution to the problem in which $\phi(\tau)=1$. Note that $A(\zeta,\tau)$ is thus given by Equation (A10). Substitution of Equation (A10) into Equation (A15) yields, after simplification,

$$\Theta(\zeta,\tau) = \phi(\tau) + \frac{2}{\pi\zeta}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\left[\phi(0) + \right.$$

$$\left.\int_0^\tau \phi'(\tau^*)e^{n^2\pi^2\tau^*}\,d\tau^*\right](\sin n\pi\zeta)e^{-n^2\pi^2\tau} \tag{A16}$$

For the case at hand, $\phi(\tau) = 1 + \beta\tau$, and Equation (A16) becomes

$$\theta(\zeta,\tau) = 1 + \beta\tau + \frac{2}{\pi\zeta} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \left[e^{-n^2\pi^2\tau} + \frac{\beta}{n^2\pi^2} (1 - e^{-n^2\pi^2\tau})\right] \sin n\pi\zeta \qquad (A17)$$

Evaluated at the center of the sphere, the solution is

$$\theta(0,\tau) = 1 + \beta\tau + 2 \sum_{n=1}^{\infty} (-1)^n \left[e^{-n^2\pi^2\tau} + \frac{\beta}{n^2\pi^2} (1 - e^{-n^2\pi^2\tau})\right] \qquad (A18)$$

The program "LINTHRY.BAS", listed in Appendix 3, uses Equation (A18) to generate a dimensionless temperature history, given a value for β.

EXPONENTIALLY CHANGING SURFACE TEMPERATURE (EXPERIMENT III)

Consider a well-mixed water bath of volume V and initial temperature T_i. Beginning at t=0, water is fed to and removed from the bath at volumetric rate v; the feed temperature is T_f. An energy balance shows that the water in the bath will have temperature

$$T_{bath} = T_i + (T_f - T_i) (1 - e^{-tv/V}) \qquad (A19)$$

If a sphere with initial temperature T_0 is immersed in the water bath at t=0, the boundary condition (A3) becomes

$$T(R,t) = F(t) = T_i + (T_f - T_i)\,(1 - e^{-tv/V}) \tag{A20}$$

In dimensionless terms Equation (A20) is

$$\Theta(1,\tau) = \phi(\tau) = 1 + \Gamma(1 - e^{-c\tau}) \tag{A21}$$

where
$$\Gamma = \frac{T_f - T_i}{T_i - T_0} \quad \text{and} \quad c = \frac{R^2 v}{\alpha V} \tag{A22}$$

Equation (A21) can be substituted into (A16) to give the solution to the exponential problem. This solution is, after simplification.

$$\Theta(\zeta,\tau) = 1 + \Gamma(1-e^{-c\tau}) + \frac{2}{\pi\zeta} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} (\sin n\pi\zeta)\, [e^{-n^2\pi^2\tau} + \frac{c\Gamma}{n^2\pi^2 - c} \left(e^{-c\tau} - e^{-n^2\pi^2\tau}\right)] \tag{A23}$$

The dimensionless temperature history at the sphere's center is

$$\Theta(0,\tau) = 1 + \Gamma(1-e^{-c\tau}) + 2 \sum_{n=1}^{\infty} (-1)^n\, [e^{-n^2\pi^2\tau} + \frac{c\Gamma}{n^2\pi^2 - c} (e^{-c\tau} - e^{-n^2\pi^2\tau})] \tag{A24}$$

The program "EXPTHRY.BAS", listed in Appendix 3, uses Equation (A24) to generate a dimensionless temperature history, given values for c and Γ.

APPENDIX 2: MODEL FOR OSCILLATOR TIME CONSTANT

MODEL Regard the oscillator as an object with mass m, heat capacity C_p, and external surface area A. The heat transfer coefficient between ambient fluid and the surface of the oscillator is h. The initial temperature of the oscillator is T_0, and its temperature at any later time t is T(t). Suppose that, at t=0, the oscillator is dropped into a fluid with (constant) temperature T_f. The equations governing the oscillator's temperature change are:

Energy balance: $$mC_p \frac{dT}{dt} = hA\,(T_f - T) \tag{A25}$$

Initial condition: $$T(0) = T_0 \tag{A26}$$

Rewrite Equation (A25) in terms of dimensionless temperature and define $t^* = mC_p/hA$:

$$-t^* \frac{d}{dt} \frac{T_f - T}{T_f - T_0} = \frac{T_f - T}{T_f - T_0} \tag{A27}$$

Integrate Equation (A27) and bring in initial condition (A26):

$$\frac{T_f - T}{T_f - T_0} = e^{-t/t^*} \tag{A28}$$

Note that at $t=t^*$, the dimensionless temperature is $(T_f - T) \,/\, (T_f - T_0) = e^{-1} = 0.37$,

so t^* is, by definition, the oscillator's thermal time constant.

CORRECTING THE OSCILLATOR MEASUREMENTS Suppose the fluid temperature is no longer constant but a function of time, $T_f(t)$. Equation (A25) can be used to convert the oscillator's measurements T(t) to the "true" temperatures $T_f(t)$. Using the definition for t^*, Equation (A25) can be rewritten

$$t^* \cdot \frac{dT}{dt} + T = T_f(t) \qquad \text{(A29)}$$

Given a history T(t) and a value for t^*, Equation (A29) gives the corrected history directly. The program "TFLUID.BAS" in Appendix 3 uses Equation (A29), the experimentally-determined value $t^* = 42.3$ sec, and numerical differentiation to generate "true" temperature histories from oscillator measurements.

RESPONSE TO SINUSOIDAL FLUID TEMPERATURE Consider a fluid temperature which varies as

$$T_f(t) = A \sin \omega t + T_{fa} \qquad \text{(A30)}$$

The homogeneous form of Equation (A29) is

$$t^* \frac{dT}{dt} + T = 0 \qquad \text{(A31)}$$

with solution

$$T_{hom} = K_1 e^{-t/t^*} \tag{A32}$$

A particular solution to Equation (A29) is

$$T_{part} = \frac{A}{1+(\omega t^*)^2} \sin\omega t - \frac{A\omega t^*}{1+(\omega t^*)^2} \cos\omega t + T_{fa} \tag{A33}$$

Addition of Equations (A32) and (A33) gives the general solution

$$T = K_1 e^{-t/t^*} + \frac{A}{1+(\omega t^*)^2} \sin\omega t - \frac{A\omega t^*}{1+(\omega t^*)^2} \cos\omega t + T_{fa} \tag{A34}$$

The long-time ($t \to \infty$) or "steady-state" solution is

$$T_{ss} = \frac{A}{1+(\omega t^*)^2} \sin\omega t - \frac{A\omega t^*}{1+(\omega t^*)^2} \cos\omega t + T_{fa} \tag{A35}$$

This function is a sinusoid with frequency ω and wave amplitude $A[1+(\omega t^*)^2]^{-0.5}$. The amplitude of oscillation has been attenuated by a factor of $[1+(\omega t^*)^2]^{-0.5}$.

APPENDIX 3: COMPUTER PROGRAMS

The BASIC programs listed below were used during the course of this research. Listings of these programs are given in the following pages.

"TIMING.BAS" -- allows the investigator to specify a temperature sampling period and to save a temperature history under a data file name. This program controls the operations of the pulse counter and converts pulse periods to temperatures using the oscillator's calibration curve.

"CONTHRY.BAS" -- given the thermal diffusivity and radius of a sphere whose surface is maintained at constant temperature, this program generates a table of time vs. dimensionless temperature at the sphere's center.

"LINTHRY.BAS" -- given a value for dimensionless β, this program generates the dimensionless temperature history of the center of a sphere whose surface temperature is changed linearly.

"EXPTHRY.BAS" -- given values for dimensionless c and Γ, this program generates the dimensionless temperature history of the center of a sphere whose surface temperature is changed exponentially.

"TFLUID.BAS" -- generates a temperature history corrected for the oscillator's thermal lag. The oscillator's temperature history and time constant are input to the program.

```
1  REM  THIS PROGRAM IS "TIMING.BAS"
2  REM
3  REM
4  REM
10 KEY OFF
20        CLEAR   ,59000!          ' GPIB-PC Rev. B.1
30        IBINIT1 = 59000!         ' BASICA Declaration File
40        IBINIT2 = IBINIT1 + 3    '
50        BLOAD "bib.m",IBINIT1
60        CALL IBINIT1(IBFIND,IBTRG,IBCLR,IBPCT,IBSIC,IBLOC,IBPPC,IBBNA,IBONL,IBR
SC,IBSRE,IBRSV,IBPAD,IBSAD,IBIST,IBDMA,IBEOS,IBTMO,IBEOT)
70        CALL IBINIT2(IBGTS,IBCAC,IBWAIT,IBPOKE,IBWRT,IBWRTA,IBCMD,IBCMDA,IBRD,I
BRDA,IBSTOP,IBRPP,IBRSP,IBDIAG,IBXTRC,IBSTA%,IBERR%,IBCNT%)
80 DIM TMP(2,4000)
90 CLS
100 DEV$="COUNTER"
110 CALL IBFIND(DEV$,CNT%)
120 IF CNT%>0 GOTO 170
130 LOCATE 11,1:PRINT "ERROR IN IBFIND. CHECK MACHINE. HIT ANY KEY TO CONTINUE"
140 A$=INKEY$:IF A$="" GOTO 140
150 LOCATE 11,1:PRINT "                                                                "
160 GOTO 110
170 CALL IBCLR(CNT%)
180 IF IBSTA%>0 GOTO 200
190 END
200 WRT$="FN7WA0"
210 PERIOD$=SPACE$(21)
220 CALL IBWRT(CNT%,WRT$)
230 PRINT "THIS PROGRAM IS USED IN CONJUNCTION WITH THE HP COUNTER. PLEASE MAKE
SURE"
240 PRINT "THAT ALL CONNECTIONS AND INSTRUMENTS ARE ON AND READY TO GO."
250 PRINT "    THIS PROGRAM WILL INPUT THE SIGNAL PERIOD FROM THE COUNTER AND "
260 PRINT "CONVERT IT TO THE TEMP OF THE PROBE BASED ON THE PROPER CALIBRATION"
270 PRINT"CURVE. IT WILL THEN SAVE THE TRIGGER TIME AND TEMPERATURE IN A "
280 PRINT "TWO-DIMENSIONAL ARRAY  (TRIGGER TIME, TEMPERATURE). YOU WILL THEN HAV
E"
290 PRINT "THE OPTION OF SAVING THE DATA ON DISK AT THE END OF THE EXPERIMENT"
300 PRINT"THE TIME INTERVAL BETWEEN READINGS IS UP TO YOU. FREE RUN IS ABOUT "
310 PRINT"3 READINGS PER SECOND."
311 PRINT"NOTE WELL--CURRENT CALIBRATION IS FOR OSCILLATOR #2"
320 LOCATE 11,1:INPUT "DO YOU WISH TO TAKE SAMPLE READINGS (Y/N) ";A$
330 IF A$="Y" THEN GOTO 350 ELSE IF A$="y" THEN GOTO 350
340 IF A$="N" THEN GOTO 410 ELSE IF A$="n" THEN GOTO 410 ELSE GOTO 320
350 LOCATE 11,1:PRINT "                                                "
360 LOCATE 11,15:PRINT "DEGREES C   (HIT ANY KEY TO STOP)"
370 CALL IBRD(CNT%,PERIOD$)
380 PERIOD=1000*(VAL(MID$(PERIOD$,7,9)))*10^(VAL(MID$(PERIOD$,17,3)))
390 LOCATE 11,1:PRINT 122.1-13.39*LOG(PERIOD)
400 A$=INKEY$:IF A$="" THEN GOTO 370
410 LOCATE 11,1:INPUT "SAMPLING PERIOD  (IN SECONDS OR 'F' FOR FREE RUN)
    ";SMP$
420 LOCATE 13,1:PRINT"TIME ELAPSED"
430 LOCATE 14,1:PRINT "TEMPERATURE"
440 IF SMP$="F" THEN GOTO 590 ELSE DT=VAL(SMP$)
450 LOCATE 11,1:PRINT "HIT ANY KEY TO BEGIN EXPERIMENT
        "
460 A$=INKEY$:IF A$="" THEN GOTO 460
```

```
470 TIME$="00:00:00"
480 LOCATE 11,1:PRINT "HIT ANY KEY TO STOP EXPERIMENT                                    "

490 B=B+DT:A=A+1
500 IF TIMER>B-.06 THEN GOTO 510 ELSE GOTO 500
510 CALL IBRD(CNT%,PERIOD$):TRGTIME=TIMER
520 PERIOD=1000*(VAL(MID$(PERIOD$,7,9)))*10^(VAL(MID$(PERIOD$,17,3)))
530 TEMP=122.1-13.39*LOG(PERIOD)
540 TMP(1,A)=TRGTIME:TMP(2,A)=TEMP
550 LOCATE 13,14: PRINT "                              "
560 LOCATE 13,14:PRINT TRGTIME
570 LOCATE 14,14:PRINT TEMP
580 A$=INKEY$:IF A$="" THEN GOTO 490 ELSE GOTO 720
590 LOCATE 11,1:PRINT "HIT ANY KEY TO BEGIN EXPERIMENT
          "
600 A$=INKEY$:IF A$="" THEN GOTO 600
610 TIME$="00:00:00"
620 LOCATE 11,1:PRINT "HIT ANY KEY TO STOP EXPERIMENT                                    "

630 A=A+1
640 CALL IBRD(CNT%,PERIOD$):TRGTIME=TIMER
650 PERIOD=1000*(VAL(MID$(PERIOD$,7,9)))*10^(VAL(MID$(PERIOD$,17,3)))
660 TEMP=122.1-13.39*LOG(PERIOD)
670 TMP(1,A)=TRGTIME:TMP(2,A)=TEMP
680 LOCATE 13,14: PRINT"                       "
690 LOCATE 13,14:PRINT TRGTIME
700 LOCATE 14,14:PRINT TEMP
710 A$=INKEY$:IF A$="" GOTO 630 ELSE GOTO 720
720 LOCATE 11,1:PRINT "EXPERIMENT LASTED ";TRGTIME;" SECONDS  -  ";A;"  DATA POI
NTS"
730 LOCATE 13,1:PRINT"                                                              "
740 LOCATE 14,1:PRINT"DO YOU WISH TO SAVE DATA ON DISK (Y/N) ?
750 A$=INKEY$:IF A$="Y" THEN GOTO 770
760 IF A$="N" THEN GOTO 840 ELSE GOTO 750
770 LOCATE 14,1:PRINT "
780 LOCATE 15,1:INPUT"DATA FILE NAME";FILE$
790 LOCATE 16,1:PRINT "WRITING DATA TO DISK"
800 OPEN "O",#1,FILE$
810 FOR C=1 TO A
820 WRITE #1,TMP(1,C),TMP(2,C)
830 NEXT:CLOSE #1:LOCATE 16,1:PRINT "
840 LOCATE 23,1:PRINT "HIT ANY KEY TO EXIT SYSTEM"
850 A$=INKEY$:IF A$="" THEN GOTO 850 ELSE SYSTEM
```

```
1  REM  THIS PROGRAM IS "CONTHRY.BAS"
2  REM
3  REM
4  REM
10 REM  THIS PROGRAM GENERATES A TABLE OF DIMENSIONLESS TEMP
11 REM  AT THE CENTER OF A SPHERE VERSUS TIME WITH
12 REM  SURFACE MAINTAINED AT CONSTANT TEMPERATURE.
13 REM  DEFINE K= ALPHA /(R^2)
20 LET PI=3.14159
30 PRINT "ALPHA/(R^2)=";
35 INPUT K
36 LPRINT
37 LPRINT " ALPHA/(R^2)= ",K
38 LPRINT
40 FOR TAU=.002 TO 1! STEP .002
50 LET SUM=0
60 FOR N=1 TO 30
70 LET M=((-1)^N)*EXP(-(N^2)*(PI^2)*TAU)
80 LET SUM=SUM+M
90 NEXT N
100 LET THETA=1+(2*SUM)
105 LET TIME=TAU/K
110 LPRINT "TIME=",TIME, "    THETA=",THETA
120 NEXT TAU
130 END
```

```
1  REM THIS PROGRAM IS "LINTHRY.BAS"
2  REM
3  REM
4  REM
10 REM THIS PROGRAM CALCULATES SPHERE
20 REM DIMENSIONLESS CENTER TEMPERATURE
30 REM FOR A LINEAR CHANGE IN SURFACE
40 REM TEMPERATURE.
50 REM INITIAL SPHERE TEMP=TO
60 REM SURFACE TEMP VARIES AS T(R,t)=A+Bt
70 REM SPHERE RADIUS AND THERMAL DIFFUSIVITY
80 REM ARE R AND ALPHA.
90 REM DEFINE BETA=(B*R*R)/(ALPHA*(A-TO))
100 REM DIMENSIONLESS CENTER TEMPERATURE
110 REM IS THETA=(T-TO)/(T(R,0)-TO)
120 REM DIMENSIONLESS TIME IS TAU=(ALPHA*t)/R^2
130 PRINT "INPUT BETA AND FINAL TAU"
140 INPUT BETA, TAUF
150 OPEN "O", #1, "LINTHRY.DAT"
155 PI=3.14159
160 TAU=.01
170 SUM=0
180 FOR N%=1 TO 30
190 F1=EXP(-N%*N%*PI*PI*TAU)
200 F2=BETA/(N%*N%*PI*PI)
210 SUM=SUM+(F1+F2*(1-F1))*(-1)^N%
220 NEXT N%
230 THETA=1+BETA*TAU+2*SUM
240 WRITE #1, TAU, THETA
250 TAU=TAU+.01
260 IF TAU>TAUF THEN GOTO 270 ELSE 170
270 CLOSE #1
```

```
1   REM  THIS PROGRAM IS "EXPTHRY.BAS"
2   REM
3   REM
4   REM
10  REM  THIS PROGRAM CALCULATES SPHERE
20  REM  DIMENSIONLESS CENTER TEMPERATURE
30  REM  FOR AN EXPONENTIAL CHANGE IN SURFACE
40  REM  TEMPERATURE.
50  REM  INITIAL SPHERE TEMPERATURE=TO
60  REM  SURFACE TEMP VARIES AS T(R,t)=
65  REM  Ti+(Tf-Ti)*(1-exp(-t*v/V))
70  REM  SPHERE RADIUS AND THERMAL DIFFUSIVITY
80  REM  ARE R AND ALPHA
90  REM  DEFINE GAM=(Tf-Ti)/(Ti-TO) AND
95  REM  DEFINE C=R*R*v/(ALPHA*V)
100 REM   DIMENSIONLESS CENTER TEMPERATURE
110 REM   IS THETA=(T-TO)/(T(R,O)-TO)
120 REM   DIMENSIONLESS TIME IS TAU=(ALPHA*t)/R^2
130 PRINT "INPUT GAM, C, AND FINAL TAU"
140 INPUT GAM,C,TAUF
150 OPEN "O", #1, "EXPTHRY.DAT"
155 PI=3.14159
160 TAU=.004
170 SUM=O
175 F2=EXP(-C*TAU)
180 FOR N%=1 TO 30
190 F1=EXP(-N%*N%*PI*PI*TAU)
210 F3=C*GAM/(N%*N%*PI*PI-C)
220 SUM=SUM+(F1+F3*(F2-F1))*(-1)^N%
230 NEXT N%
240 THETA=1+GAM*(1-F2)+2*SUM
250 WRITE #1, TAU, THETA
260 TAU=TAU+.004
270 IF TAU<TAUF THEN GOTO 170
280 CLOSE #1
```

```
1   REM  THIS PROGRAM IS "TFLUID.BAS"
2   REM
3   REM
4   REM
10  OPEN "I", #1, "EXPT5A.DAT"
20  OPEN "O", #2, "TFL5A.DAT"
30  LET TC=42.3
40  INPUT #1, T1, TOSC1, T2, TOSC2
50  LET DERIV=(TOSC2-TOSC1)/(T2-T1)
60  LET TOSC=(TOSC1+TOSC2)/2
70  LET TIME=(T1+T2)/2
80  LET TFL=(TC*DERIV)+TOSC
90  WRITE #2, TIME, TFL
95  IF T2>1029.8 GOTO 130
100 LET T1=T2
110 LET TOSC1=TOSC2
120 INPUT #1, T2, TOSC2
125 GOTO 50
130 CLOSE #1
140 CLOSE #2
```

APPENDIX 4: PHYSICAL PROPERTIES OF DOW CORNING 200 FLUID 20 cS SILICONE OIL

Source: Dow Corning U.S.A.

Specific Gravity at 25/15.6°C	0.949
Kinematic Viscosity, cS	
at 25°C	20
at 50°C	13
at 75°C	9.3
Coefficient of Expansion, $(°C)^{-1}$	0.00107
Thermal conductivity at 50°C, cal/cm sec. °C	0.00034
Specific Heat* at 25°C, cal/g.°C	0.357

*Estimated from information provided by Dow Corning for fluids of similar viscosity.

APPENDIX 5: DIRECTIONS FOR OPERATING THE EQUIPMENT

Suppose for the sake of illustration that room temperature silicone oil, containing the floating ball-and-oscillator, is to be heated in a jacketed glass vessel. Measurements of the oscillator's temperature are to be taken, recorded, and saved in a data file.

PREPARATION The calibration for the oscillator to be used must be entered in lines 390, 530, and 660 of "TIMING.BAS" (see Appendix 3). The IBM PC-XT and Hewlett Packard pulse counter should each be turned on. An AM radio, tuned to 1400 kHz, must be on and placed close enough to the vessel to receive the oscillator signals. A cable must connect the pulse counter's Channel A input to the earplug jack on the radio; the radio connection should not be made, however, until after the oscillator has started to pulse. Pulse counter settings are as follows:

Blue selector button pushed in and FREQ A/PER A button set to PER A.

Channel A Trigger Level/Sensitivity button set to Trigger Level (the out position).

Slope button set to trigger period measurements on negative slope.

AC/DC button set to DC (in position).

Attenuation set at X1.

FILTER NORM/100 kHz button set at 100 kHz.

STARTING THE EXPERIMENT To begin the experiment, charge the vessel's jacket with hot water and listen to the radio for the oscillator signal. The device

will commence pulsing when the transistor's temperature is between 30 and 35°C. When the pulsing starts, plug the pulse counter cable into the radio earplug jack; the pulse counter's numeric display will indicate the oscillator period in milliseconds.

Type HELP on the personal computer. This activates the program "TIMING.BAS", which then poses some questions to the terminal user:

1. Do you wish to take sample measurements? If "yes" is answered, the terminal flashes the oscillator's changing temperature until any key is pressed. These measurements cannot be saved in a data file. If the user answers "no", the next question appears.

2. Sampling period? The user may now specify the time between temperature measurements. Measuring starts when any key is depressed.

ENDING THE EXPERIMENT At the end of a run the user can stop the computer's recording of oscillator temperatures by pressing any key. He then may elect to save the temperature history in a data file under any file name. Such a file would consist of several lines of (time, temperature) pairs.

APPENDIX 6: DIMENSIONAL TEMPERATURE HISTORIES MEASURED BY THE OSCILLATOR IN EXPERIMENTS I - X

EXPT1A.DAT (Pure Polyurethane)

Time (sec), Temp. (°C)

30.48,43.33383
60.52,43.32961
.72999,43.32998
120.12,43.32426
150.33,43.32536
180.59,43.32512
210.8,43.32563
240.18,43.33064
270.39,43.33726
300.16,43.34315
330.32,43.35256
360.47,43.35724
390.57,43.37978
420.67,43.39241
450.71,43.41326
480.65,43.43155
510.58,43.45669
540.46,43.48551
570.23,43.51506
600.77,43.55174
630.37,43.59062
660.25,35.73136
690.46,35.77876
720.56,43.73061
750.5,43.7828
780.71,35.93894
810.31,43.90287
840.63,43.97092
0.73,44.04059
900.66,44.11083
930.38,44.18795
960.6999,44.26265
990.0299,44.34176
1020.73,44.42752
1050.45,44.51073
1080.65,44.59834

1110.7,44.6886
1140.47,44.77555
1170.02,44.86565
1200.06,44.95516
1230.66,45.0536
1260.21,45.14439
1290.3,45.23995
1320.13,45.33407
1350.39,45.42857
1380.44,45.52412
1410.21,45.62096
1440.47,45.7162
1470.46,45.81109
1500.17,45.90765
1530.38,46.00046
1560.32,46.09587
1590.31,46.18838
1620.41,46.28284
1650.29,46.37789
1680.61,46.46871
1710.59,46.56161
1740.42,46.65182
1770.63,46.74308
1800.56,46.83139
1830.33,46.91885
1860.43,47.00788
1890.04,47.09189
1920.36,47.1793
1950.4,47.26554
1980.28,47.34619
2010.21,47.4311
2040.2,47.50954
2070.03,47.59325
2100.24,47.67295
2130.17,47.75205
2160.54,47.83068
2190.42,47.90854
2220.08,47.9811
2250.4,48.05775
2279.95,48.12953
2310.49,48.20349
2340.21,48.27365
2370.36,48.3483
2400.02,48.41508
2430.34,48.48283
2460.44,48.55172
2490.43,48.61977
2520.2,48.68377
2550.35,48.74977
2580.34,48.81122
2610.11,48.87231
2640.04,48.93561
2670.09,48.99452
2700.46,49.0551
2730.18,49.11075
2760,49.17019
2790.43,49.22558
2820.25,49.28071
2850.13,49.33378
2880.18,49.38718
2910,49.43926
2940.27,49.4929
2970.37,49.54137
3000.35,49.59237
3030.18,49.64377

3090.49,49.74314
3120.42,49.78804
3150.25,49.83438
3179.96,49.87922
3210.06,49.92286
3239.99,49.9686
3270.37,50.0137
3300.08,50.0544
3330.18,50.09826
3360.17,50.13743
3390.05,50.18065
3420.32,50.22205
3450.41,50.26055
3480.02,50.29726
3510.39,50.33509
3540.27,50.37351
3570.26,50.41128
3600.36,50.44756
3630.35,50.48247
3660.28,50.51518
3690.11,50.55225
3720.32,50.58098
3749.98,50.61742
3780.02,50.65107
3810.18,50.68154
3840.06,50.7124
3870.26,50.74477
3900.2,50.77018
3930.3,50.80366
3960.07,50.83438
3989.95,50.86176
4020.27,50.89212
50.26,50.92075
4080.41,50.9471
4110.01,50.97195
4140,51.00178
4170.16,51.02672
4199.98,51.05239
4230.25,51.0783
4260.4,51.10288
4290.06,51.12676
4320.1,51.15195
4350.04,51.17602
4380.41,51.20005
4410.24,51.22201
4440.28,51.24303
4470.44,51.2647
4500.1,51.28747
4530.14,51.30933
4560.13,51.33076
4590.06,51.34874
4620.38,51.3681
4650.21,51.38956
4680.42,51.41059
4710.13,51.42895
4740.23,51.44868
4770.27,51.46797
4800.1,51.4838
830.03,51.50521
4860.13,51.52098
4890.23,51.53649
4920.06,51.55622
4950.05,51.56976
4980.14,51.58974
5010.24,51.60634

5070.33,51.63932
5100.1,51.65512
5130.04,51.66859
5160.35,51.68537
5190.23,51.6983
5220.06,51.70962
5250.27,51.72773
5280.42,51.74094
5310.3,51.75392
5340.02,51.76623
5370.06,51.78174
5400.27,51.79242
5430.26,51.80797
5460.19,51.819
5490.13,51.83199
5520.01,51.8445
5550.27,51.85721
5580.1,51.86886
5610.08,51.88155
5640.24,51.8906
5670.01,51.90274
5700.11,51.91361
5730.37,51.9249
5760.03,51.93625
5790.08,51.94757
5820.07,51.9565
5850.22,51.96538
5880.15,51.97523
5910.31,51.98634
5940.19,51.99504
5970.07,52.00617
6000.28,52.01424
6030.1,52.02425
6060.31,52.03313
6090.08,52.04068
6120.01,52.04982
6150.17,52.05508
6180.27,52.06696
6210.37,52.07396
6240.03,52.08313
6270.07,52.08942
6300.28,52.10025
6330.27,52.10509
6360.28,52.11278
6390.03,52.1202
6420.35,52.12782
6450.28,52.13338
6480.21,52.14135
6510.26,52.14419
6540.14,52.15453
6570.02,52.16099
6600.23,52.16532
6630.05,52.17352
6660.04,52.18275
6690.25,52.18576
6720.02,52.19204
6749.95,52.19579
6780.11,52.20319
6810.26,52.2092
6840.36,52.21465
6870.08,52.22162
6900.12,52.22247
6930.22,52.22993
6960.04,52.2354
6990.09,52.24173
7020.13,52.24385

7050.12,52.25312
7080.33,52.2543
7110.32,52.25943
7140.31,52.26354
7170.24,52.26579
7200.23,52.27336
7230.17,52.27614
7260.1,52.281
7289.98,52.28596
7320.3,52.29142
7350.18,52.29557
7380.11,52.29745
7410.38,52.30284
7440.2,52.30557
7470.08,52.30888
7500.35,52.31417
7530.17,52.31691
7560.38,52.3197
7589.98,52.32556
7620.19,52.32821
7650.02,52.33062
7680.01,52.33397
7710.16,52.33776
7740.32,52.34183
7770.08,52.34221
7800.24,52.34812
7830.01,52.34737
7860.16,52.35247
7890.1,52.35528
7920.2,52.35554
7950.3,52.35939
7980.01,52.36585
8010.11,52.36785
8040.21,52.36785
8070.31,52.3733

Raw Data from Expt. # 1D

(Polyurethane + 11% Al)

Time (sec) → Temp. (°C)

15.37,68.93535
30.04,68.93481
45.09,68.93173
60.14,68.93065
75.19,68.92592
90.01999,68.92615
105.07,68.91722
120.12,68.89819
135.06,68.87693
150.16,68.85463
165.1,68.8225
180.1,68.78761
195.15,68.74508
209.98,68.70366
225.02,68.65036
240.02,68.59068
255.07,68.51711
270.06,68.4498
285.11,68.3637
300.11,68.27018
315.05,68.16504
330.1,68.0549
345.09,67.93395
0.09,67.81224
375.03,67.6714
390.13,67.52863
405.07,67.37795
419.96,67.22023
435.06,67.0547
450.22,66.87208
465.16,66.69702

480.1,66.50847
495.04,66.31801
509.98,66.12625
525.03,65.91974
540.13,65.71336
555.18,65.50545
570.01,65.29839
[illegible]5.01,65.07936
[illegible]0.06,64.86546
615.16,64.63531
630.05,64.4134
644.99,64.18367
660.09,63.95432
674.97,63.73152
690.13,63.48268
705.07,63.24646
720.12,63.01419
735.12,62.77173
750.06,62.53242
765.05,62.31388
780.16,62.05913
794.99,61.81462
810.09,61.6001
825.09,61.35699
840.19,61.12582
855.13,60.89349
870.12,60.67092
885.01,60.45328
900.11,60.22639
915.05,60.00511
930.05,59.78305
945.1,59.56364
960.1499,59.35298
[illegible]5.0299,59.15297
990.1399,58.93665
1005.02,58.72701
1020.13,58.52123
1035.01,58.32823
1050.12,58.1206
1065.22,57.91906
1080.05,57.73039
1095.04,57.53989
1110.09,57.34846
1125.03,57.15769
1140.25,56.97242
1155.13,56.79131
1170.18,56.61415
1185.18,56.43762
1200.12,56.25886
1215,56.08737
1230.05,55.9122
1245.27,55.74134
1260.15,55.58283
1275.15,55.41851
1290.08,55.25708
1305.19,55.09173
1320.07,54.94285
1335.23,54.78341
[illegible]50.23,54.63467
[illegible]65,54.48594
1380.05,54.33556
1395.27,54.19131
1410.04,54.04809
1425.26,53.9046
1440.31,53.76281

1485.07,53.36949
1500.07,53.24028
1515.22,53.10742
1530.16,52.98194
1545.27,52.85395
1560.1,52.73884
1575.09,52.61414
1590.25,52.49978
1605.14,52.378
1620.19,52.26
1634.96,52.15768
1650.29,52.0408
1665.28,51.93316
1680.11,51.82581
1695.38,51.71488
1710.37,51.61962
1725.15,51.51061
1740.36,51.40944
1755.36,51.31362
1770.02,51.2152
1785.24,51.12027
1800.12,51.02645
1815.12,50.93335
1830.22,50.84173
1845,50.75369
1860.32,50.66169
1875.32,50.57302
1890.42,50.48915
1905.2,50.40487
1920.03,50.3281
1934.97,50.24076
1950.01,50.16191
1965.12,50.08364
1980.33,50.00352
1995.22,49.93069
2010.16,49.85523
2025.21,49.78096
2040.31,49.7064
2055.09,49.64011
2070.36,49.56694
2085.24,49.49983
2100.02,49.43183
2115.29,49.36439
2130.39,49.2965
2145.17,49.23694
2160.43,49.16635
2175.32,49.10653
2190.26,49.04838
2205.25,48.98872
2220.36,48.92627
2235.02,48.87004
2250.24,48.81428
2265.07,48.76371
2280.39,48.70114
2295.33,48.64731
2310.33,48.59629
2325.38,48.54223
2340.48,48.48979
2355.15,48.44081
2370.36,48.38939
2385.13,48.33908
2400.46,48.29416
2415.34,48.24712
2430.28,48.20069
2445.28,48.15727

2475.43,48.06482
2490.1,48.01718
2505.26,47.9777
2519.98,47.93501
2535.3,47.89553
2550.13,47.85453
2565.51,47.81207
2580.39,47.77712
2595.33,47.73664
2610.33,47.69728
2625.38,47.65924
2640.48,47.62131
2655.09,47.5893
2670.25,47.55348
2685.47,47.51915
2700.13,47.48309
2715.46,47.45067
2730.23,47.41811
2745.06,47.38546
2760.44,47.35351
2775.11,47.32009
2790.05,47.29335
2805.53,47.26133
2820.53,47.2285
2835.03,47.20245
2850.08,47.1703
2865.18,47.14413
2880.29,47.11482
2895.45,47.08706
2910.11,47.06346
2925.33,47.03041
2940.05,47.00817
2955.32,46.98355
2970.09,46.95636
2985.47,46.93471
3000.25,46.90827
3015.13,46.88462
3030.01,46.85894
3045.45,46.83615
3060.39,46.81452
3075.33,46.79386
3090.27,46.76887
3105.26,46.74935
3120.31,46.7265
3135.36,46.70833
3150.41,46.6861
3165.52,46.66567
3180.07,46.64459
3195.23,46.62618
3210.39,46.60797
3225,46.58869
3240.21,46.5706
3255.43,46.55216
3270.09,46.53784
3285.36,46.51526
3300.08,46.5003
3315.41,46.48346
3330.13,46.46559
3345.51,46.44581
3360.28,46.43251
3375.11,46.41522
3390.49,46.39952
3405.32,46.38108
3420.21,46.37059
3435.09,46.35278

3465.46,46.32707
3480.4,46.30888
3495.34,46.29882
3510.28,46.28537
3525.28,46.27439
3540.22,46.2617
[illegible]55.21,46.24539
3570.26,46.2348
3585.26,46.22027
3600.31,46.207
3615.41,46.19477
3630.46,46.18398
3645.24,46.17184
3660.34,46.1633
3675.44,46.15699
3690.55,46.14237
3705.1,46.12752
3720.26,46.11431
3735.42,46.10636
3750.03,46.09846
3765.19,46.08808
3780.41,46.07621
3795.02,46.06507
3810.23,46.05697
3825.45,46.0486
3840.11,46.04052
3855.38,46.03027
3870.05,46.01927
3885.31,46.00912
3900.58,46.00228
3915.3,45.99738
[illegible]929.97,45.98815
[illegible]945.29,45.97605
3960.01,45.9618
3975.34,45.96
3990.11,45.95109
4005.44,45.94423
4020.21,45.93812
4035.54,45.93534
4050.37,45.92259
4065.14,45.91509
4080.25,45.90747
4095.02,45.90361
4110.4,45.89282
4125.23,45.89002
4140.06,45.88374
4155.49,45.87921
4170.32,45.87424
4185.21,45.86491
4200.04,45.85597
4215.47,45.84774
4230.36,45.84468
4245.24,45.84099
4260.13,45.83431
4275.01,45.82786
4290.5,45.82379
4305.38,45.81755
[illegible]320.27,45.80875
4335.21,45.80016
4350.09,45.80136
4365.03,45.79753
4380.58,45.79186
4395.52,45.78803
4410.46,45.78127
4425.07,45.77659

4440.01,45.77068
4454.95,45.76954
4470.55,45.76811
4485.49,45.76139
4500.48,45.75388
4515.42,45.75128
4530.41,45.74895
4545.41,45.74023
4560.4,45.74011
4575.34,45.73776
4590.34,45.73169
4605.33,45.72998
4620.05,45.72285
4635.05,45.71942
4650.37,45.72157
4665.37,45.71553
4680.42,45.70876
4695.41,45.71193
4710.46,45.69819
4725.51,45.69709
4740.5,45.69737
4755.55,45.69783
4770.6,45.69041
4785.05,45.68209
4800.1,45.68589
4815.15,45.68133
4830.2,45.67853
4845.25,45.67618
4860.3,45.67027
4875.07,45.66813
4890.12,45.665
4905.23,45.66238
4920.28,45.65704
4935.38,45.66064
4950.43,45.65738
4965.53,45.6512
4979.98,45.65296
4995.41,45.65141
5010.46,45.6435
5025.57,45.64401
5040.07,45.6423
5055.17,45.63726
5070.28,45.63931
5085.38,45.63398
5100.49,45.63291
5115.59,45.6283
5130.09,45.62706
5145.53,45.62655
5160.03,45.62384
5175.13,45.62511
5190.29,45.6232
5205.39,45.61985
5220.5,45.61609
5235.05,45.61522
5250.16,45.61355
5265.26,45.61068
5280.42,45.61096
5295.53,45.60504
5310.08,45.60681
5325.24,45.60604
5340.38,45.60398
5355.51,45.60131
5370.01,45.60368
5385.16,45.60533
5400.32,45.59848

5445.14,45.59429
5460.3,45.59063
5475.13,45.58346
5490.29,45.59591
5505.45,45.59142
5520.01,45.59075
[illegible]35.17,45.58626
5550.33,45.58834
5565.49,45.58327
5580.04,45.58223
5595.2,45.58404
5610.36,45.57958
5625.52,45.57998
5640.13,45.58081
5655.29,45.57726
5670.45,45.57879
5685,45.5751
5700.16,45.57669
5715.38,45.57574
5730.54,45.57425
5745.09,45.56887
5760.25,45.57705
5775.47,45.57008
5790.02,45.56671
5805.18,45.56896
5820.07,45.56529
5835.28,45.56462
5850.44,45.57185
5864.99,45.56591
5880.21,45.5634
5895.37,45.55731
[illegible]910.58,45.56248
[illegible]925.14,45.5621
5940.35,45.56002
5955.51,45.55932
5970.12,45.55668
5985.28,45.55915
6000.5,45.55948
6015.05,45.55802
6030.26,45.56087
6045.42,45.55901
6060.03,45.5551
6075.25,45.55755
6090.41,45.55544
6105.02,45.55308
6120.23,45.55386
6135.39,45.55231
6150,45.55001
6165.22,45.55122
6180.38,45.54608
6195.59,45.55698
6210.2,45.55548
6225.36,45.55155
6240.57,45.54777
6255.18,45.55292
6270.4,45.54624
6284.95,45.54933
[illegible]300.17,45.54799
6315.38,45.54225
6330.6,45.54791
6345.15,45.54595
6360.37,45.54587
6375.58,45.54907
6390.19,45.55222
[illegible]

6420.02,45.54734
6435.18,45.54226
6450.12,45.54307
6465.33,45.54171
6480.54,45.54385
6495.1,45.54511
6510.31,45.54017
6525.53,45.54199
6540.14,45.54635
6555.35,45.53983
6570.57,45.54178
6585.18,45.53858
6600.39,45.54341
6615,45.53968
6630.22,45.5373
6645.1,45.53817
6660.32,45.53842
6675.53,45.53691
6690.14,45.53934
6705.35,45.53769
6720.57,45.53578
6735.45,45.53606
6750.06,45.53571
6765.28,45.53618
6780.49,45.53981
6795.1,45.53931
6810.32,45.53517
6825.53,45.53812
6840.14,45.53952
6855.36,45.53764
6869.97,45.53298
6885.18,45.53299
6900.39,45.53285
6915,45.53635
6930.22,45.53924
6945.49,45.5336
6960.04,45.53477
6975.31,45.53462
6990.53,45.53885
7005.14,45.53429
7020.35,45.53031
7035.57,45.53138
7050.18,45.53605
7065.39,45.53276
7080,45.53014
7095.22,45.53201
7110.43,45.52967
7125.04,45.53207
7140.25,45.53272
7155.47,45.53431
7170.08,45.53418
7185.29,45.5364
7200.56,45.52963
7215.17,45.53114
7230.39,45.53306
7245.6,45.53092
7260.21,45.52895
7275.43,45.53376
7290.04,45.53422
7305.25,45.53186
7320.46,45.53203
7335.07,45.52889
7350.29,45.53882
7365.56,45.53281
7380.17,45.53382

7410.27,45.53627
7425.48,45.52925
7440.09,45.53643
7455.31,45.53627
7470.58,45.53413
7485.19,45.53144
7500.4,45.5276
7515.01,45.53044
7530.23,45.53226
7545.44,45.53321
7560.05,45.53304
7575.26,45.53701
7590.48,45.53157
7605.09,45.52998
7620.3,45.53388
7635.52,45.53623
7650.13,45.5337
7665.34,45.53485
7680.01,45.53247
7695.22,45.53247
7710.44,45.53392

"EXPT 2 .DAT" (Linear Surface Temp.)

Raw oscillator data for Expt. # 2

Time (sec) ↓ Temp. (°C) ↙

Initial temp = 68.36°C

```
15.21,68.37694
75.08,68.37279
90.01999,68.36948
105.12,68.36237
120.06,68.34468
135.06,68.33468
150.05,68.30565
[illegible].05,68.27896
[illegible].1,68.24893
195.04,68.20889
209.98,68.16389
225.02,68.12101
240.07,68.06937
255.07,68.00377
270.12,67.93328
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285.06,67.8616
300.11,67.76942
315.05,67.67997
330.15,67.57926
345.15,67.47545
360.14,67.35509
[illegible].08,67.22131
[illegible].13,67.0916
404.96,66.95012
420.01,66.81094
435,66.65015
450.16,66.48691
465.16,66.32468
480.15,66.16275
495.2,65.98573
510.14,65.80046
525.14,65.61898
540.19,65.42891
555.02,65.23666
570.01,65.0494
585.06,64.85201
600,64.65415
615,64.44864
630.1,64.2397
645.15,64.03228
660.09,63.82385
675.14,63.60586
690.08,63.3997
705.13,63.18784
720.01,62.9839
735.06,62.77739
750.11,62.57762
[illegible].05,62.37227
780.05,62.17577
795.1,61.97648
809.98,61.78522
825.14,61.58566
840.0799,61.39775
855.13,61.21029
870.12,61.01934
885.17,60.84225
900,60.66388
915.05,60.48842
930.1,60.31237
945.1,60.14315
960.1499,59.97721
975.1399,59.81031
990.1399,59.65125
1005.08,59.49004
1020.18,59.33388
1035.01,59.18478
1050.06,59.03752
1065,58.89119
1080.1,58.74636
1095.21,58.61251
1110.15,58.47629
1125.09,58.33832
[illegible]0.14,58.20963
[illegible]5.08,58.07961
1170.18,57.95923
1185.12,57.83744
1200.01,57.71807
1215.06,57.608
1230.16,57.49596
1245.21,57.39103

1275.09,57.18086
1290.19,57.07676
1305.13,56.98144
1320.18,56.88978
1335.12,56.79949
1350.12,56.70587
1365,56.62396
1[illegible]0.16,56.53836
1[illegible]5.21,56.45352
1410.1,56.38234
1424.98,56.30653
1440.03,56.23432
1455.14,56.16633
1470.02,56.09698
1485.02,56.02868
1500.07,55.9679
1515.17,55.90896
1530.22,55.84934
1560.21,55.73873
1605.19,55.59358
1620.13,55.54499
1650.07,55.47118
1665.01,55.42675
1710.16,55.31901
1725.09,55.28801
1740.09,55.26079
1755.14,55.23146
1770.19,55.20897
1785.02,55.18687
1800.12,55.16056
1815.23,55.14181
1830.11,55.12097
1845,55.10626
1[illegible]0.21,55.08888
1875.1,55.07291
1890.04,55.062
1905.03,55.05195
1920.25,55.04122
1935.24,55.03269
1950.23,55.02844
1965.23,55.01938
1980.17,55.01425
1995.05,55.00913
2025.04,55.00694
2040.04,55.01168
2070.03,55.01428
2085.02,55.02004
2100.02,55.02442
2114.96,55.03498
2130.23,55.04084
2145.22,55.04988
2160.16,55.05603
2175.1,55.07131
2190.04,55.07987
2205.2,55.10021
2220.14,55.10945
2235.02,55.11915
2250.18,55.13543
[illegible]5.01,55.15653
[illegible]0.12,55.17317
2295.22,55.19078
2310,55.20794
2325.1,55.23496
2340.1,55.25144
2355.15,55.27013
[illegible]

2385.08,55.32073
2400.02,55.34577
2415.07,55.36302
2429.95,55.39439
2445.11,55.41588
2460.22,55.4439
[illegible]5.05,55.46907
[illegible].1,55.49829
2505.15,55.51949
2520.25,55.55462
2535.19,55.58021
2550.13,55.61577
2565.02,55.64703
2580.17,55.67386
2595,55.70226
2610.11,55.73887
2625.1,55.76905
2640.15,55.80174
2655.09,55.83559
2670.03,55.87039
2685.19,55.90565
2700.02,55.93935
2715.13,55.97642
2730.18,56.00941
2745.23,56.04656
2760.17,56.08522
2775.11,56.12056
2790.26,56.15811
2805.09,56.19824
2820.2,56.23377
2835.25,56.27328
2850.24,56.31157
[illegible]5.18,56.35092
2880.07,56.39192
2895.23,56.42434
2910,56.4694
2925.05,56.51206
2940.05,56.54875
2955.15,56.58858
2970.04,56.62992
2985.2,56.67221
3000.03,56.71276
3015.02,56.75791
3030.01,56.79047
3045.23,56.83925
3060.11,56.88282
3075.22,56.92829
3090.05,56.96633
3105.04,57.00531
3120.26,57.05049
3135.14,57.0946
3150.03,57.13867
3165.13,57.1797
3180.13,57.22615
3195.12,57.27271
3210.06,57.3125
3225.17,57.36317
[illegible]0.27,57.40319
[illegible]5.04,57.44495
3269.98,57.48501
3285.2,57.5396
3300.08,57.57821
3315.13,57.62613
3330.18,57.66981
3345.18,57.71185

3374.95,57.8052
3390.05,57.84474
3405.05,57.89341
3420.04,57.93821
3435.2,57.98597
3450.03,58.0285
3465.13,58.07158
[illegible]0.13,58.12316
[illegible]5.07,58.16616
3510.01,58.21188
3525.06,58.25659
3540.11,58.3055
3555.1,58.34427
3570.04,58.3929
3585.15,58.43666
3599.98,58.48749
3615.03,58.5307
3629.97,58.57583
3645.13,58.61971
3660.01,58.66817
3675.06,58.71117
3690.05,58.75869
3705.21,58.80178
3720.1,58.8519
3735.15,58.89065
3750.2,58.93997
3765.14,58.98662
3780.02,59.03113
3795.13,59.07334
3810.18,59.12029
3825.17,59.1653
3840.06,59.21416
3855.16,59.25582
3[illegible]9.99,59.30103
3884.98,59.34068
3900.14,59.38944
3915.08,59.43885
3930.13,59.48038
3945.13,59.52219
3960.12,59.56586
3975.01,59.60916
3990.11,59.65502
4005.11,59.71085
4020.1,59.74375
4035.04,59.79198
4050.09,59.84408
4065.14,59.88487
4080.14,59.92613
4095.07,59.96425
4110.18,60.01049
4125.01,60.05963
4140,60.10069
4155.16,60.14093
4170.05,60.18673
4185.1,60.23161
4200.09,60.27661
4215.03,60.32567
4230.14,60.36576
[illegible]5.02,60.40904
[illegible]0.02,60.4565
4275.01,60.49768
4290.12,60.53953
4305.17,60.57397
4320.16,60.62092
[illegible]

4365.14,60.7522
4380.14,60.7907
4395.13,60.8424
4410.02,60.88296
4425.12,60.92464
4440.12,60.9621
4[illegible]5.11,61.00675
4[illegible]0.05,61.05173
4485.1,61.09008
4500.15,61.13676
4515.09,61.17887
4530.03,61.22337
4545.08,61.26464
4575.12,61.33638
4590.06,61.38345
4605.11,61.42568
4620.16,61.46949
4635.16,61.49306
4650.1,61.54399
4665.15,61.58655
4679.98,61.62171
4694.97,61.66839
4710.13,61.7108
4725.02,61.74713
4740.01,61.79054
4755,61.82179
4770.16,61.8654
4830.03,62.02808
4845.08,62.0655
4860.13,62.09986
4875.13,62.14872
4[illegible]90.07,62.18871
4[illegible]4.95,62.22098
4920,62.25376
4935.1[illegible],62.30071
4950.1,62.33483
4965.04,62.37198
4980.09,62.41069
4995.08,62.45153
5010.02,62.49219
5025.07,62.52481
5040.12,62.5576
5055.12,62.59966
5070.06,62.64222
5085.16,62.67294
5100.05,62.70915
5115.04,62.74565
5130.15,62.78337
5145.09,62.82525
5160.08,62.86242
5175.07,62.90734
5190.07,62.93506
5204.95,62.96559
5235,63.04409
5265.04,63.11945
5280.09,63.15792

"EXPT3 .DAT"

Raw data from oscillator for Expt. # 3

Time (sec)

Temp. (°C)

15.37,70.25698
30.09,70.256
105.12,70.24455
120.12,70.235
134.95,70.21986
[illegible].22,70.20006
165.1,70.16848
180.15,70.14346
195.09,70.10376
210.03,70.06025
225.08,70.01249
240.13,69.95284
255.17,69.88764

269.95,69.80705
285.11,69.71702
300.16,69.61898
315.16,69.51253
330.04,69.38827
345.09,69.25526
360.09,69.10425
375.19,68.94484
390.13,68.77385
405.07,68.58467
435.11,68.17236
450.05,67.94104
465.05,67.70422
480.04,67.45009
495.09,67.17599
510.14,66.89537
525.14,66.60112
540.02,66.308
555.13,65.98471
570.01,65.65349
585.01,65.31427
600,64.95711
615.16,64.56958
630.05,64.17899
645.09,63.77748
660.09,63.3908
675.08,62.9761
690.08,62.56307
705.13,62.14678
719.96,61.73104
735.12,61.30387
749.95,60.87627
765.11,60.43594
780.16,60.00028
795.1,59.5632
810.09,59.12013
825.09,58.67862
840.19,58.22739
855.0799,57.79074
870.18,57.33903
885.06,56.89619
900.17,56.44702
915.22,56.00068
930.2099,55.55203
945.2099,55.10877
960.04,54.67032
975.0299,54.22342
990.0799,53.78273
1005.13,53.3444
1020.29,52.89964
1035.29,52.46761
1050.06,52.03783
1065.27,51.60613
1080.21,51.18177
1095.21,50.75741
1110.31,50.33189
1124.98,49.92193
1140.14,49.50147
1155.3,49.08637
1170.02,48.68859
1185.18,48.28004
1200.28,47.87563
1215.33,47.47698
1230.27,47.08779
1245.43,46.69164

1275.31,45.92657
1290.58,45.54211
1305.41,45.17373
1319.96,44.81209
1335.62,44.43447
1350.34,44.07825
1365.5,43.71816
1380.33,43.36956
1395.6,43.0169
1410.48,42.67104
1425.75,42.3246
1440.64,41.99308
1455.08,41.66954

Expt. #4 Raw Data

t (sec) , T (°C)

4.06,34.98209
5.87,35.01872
7.9,35.06234
9.88,35.10491
13.84,35.17974
17.79,35.22527
19.77,35.24542
21.75,35.26737
23.67,35.29165
25.65,35.31986
27.57,35.35127
31.47,35.40984
33.44,35.44024
35.37,35.46433
37.29,35.48654
39.21,35.50617
41.19,35.52751
43.11,35.54168
45.03,35.5576
46.96,35.57234
48.88,35.58552
50.8,35.59586
52.67,35.60467
54.59,35.61622
56.51,35.62186
58.44,35.62644
60.36,35.62493
62.28,35.62026
64.2,35.62191
66.07,35.6228
69.92,35.60278
71.84,35.59281
73.76,35.55652
75.68,35.44382
77.66,35.2709
79.64,35.06407
81.67,34.86585
85.79,34.50645
87.93,34.26862
90.07,33.92277
102.54,33.30306
118.08,31.02134
123.14,31.94891
128.14,32.19745
130.61,32.19533
133.08,32.28339
135.5,32.64341
137.8,33.00092
140.11,33.24183
142.36,33.34823
144.67,33.35105
146.92,33.32253
149.17,33.30686
151.48,33.31159
153.73,33.36472
155.98,33.46667
158.24,33.59676

162.83,33.78934
164.83,33.85209
167.02,33.90698
169.17,33.96501
171.31,34.01772
173.45,34.07726
175.65,34.13468
177.73,34.19576
179.88,34.2639
181.96,34.32304
184.11,34.38798
186.19,34.4413
188.28,34.4804
190.37,34.4969
193.11,34.50858
195.2,34.50126
197.29,34.48955
199.37,34.4781
201.46,34.45885
205.64,34.40874
207.72,34.37739
216.18,34.18778
219.75,34.14951
221.89,34.14427
226.18,34.13904
228.32,34.13942
234.03,34.19095
236.12,34.22996
248.2,34.10071
252.49,34.22509
254.63,34.30343
256.72,34.3731
258.8,34.43862
260.89,34.50316
262.98,34.55674
265.01,34.59926
267.1,34.64419
269.13,34.66615
271.22,34.63874
273.25,34.55467
275.34,34.46806
277.48,34.39411
279.57,34.34773
281.65,34.32226
283.8,34.31869
285.88,34.31992
288.02,34.32084
292.2,34.30404
294.34,34.30198
296.43,34.30607
298.57,34.32153
300.66,34.33336
304.89,34.38662
306.97,34.41354
309.06,34.43987
311.15,34.4558
313.24,34.45995
317.41,34.41426
319.5,34.37425
321.64,34.28715
323.78,34.11589
325.92,33.79886
328.23,33.33215
330.59,32.52451
363.99,31.36823
366.46,32.08226

368.93,32.51084
371.29,32.83917
373.6,33.07487
375.91,33.25709
378.16,33.40392
380.41,33.47215
382.66,33.35008
385.02,32.72553
410.01,31.98985
412.38,32.63962
416.28,33.14875
420.83,33.40238
423.03,33.47146
425.28,33.54054
427.54,33.60494
431.93,33.73393
434.13,33.78399
436.32,33.83617
438.52,33.86971
440.72,33.91481
442.86,33.95052
445,33.98908
447.2,34.00967
449.34,33.94405
451.54,33.72376
453.79,33.38289
458.46,33.0157
460.76,33.07759
463.07,33.10897
465.38,32.9146
467.85,32.11549
509.98,32.52353
512.34,32.87441
517.67,33.36462
522.12,33.61353
525.8,33.75131
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Expt. #5C Raw Data

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Expt. #6 Raw Data

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Expt. #7P Raw Data

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Expt. # 10 Raw Data

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Expt. #9B Raw Data

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Expt. # 10A Raw Data

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Expt. #10B Raw Data

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