Department LIGO-T020132-00-D

Subject Heat Capacity Measurement

Name Michael / Hareem / Riccardo

Address Ligo 18-34

x-2063 x-2968

X-2628

National® Brand

Computation Notebook

11 3/4" x 9 1/4", 4 x 4 Quad., 75 Sheets **43-648**

0 73333 43648 8

AVERY DENNISON
Office Products
Chicopee, MA 01022

September 9, 2002

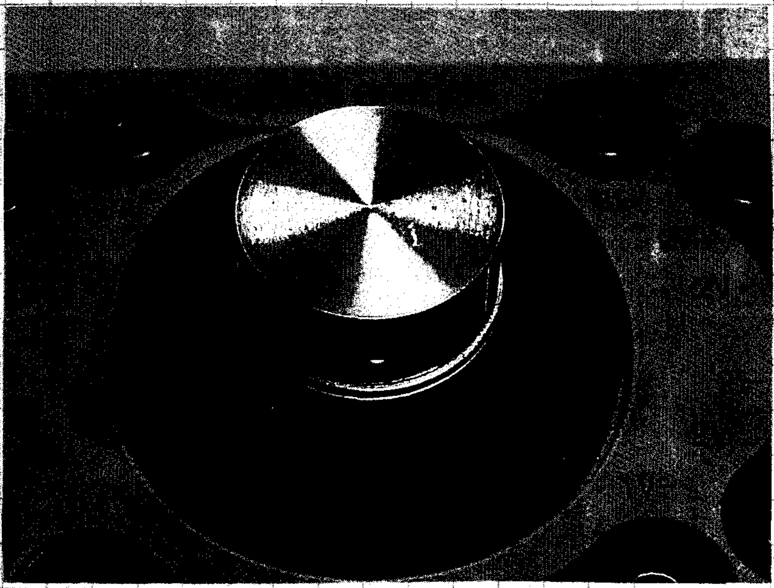
Our Work Towards A Heat Capacity Measurement

Quantum Design sells a Heat Capacity Measurement option for use with its Cryostat, but for a price that exceeds \$20,000. Since we realized that the TTO software does a very poor job at making thermal transport measurements, we did not want to use any more of their software. Therefore, this measurement must be designed by ourselves.

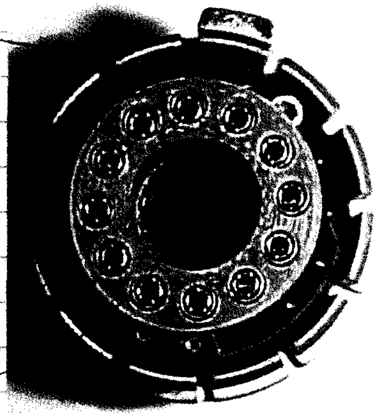
The only piece of hardware purchased specifically for this measurement is the Quantum Design Heat Capacity Puck, described below.

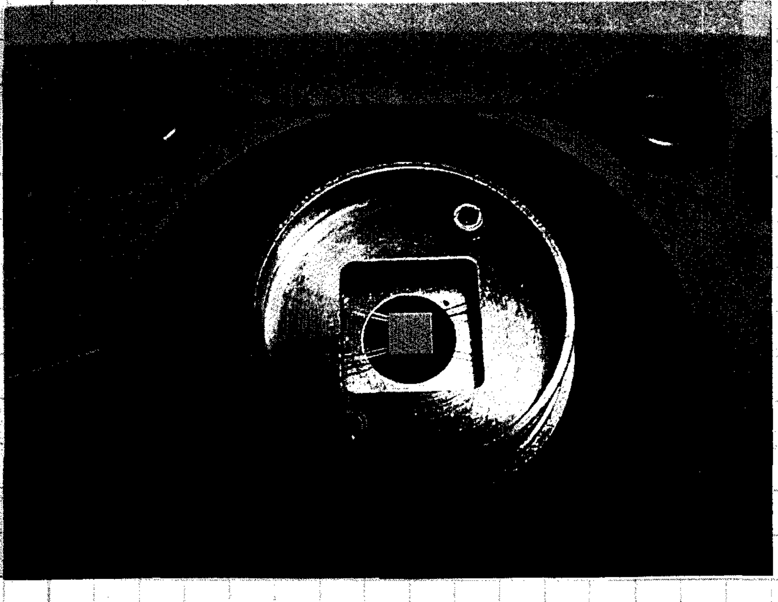
The Heat Capacity Puck

Pictures of the heat capacity puck are displayed below:



To the left is a picture w/ the radiation shield attached.





To the left is a picture w/ the radiation shield removed. Notice the platform (where the sample will be mounted) and the eight thin wires that hold it suspended in air.

These are described in more detail on the following page.

To the right is an exploded view of the Heat Capacity Puck. The wires shown are <u>extremely</u> fragile and special care <u>must</u> be taken when handling the puck, as will be described later.

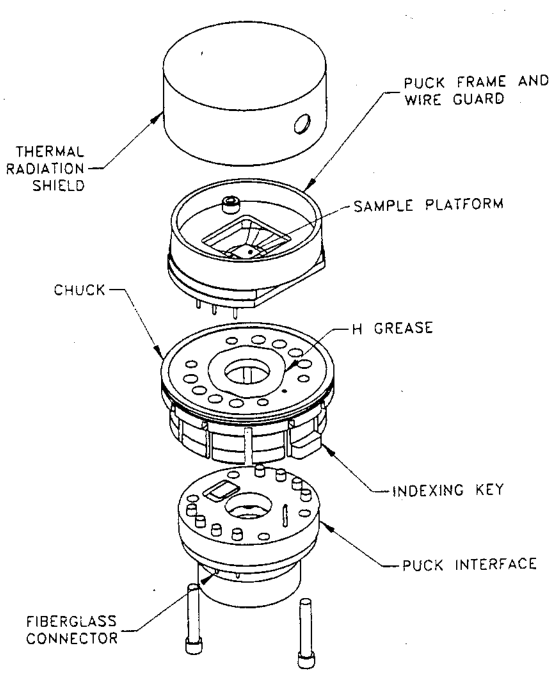


Figure 3-1. Exploded View of Calorimeter Puck

Below is a diagram which describes how a sample is mounted onto the puck. The application of the grease is extremely important. The thermometer & heater can be seen on the previous page.

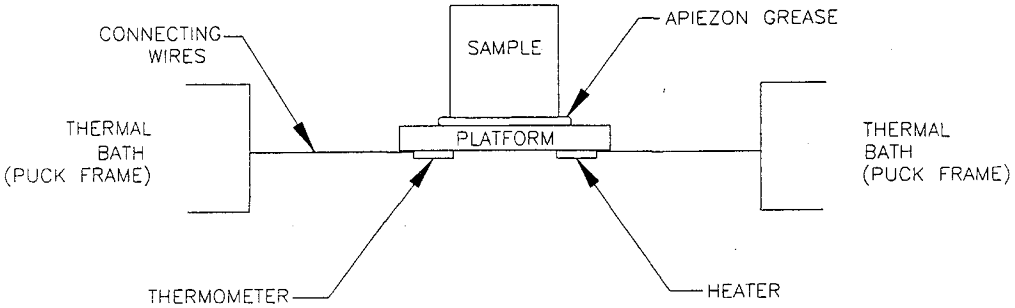


Figure 1-1. Thermal Connections to Sample and Sample Platform in PPMS Heat Capacity Option

How can we Measure the Heat Capacity?

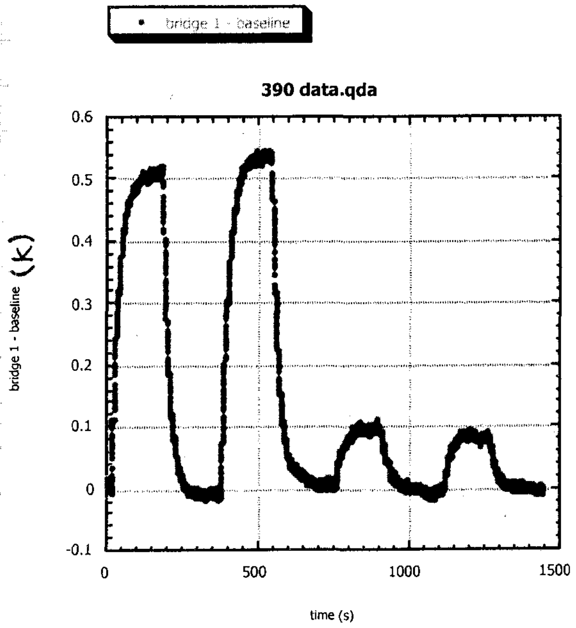
A very simple description is as follows: The puck reaches the temperature of the thermal bath. Then the heater heats the platform, sample, and grease. At some time this system reaches an equilibrium state (because heat also goes through the 8 wires to the thermal bath). The heater turns off. After reaching equilibrium, the thermal bath temperature is changed to take another measurement.

How do we fit the data?

Relative pulse hight

We don't have a highly developed method at this time, but the general idea is as follows...

Some sample data can be seen on the right. This was taken at 2 different powers as can be seen by the different pulse sizes.



In a thermal conductivity measurement, we are concerned with the pulse amplitudes (ΔT), whereas in a heat capacity measurement, the time constants are most important (RC). The general equation we expect to fit the data is as follows:

$$\boxed{T(t) = T_\infty \, e^{\left(\frac{-t}{R_8 (C_P + C_G + C_S)}\right)}}$$

where:

T_∞ ≡ temperature when $t \to \infty$
R_8 ≡ thermal resistance of the 8 wires
C_P ≡ heat capacity of the platform
C_G ≡ heat capacity of the grease
C_S ≡ heat capacity of the sample.

We can first say that

$$C_P + C_G = C_A$$

where:

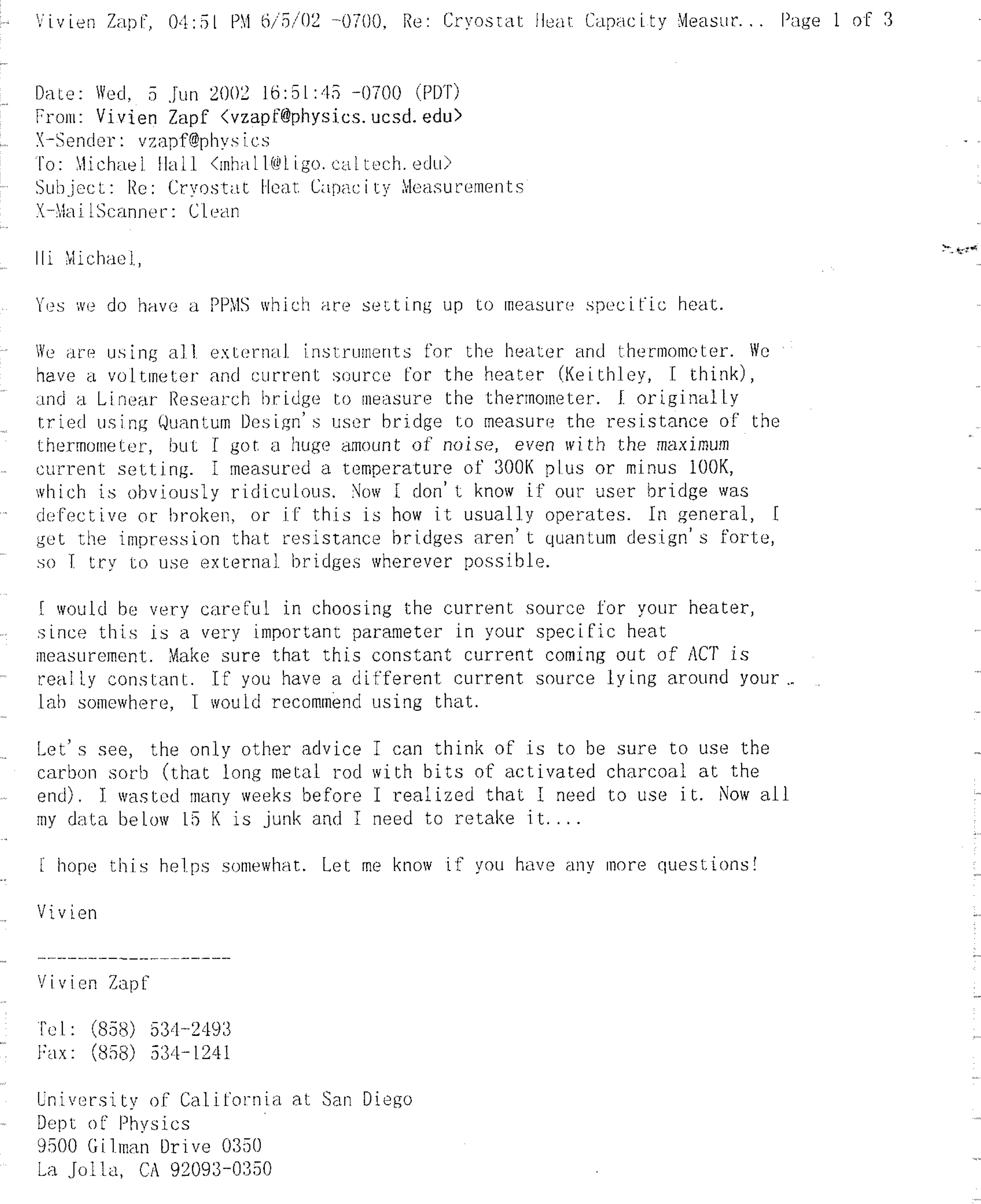
C_A ≡ heat capacity of the addenda

R_8 can be measured much the same way as a normal thermal conductivity measurement works, by analyzing the ΔT of the waveform.

4

Is there anybody else developing this measurement?

Quantum Design gave us a contact at UC San Diego who is developing a heat capacity measurement. Her information is listed in the letter attached below:



Vivien Zapf, 04:51 PM 6/5/02 -0700, Re: Cryostat Heat Capacity Measur... Page 1 of 3

Date: Wed, 5 Jun 2002 16:51:45 -0700 (PDT)
From: Vivien Zapf <vzapf@physics.ucsd.edu>
X-Sender: vzapf@physics
To: Michael Hall <mhall@ligo.caltech.edu>
Subject: Re: Cryostat Heat Capacity Measurements
X-MailScanner: Clean

Hi Michael,

Yes we do have a PPMS which are setting up to measure specific heat.

We are using all external instruments for the heater and thermometer. We have a voltmeter and current source for the heater (Keithley, I think), and a Linear Research bridge to measure the thermometer. I originally tried using Quantum Design's user bridge to measure the resistance of the thermometer, but I got a huge amount of noise, even with the maximum current setting. I measured a temperature of 300K plus or minus 100K, which is obviously ridiculous. Now I don't know if our user bridge was defective or broken, or if this is how it usually operates. In general, I get the impression that resistance bridges aren't quantum design's forte, so I try to use external bridges wherever possible.

I would be very careful in choosing the current source for your heater, since this is a very important parameter in your specific heat measurement. Make sure that this constant current coming out of ACT is really constant. If you have a different current source lying around your lab somewhere, I would recommend using that.

Let's see, the only other advice I can think of is to be sure to use the carbon sorb (that long metal rod with bits of activated charcoal at the end). I wasted many weeks before I realized that I need to use it. Now all my data below 15 K is junk and I need to retake it....

I hope this helps somewhat. Let me know if you have any more questions!

Vivien

Vivien Zapf

Tel: (858) 534-2493
Fax: (858) 534-1241

University of California at San Diego
Dept of Physics
9500 Gilman Drive 0350
La Jolla, CA 92093-0350

On Wed, 5 Jun 2002, Michael Hall wrote:

> Vivian,
>
> Hi, my name is Michael Hall and I'm an undergraduate at Caltech working on the LIGO project. We purchased the Quantum Design PPMS last October with the high vacuum (cryopump), AC Transport, Resistivity, and thermal transport options. Now we are interested in making a heat capacity measurement. We talked to Neil Dilly from Quantum Design, and he mentioned that you guys at UCSD had made a similar experimental setup so he gave us your email address.
>
> I was hoping that you could give us an idea of what kind of setup you decided to use and how successful it has been since its completion. I see there may be a few ways to go about doing this. What I am thinking right now is as follows:
>
> It looks like I can use the user bridge board to measure both the temperature of the puck and the temperature of the sample. (We are going to use Quantum Designs Heat Capacity puck, but not their other hardware.) I need to feed a current into the heater as well as monitor the voltage across the heater, and the AC Transport hardware (Model 7100) seems to be ideally suited for this. The problem is that the AC Transport software doesn't seem to be designed to provide a steady current over extended periods of time. The ACT software, instead, is designed to ramp the current up and down to take IV measurements, etc.
>
> However, the thermal transport option comes with a DSP that forces the Model 7100 to feed a steady current through the heater (which is exactly what we need!). So, I was thinking of using the TTO software to make my measurements. The only problem then, looks like the TTO cable, which is wired for the TTO puck and not for the heat capacity puck. Making a new cable is not very difficult, however.
>
> It seems like this route is feasible, but before I get into the development of this experiment, I was hoping that you might be able to provide some insight. Especially useful would be information regarding what setup you decided to use, how successful it was, and if there are any pitfalls that I may be able to avoid along the way.
>
> Thanks in advance for any information or guidance you might be able to provide,
>
> Michael Hall
> California Institution of Technology
> (626)-395-2063
> mhall@ligo.caltech.edu
>

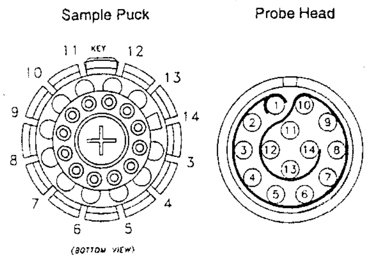
At this point, we seem to have chosen different measurement methods. Our method seems okay, and if it works, it may be a good idea to share our information with her.

The creation of a simulation puck.

Because we did not buy Quantum Design's software, we need to develop our own method for controlling the heat capacity puck. However the puck is both expensive and fragile, and without their software, we risk burning out the small heater or destroying the wires. Therefore, a more sturdy simulation puck was constructed to perform tests. This way, we would instead merely burn out a cheap resistor instead of ruin the expensive puck.

Since it must be built to mimic the real puck, we need to learn a bit more about how it works. The following is a pin-out for the real puck:

Table 3-1. Sample Connections for Pin Numbers



PUCK	GRAY LEMO CONNECTOR AT PROBE HEAD	DESCRIPTION
3	3	Heater I+
4	4	Heater I–
5	5	Heater V+
6	6	Heater V–
7	7	Chip Therm I+
8	8	Chip Therm I–
9	9	Chip Therm V+
10	10	Chip Therm V–
11	11	Puck Therm I+
12	12	Puck Therm I–
13	13	Puck Therm V+
14	14	Puck Therm V–
		Ground

The heater is used to heat the sample. The chip thermometer is located next to the heater underneath the platform. The puck thermometer is located in the thermal bath on the base of the puck.

Each device uses four wires because a 4-wire resistance measurement is used for each device. This is described on the next page.

September 10, 2002

What is a 4-wire resistance measurement?

1.2.1 Advantage of Four-Wire Resistance Measurements

Using four wires to attach a sample to a sample puck greatly reduces the contribution of the leads and joints to the resistance measurement. In a four-wire resistance measurement, current is passed through a sample via two current leads, and two separate voltage leads measure the potential difference across the sample (figure 1-2). The voltmeter has a very high impedance, so the voltage leads draw very little current. In theory, a perfect voltmeter draws no current whatsoever. Therefore, by using the four-wire method, it is possible to know, to a high degree of certainty, both the current and the voltage drop across the sample and thus calculate the resistance with Ohm's law.

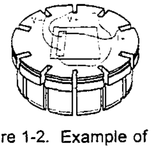


Figure 1-2. Example of four-wire resistance measurement with sample mounted on standard PPMS sample puck.

What is needed for the simulation puck?

We wanted to create a simulation puck that was as close as possible to the real puck, so we measured the resistance of the heater & thermometers

Heater Resistance: 1.15 KΩ

@ room temperature
Chip Thermometer: 60.6 Ω
Puck Thermometer: 62.3 Ω
Negative Thermal Coefficient (NTC)

The heater is a simple resistor. The thermometers are NTC thermistors with a room temperature resistance ≈ 60 Ω.

On the following pages, I have included some useful information regarding the parts I have ordered for the simulation puck. First is a useful 3-page document from Vishay-Dale regarding the selection of a thermistor. Secondly are the part numbers & details of the devices that are used in the puck.

HOW TO SELECT AN NTC THERMISTOR

1. *Dissipation Constant (D.C.)*

The dissipation constant is the amount of power (expressed in milliwatts) required to self-heat the thermistor suspended by its two inch leads in still air 1°C above its environment. The dissipation constant of NTC thermistor/NTC thermistor sensor assembly is typically defined as the ratio (at a specified ambient temperature) of the power dissipated in the thermistor to the resultant change in the temperature of the thermistor.

This constant (expressed as the power in milliwatts required to self-heat the thermistor 1°C above ambient temperature) increases slightly with increasing temperature. The lead length and type of lead, the type of encapsulating material (epoxy, Durez, stainless steel probe, thermoplastic probe, etc.) the mounting of the NTC thermistor/assembly, the medium of the surrounding environment (flowing gas, still air, water, oil, etc.) and other factors generally determine the dissipation constant of an NTC thermistor/NTC thermistor sensor assembly.

Given the variables that affect D.C., it is recommended that a prototype should be tested under actual operating conditions to determine the maximum allowable input current. The current through the thermistor must be small enough to produce negligible self-heating error in the thermistor at the maximum measuring or controlling temperature. At the same time, the current should be as large as possible to maximize system sensitivity.

If the rate of heat loss under actual operating conditions could be fixed and was constant from system to system, the D.C. would only be a consideration for determining the maximum power dissipated and an offset allowance could be made. For example, if the D.C. of a thermistor assembly had been determined as 3mW/°C in a stirred oil bath (the medium to be measured) and it was desired to measure the oil bath to an absolute temperature accuracy of ± 0.1°C, the maximum power that should be developed in the thermistor by the measuring current is 0.15mW. This is to keep the self-heat factor to 50% or less of the measurement accuracy.

The formula for this is:

$$3\text{mW/°C} \times 0.1\text{°C} \times 50\% = 0.15\text{mW}$$

The D.C. of an NTC thermistor/NTC thermistor assembly can be determined by first measuring the zero-power resistance of the NTC thermistor at two temperature points 10°C to 25°C apart. The thermistor is then placed in series with a variable voltage supply, a current meter, and a sufficiently large enough resistor to prevent too much current flowing through the circuit and allowing the thermistor to "run-away." A high-*resistance voltmeter* is connected across the thermistor. The power supply is then gradually increased until the voltage across the thermistor and the current through it indicate a resistance equal to the measured resistance at the upper temperature. This is determined by using Ohm's Law E ÷ I = R (E = volts, I = current, R = resistance). The D.C. is then calculated by dividing the power dissipated in the NTC thermistor by the temperature difference between the two measured temperatures. Power is calculated by using Ohm's Law, P = E x I.

2. Time Constant (T.C.)

The time constant is the time in seconds required for the thermistor to change through 63.2% of the difference between its initial and final body temperatures, when subjected to a step change in temperature under zero-power conditions. Since the NTC thermistor's T.C. is determined by the same factors as D.C. (i.e., encapsulation, mounting, lead length, etc.), a prototype should be built if T.C. is important.

The time constant is determined by measuring the resistance of the thermistor at three temperature points, the middle point being 63.2% of the difference between the upper one and the lower one. A precision bridge is set for the middle temperature resistance with the bridge voltage supply set so as not to produce the *self-heat error.* An auxiliary bridge voltage is set for the higher temperature resistance. The thermistor is placed in the operating medium at the lower temperature and is connected to the auxiliary bridge. The auxiliary bridge is adjusted to balance the bridge, which in effect, will self-heat the thermistor to the upper temperature. The thermistor is then immediately switched to the precision bridge.

The time required for the precision bridge to balance *is the time constant of the NTC thermistor/NTC* thermistor sensor assembly in the operating medium.

3. Selection Of Resistance Value

Typically, NTC thermistors are specified and/or referenced to + 25°C. However, it is equally important to consider the minimum and maximum resistance values at the extremes of the operating temperature range.

The minimum resistance at the maximum temperature point must not be too low to meet the input requirements of the measuring circuit. If the resistance is too low, errors due to contact resistance, line resistance and self-heating increase.

It is recommended to have at least 500 ohm - 1000 ohm at the high end of the temperature range.

Conversely, the maximum resistance at the minimum *temperature point must not be too high for the* measurement circuit input. Range switching with two or more probes should be considered if the minimum/maximum resistance values cannot be met with one thermistor.

Sensitivity also is an important consideration in the selection of the correct resistance value. Usually, the minimum and maximum allowable resistance values typically limit this selection. It then must be determined *which resistance values maximizes the output of the* measuring system over the entire range, taking into consideration the maximum input current as determined by the dissipation constant and allowable self-heat error.

4. R-T Curve Selection

At present, eleven R-T curves are available from Vishay Dale. Each material has a different R-T characteristic. Given the different resistivities of the *different R-T materials and the desirability of* maintaining uniformity in size, not all resistance values (R25) are available in all R-T curves.

Once the minimum resistance at the maximum temperature is determined, divide this resistance value by a given R-T/R25 ratio from one of any of the R-T curves to determine an approximate R25 value. (**NOTE:** R-T ratio tables in 1°C increments are included on pages 18 - 23.) If the R25 value is not *available in one R-T curve, select another until an* appropriate R-T curve is determined. Then select a standard R25 value that is closest to the approximate value. Calculate the maximum resistance at the minimum temperature by multiplying the selected R25 by the given R-T/R25 ratio. If the selected R-T curve and R25 value meet the pre-determined minimum resistance, maximum resistance and sensitivity of the measurement system, then tolerance is the next consideration.

5. Tolerance

Most temperature measurement or control applications express their limitations or accuracy in temperature units (i.e. ± 1.0°C). When designing a system, it is important to consider the overall measurement accuracy of all components. A ± 1.0°C thermistor, coupled with a ± 1.0°C system, will insure measurement accuracy to ± 2.0°C.

Thermistors may be specified with either a temperature tolerance or a resistance tolerance at either a single temperature point or over a temperature range. If the required temperature measurement accuracy is over a temperature range, it is more practical to specify a temperature tolerance in lieu of a resistance tolerance. This is because a resistance tolerance specification *over a range will not necessarily guarantee that the* required system accuracy will be met unless the non-linear NTC (negative temperature coefficient) is taken into consideration.

NTC is expressed in % resistance change per degree C. Since one NTC resistance change is approximately equivalent to a 1° temperature change, NTC is useful in specifying temperature tolerances. NTC's are given on the Vishay Dale Specification Sheet in ten degree increments; however, the NTC may be calculated at any temperature point using a 1°C R-T table.

$$\left(\text{NTC} = \frac{1}{R} \cdot \frac{dR}{dT}\,100\right)$$

Example: What is the NTC of 10,000 ohm (R25) of a Curve 1 thermistor at + 44°C?

$$100\left(\frac{1}{4543\Omega\ @\ 44°\text{C}} \times \frac{4368\Omega\ @ + 45°\text{C} - 4725\Omega\ @ + 43°\text{C}}{2}\right) = 3.9\%$$

To determine the resistance tolerance at any given temperature point, simply multiply the specified temperature tolerance by the NTC at the given temperature.

Example: What are the resistance tolerances at 0°C, + 25°C and + 70°C for a Curve 1 thermistor with a ± 0.5°C temperature tolerance over the range of 0°C to + 70°C?

R0 = ± 0.5°C x - 5.1% = ± 2.55% resistance tolerance
R25 = ± 0.5°C x - 4.4% = ± 2.2% resistance tolerance
R70 = ± 0.5°C x - 3.4% = ± 1.7% resistance tolerance

Selecting NTC Thermistors

Vishay Dale

It may now be clear why a single resistance tolerance over a temperature range may not be practical for a particular temperature measurement application.

If a single temperature point is the only design specification, NTC and Manufacturing Tolerances are useful in determining temperature tolerances at other temperature points. Manufacturing Tolerance is given on the Vishay Dale Specification Sheet in a ± % resistance tolerance. Point-matched specifications must have the difference in deviation between the specified temperature point and any other temperature point of interest added to the resistance tolerance at the specified temperature.

Example: What are the resistance tolerances at 0°C and + 50°C for a standard 1M1002?

R0 = ± 10% + ± 1.1% = ± 11.1% resistance tolerance.
R25 = ± 10% + ± 0.0% = ± 10% resistance tolerance.
R50 = ± 10% + ± 1.1% = ± 11.1% resistance tolerance.

To determine the temperature tolerance at any temperature point, divide the resistance tolerance by the NTC at that point.

Example: What is the temperature tolerance at 0°C for a 1M1002?

± 11.1% ÷ - 5.1% = ± 2.2°C temperature tolerances.

It should be noted that the Manufacturing Tolerances listed on the Vishay Dale Specification Sheet are all *referenced at + 25°C. If the thermistor is referenced* at a temperature other than + 25°C, then the total difference in deviation between the two points, if the + 25°C is between them, is the sum of the maximum deviations listed at each point.

Example: What is the maximum resistance tolerance of a Curve 1 thermistor at 0°C if the specified tolerance is ± 5% at + 70°C?

(± 5% resistance tolerance at + 70°C) + (MT ± 1.8% at + 70°C) + (MT ± 1.1% at 0°C) = ± 7.9% resistance tolerance at 0°C.

6. Tolerance Availability vs R-T Curve

Not all temperature/resistance tolerances are available in all R-T curves. If a temperature tolerance over an extended temperature range is required, then at present, Curves 1, 2, 4, 8 or 9 may be selected. All other curves may be specified to a resistance or temperature tolerance at a single temperature point. Curves 12 and 13 may only have ± 5% or ± 10% resistance tolerances specified. Contact the factory for further information.

7. Tolerance Availability vs Configuration

Not all temperature/resistance tolerances are available in all configurations. Basically, Hybrids, uncoated NTC thermistors without leads and uncoated NTC thermistors with leads are only available in ± 5% or ± 10% point-matched resistance tolerances.

8. Measurement Accuracy

Thermistor resistance measurements must be made at precisely controlled temperature while applying essentially zero-power to assure measurement accuracy.

RESISTANCE-TEMPERATURE RELATIONSHIP

Many empirical equations have been developed over the years in an attempt to accurately describe the non-linear resistance-temperature dependence of NTC thermistors.

An early equation called the "Beta" formula proved to be useful over narrow temperature ranges for broad tolerances. The Beta formula may be written using a single material dependent constant B as:

$$R(T) = R(To) \exp\left[B\left(\frac{1}{T} - \frac{1}{To}\right)\right]$$

where R (T) is the resistance at the temperature T in Kelvin and R (To) is a reference point at temperature To. The Beta formula requires a two-point calibration, but under the best of conditions is not accurate to ± 1°C over the range of 0°C to + 100°C and typically not to ± 5°C over our published temperature ranges.

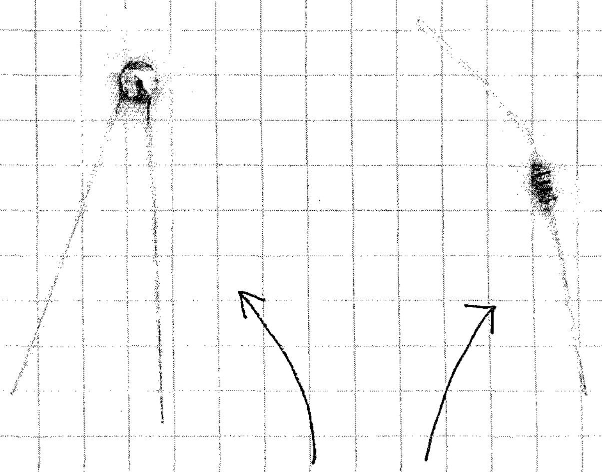
The best empirical expression published to date is the Steinhart-Hart equation written explicitly in temperature T as:

$$\boxed{\frac{1}{T} = A + B(\ln R) + C(\ln R)^3}$$

where ln R is the natural logarithm of the resistance R at temperature T and the A, B and C's are derived coefficients from actual measurement. This form of the Steinhart-Hart equation requires a minimum of three calibration points to determine the derived coefficients. Typical accuracies would be less than ± 0.15°C over the range of - 50°C to + 150°C.

If the temperature points selected from the R-T tables to calculate A, B and C lie within a + 100°C range, the accuracy is better than ± 0.01°C, assuming measurement accuracy to at least four significant figures and preferably five.

The Steinhart-Hart equation is an approximation. If a tighter tolerance than guaranteed is desired, then each thermistor must be individually calibrated.

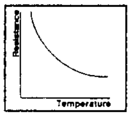


a sample of the devices used in the simulation pucl.

Resistance
vs. Temperature
Calibration
Technique

THERMOMETRICS
GLOBAL BUSINESS

NTC Thermistors



NTC (Negative Temperature Coefficient) Thermistors decrease in resistance as temperature increases. Temperature coefficients range from −20%/°C to −5%/°C @ 25°C. Maximum operating temperature: 150°C. Tolerance: ±20% 100-5Ω; ±10% 1K-100KΩ.

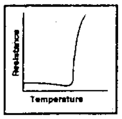
Res. @ 25°C (Ω)	Res. Ratio ††	D.C.†	Dim. A (mm)	Digi-Key Part No.	Price Each 1	10	100	250
100	5.53	2.5	2.79	KC001N-ND*	2.76	2.48	1.96	1.55
50	5.53	6.5	5.59	KC012N-ND*	2.19	1.97	1.55	1.23
25	5.53	6.5	5.59	KC011N-ND*	2.19	1.97	1.55	1.23
10	5.53	7.0	8.13	KC021N-ND*	2.24	2.02	1.59	1.26
5	5.53	10.0	12.19	KC024N-ND*	2.40	2.16	1.71	1.35
1K	6.85	2.8	2.79	KC003N-ND*	2.72	2.45	1.93	1.53
500	6.85	2.5	2.79	KC002N-ND	2.72	2.45	1.93	1.53
300	6.85	6.5	5.59	KC015N-ND*	2.14	1.93	1.52	1.21
200	6.85	6.5	5.59	KC014N-ND*	2.14	1.93	1.52	1.21
100	6.85	6.5	5.59	KC013N-ND	2.14	1.93	1.52	1.21
50	6.85	7.5	9.40	KC022N-ND	2.19	1.98	1.56	1.24
10K	9.60	2.5	2.79	KC025N-ND*	2.72	2.45	1.93	1.53
5K	9.10	2.5	2.79	KC005N-ND*	2.72	2.45	1.93	1.53
3K	9.10	2.5	2.79	KC004N-ND*	2.72	2.45	1.93	1.53
2K	9.10	6.5	5.59	KC017N-ND*	2.14	1.93	1.52	1.21
1K	9.10	6.5	5.59	KC016N-ND	2.14	1.93	1.52	1.21
300	9.10	9.0	10.92	KC023N-ND	2.36	2.13	1.68	1.33
25K	11.41	2.8	2.79	KC007N-ND*	2.88	2.60	2.05	1.62
10K	11.41	7.2	5.59	KC018N-ND	2.44	2.20	1.73	1.38
100K	12.90	2.7	2.79	KC009N-ND*	2.88	2.60	2.05	1.62
50K	12.90	2.5	2.79	KC008N-ND	2.88	2.60	2.05	1.62
25K	12.90	6.5	5.59	KC019N-ND	2.35	2.12	1.67	1.33
200K	13.82	2.5	2.79	KC010N-ND*	2.88	2.60	2.05	1.62
100K	13.82	6.5	5.59	KC020N-ND	2.35	2.12	1.67	1.33

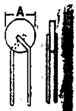
† D.C. — Dissipation Constant (MW/°C)

†† Resistance Ratio — ratio of zero power resistance @ 0°C to zero power resistance @ 50°C; AWG.

* KCNTC-KIT-ND *Digi-Key® NTC Thermistors Kit* 2 each of 15 values denoted (30 total pieces). Notebook style storage case and bin storage guide included. $39.95

PTC Thermistors





PTC (Positive Temperature Coefficient) Thermistors are thermally sensitive resistors made of polycrystalline ceramic materials. They are characterized by an extremely large resistance change in a small temperature span. All PTC resistances ±30% at 25°C. Tolerance on transition temperature is ±7°C.

Oper. Volt.	R @ 25°C (Ω)	Transition Temp.	D.C.†	Dim. A (mm)	Digi-Key* Part No.	Price Each 1	10	100
12	1	120°C	14.0	15.24	KC012P-ND	2.98	2.68	2.11
12	2	120°C	14.0	15.24	KC013P-ND	2.98	2.68	2.11
12	10	110°C	7.0	8.89	KC014P-ND	2.98	2.68	2.11
12	25	110°C	7.0	8.89	KC015P-ND	2.54	2.28	1.80
25	50	30°C	7.0	7.62	KC001P-ND*	2.54	2.28	1.80
25	50	40°C	7.0	7.62	KC002P-ND*	2.54	2.28	1.80
25	50	50°C	7.0	7.62	KC003P-ND*	2.54	2.28	1.80
25	50	60°C	7.0	7.62	KC004P-ND*	2.54	2.28	1.80
25	50	70°C	7.0	7.62	KC006P-ND*	2.54	2.28	1.80
25	50	80°C	7.0	7.62	KC007P-ND*	2.54	2.28	1.80
25	50	90°C	7.0	7.62	KC008P-ND*	2.54	2.28	1.80
25	50	100°C	7.0	7.62	KC009P-ND*	2.54	2.28	1.80
25	50	110°C	7.0	7.62	KC010P-ND*	2.54	2.28	1.80
25	50	120°C	7.0	7.62	KC011P-ND*	2.54	2.28	1.80
50	5	65°C	14.0	15.24	KC016P-ND	2.98	2.68	2.11
50	10	110°C	10.0	11.43	KC017P-ND	3.26	2.93	2.31
50	50	110°C	12.0	11.43	KC018P-ND	2.98	2.68	2.11
50	200	110°C	9.0	10.16	KC019P-ND	3.26	2.93	2.31
120	10	120°C	20.0	20.32	KC020P-ND	3.81	3.43	2.70
120	20	120°C	18.0	16.51	KC021P-ND	3.05	2.74	2.16
120	25	60°C	15.0	15.24	KC022P-ND	3.05	2.74	2.16
120	50	120°C	12.0	12.70	KC023P-ND	2.98	2.68	2.11
240	40	110°C	18.0	16.51	KC024P-ND	3.26	2.93	2.31
240	50	65°C	17.0	15.24	KC025P-ND	3.26	2.93	2.31
240	50	110°C	18.0	16.51	KC026P-ND	3.26	2.93	2.31
240	100	120°C	18.0	16.51	KC027P-ND	3.26	2.93	2.31
240	1500	100°C	12.0	8.89	KC028P-ND	3.29	2.93	2.31
480	1000	100°C	18.0	19.05	KC029P-ND	3.81	3.43	2.70
480	2000	100°C	15.0	13.97	KC030P-ND	2.98	2.68	2.11
480	5000	100°C	12.0	8.89	KC031P-ND	3.26	2.93	2.31

† D.C. – Dissipation Constant (MW/°C)

* KCPTC1-KIT-ND *Digi-Key® PTC Thermistors Kits* 2 each of all values denoted (20 total pieces). Notebook style storage case and bin storage guide included. $37

YAGEO 5% Carbon Film Resistors

Available In 1/8, 1/4 and 1/2 Watt

Standard Resistor Values

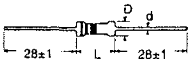
See below for complete part numbers when ordering.

1.0	1.8	3.3	5.6	10	18	33	56	100	180	330	560	1.0K	1.8K	3.3K	5.6K	10K	18K	33K	56K	100K	180K	330K	560K	1.0M	1.8M	3.3M	5.6M	10M
1.1	2.0	3.6	6.2	11	20	36	62	110	200	360	620	1.1K	2.0K	3.6K	6.2K	11K	20K	36K	62K	110K	200K	360K	620K	1.1M	2.0M	3.6M	6.2M	
1.2	2.2	3.9	6.8	12	22	39	68	120	220	390	680	1.2K	2.2K	3.9K	6.8K	12K	22K	39K	68K	120K	220K	390K	680K	1.2M	2.2M	3.9M	6.8M	
1.3	2.4	4.3	7.5	13	24	43	75	130	240	430	750	1.3K	2.4K	4.3K	7.5K	13K	24K	43K	75K	130K	240K	430K	750K	1.3M	2.4M	4.3M	7.5M	
1.5	2.7	4.7	8.2	15	27	47	82	150	270	470	820	1.5K	2.7K	4.7K	8.2K	15K	27K	47K	82K	150K	270K	470K	820K	1.5M	2.7M	4.7M	8.2M	
1.6	3.0	5.1	9.1	16	30	51	91	160	300	510	910	1.6K	3.0K	5.1K	9.1K	16K	30K	51K	91K	160K	300K	510K	910K	1.6M	3.0M	5.1M	9.1M	

Characteristics

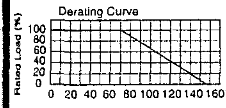
Terminal Strength	Soldering	Temperature Change	Vibration	Moisture Resistance	*Load Life*	Dielectric Strength	Insulation Resistance	Short-Time Overload	Voltage Coefficient	Solvents Resistance
0.6mm load 10N (1kg): 10s Δ Rmax. 0.25% + 0.05Ω	2s 230°C 0.5% activated flux Δ Rmax. 0.25% + 0.25Ω	½ hr. @ −55°C, ½ hr. @ +155°C 5 cycles: Δ Rmax. 0.25% + 0.25Ω	1.5mm displacement @ 10 to 500 Hz; Δ Rmax. 0.25% + 0.05Ω	Δ Rmax. ±3%	Δ Rmax. ±2.5%	1000 hrs.: 70°C: Pnom or Vmax. Δ Rmax. 1% + 0.05Ω	500Vrms appl. for 1 min.: No breakdown	Room temp., dissipation 6.25× Pnom. 10 cycles; 5 sec. on, 45 sec. off; Δ Rmax. 0.25% +0.05Ω	5 ppm	No damage

CFR Series



Features

- Industry's lowest cost!
- Available in 1/8, 1/4, 1/2 watt; packaged in bulk or tape/reel (except 1/2 watt)
- Exceeds carbon comp MIL-R-11 performance
- Standard tolerance: 65%
- Exceptional long-term stability



General Specifications

Type (Power Rating)	Dimensions (mm) L	D	d	Max. Working Voltage	Max. Overload Voltage	Rated Ambient Temperature	Temperature Cycling	Resistance Range	Resistance Tolerance
1/8 Watt *	3.3 ± 0.4	1.8 ± 0.3	0.5 ± 0.05	200V	400V	70°C	−55°C to +155°C	1.0Ω to 10 MΩ	±5%
1/4 Watt	6.3 ± 0.5	2.3 ± 0.3	0.6 ± 0.05	250V	500V	70°C	−55°C to +155°C	1.0Ω to 10MΩ	±5%
1/2 Watt	9.0 ± 0.5	3.2 ± 0.5	0.6 ± 0.05	350V	700V	70°C	−55°C to +155°C	1.0Ω to 10MΩ	±5%

Description	Digi-Key Part No.	Pricing 5	200	1M	5M	10M	50M
1/8 Watt, 5% Carbon Film Resistors (* Power rating at 70°C = 1/6W) Bulk Package	(Value)EBK-ND (i.e. 1.0EBK-ND)	.28	4.70	13.63	12.22/M	11.28/M	10.34/M
1/8 Watt, 5% Carbon Film Resistors — Tape and Reel (* Power rating at 70°C = 1/6W) (5,000 pcs./reel — Order in multiples of 5,000)	(Value)ETR-ND (i.e. 1.0ETR-ND)	—	—	—	14.95/M	13.80/M	11.04/M
1/4 Watt, 5% Carbon Film Resistors Bulk Package	(Value)QBK-ND (i.e. 1.0QBK-ND)	.28	3.89	8.70	8.27/M	7.69/M	6.24/M
1/4 Watt, 5% Carbon Film Resistors — Tape and Reel (5,000 pcs./reel — Order in multiples of 5,000)	(Value)QTR-ND (i.e. 1.0QTR-ND)	—	—	—	8.94/M	8.25/M	6.60/M
1/2 Watt, 5% Carbon Film Resistors Bulk Package	(Value)H-ND (i.e. 1.0H-ND)	.27	3.96	12.87	11.88/M	10.89/M	9.90/M

"E" = Eighth Watt; "Q" = Quarter Watt; "H" = Half Watt. Please be sure to specify. Half watt available in bulk package only.

Digi-Key® 1/8 Watt Resistor Assortment

RSE200-ND 200 each of all std. values 5% 1/8 watt carbon film resistors in the series 1.0 - 10 megohms (33,800 total pcs.) $409.00

RS112-ND Set of 5 each of 73 standard 5% 1/8 watt carbon film resistors in the series 1.0, 1.2, 1.5, 1.8, 2.2, etc., through 1.0 megohm (365 total pieces) $16.96

RS212-ND Set of 5 each of the 72 standard 5% 1/8 watt carbon film resistors in the series 1.1, 1.3, 1.6, 2.0, 2.4, etc., through 910 kilohm (360 total pieces) $16.99

Digi-Key® 1/4 Watt Resistor Assortment

RSQ200-ND 200 each of all std. values 5% 1/4 watt carbon film resistors in the series 1.0 - 10 megohms (33,800 total pcs.) $239.00

RS125-ND Set of 5 each of 73 standard 5% 1/4 watt carbon film resistors in the series 1.0, 1.2, 1.5, 1.8, 2.2, etc., through 1.0 megohm (365 total pieces) $14.95

RS225-ND Set of 5 each of the 72 standard 5% 1/4 watt carbon film resistors in the series 1.1, 1.3, 1.6, 2.0, 2.4, etc., through 910 kilohm (360 total pieces) $14.95

Digi-Key® 1/2 Watt Resistor Assortment

RSH200-ND 200 each of all std. values 5% 1/2 watt carbon film resistors in the series 1.0 - 10 megohms (33,800 total pcs.) $335.00

RS150-ND Set of 5 each of 73 standard 5% 1/2 watt carbon film resistors in the series 1.0, 1.2, 1.5, 1.8, 2.2, etc., through 1.0 megohm (365 total pieces) $16.95

RS250-ND Set of 5 each of the 72 standard 5% 1/2 watt carbon film resistors in the series 1.1, 1.3, 1.6, 2.0, 2.4, etc., through 910 kilohm (360 total pieces $16.95

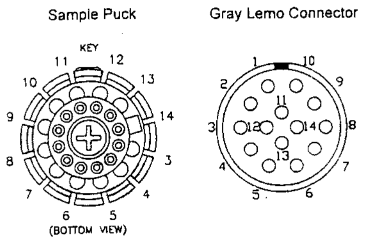
Three types of resistors were ordered because it wasn't known which power was appropriate.

The thermistors were chosen because they were as close as possible to mimic the real puck. These resistors were chosen because they are small and the power should be high enough to heat up the sample.

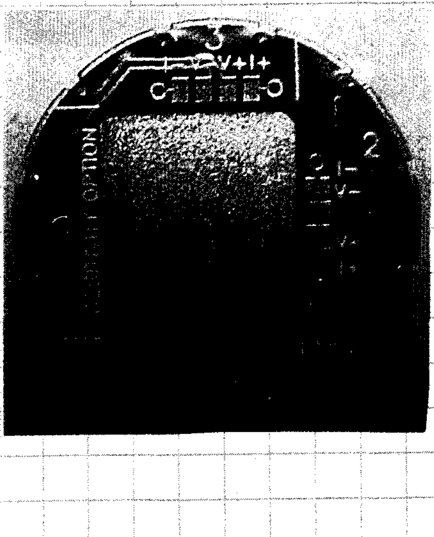
Pin-Out for the Resistivity Puck

I decided to use the resistivity puck for the mounting of the simulation puck because it has a convenient mounting area and 3 4-wire channels ... just what I needed. The pin-out is below:

Table 2-1. Sample Connections with User Bridge Cable Connected



SAMPLE PUCK	SAMPLE CONNECTOR	GRAY LEMO CONNECTOR	USER BRIDGE BOARD FUNCTION
			Cur Driver 1+ (unused)
			Cur Driver 1– (unused)
			Cur Driver 2+ (unused)
			Cur Driver 2– (unused)
3	3	3	Channel 1 I+
4	4	4	Channel 1 I–
5	5	5	Channel 1 V+
6	6	6	Channel 1 V–
7	7	7	Channel 2 I+
8	8	8	Channel 2 I–
9	9	9	Channel 2 V+
10	10	10	Channel 2 V–
11	11	11	Channel 3 I+
12	12	12	Channel 3 I–
13	13	13	Channel 3 V+
14	14	14	Channel 3 V–
			Channel 4 I+
			Channel 4 I–
			Channel 4 V+
			Channel 4 V–
			Shield



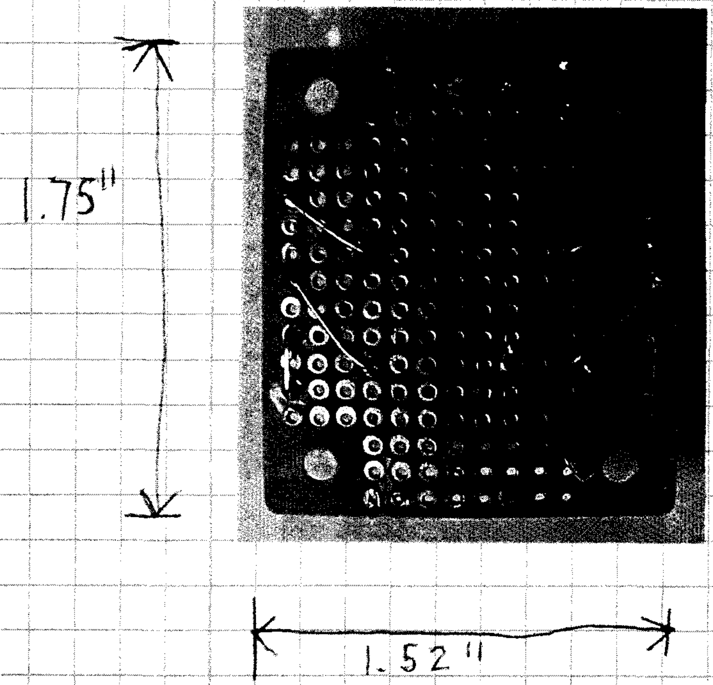
To the left is an image of the resistivity puck.

Where can I mount the circuit?

The circuit cannot be mounted directly to the puck, because the mounting area is electrically conductive. Therefore, I purchased a prototype board from MarVac electronics.

MarVac Electronics
1795 Colorado Blvd (North Side)
-by Colorado and Meredith

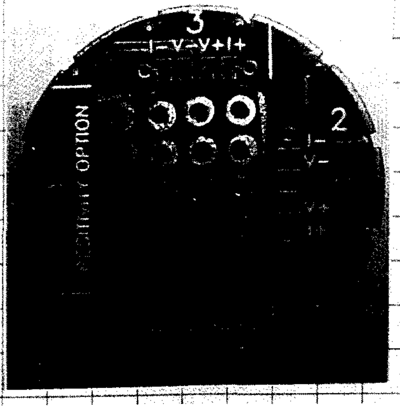
I purchased 4 small, cheap ($0.49) prototype boards. Their dimensions are listed below along with the information on the included tag, but the salesperson said they would not carry them much longer.



Tag Details

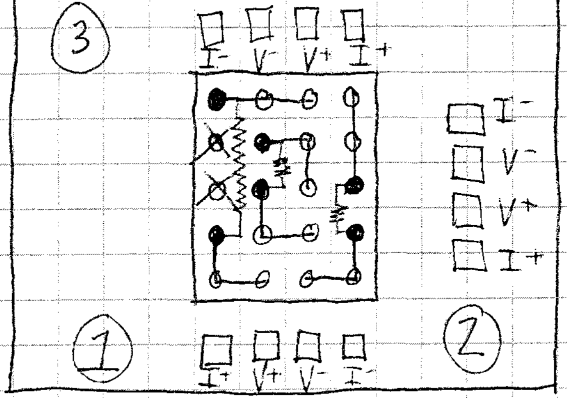
PRO 14951
1108931
PERF 1-½" x 1-¾" 0.1" Squ.

I cut a piece to fit the resistivity puck that had enough connections to facilitate my entire circuit.



Simulation Puck Circuit Diagram

Below is the circuit diagram for the simulation puck:

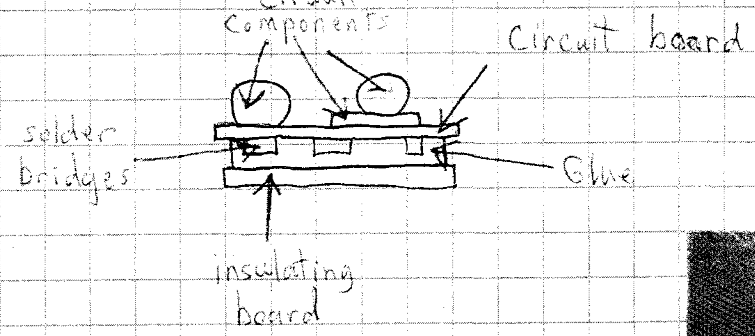


The red marks represent physical components.

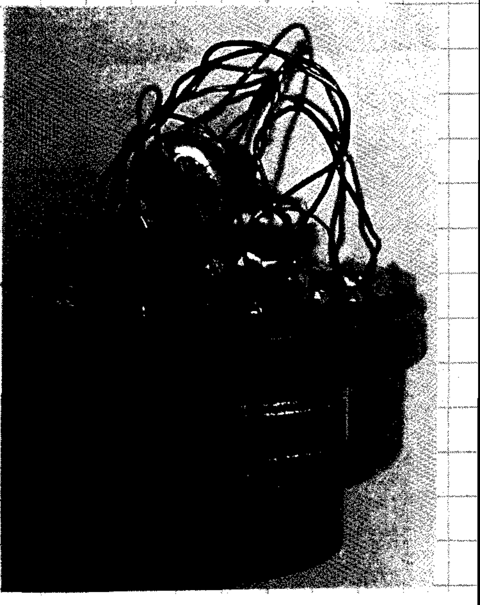
The blue marks represent "bridges" underneath the board which will be used to connect the devices to the puck terminals.

Insulation Layer

Because of these "bridges" underneath the board, an insulation layer must be installed to prevent the puck's copper mounting station from shorting the circuit. The following diagram illustrates this:



The picture on the right shows how this insulating layer looks after the puck is completed.

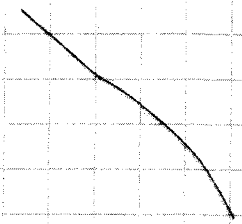


The entire circuit (including insulation layer) is attached to the copper surface of the puck by a single piece of double-sided tape, so the puck is not permanently damaged.

Attaching the wires.

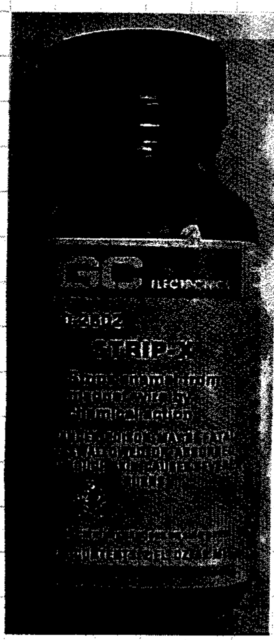
To attach the circuit to the puck terminals I used a piece of Belden wire and cable, as attached below:

Belden
Wire and cable



An acid is used to strip the insulation from the ends. A picture is below:

It is dangerous, so care must be taken during this procedure.



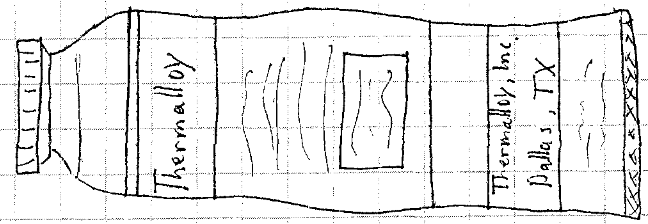
I decided to attach the devices in the following way:

Channel 1	Heater
Channel 2	Chip Thermometer
Channel 3	Puck Thermometer

Making thermal contact with the heater.

To simulate the real puck, the chip thermometer must have a good thermal contact with the heater while the puck thermometer is relatively isolated.

To achieve this, the puck thermistor and heater were placed as far as possible from each other and some thermal grease was used to attach the heater to the chip thermometer. The grease used is described below:



Thermalcote

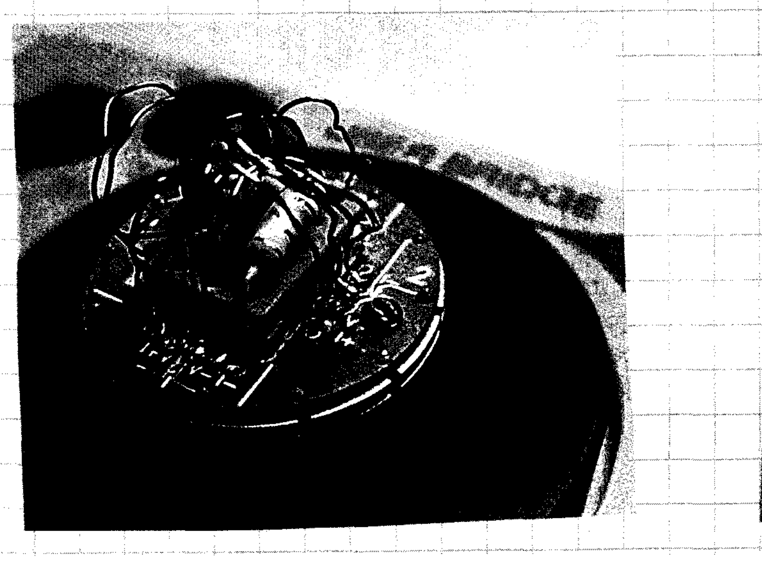
Thermal Joint Compound
Thermalloy Inc.

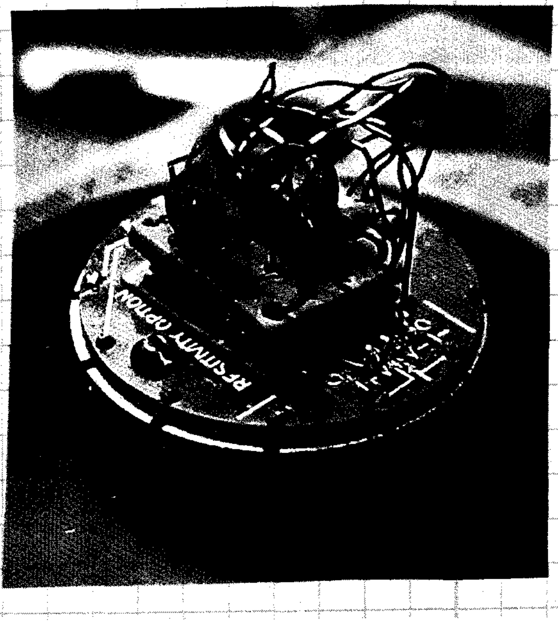
Temp. Range:	-40 to 400°F
Thermal Conductivity:	0.43 $\frac{\text{Btu}\cdot\text{ft}}{\text{Hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}}$
Dielectric Strength:	300 $\frac{V}{mil}$
Volume Resistivity:	4×10^{14} ohm-cm
Solvent:	Acetone

This was borrowed from the students electronics lab in east bldgs, second floor.

It worked quite well. It makes a non-permanent attachment that is very easy to remove.

Below are two pictures of the finished simulation puck. It was tested and all connections were operational.





How can we use the heat capacity pucks?

Because we did not purchase Quantum Design's Heat Capacity package, we need our own way of controlling the pucks, collecting data, and our own cable.

Before the cable can be created, a system of puck operation must be developed.

Three methods were originally proposed and their advantages and disadvantages will be discussed in the following pages.

1.) Use the TTO software to operate the Heat Capacity Puck by tricking it into thinking its measuring the thermal conductivity.

2.) Use the AC Transport software to generate the heat pulses.

3.) Use the User Bridge to drive the heater and measure the temperatures.

How can TTO software be used to measure Heat Capacity?

This option looks attractive for several reasons. First, it is mostly automated, so if there is a way to trick it into measuring heat capacity, not much more needs to be done other than rearranging where the wires go (by creating a new cable).

There are many similarities between the two measurements which make it appear possible to trick the software into measuring heat capacity (which will be described). Plus, it is not possible to manually drive the AC Transport hardware (which would be another solution) because Quantum Design does not release the source code for the GPIB commands. TTO makes use of this hardware, so we can control it indirectly.

Let's discuss this option in greater detail...

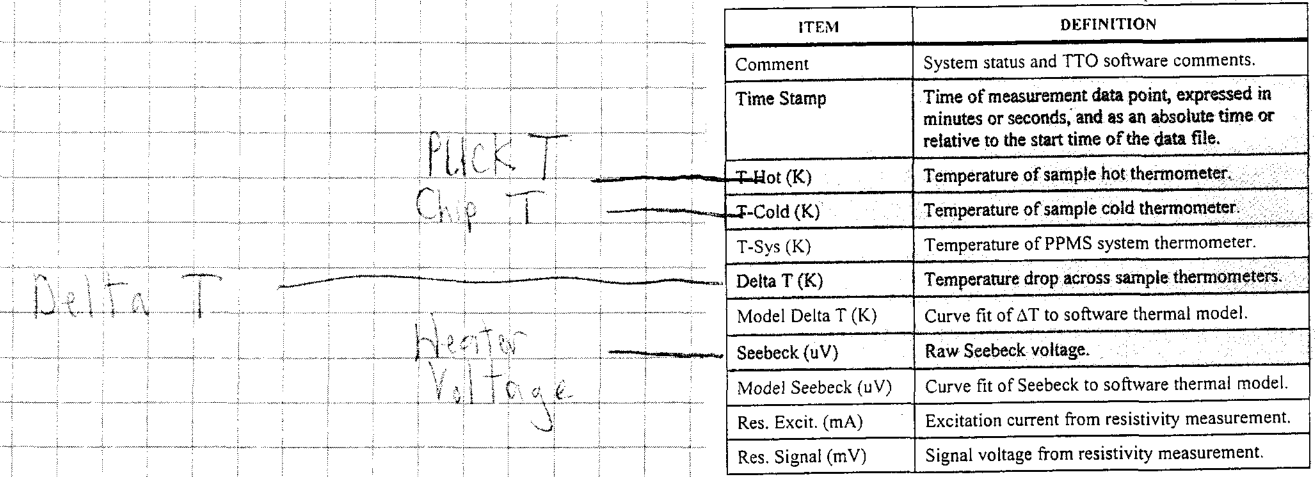
How are TTO and Heat Capacity measurements similar?

The TTO cable connects the TTO puck to 3 sources: A voltmeter on the AC Transport hardware, a current source on the AC Transport hardware, and the user bridge, where 4-wire measurements are made. The chart below shows the similar requirements of both measurements and which devices could be used to fulfill those requirements...

Device	TTO Requirement	HC Requirement
AC Transport Voltmeter	-Reads Sample Voltage During Resistivity Measurements	-Records heater voltage needed for heater power calculations.
AC Transport Current Source	-Provides heater current. -Provides sample current for resistivity measurements.	-Provides heater current.
User Bridge	-Provides 4-wire resistance measurements for 2 thermometers.	-Provides 4-wire resistance measurements for 2 thermometers.

At first glance it appears that one would only need to create a new cable to ensure the connections are correct for the HC puck. Then the TTO software could automate the process and record all the data, as normal.

Following is a list of what the TTO software records. Highlighted are the entries useful for HC measurements.



ITEM	DEFINITION
Comment	System status and TTO software comments.
Time Stamp	Time of measurement data point, expressed in minutes or seconds, and as an absolute time or relative to the start time of the data file.
T-Hot (K)	Temperature of sample hot thermometer.
T-Cold (K)	Temperature of sample cold thermometer.
T-Sys (K)	Temperature of PPMS system thermometer.
Delta T (K)	Temperature drop across sample thermometers.
Model Delta T (K)	Curve fit of ΔT to software thermal model.
Seebeck (uV)	Raw Seebeck voltage.
Model Seebeck (uV)	Curve fit of Seebeck to software thermal model.
Res. Excit. (mA)	Excitation current from resistivity measurement.
Res. Signal (mV)	Signal voltage from resistivity measurement.

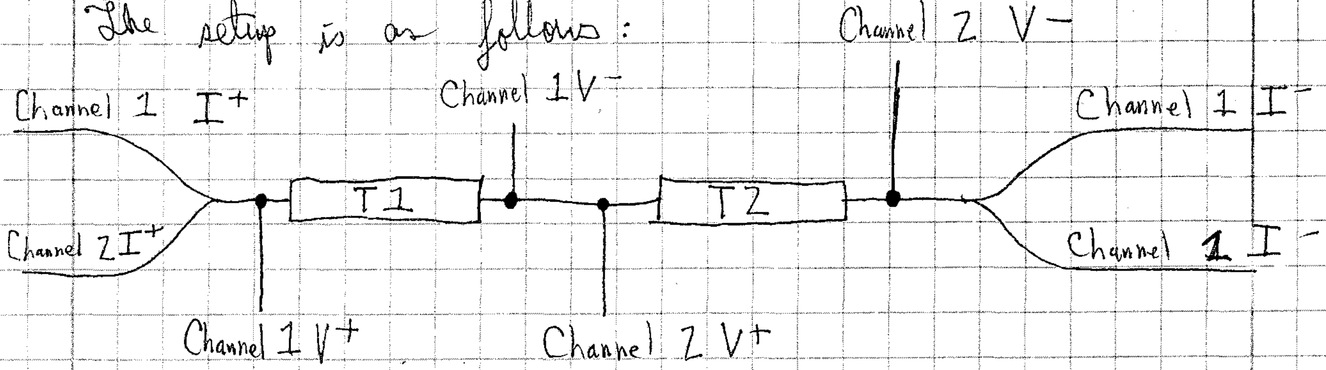
ITEM	DEFINITION
Time Stamp	Time of measurement data point, expressed in minutes or seconds, and as an absolute time or relative to the start time of the data file.
Status (code)	PPMS system status. Identical to General Status in table 3-1.
Error (code)	TTO error code. Appendix B describes how to interpret the code.
Magnetic Field (Oe)	Magnetic field.
Sample Temp. (K)	Average sample temperature during measurement.
Conductivity (W/K-m)	Sample thermal conductivity.
Cond. Std. Dev.	Error (standard deviation) in thermal conductivity measurement.
Seebeck Coef. (uV/K)	Sample Seebeck coefficient in units of μV/K.
Seebeck Std. Dev.	Error in Seebeck coefficient measurement.
Resistivity (Ohm-m)	Sample resistivity.
Resist. Std. Dev.	Error in resistivity measurement.
Figure of Merit [ZT]	Dimensionless thermoelectric figure of merit ZT.
Merit Std. Dev.	Error in ZT measurement.
Delta Temp. (K)	Extrapolated (asymptotic) temperature drop ΔT across heated sample.
Conductance (W/K)	Net thermal conductance of sample. See section 1.5.5.
Raw Conductance (W/K)	Raw thermal conductance, that is, (Heater Power)/(Delta Temp.).
Seebeck Volt. (uV)	Extrapolated (asymptotic) Seebeck ΔV across heated sample.
Resistance (Ohm)	Sample resistance.

ITEM	DEFINITION
Min. Temp. (K)	Minimum temperature at either hot or cold thermometer during measurement.
Max. Temp. (K)	Maximum temperature at either hot or cold thermometer during measurement.
Temp. Rise (K)	Rise in temperature of the hot thermometer due to the applied heat pulse. Should be close to user-requested value set in **Thermal** tab.
Req. Htr. Power (W)	Requested heater power, in watts.
Heater Power (W)	Actual heater power.
Rad. Loss (W)	Estimated power loss due only to radiation from sample. See section 1.5.5.
Cond. Pwr. (W)	Estimated net power conducted through sample.
Heater Current (mA)	Current through heater.
Res. Drive (mA)	Current drive used for resistivity measurement.
Res. Freq. (Hz)	Frequency used for resistivity measurement.
Period (sec.)	Period for heater on/off square-wave pulse.
Period Ratio	Ratio of period/tau1.
tau1 (sec.)	Long thermal time-constant of sample and shoes.
tau2 (sec.)	Short thermal time-constant of sample and shoes.
Seebeck Gain	Total gain (preamp and DSP) for Seebeck data point.
Resist. Gain	Total gain (preamp and DSP) for resistivity.
System Temp. (K)	PPMS block system temperature.
Sample Position (deg.)	Used with rotator probes; not used in TTO*.
Brg Ch 1–4 Resistance	Resistance of selected user bridge channel.
Brg Ch 1–4 Excitation	Excitation current of selected user bridge channel.
Sig Ch 1–2 Input Voltage	Input voltage for selected signal channel.
Digital Inputs (code)	Eight-bit status of selected inputs.
Dr Ch 1–2 Current	Current delivered by selected driver output channel.
Dr Ch 1–2 Power	Power delivered by selected driver output channel.
Pressure	Sample chamber pressure, in torr.
Map 20–29 Map 21–22	User-designated data items. Reserved for hot and cold sample thermometers.

Although it appears as though all the required data would be collected, there is the fear that it could be too automated. After all, we have had problems with the TTO software when taking a TTO measurement. It's even more likely to have a problem when measuring heat capacity.

However, the problem that makes it seem unfeasible is the way in which the two thermometers are mounted. The TTO measurement requires more pins than the puck has available, so it uses the same current source for both thermometers (to save 2 pins).

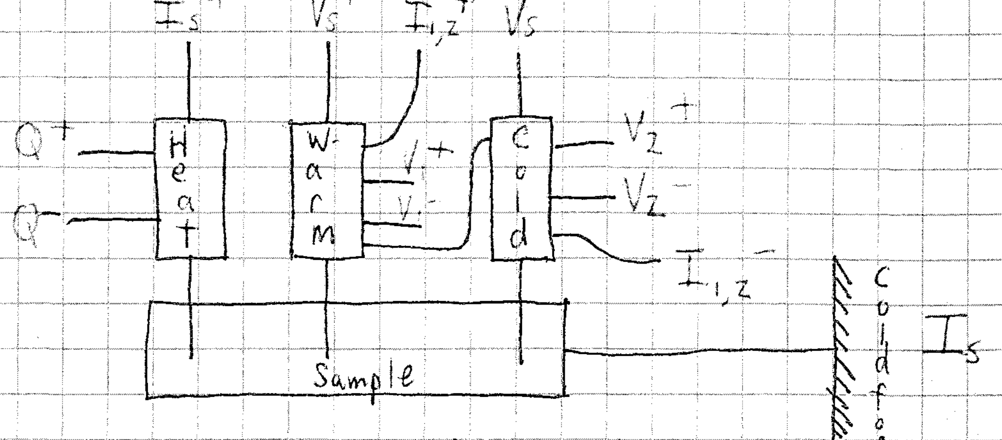
The setup is as follows:



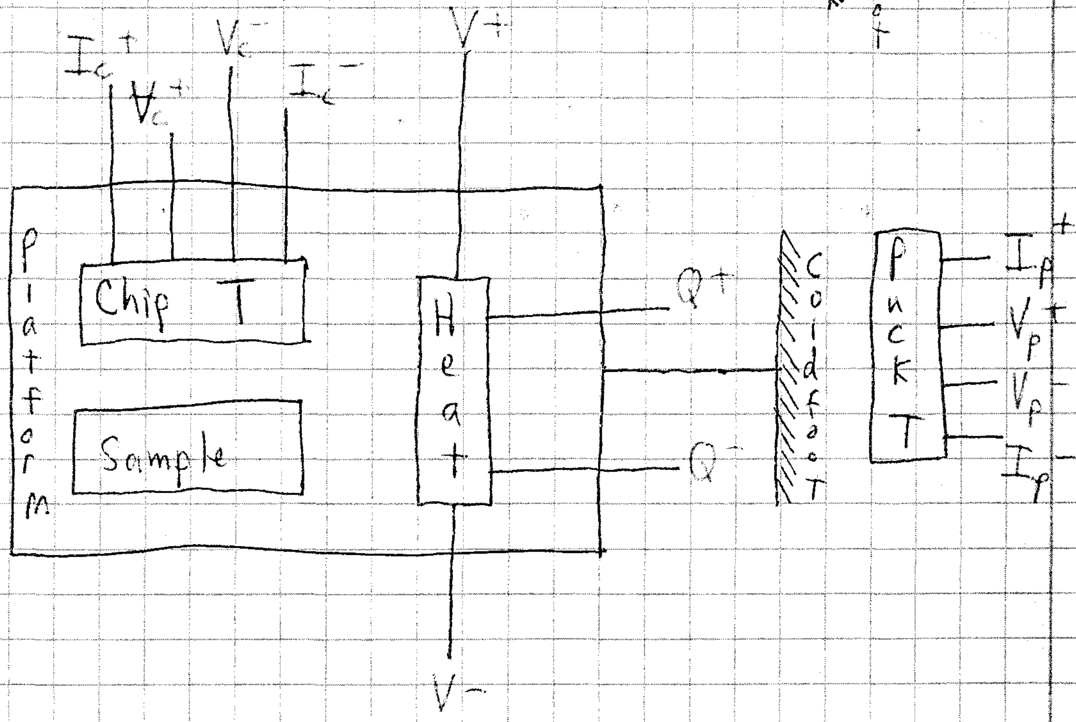
The currents (Channel 1 and Channel 2) are connected to the same pin. The channels are switched inside the user bridge. This allows two channels to access one set of pins. Knowing this, we can compare the 2 measurements and jitter on the following page.

Detailed Comparison of TTO and HC Measurements.

TTO Puck



Heat Capacity Puck



TTO Measure

① Set $Q^\pm$.
② Read Warm/Cold.
③ Read "Seebeck Voltage".

Heat Capacity Measure

① Set $Q^\pm$.
② Read Chip/Puck.
③ Read Heater Voltage.

Notes

① $Q^\pm$ are the same.
② $I_s^\pm$ (TTO) are not used for HC.
③ $V_s^\pm$ (TTO) are $V^\pm$ (HC).
④ $I_c^\pm$ and $I_p^\pm$ (HC) are $I_{1,2}^\pm$ and $I_s^\pm$ (TTO).
⑤ $V_p^\pm$ and $V_c^\pm$ (HC) are $V_1^\pm$ and $V_2^\pm$ (TTO).

Why won't the TTO method work?

The measurements are compatible except for the fact that the TTO thermometers are in series. There doesn't seem to be any sure way to ensure that the method will work as expected. Besides, there is no need to introduce automation when we know it gives us trouble in the TTO measurement.

Although it *might* be possible, there is an easier and more efficient solution.

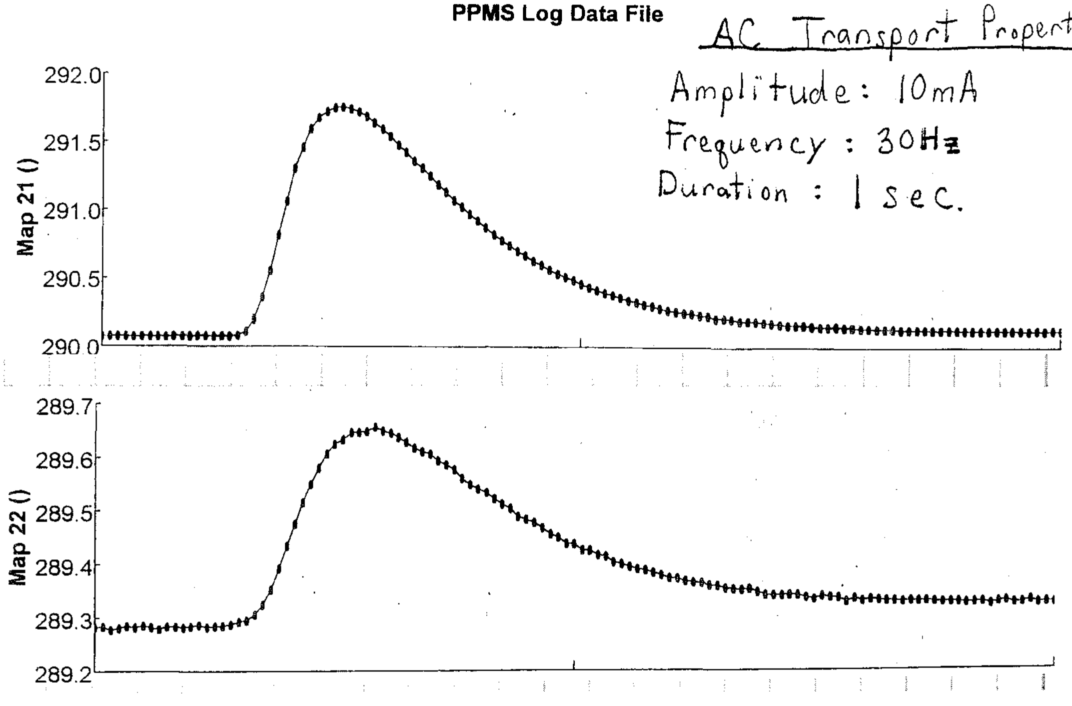
How can the AC Transport hardware be used to measure heat capacity?

Using the AC Transport hardware for this measurement seems an attractive option because it provides a reliable (and fast) voltmeter and a steady current source for our heater. The thermometers could be monitored by the user bridge.

There are some aspects that make this unfeasible. First, the AC Transport hardware cannot be operated manually because Quantum Design says that they will not release their source code to us. This source code includes all of the GPIB commands for the AC Transport hardware.

Therefore, the AC Transport hardware must be operated through the software and this puts some constraints on what we are capable of doing (just as in the previous case).

Warm & Cold Temperature Reaction From AC Transport Heater Control



AC Transport Properties

Amplitude: 10mA

Frequency: 30Hz

Duration: 1 sec.

The previous page shows the reaction of the 2 thermometers when being controlled with the AC Transport software. Notice the behavior is not what we have expected.

Because the software puts constraint on us, learning the details of the ACT software would take alot of time, and initial test show behavior which is undesirable, it was decided to discard this option.

September 11, 2002

How can the User Bridge hardware be used to measure heat capacity?

The user bridge board gives us access to four 4-wire resistance channels and two heater current driver channels (which record both current and power). See the diagram below:

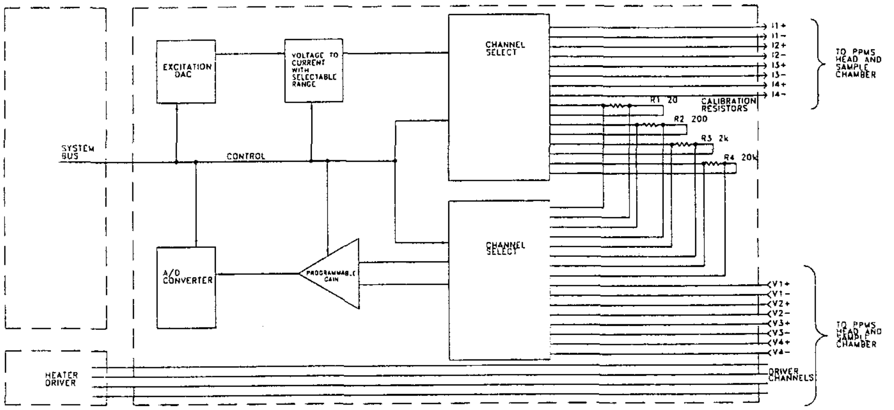


Figure 2-1. Block Diagram of Bridge Board

There is no problem in connecting the 2 thermometers to the first 2 channels and the heater to the first current driver. There were initiall concerns regarding the data collection speeds (which go only as fast as 4 times per second, or 4Hz) as well as the resolution of the current driver, which accepts digital values for output current.

The picture on the right shows the function of each pin on the user bridge parallel port.

The current drivers say "(unused)" because it is referring to the resistivity measurement, in which case they are not used.

Instead of using 4 wires for the heater (2 for current and 2 for voltage), the current driver uses only 2 (for current), but is also capable of reporting power (and therefore voltage).

P1–USER BRIDGE "D" CONNECTOR	USER BRIDGE BOARD FUNCTION
1	Cur Driver 1+ (unused)
14	Cur Driver 1– (unused)
2	Cur Driver 2+ (unused)
15	Cur Driver 2– (unused)
5	Channel 1 I+
18	Channel 1 I–
6	Channel 1 V+
19	Channel 1 V–
7	Channel 2 I+
20	Channel 2 I–
8	Channel 2 V+
21	Channel 2 V–
9	Channel 3 I+
22	Channel 3 I–
10	Channel 3 V+
23	Channel 3 V–
11	Channel 4 I+
24	Channel 4 I–
12	Channel 4 V+
25	Channel 4 V–
13	Shield

What is the resolution of the user bridge board?

Limits and Resolution

The user bridge board automatically adjusts the excitation current of its active channels, but you can specify the maximum allowable current, power, and voltage for each channel (see table 2-2). The excitation current is limited by the specified maximum current, voltage, or power—whichever parameter setting limits the excitation current to a lower value.

Table 2-2. Current, Power, and Voltage Limits

PARAMETER	VALUES
Current Limit	±0.01–5000 µA
Power Limit	0.001–1000 µW
Voltage Limit	1–95 mV

The information on the right is referring to the 4-wire measurements made on the 2 thermometers. Notice, in particular, the ~~[illegible]~~ errors in resistance. →

The nominal resolution of the user bridge board is determined by the resolution of the A/D converter and by the maximum applicable current. **Accordingly, nominal resolution on the most sensitive range** is 3.81 nV/5.00 mA = 0.762 µΩ. **In practice, environmental and internal noise sources usually limit measurement precision to around 20 nV, or 4 µΩ with a 5-mA excitation.** Measurement resolution also depends on the internal gain setting and the excitation current, which can be affected by the resistance being measured and by the specified limits for current, power, and voltage.

The maximum measurable resistance is computed from the maximum potential drop that can be measured and from the minimum useful excitation current, which is determined by the user bridge's DAC resolution. **The nominal maximum measurable resistance is thus 95 mV/2.44 nA = 38.9 MΩ.** However, such a measurement would require an excitation current very near the DAC resolution. In practice, user bridge board error increases drastically above approximately 4 MΩ. **Errors in excess of 1% can be anticipated when measuring resistances greater than 4 MΩ. The expected error increases to 5–10% around 9 MΩ.**

We should not have to worry about going as high as 4MΩ, since our thermistors seem to have a range of 30Ω to 6KΩ.

2.2.2 Internal Excitation Current Range Selection

This gives the resolution of the current for both the 4-wire measurement and the current drivers.

The excitation current range selection for the user bridge board is performed internally. However, it is useful to understand the range selection process. Table 2-3 lists the four excitation current ranges and the corresponding step sizes.

The bridge board uses the range resulting in the smallest step size while still providing the necessary current. For display purposes, the excitation current is rounded to the nearest step value.

Step size is calculated by

$$\text{Step Size} = \frac{\text{Max Current}}{2^{11}}$$

because the excitation DAC is 11 bits (bit 12 designates the current's sign).

Table 2-3. Current Ranges

MAXIMUM CURRENT	STEP SIZE
5.0 mA	2.44 µA
0.5 mA	244.00 nA
50.0 µA	24.40 nA
5.0 µA	2.44 nA

This table is for 4-wire measurements.

The maximum allowable current for the current driver is 1000 mA. The step size is:

$$\boxed{\frac{1000\,\text{mA}}{2^{11}} = \frac{1000\,\text{mA}}{2048} \cong 0.49\,\text{mA} = 490\,\mu\text{A}}$$

There was a concern that even the lowest heater current (0.49mA) was too great for the real heat capacity puck, but as it turns out, it is alright (and will be shown later).

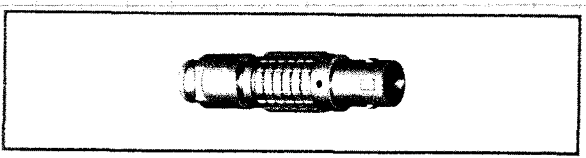
Connecting the puck to the PPMS user bridge board.

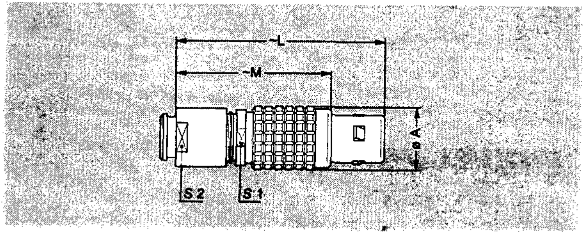
Now that we know how we can control the puck, an appropriate cable must be constructed. The pin-out is listed below:

Function	Puck / Gray Lemo	P1 (Model 6000)
Heater I +	3	1
Heater I −	4	14
Heater V +	5	—
Heater V −	6	—
Chip T I +	7	5
Chip T I −	8	18
Chip T V +	9	6
Chip T V −	10	19
Puck T I +	11	7
Puck T I −	12	20
Puck T V +	13	8
Puck T V −	14	21
	See pg. 6	See pg. 23

The creation of a heat capacity cable.

The following parts were ordered from Neumann Electronics, Inc. (http://www.eneumann.com), although they may also be ordered directly from LEMO, whose staff had been overwhelmingly helpful. (http://www.lemo.co

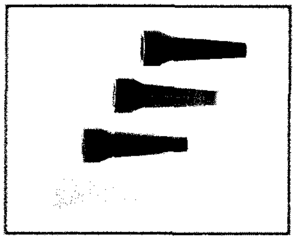


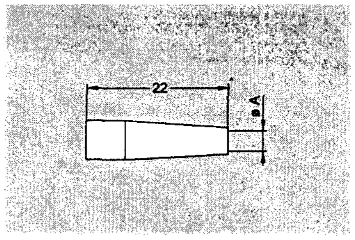


FGG **Straight plug, key (G) or keys (A...M), cable collet and nut for fitting a bend relief**

		Dimensions (mm)				
Model	Series	A	L	M	S1	S2
FGG	00[1]	6.4	27.5	18.5	5.5	5
FGG	0B	9.5	35.0	25.0	8.0	7
FGG	1B	12.0	42.0	33.0	10.0	9
FGG	2B	15.0	48.0	36.0	13.0	12
FGG	3B	18.0	56.5	41.5	15.0	15
	4B	25.0	71.0	53.0	21.0	20

Note: [1] the surface design of the 00 series is different. The bend relief must be ordered separately.





GMB **Strain relief**

	ø Cable		Dim.	Nut for fitting the *strain relief part nb*
	max	min	A	
GMB.00.025.DG	2.8	2.5	2.5	FFM.00.130.LN
GMB.00.028.DG	3.1	2.8	2.8	FFM.00.130.LN
GMB.00.032.DG	3.5	3.2	3.2	FFM.00.130.LN

Note:
a) for use with all crimp models and nut for fitting a strain relief
b) the last letter of the part number "G" specifies the colour grey. Refer to the table to the left to define another colour and replace the letter "G" by the one corresponding to the *colour required.*

Ref.	Colour
A	blue
B	white
G	grey

Ref.	Colour
J	yellow
M	brown
N	black

Ref.	Colour
R	red
S	orange
V	green

- Material: Polyurethan (Desmopan 786)
- Operating temperature: -40°C + 80°C

The model numbers are unnecessarily difficult to construct and so the best option would be to discuss your application to a sales representative so they can build it for you. Their phone number is as follows:

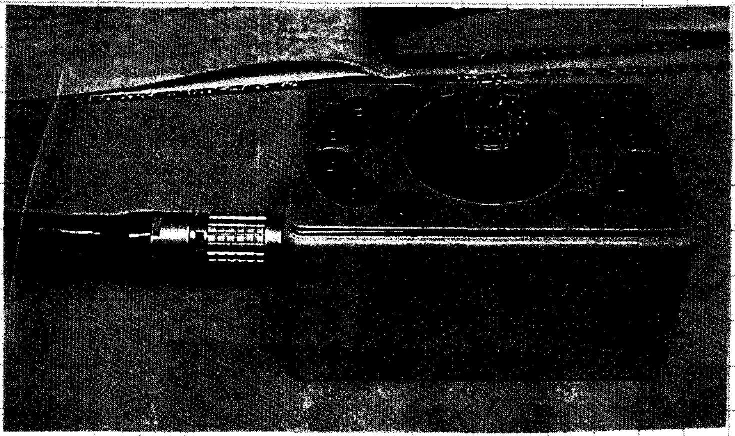
LEMO USA
www.lemo.com
1-(800)-444-5366

The model numbers of the pieces I used are as follows:

Connector (14-pin)	FGG.3B.314.CLAD92Z
Strain Relief (Orange)	GMA.3B.080.DS

First tests for the simulation puck. - In atmosphere

Now that the simulation puck and the cable were completed, I could start testing and move up to the real puck in slow and careful steps. First, I tested the simulation puck in atmosphere, as in the picture below:

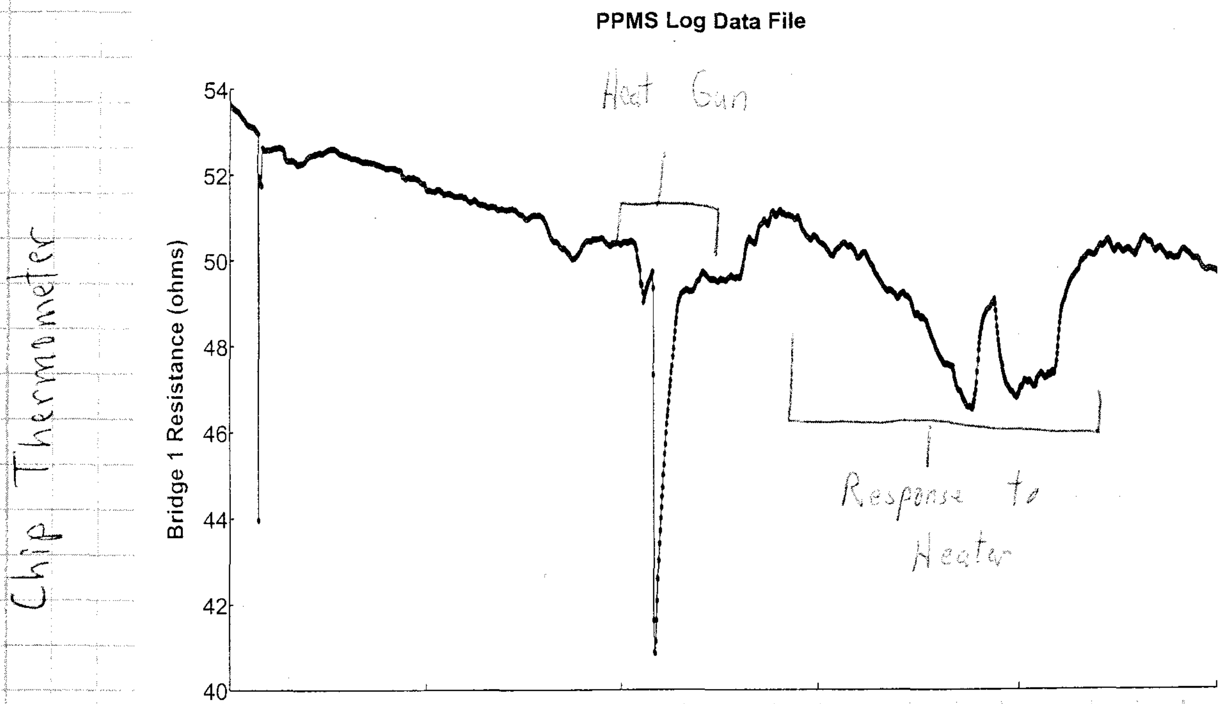


Mounting the puck outside the dewar allowed me to use the heat gun, because initially I feared the resistor power was too small to be noticed by the thermistor.

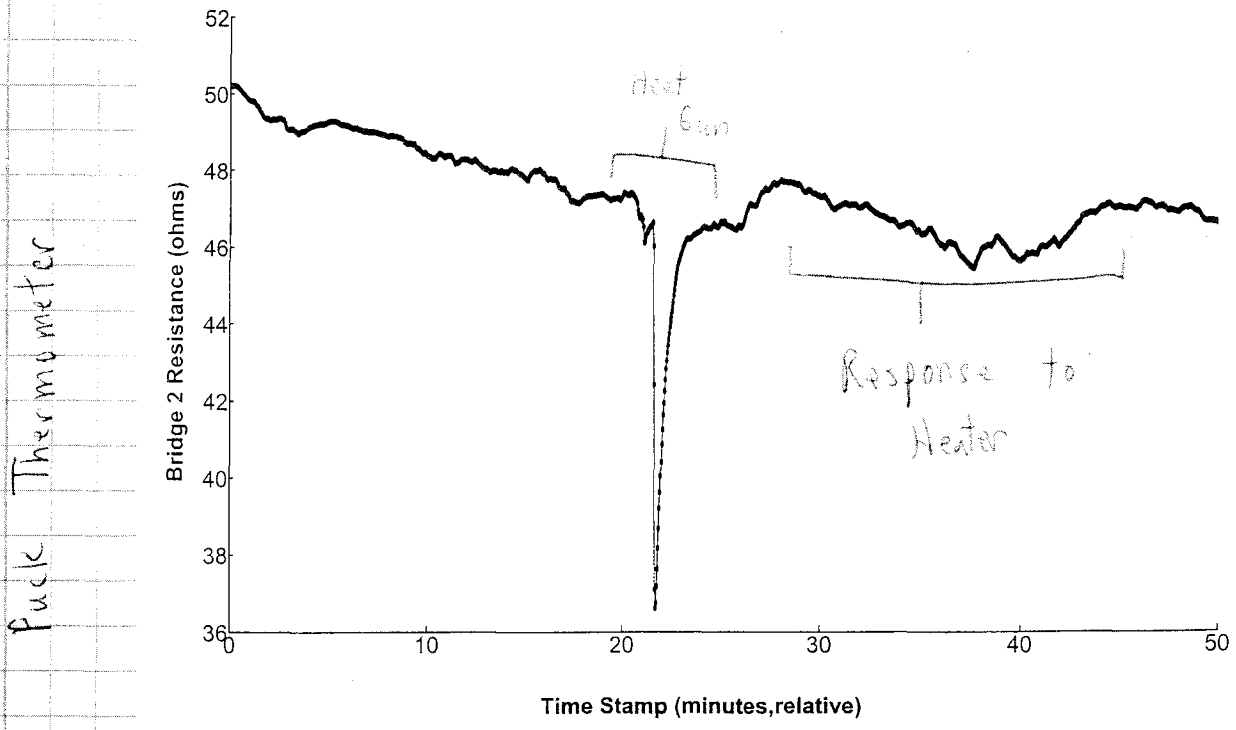
I tried a combination of Cryostat effects with my own outside influences. The following page shows the reaction of both thermometers, and the following pages after that details the behavior.

The large valley at ≈ 20 minutes is due to the heat gun.

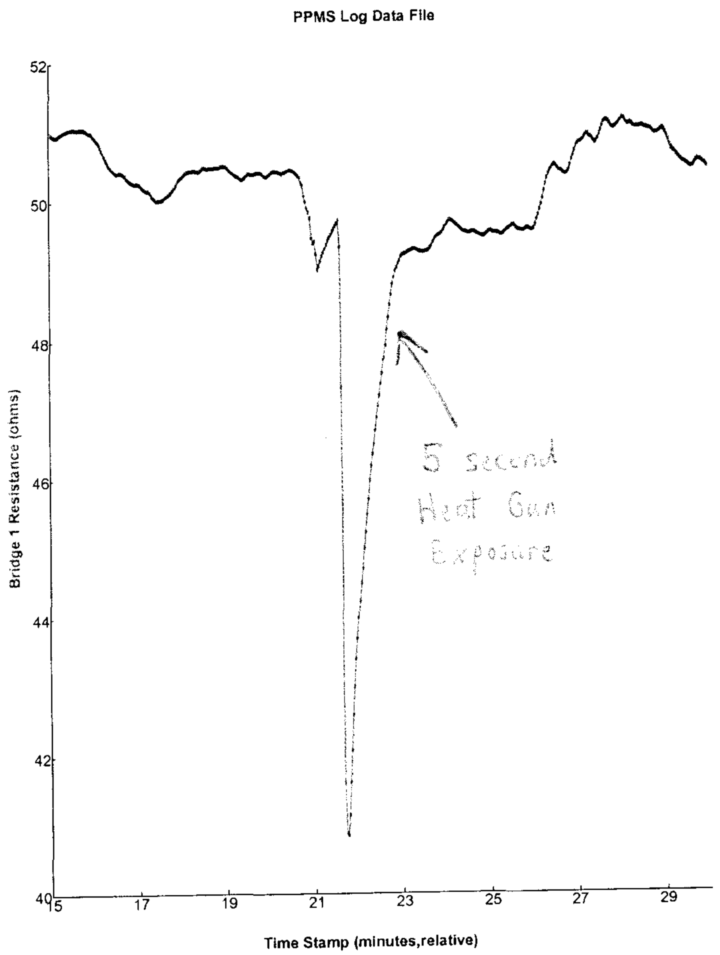
Initial small power levels made no apparent changes in temperature. Between 30 and 40 minutes I put a much greater heater pulse into the system and was finally able to see a response.



It is no surprise that Bridge 1 responds better to the heater.



Chip Thermometer



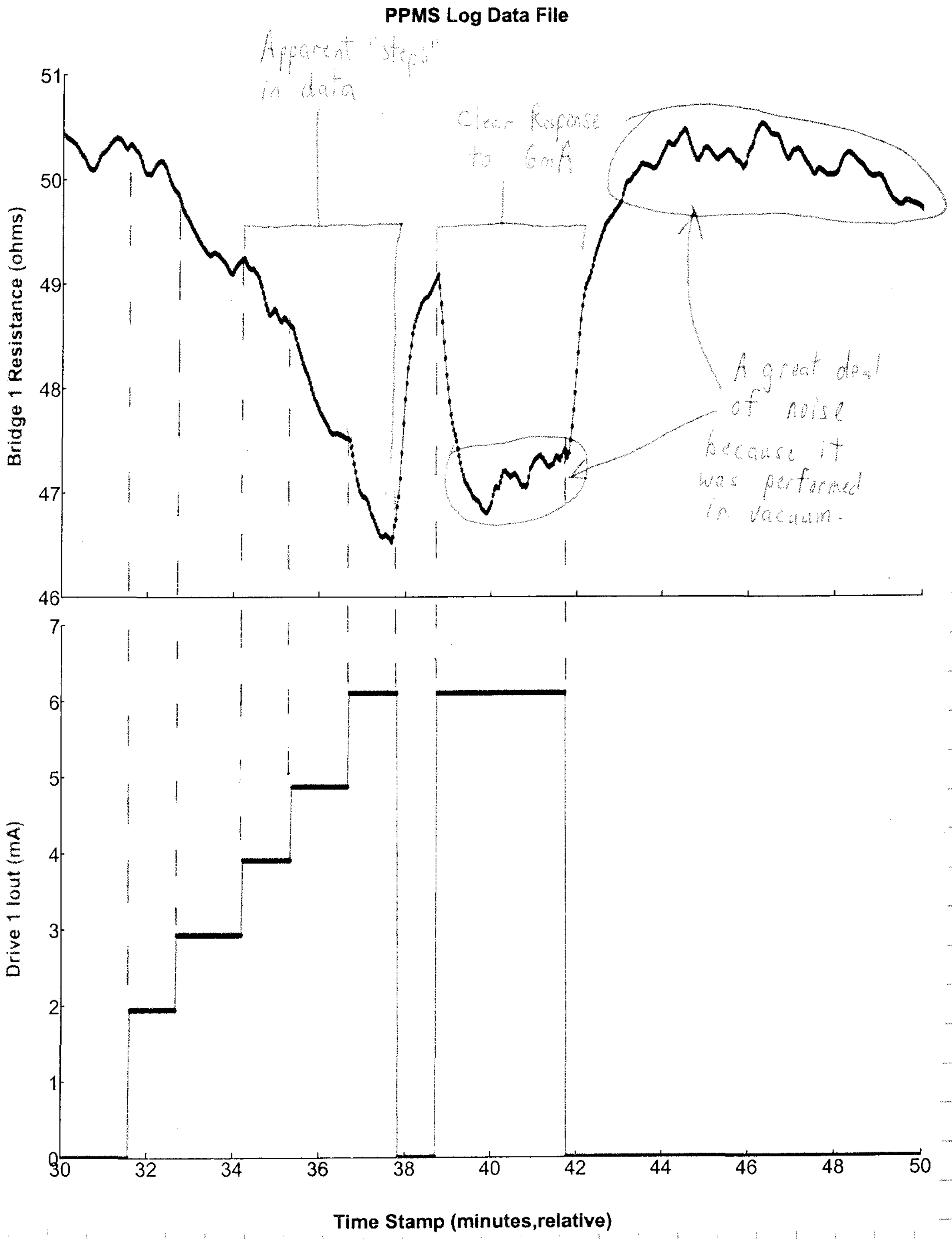
As expected, both thermometers responded similarly to the heat gun exposure, because it was directed at the entire puck. (5 second exposure)

The resistance drops sharply in response to a large change in temperature.

The heat gun was used after a two smaller pulses did not generate a signal that was discernible above the noise level, and served as the first indication that the puck was operating properly.

I wanted to make sure the system was responding properly before inputting a current greater than 2 mA.

Chip Thermometer



It's hard to discern a signal below 4 mA, but above 4 mA gives a clear signal response!

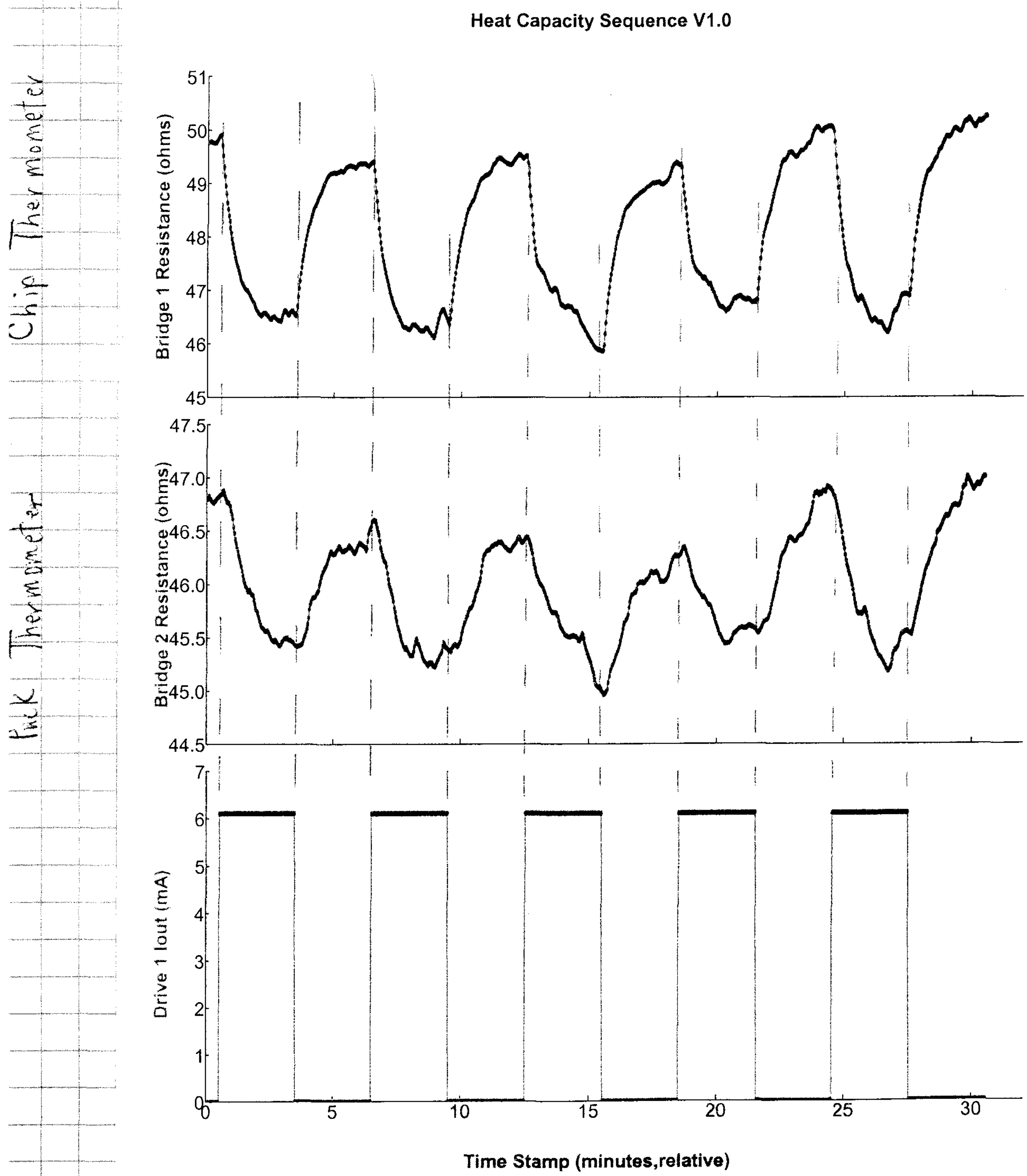
There is a lot of noise due to atmospheric losses.

Creating Our first sequence – In atmosphere.

```
Sequence File: HCv1.0

1:  LogData Start New 2.00 622839 2094079 7 "C:\WINDOWS\Desktop\LogPpmsSeq.da
    t" "Heat Capacity Sequence V1.0" "First Test of Mock Puck w/ Orange Cable
    "
2:  Wait For Delay 30 secs, No Action
3:  Scan Time 0.0 secs in 5 steps
4:      Driver Output Channel 1, 6.0mA, 0.1W
5:      Wait For Delay 180 secs, No Action
6:      Driver Output Channel 1, 0.0mA, 0.1W
7:      Wait For Delay 180 secs, No Action
8:  End Scan
9:  LogData Stop "First Test of Mock Puck w/ Orange Cable"
```

Ran on 6/20/02



The first heat capacity sequence is shown on the left. A pulse of 6mA was chosen because it produced a significant signal on the previous trial.

There is a clean response to the heater pulse, and is seems to take the general expected shape. It is no surprise that the bridge 1 signal is sharper than bridge 2, because it is thermally attached to the heater while bridge 2 has the separation of the atmosphere

Creating the first sequence at High Vacuum.

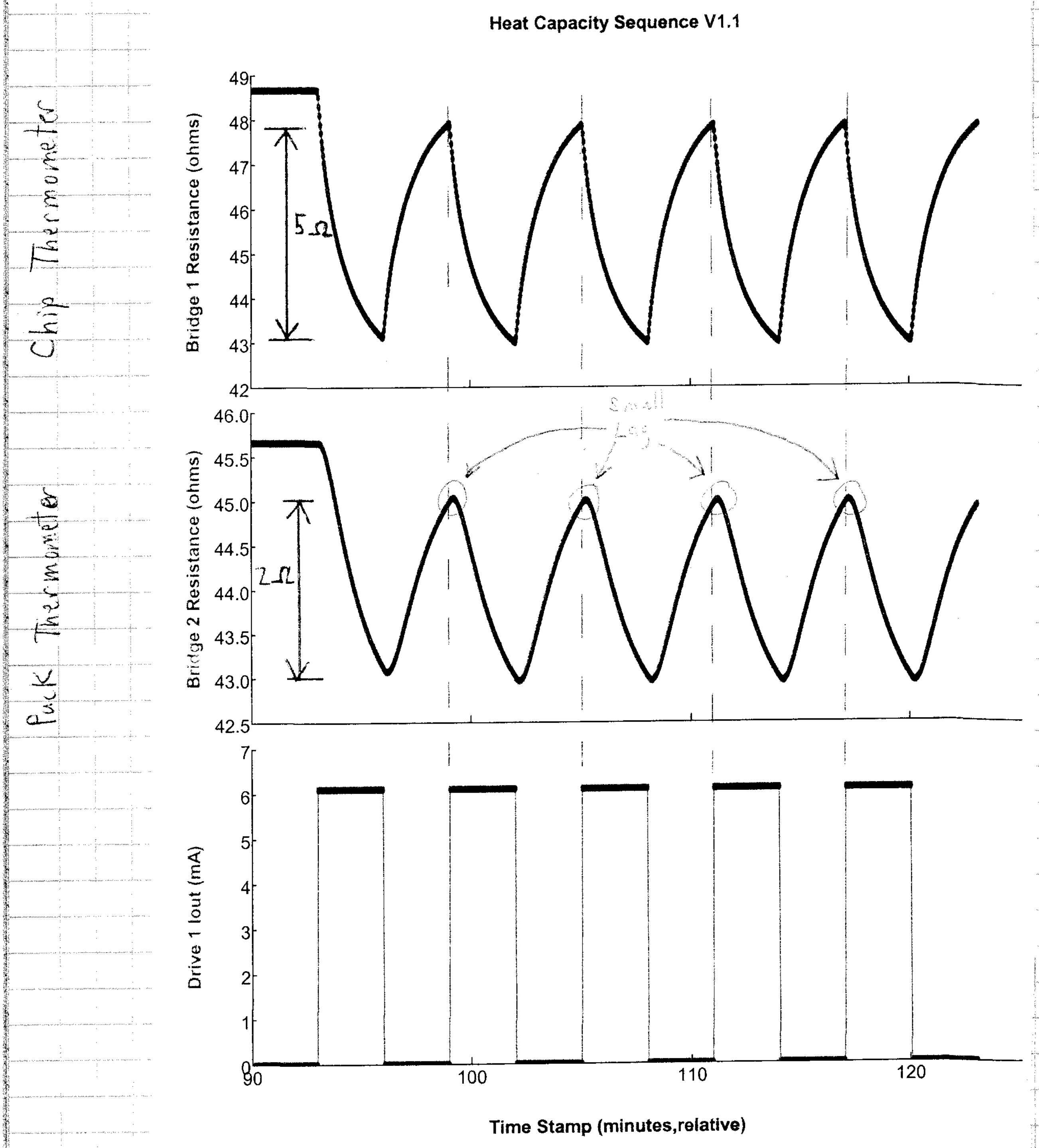
The puck showed no signs of malfunctioning, so the next step was to see if operating at a high vacuum would remove the noise. The sequence run is copied below:

```
Sequence File: HCv1.1


 1:  LogData Start New 2.00 622839 2094079 7 "C:\cryolab\06-21-2002\HCv1.1_Log
     PPMS.dat" "Heat Capacity Sequence V1.1" "First Test of Mock Puck w/ Orang
     e Cable"
 2:  Chamber Vent then Seal
 3:  Wait For Chamber, Delay 0 secs, No Action
 4:  Chamber Purge then Seal
 5:  Wait For Chamber, Delay 0 secs, No Action
 6:  Chamber High Vacuum
 7:  Wait For Chamber, Delay 3600 secs, No Action
 8:  Wait For Delay 30 secs, No Action
 9:  Scan Time 0.0 secs in 5 steps
10:      Driver Output Channel 1, 6.0mA, 0.1W
11:      Wait For Delay 180 secs, No Action
12:      Driver Output Channel 1, 0.0mA, 0.1W
13:      Wait For Delay 180 secs, No Action
14:  End Scan
15:  LogData Stop "First Test of Mock Puck w/ Orange Cable"
```

Run on 6/21/02.

The results are displayed on the following page.



The results of the high vacuum measurement was a huge success. It shows that the puck, cable, and measurement method work properly and that the measurement should be feasible.

Notice the delay between the chip and puck thermometer response. It's very small but noticeable. It makes sense due to the distance between the heater and puck thermometer.

Also notice how the amplitude of the chip resistance is higher than the puck resistance amplitude.

In the real puck, I expect the required heat pulse will be much lower (due to less losses and better ~~thermal~~ contact). It appears the period of the measurement must also be increased to allow more time to reach equilibrium. Lowering the heater current will also cause the puck thermometer to stabilize (in other words, it should not respond to the chip heater).

September 13, 2002

First tests of the real heat capacity puck - in atmosphere.

After it was certain that the heat capacity set-up would function properly, the next step was testing the real heat capacity puck.

Riccardo and I spent a few hours with the puck trying the lowest powers possible, so we could ramp up to the correct power without destroying the puck. First, like the other puck, we decided to test it in atmosphere. That way if the power was too high, the heat could be dissipated into the air, instead of all of it traversing the 8 fragile wires.

The setup is shown on the right and is the same as the previous (simulation) puck.

The sequence is below:

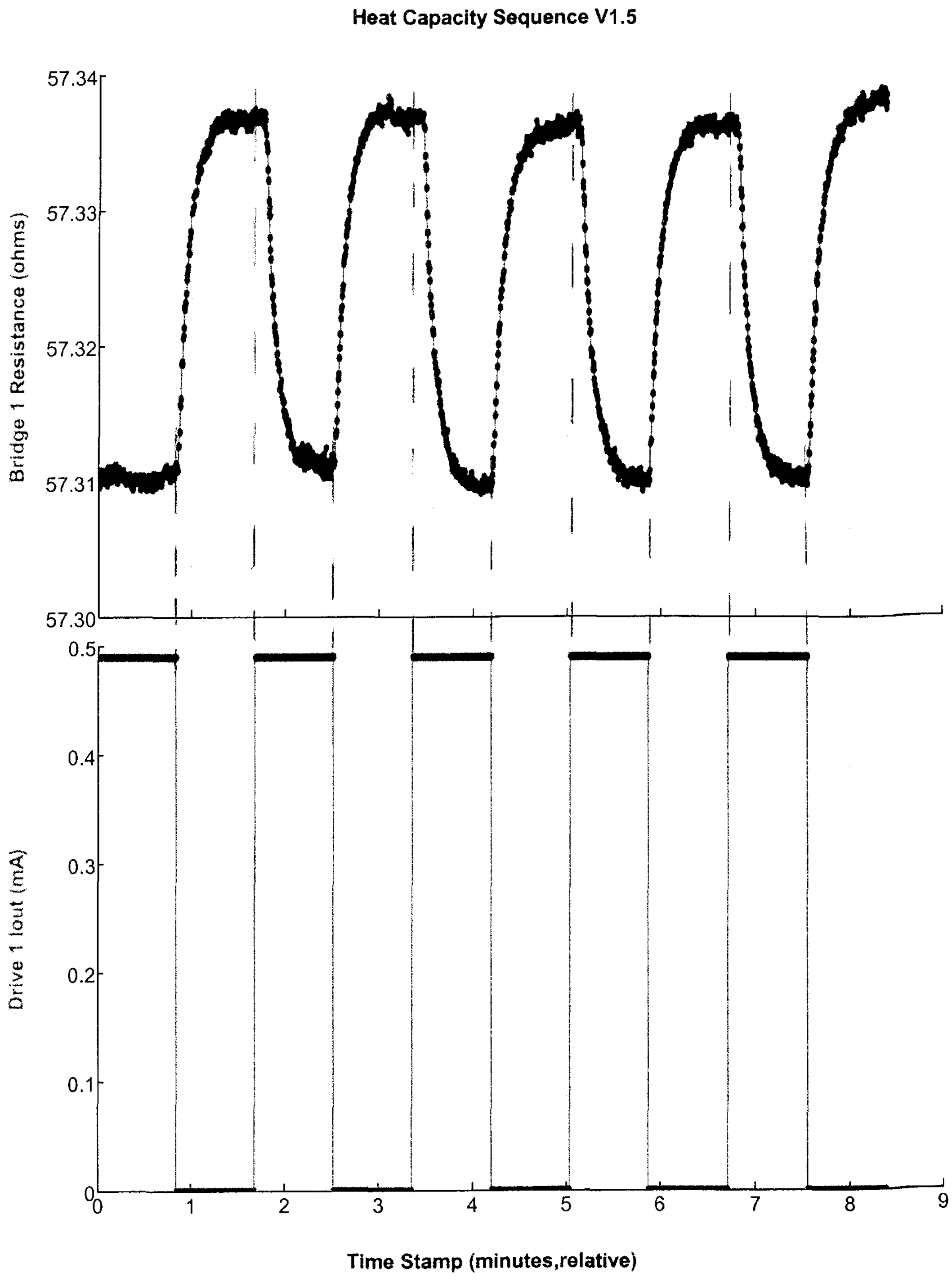
```
Sequence File: RealHCPuckTest1

    1:  LogData Start New 0.25 1073741823 2094079 7 "C:\cryolab\07-24-2002\RealHC
        PuckTest(Cryo)_LogPPMS.dat" "Heat Capacity Sequence V1.5" "Second Test of
        Mock Puck w/ Orange Cable"
    2:  Scan Time 0.0 secs in 5 steps
    3:      Driver Output Channel 1, 0.5mA, 0.1W
    4:      Wait For Delay 180 secs, No Action
    5:      Driver Output Channel 1, 0.0mA, 0.1W
    6:      Wait For Delay 180 secs, No Action
    7:  End Scan
    8:  LogData Stop "First Test of Mock Puck w/ Orange Cable"
```

→ 50 seconds

Run on 7/24/02.

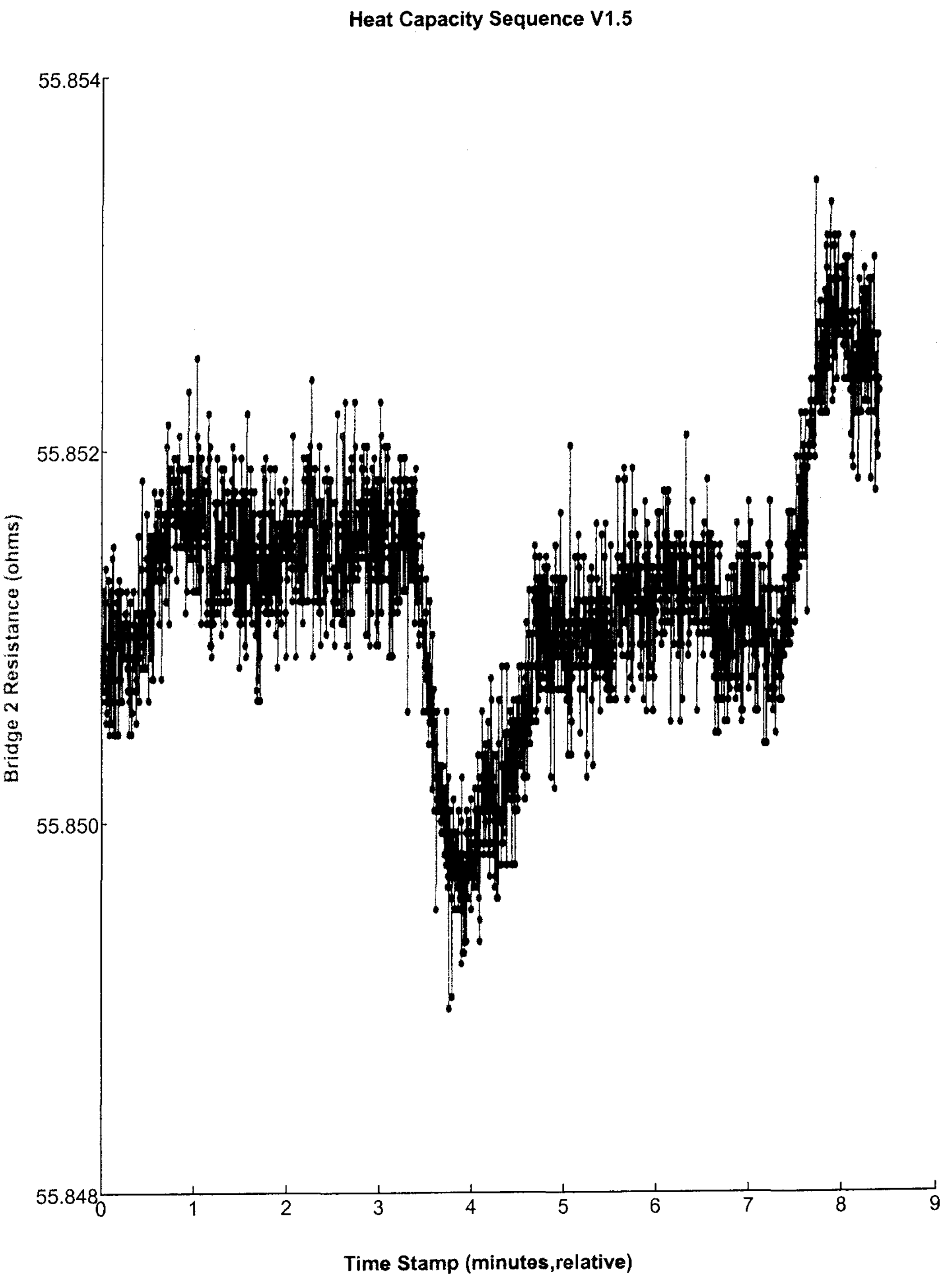
Chip Thermometer



Running the real puck in atmosphere shows success w/ a current as low as 0.49mA. The signal is a little noisy in atmosphere, but not as noisy as the simulation puck, a clear sign of better puck quality.

Until the thermistors are calibrated, it is unclear as to what pulse height corresponds to a 0.03Ω pulse.

Puck Thermometer



Here is the behavior of the puck thermometer in atmosphere. It fluctuates, but the scale is tiny. It is still unclear as to the fluctuation in terms of temperature.

This test was a success so the next step is testing the real puck @ HiVac in the Cryostat. The signal should be clearer.

Testing the real heat capacity puck at high vacuum.

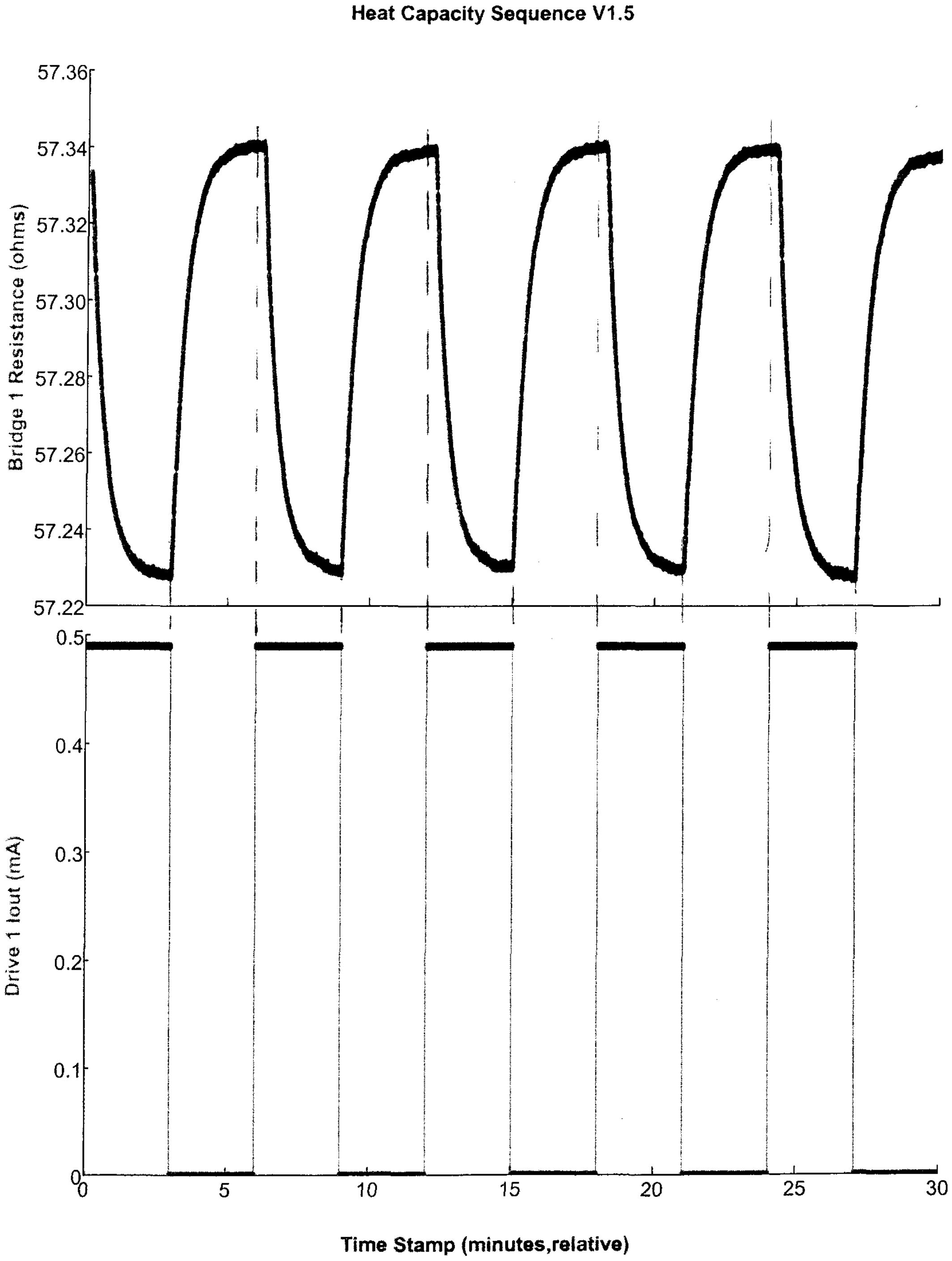
The following is the sequence file and resulting data:

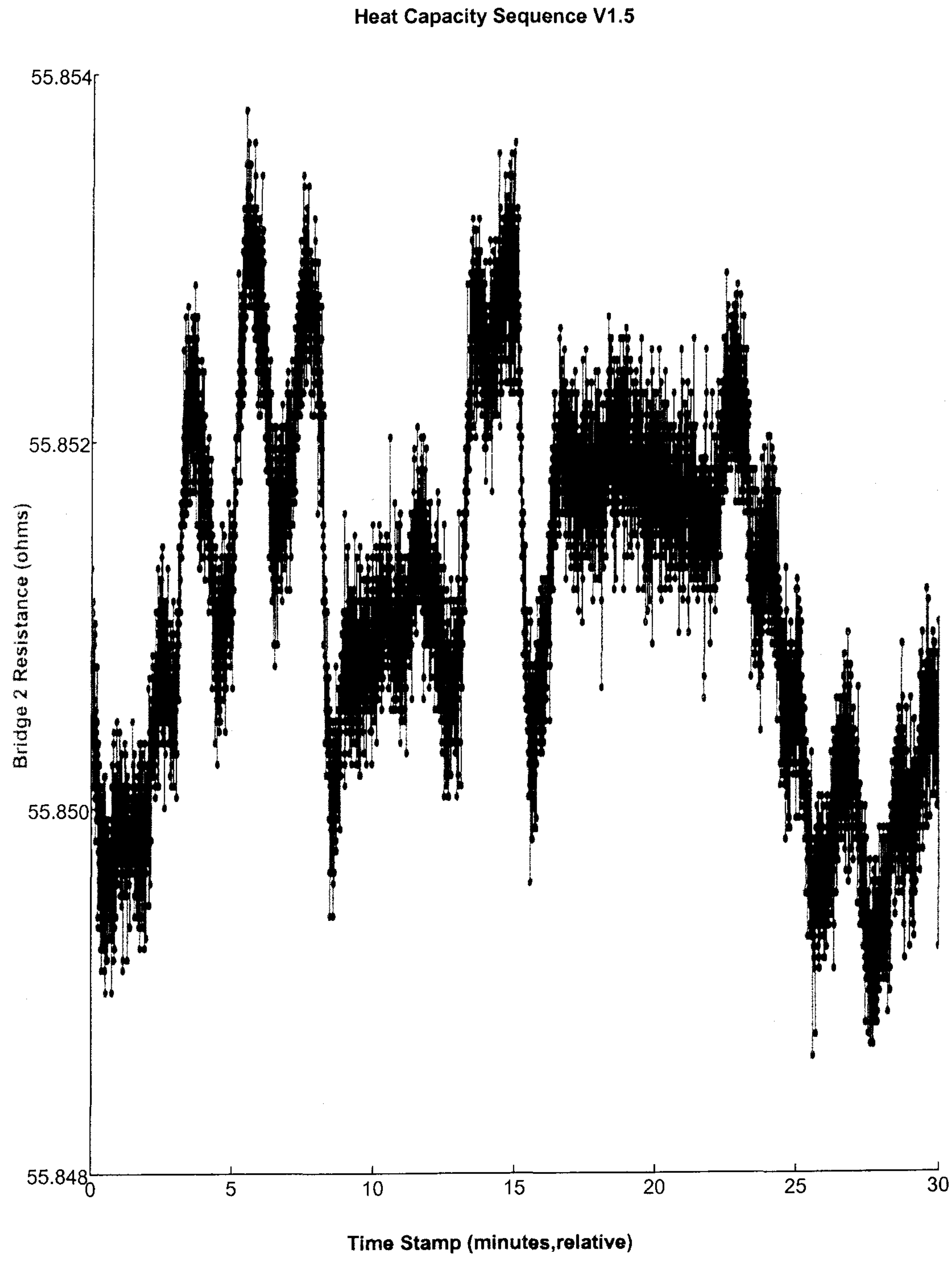
```
Sequence File: RealHCPuckTest1

1:  LogData Start New 0.25 1073741823 2094079 7 "C:\cryolab\07-24-2002\RealHC
    PuckTest(Cryo)_LogPPMS.dat" "Heat Capacity Sequence V1.5" "Second Test of
     Mock Puck w/ Orange Cable"
2:  Scan Time 0.0 secs in 5 steps
3:      Driver Output Channel 1, 0.5mA, 0.1W
4:      Wait For Delay 180 secs, No Action
5:      Driver Output Channel 1, 0.0mA, 0.1W
6:      Wait For Delay 180 secs, No Action
7:  End Scan
8:  LogData Stop "First Test of Mock Puck w/ Orange Cable"
```

Run on 7/24/02.

Chip Thermometer

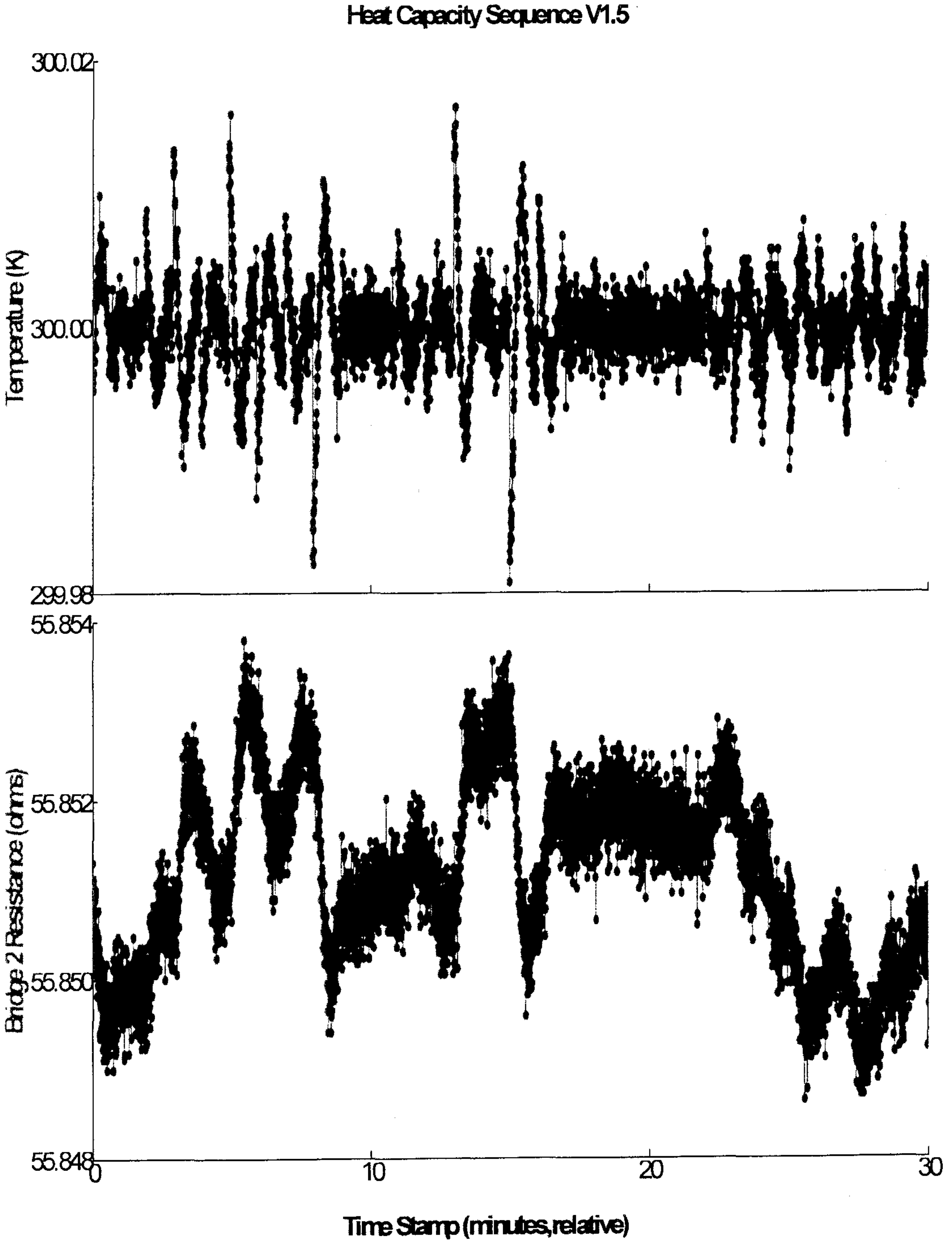




Puck Thermometer

The signal (previous page) is much cleaner due to the thermal isolation of the vacuum. The pulse amplitude is higher for the same reason.

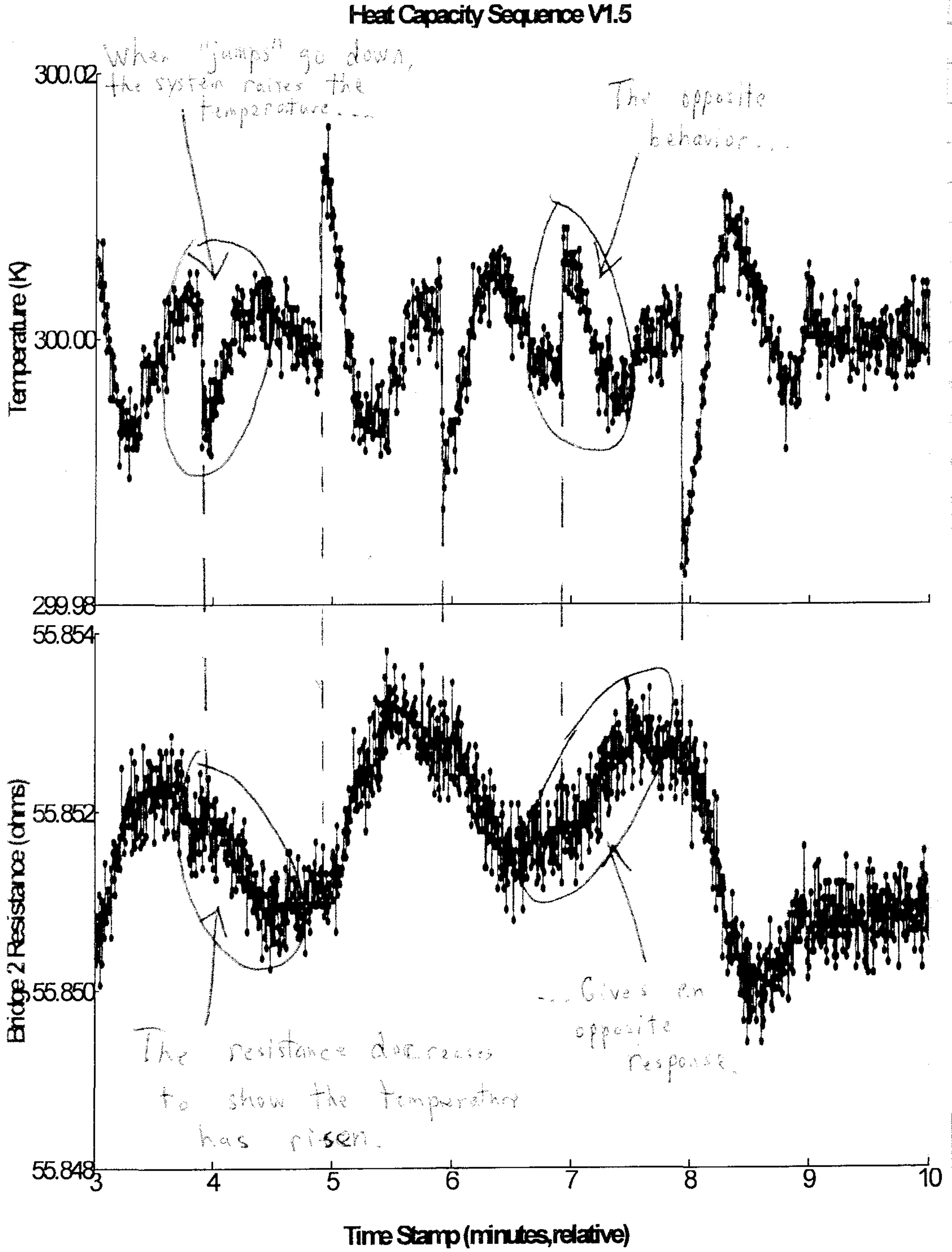
The plot above shows a similar noise amplitude as before though it appears to shift more often. The next page attempts to explain this.



Puck Thermometer

The puck thermometer should be measuring a temperature similar to the sample temperature. Comparison of the two plots shows its possible that a correlation exists.

Closer looks at the sample temperature shows there may be discontinuities. This "jumps" appear to correspond to larger fluctuations in the puck thermometer.



When "jumps" go down, the system raises the temperature...

The opposite behavior...

The resistance decreases to show the temperature has risen.

...Gives an opposite response.

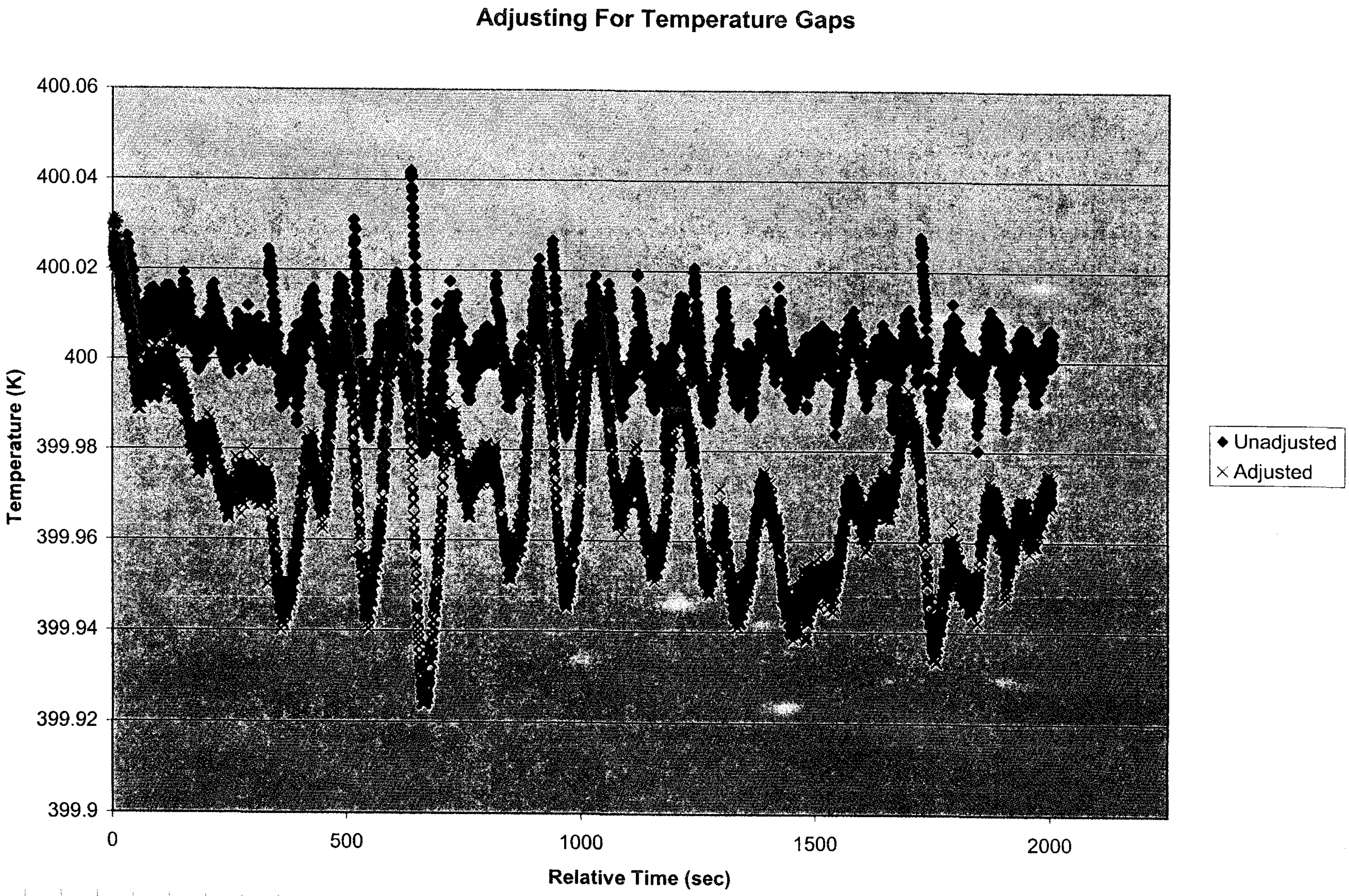
Puck Thermometer

The plot above shows what is happening. Something causes the system temperature to jump (This is unphysical, and probably is due to a voltage jump in the ~~[illegible]~~ system bridge board or the National Instruments card.) The Cryostat thinks it is a legitimate fluctuation & attempts to return to equilibrium, when in actuality it is only causing greater fluctuations.

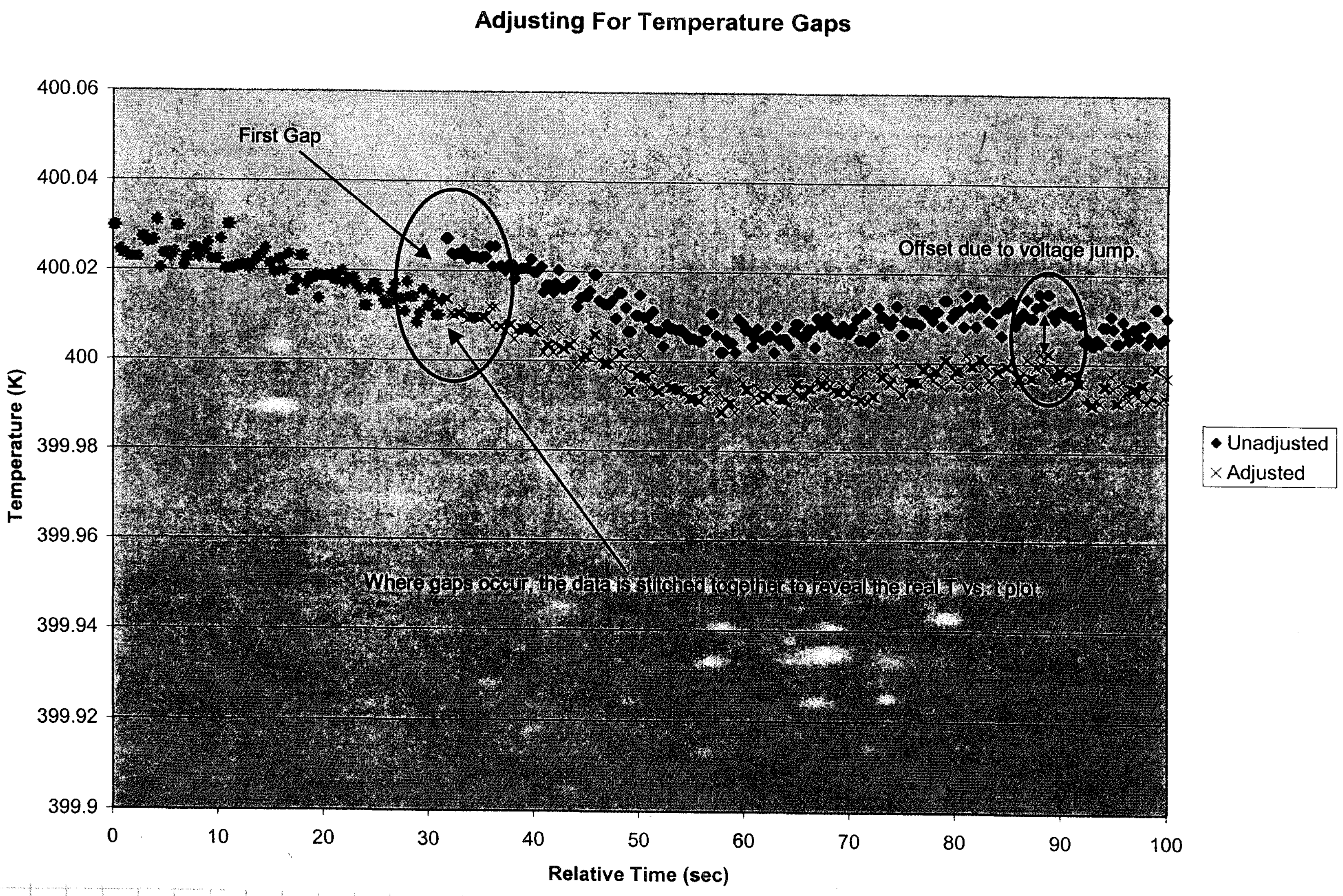
These fluctuations are seen in our measurement.

Characterization of the temperature discontinuities.

The following pages detail my findings with the temperature discontinuities.



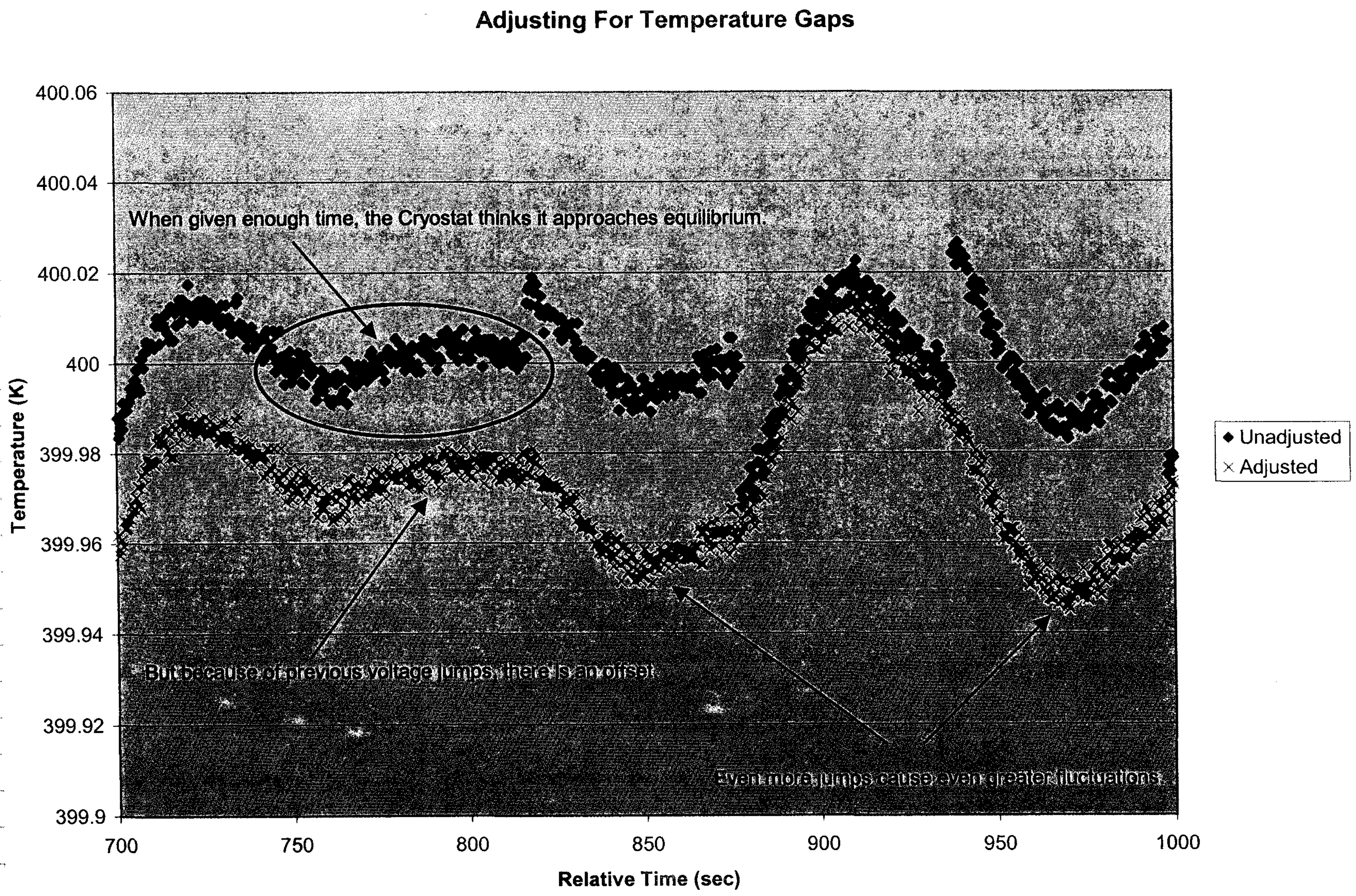
Here is a piece of data I analyzed before & after correcting for the discontinuities.



First Gap

Offset due to voltage jump.

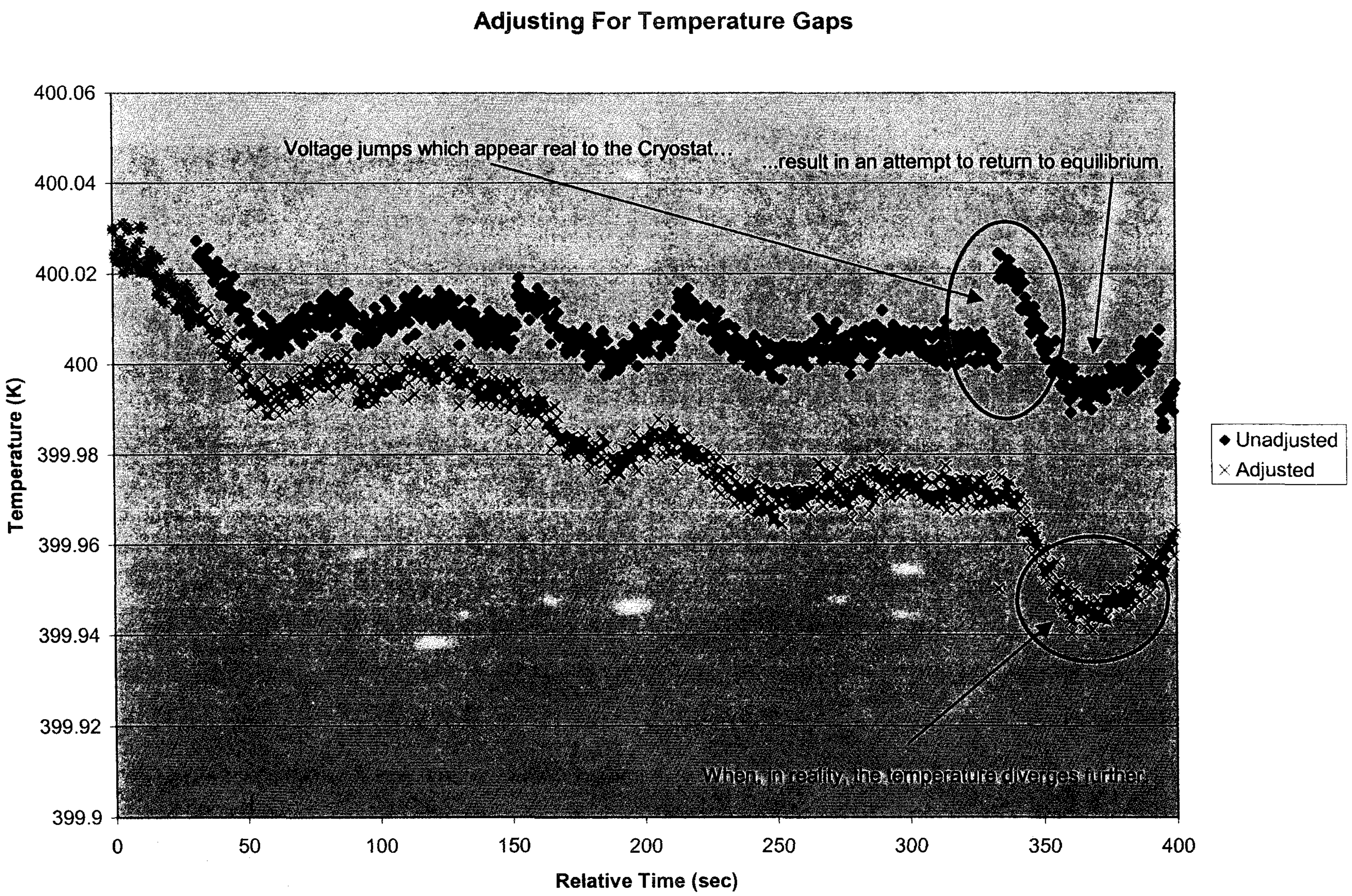
Where gaps occur, the data is stitched together to reveal the real T vs. t plot.



When given enough time, the Cryostat thinks it approaches equilibrium.

But because of previous voltage jumps, there is an offset.

Even more jumps cause even greater fluctuations.

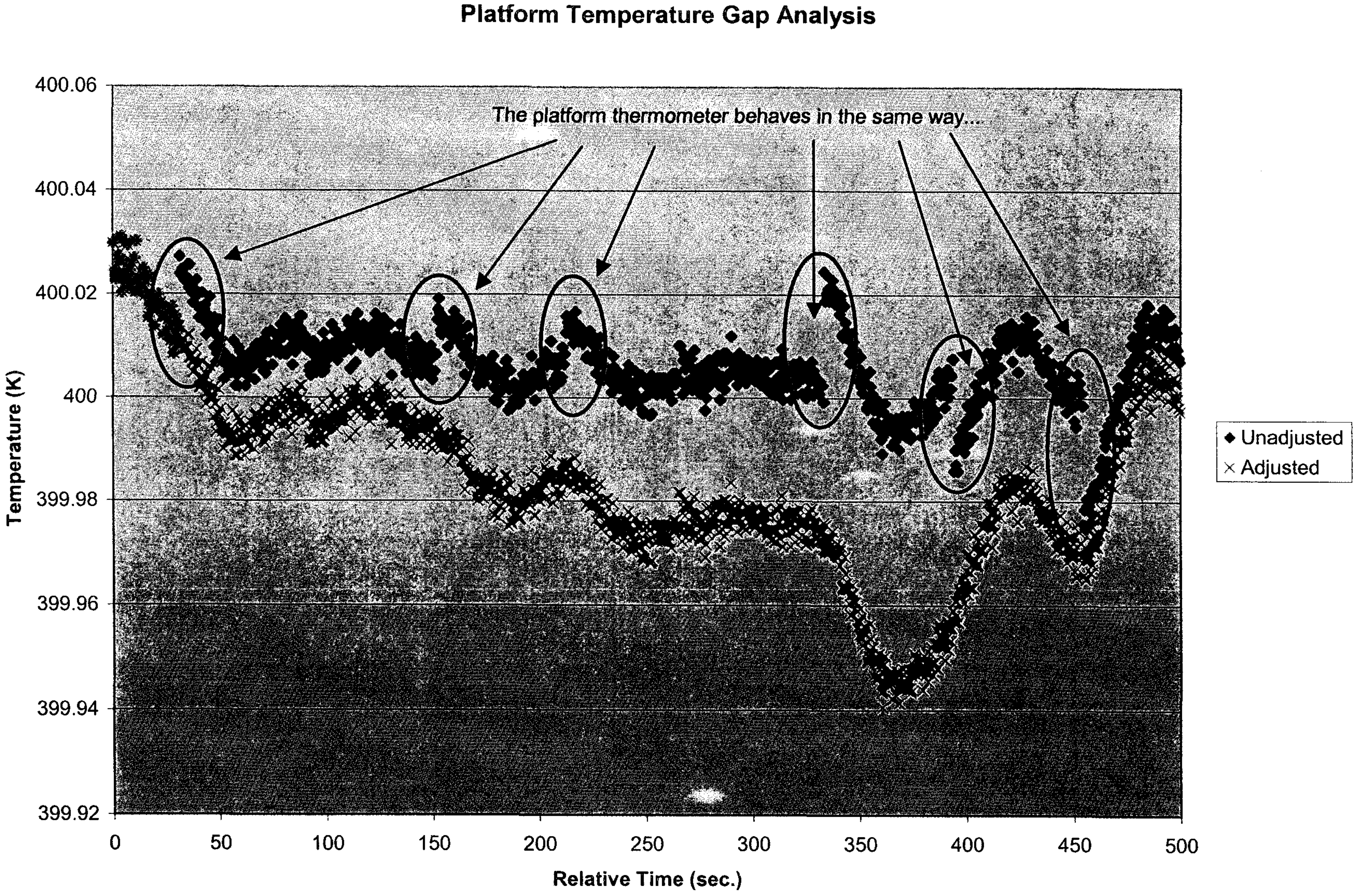


Adjusting For Temperature Gaps

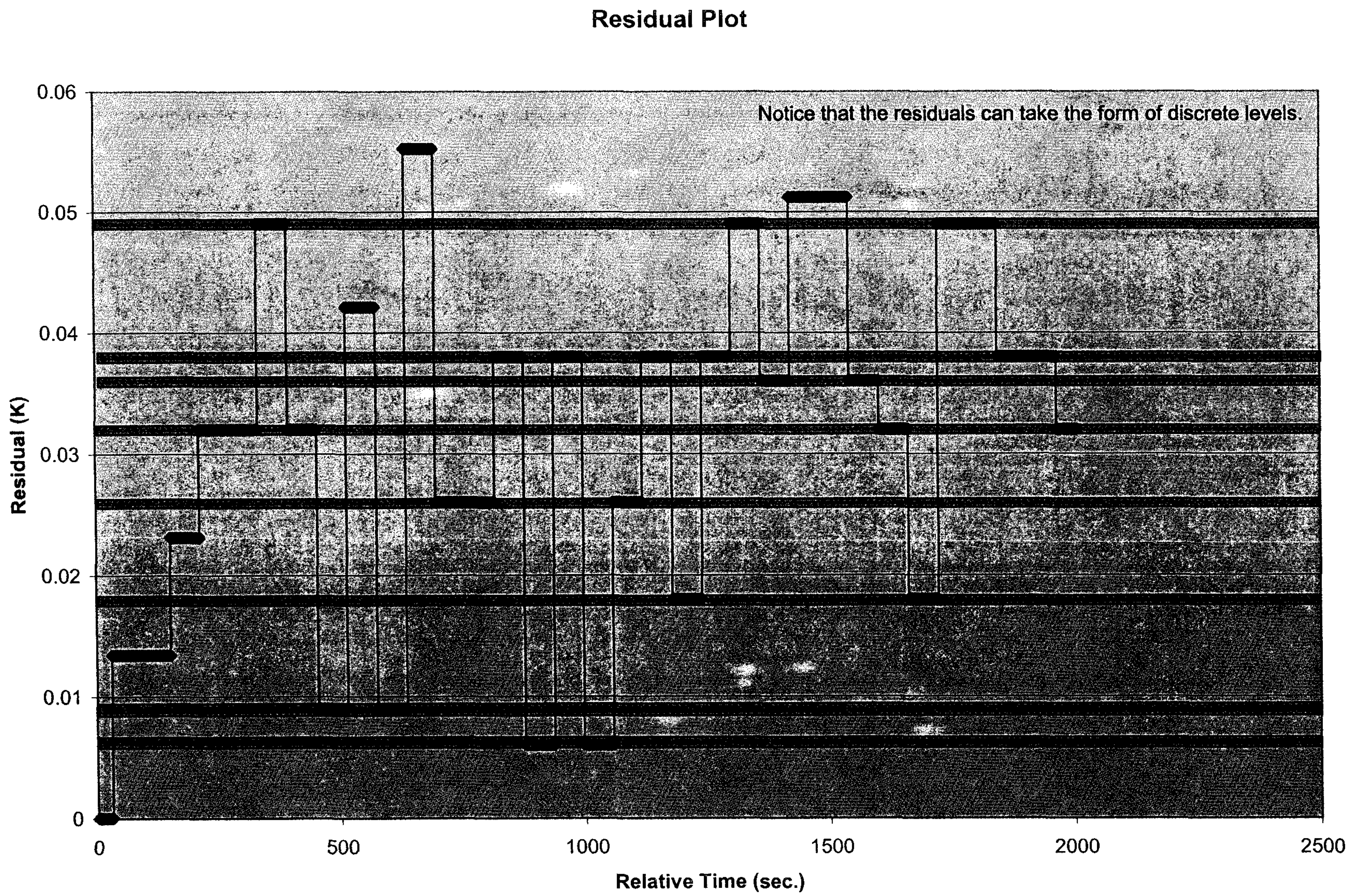
Voltage jumps which appear real to the Cryostat...

...result in an attempt to return to equilibrium.

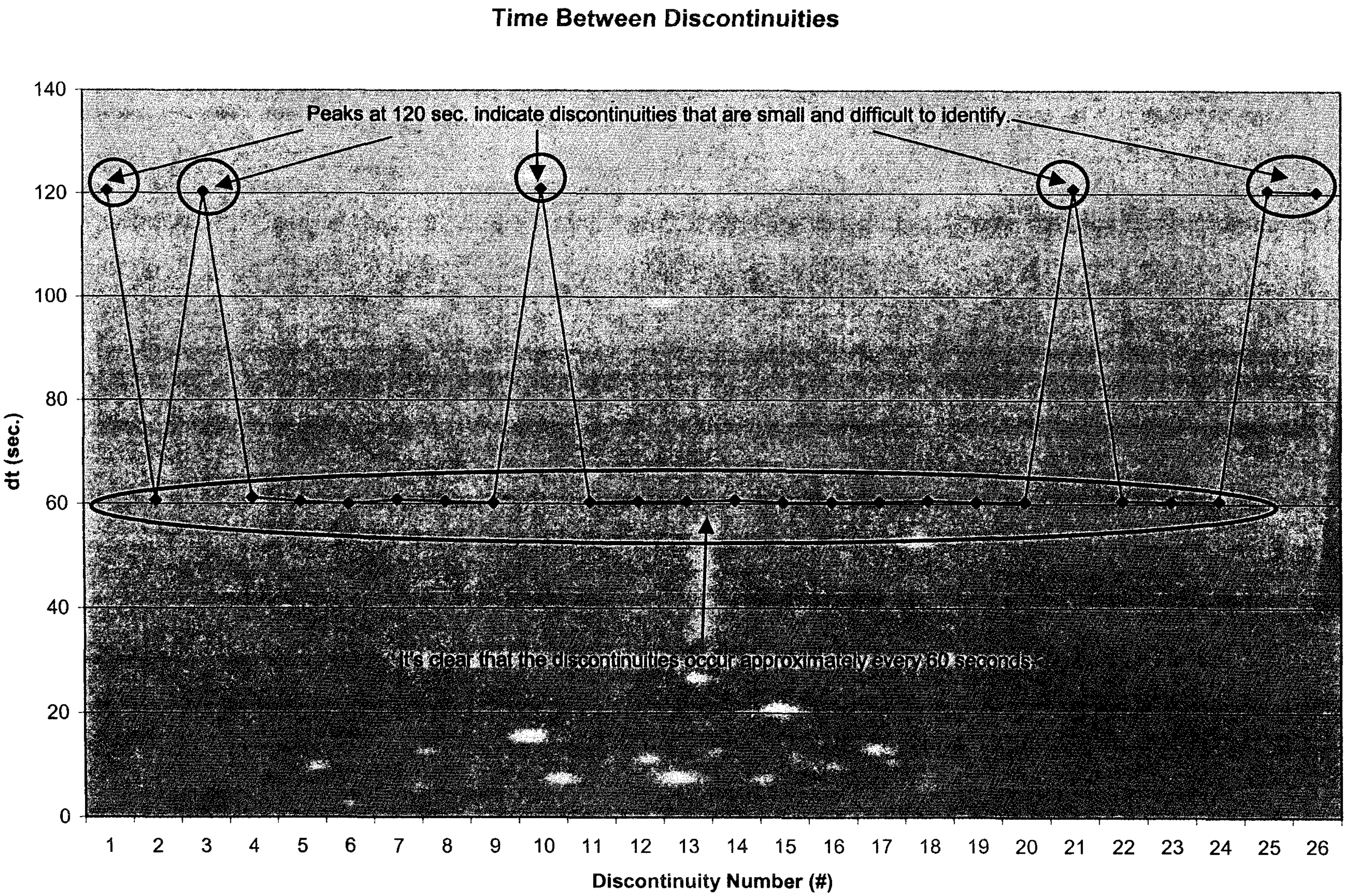
When, in reality, the temperature diverges further.



The platform thermometer behaves in the same way...



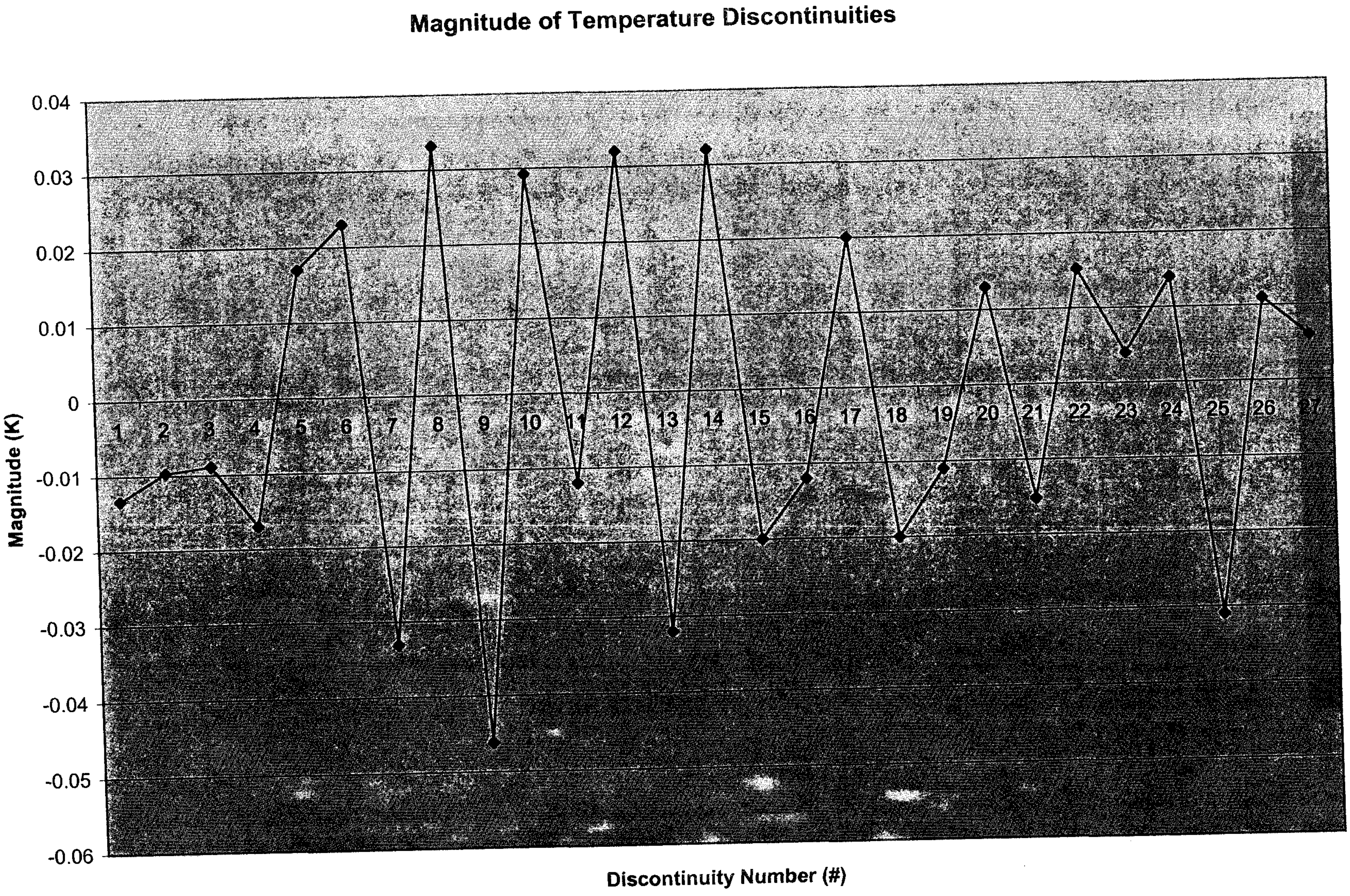
Notice that the residuals can take the form of discrete levels.

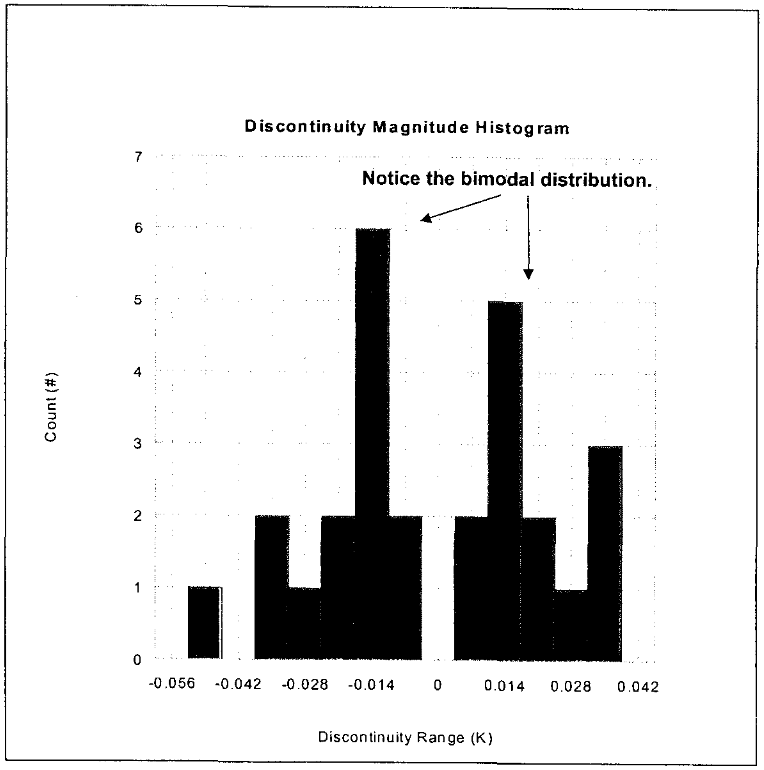


Time Between Discontinuities

Peaks at 120 sec. indicate discontinuities that are small and difficult to identify.

It's clear that the discontinuities occur approximately every 60 seconds.

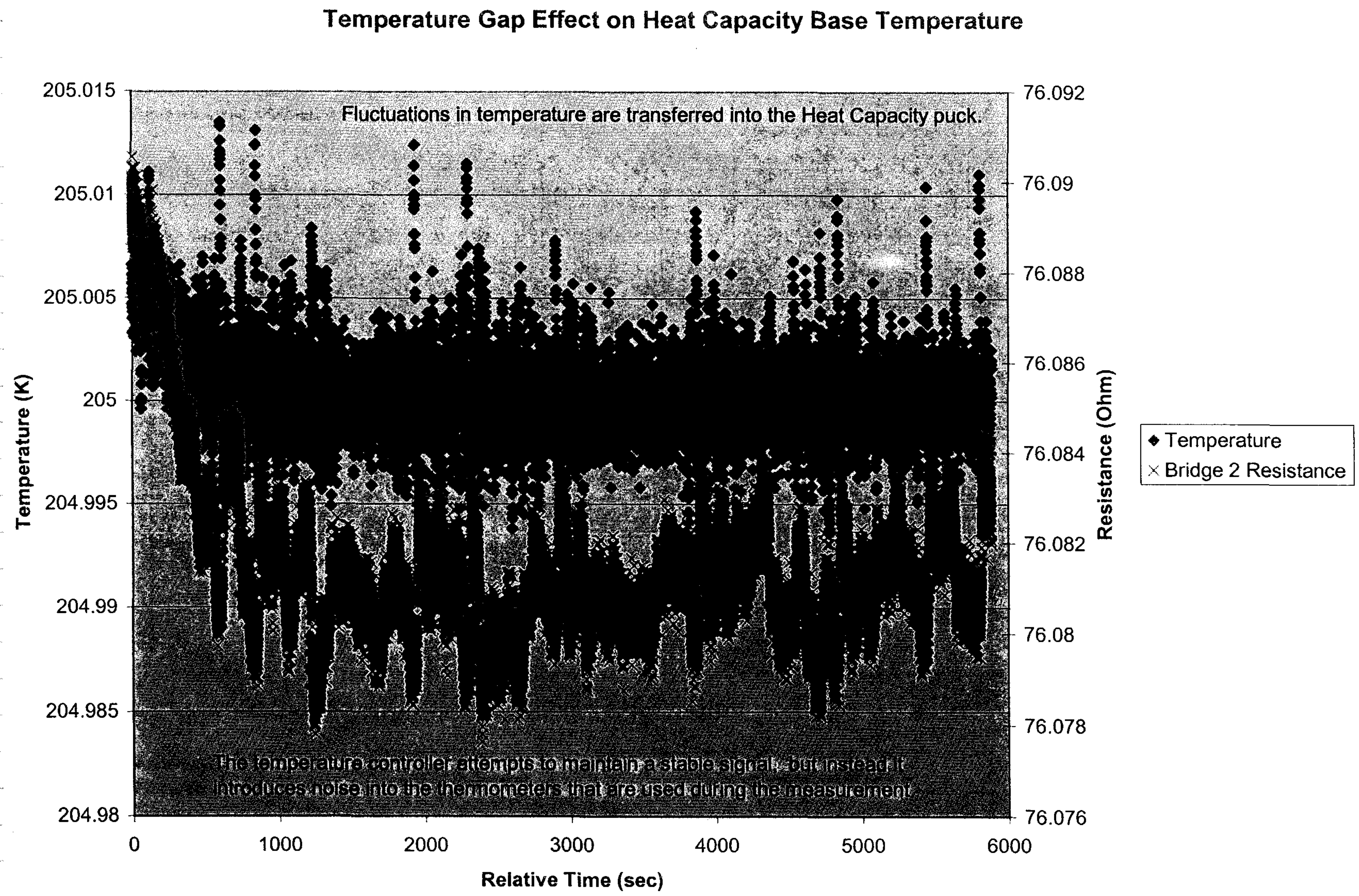

Magnitude of Temperature Discontinuities
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
Magnitude (K)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
Discontinuity Number (#)



Notice the bimodal distribution.

	Left Mode	Right Mode
Minimum	-0.0462	0.004
Maximum	-0.0089	0.0331
Sum	-0.2815	0.2495
Points	14	13
Mean	-0.020107143	0.019192308
Median	-0.0161	0.017
RMS	0.02283004	0.02145351
Std Deviation	0.011220823	0.009978348
Variance	0.000125907	9.96E-05
Std Error	0.002998891	0.002767496
Skewness	-1.0242516	0.10006124
Kurtosis	-0.011731532	-1.2514871

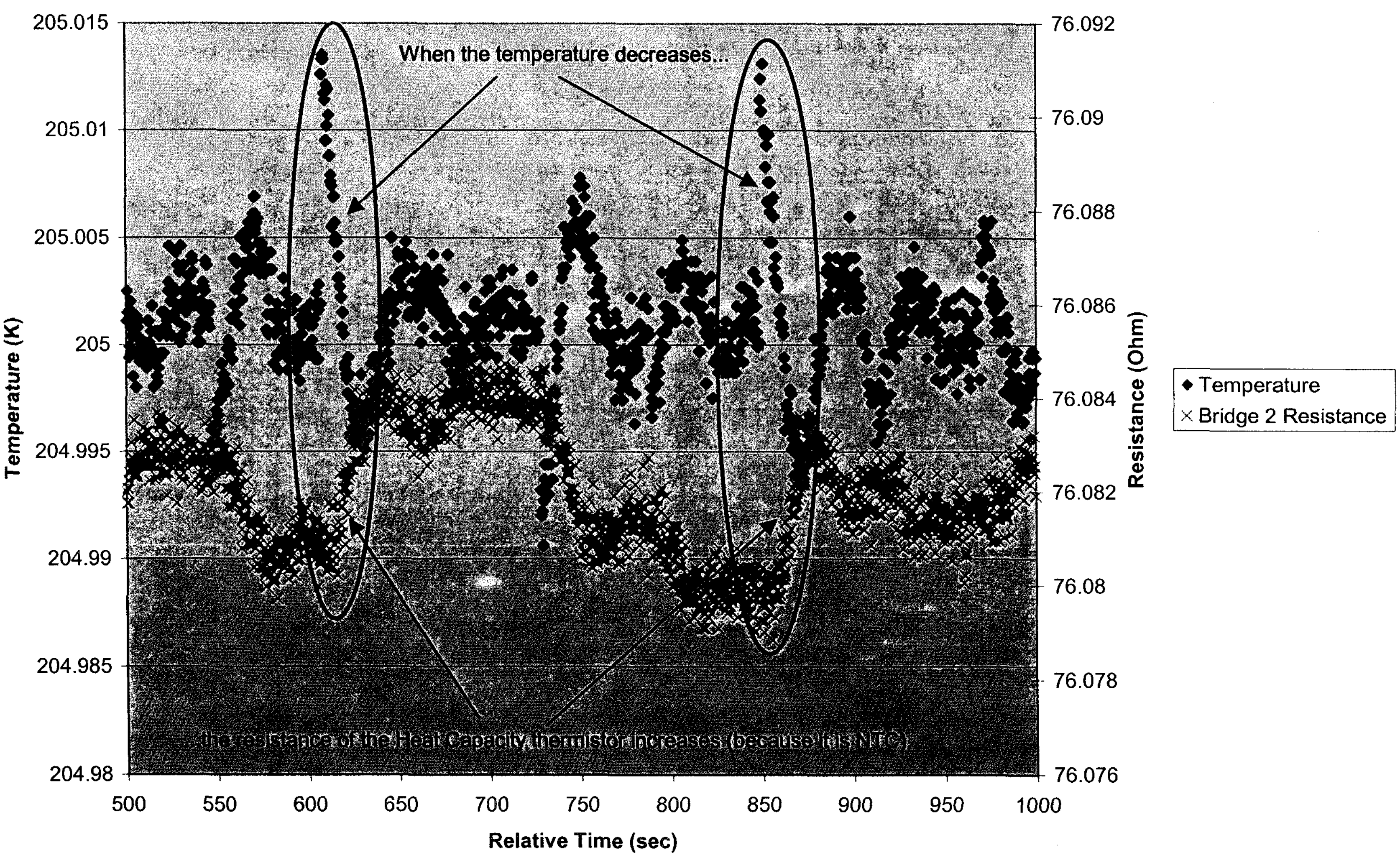
Gaussian fits indicate the distribution is approximately symmetric.

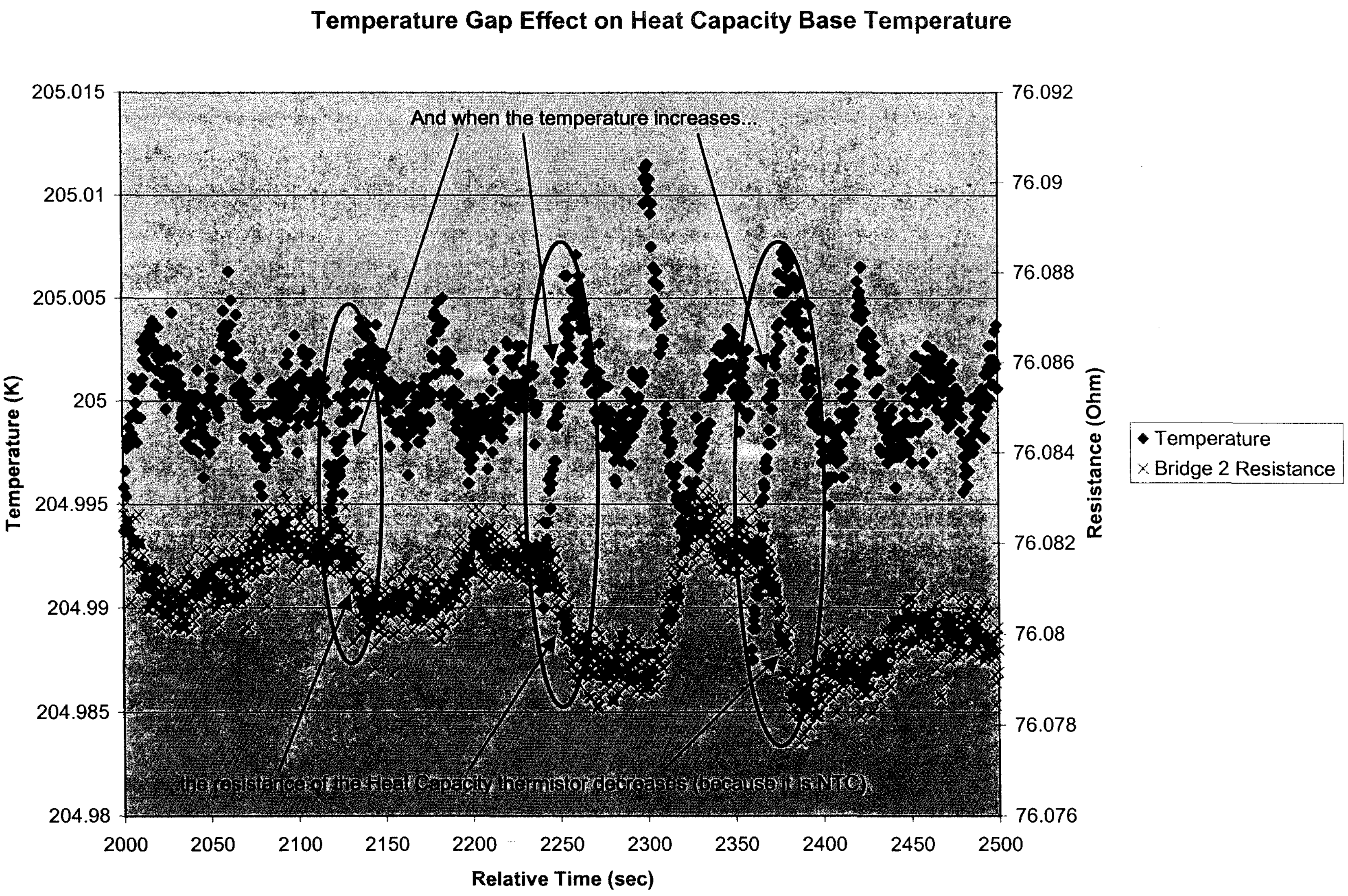


Fluctuations in temperature are transferred into the Heat Capacity puck.

The temperature controller attempts to maintain a stable signal, but instead it introduces noise into the thermometers that are used during the measurement.

At this time, the puck thermometer hasn't been calibrated, so we must plot it in terms of resistance.


Temperature Gap Effect on Heat Capacity Base Temperature



Temperature Gap Effect on Heat Capacity Base Temperature

And when the temperature increases...

...the resistance of the Heat Capacity thermistor decreases (because it is NTC).

The previous plots were e-mailed to Quantum Design and a copy of my letter follows:

To: Mark Seebach
<mark.seebach@qdusa.com>,dinesh.martien@qdusa.com,neil.dilly@qdusa.com
From: Michael Hall <mhall@ligo.caltech.edu>
Subject: Discontinuities in the Temperature
Cc: desalvo_r@ligo.caltech.edu,hareem <htariq@ligo.caltech.edu>
Bcc:
Attached: C:\WINDOWS\Desktop\QD-Temperature.xls;

To whom it may concern:

I am writing to you in reference to a problem that was recently discovered at Caltech in the data taken by the Cryostat. Although this problem exists in your system, we do not at this time believe it to be a problem with your software. We see similar problems in other experimental setups and suspect that the problem lies within the National Instruments data acquisition board.

If this is true, we are interested in discussing the problem further with National Instruments. Because National Instruments data acquisition boards are such a crucial part of your products, we think that it may be beneficial to discuss this idea with you before making contact with National Instruments. I will describe the problem briefly:

On at least three different National Instruments data acquisition boards (Two PCI-6031E boards and your PCI-GPIB board), we are experiencing random fluctuations in voltage which correspond to discontinuities in the measured parameters (such as displacements or temperatures) that are unphysical in nature. For example, these fluctuations occur every 60 seconds in the Cryostat on the following channels:

System Temperature
Platform Temperature
Neck Temperature

And it appears as though they may also occur on the following channels:

Block Heater
Block Heater Power
Block Heater Current
Neck Heater Current
Neck Heater Power

Attached to this e-mail is a Microsoft Excel workbook which details some of these gaps. In the case of temperature, the voltage fluctuations make it appear that the temperature has left equilibrium and so the Cryostat attempts to re-attain equilibrium, but because the temperature fluctuations are often times the result of a voltage fluctuation of the data acquisition board, the Cryostat is using a noisy signal as a feedback source. As the attatched plots show, as the Cryostat attempts to bring the system back into equilibrium, it is instead causing much greater fluctuations in temperature, which can be transferred into more important thermometers that are used for TTO or Heat Capacity measurements.

We are interested to know if you have discovered this problem in the past and if you can find

any similar errors with the data you have collected. We think it may be beneficial to discuss this problem together with the possbility of discussing it further with National Instruments in the coming weeks. Please let us know what kind of information you have available.

If possible (and if the problem requires further discussion and analysis) we would be interested in meeting with you the week of September 16.

Regards,

Michael Hall
(626)-395-2063
mhall@ligo.caltech.edu

September 16, 2002

Quantum Design's response follows:

Mark Seebach, 10:49 AM 9/11/02 -0700, Re: ATTN: Mark Seebach Page 1 of 1

From: Mark Seebach <mark.seebach@qdusa.com>
To: Michael Hall <mhall@ligo.caltech.edu>
Date: Wed, 11 Sep 2002 10:49:23 -0700
Subject: Re: ATTN: Mark Seebach
Priority: normal
X-mailer: Pegasus Mail for Windows (v2.54)

Michael, The new shoes shipped out yesterday, they should be there, let me know if not. Regarding coming down and meeting, i'm on vacation 9-16 to 9-20 but if the 17th works, you could meet with Dinesh and Neil, I'm sure they can help.

However, in discussing the 60 sec. jump, we were looking at the data and the measurements you show are being taken with our bridge board not the NI card. The maximum jump is about 0.01%. Most of the jumps are ~0.005%. The jumps occur every 60 sec. because the bridge card calibrates itself on internal resistors once/60 sec. The accuracy of these calibrations is limited to 0.01% so a jump will be observed ea. time a calib. occurs.

This is typical system performance and about the only suggestion might be to replicate your studies here (what sample, sequence & settings) and see if we observe similar results. The only (and it's a shot in the dark) improvement may be to try different bridge boards to see if it improves. We will try to do this prior to Sept. 17. With the above info. if you and Rico still want to come down, no problem, I just don't want you to make a special trip to find out, "that's as good as the system can do". I will send your data over to Steve Lauridsen our PPMS application scientist to see if he can get system time to begin the tests. Can you send me the sequence, settings and info. on the sample you were measuring when the jumps occured?

Thanks.
Mark.

Riccardo and I were confident the problem was with the National Instruments card, but Mark Seebach admits the problem is probably because of their user bridge board.

It would be very beneficial to plot the temperature (after stitching the jumps) next to the punch ~~temperature~~. To do so, we need to calibrate the thermistors and that is described on the following pages

How do we calibrate the heat capacity thermometers?

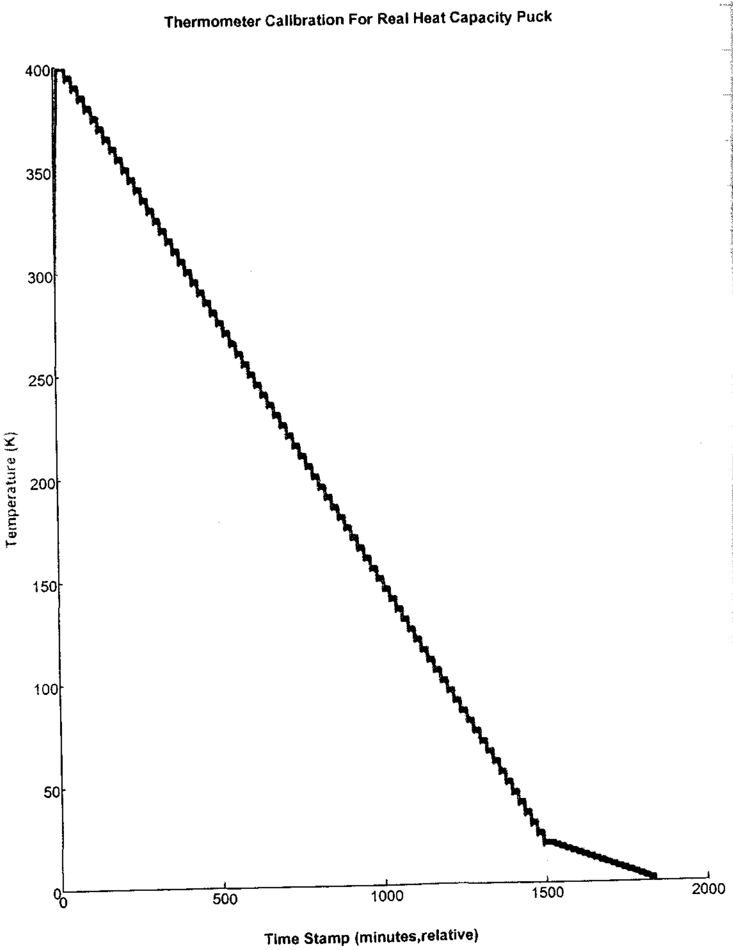
The sequence used to collect the data follows below. I just stabilized the system at several temperatures + then found where the mean was located. The entire process is described below:

```
Sequence File: ThermometerCalibration


 1:  LogData Start New 0.25 1073741823 1073741823 1073741823 "C:\cryolab\07-25
     -2002\Thermometer Calibration For HC Puck\secondattemptatcalibration.dat"
      "Thermometer Calibration For Real Heat Capacity Puck" "At 15 minute stab
     ility times..."
 2:  Set Temperature 400.00K at 20.00K/min. Fast Settle
 3:  Wait For Temperature, Delay 300 secs, No Action
 4:  Scan Temp from 400.0K to 20.0K at 20.0K/min, in 77 steps, Uniform, Fast
 5:      Wait For Temperature, Delay 900 secs, No Action
 6:  End Scan
 7:  Scan Temp from 20.0K to 2.0K at 20.0K/min, in 19 steps, Uniform, Fast
 8:      Wait For Temperature, Delay 900 secs, No Action
 9:  End Scan
10:  Set Temperature 300.00K at 20.00K/min. Fast Settle
11:  LogData Stop "At 15 minute stability times..."
```

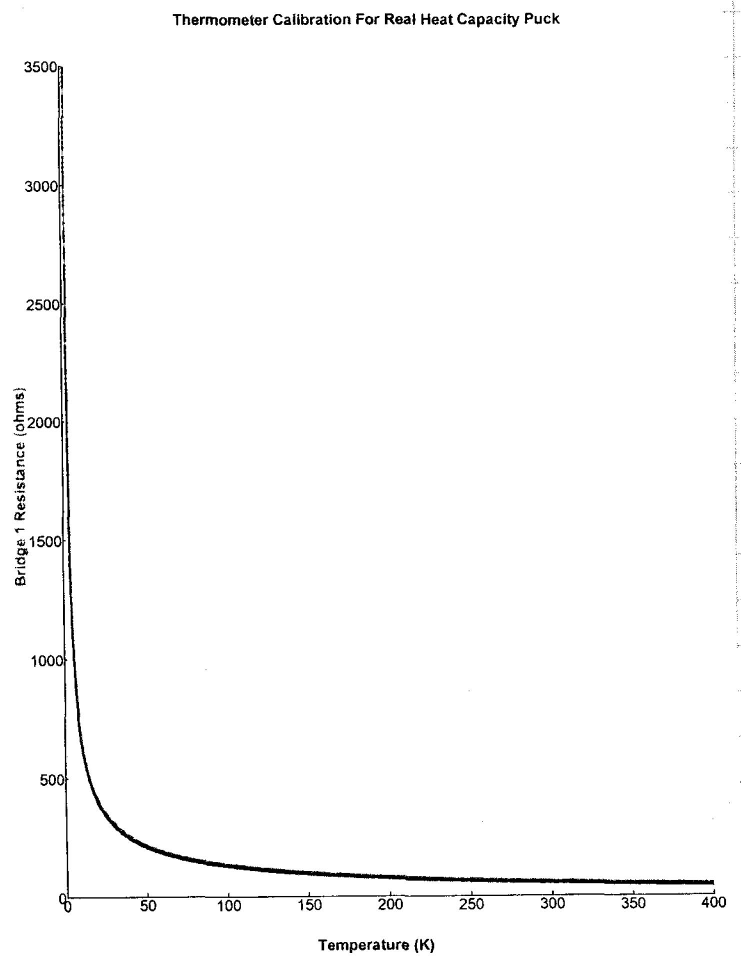
The plot on the right is the resultant data from the sequence above.

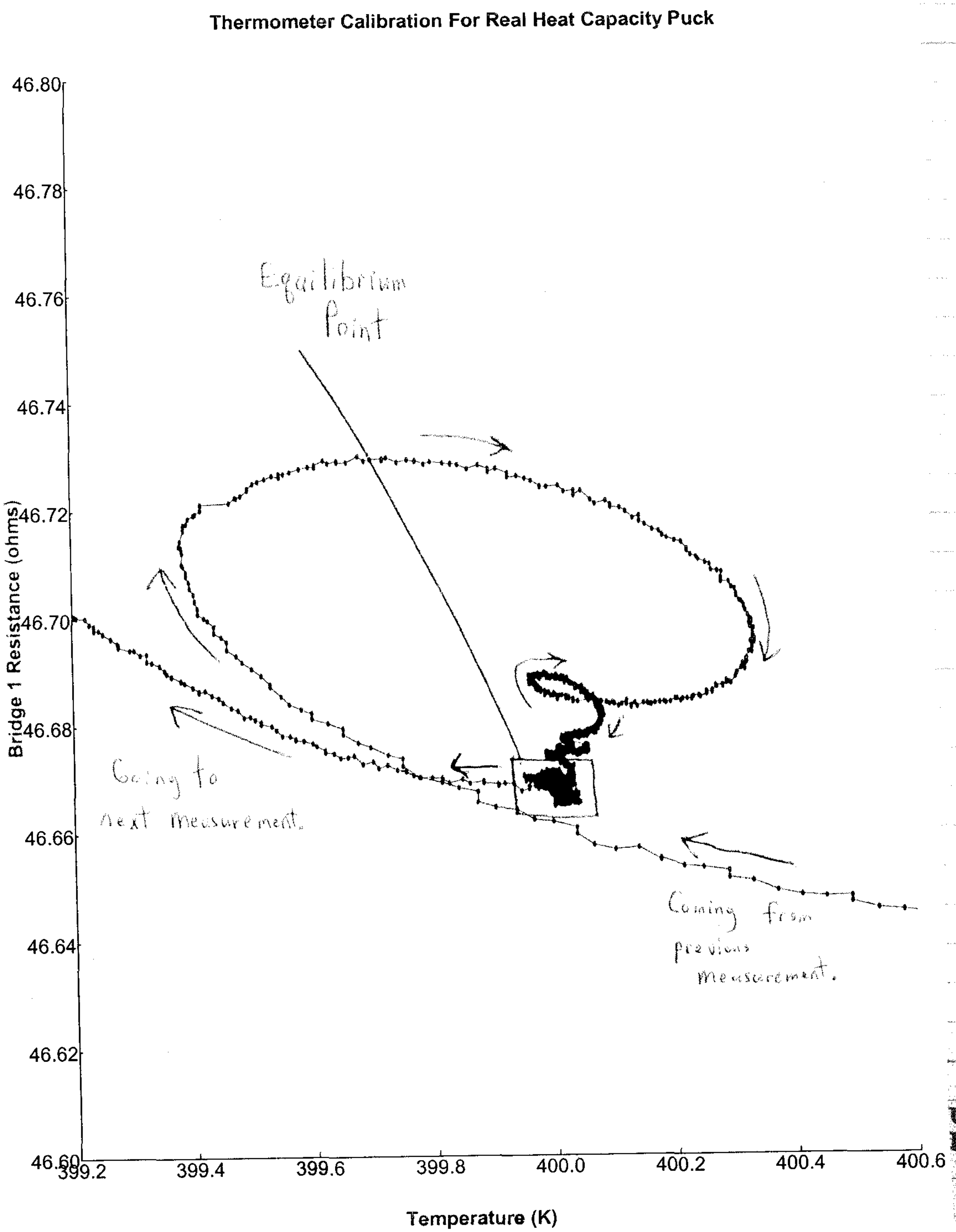
At lower temperatures measurements were taken more often because the slope of the resistance vs. temperature curve will change rapidly under 50K.



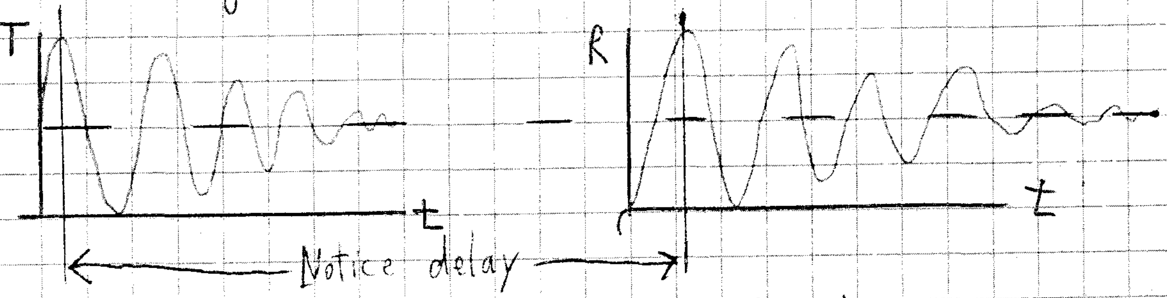
Below is what the resistance vs. temperature looks like for the chip thermometer, when zoomed out.

As you zoom closer, spirals and equilibrium point are observed when the temperature stabilized.

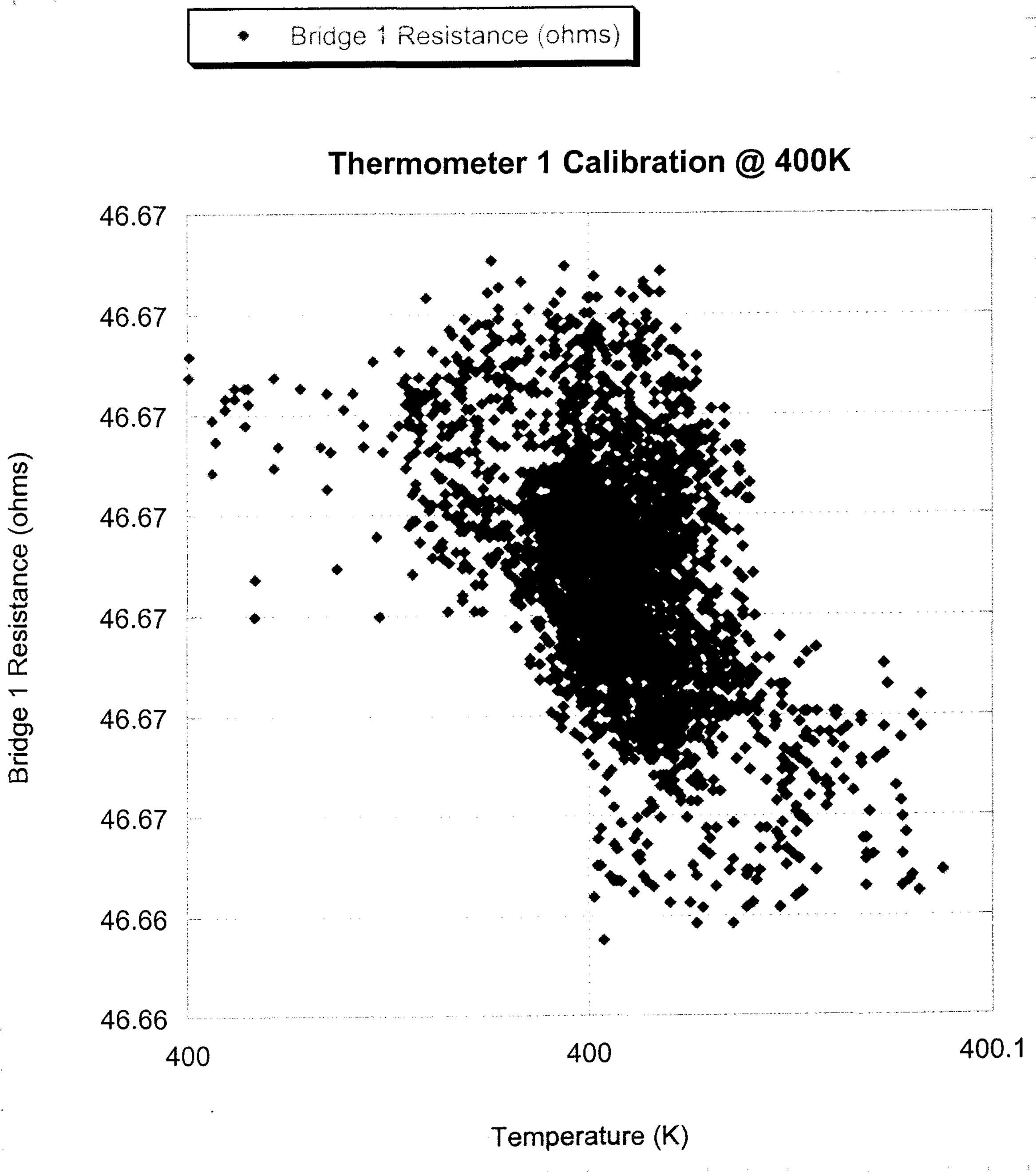




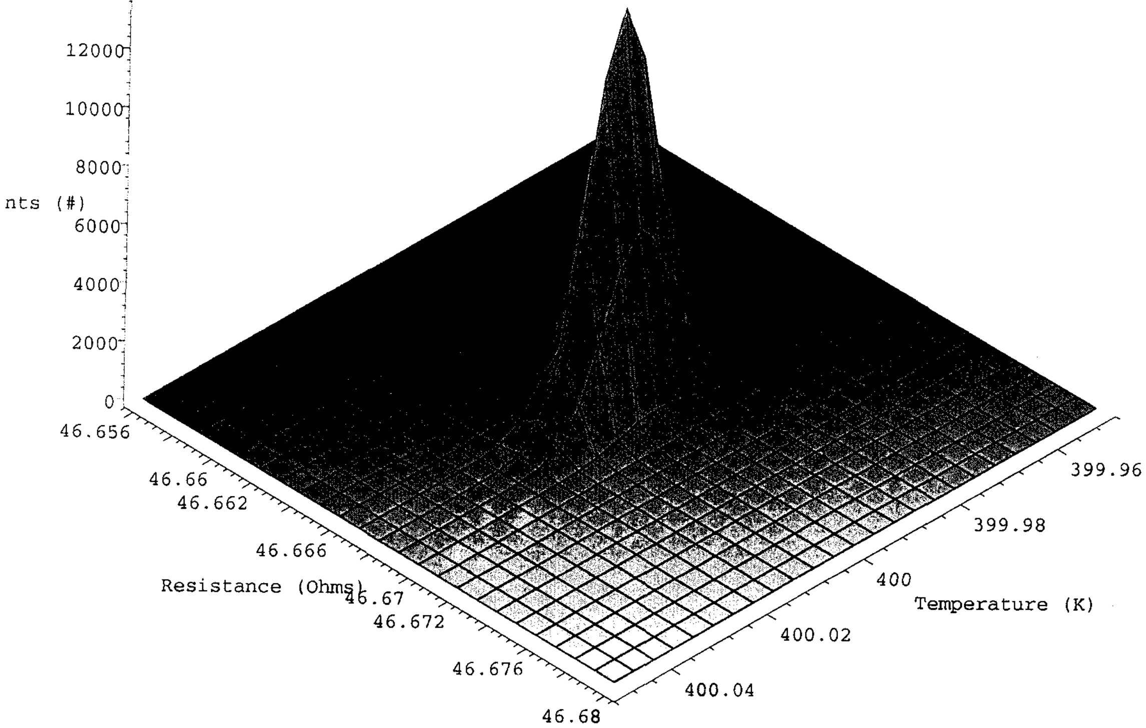
The reason for the spiral is simple. As the temperature approaches equilibrium it fluctuates around that point. Because the resistance is a function of T it also fluctuates about its equilibrium point, but there is a small delay between these:



Zooming in on the equilibrium point yields:



We can fit a Gaussian along each axis if we assume the equilibrium point to resemble the plot below:

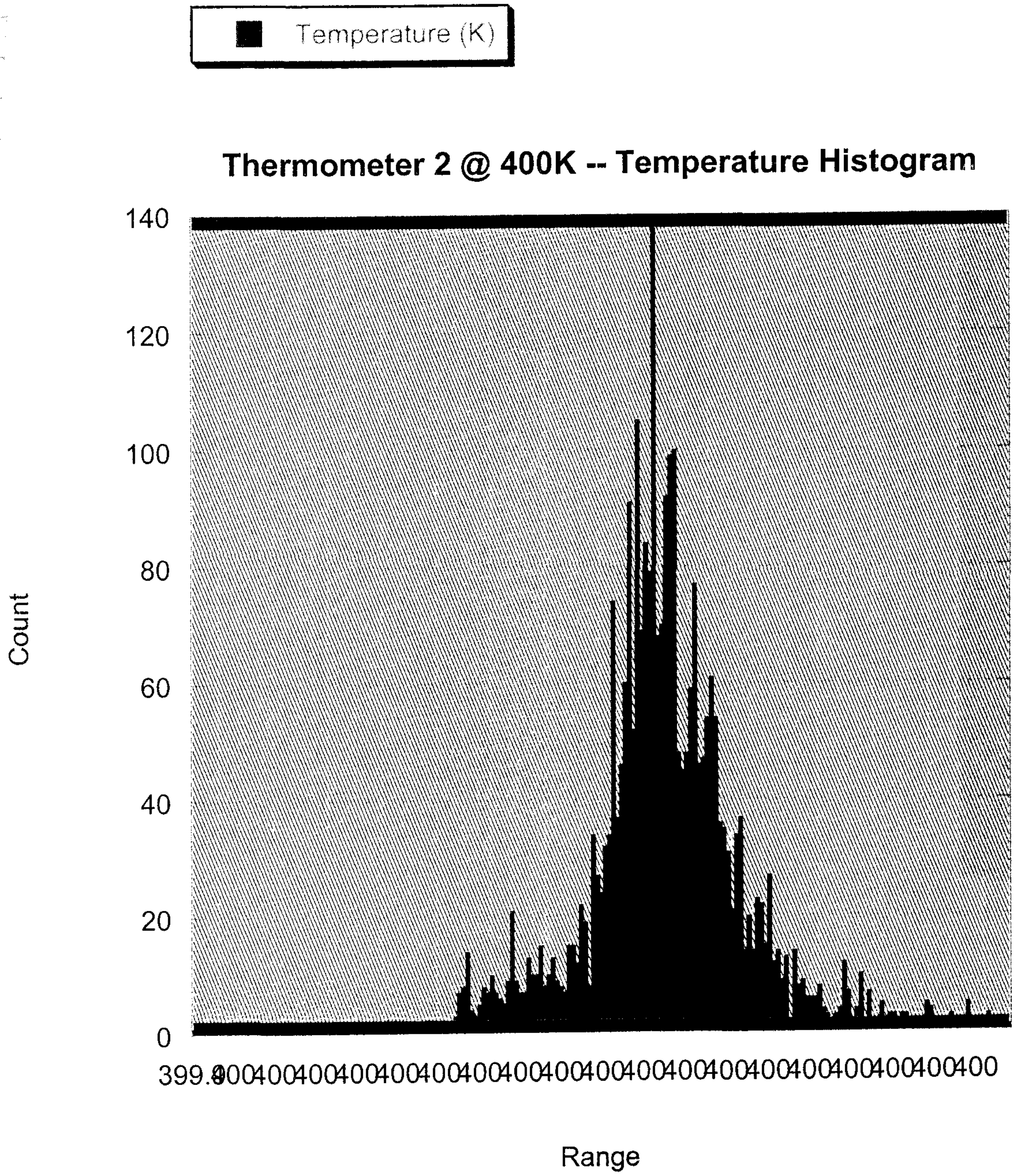


In this way, we can construct an entire R vs. T plot for each thermometer.

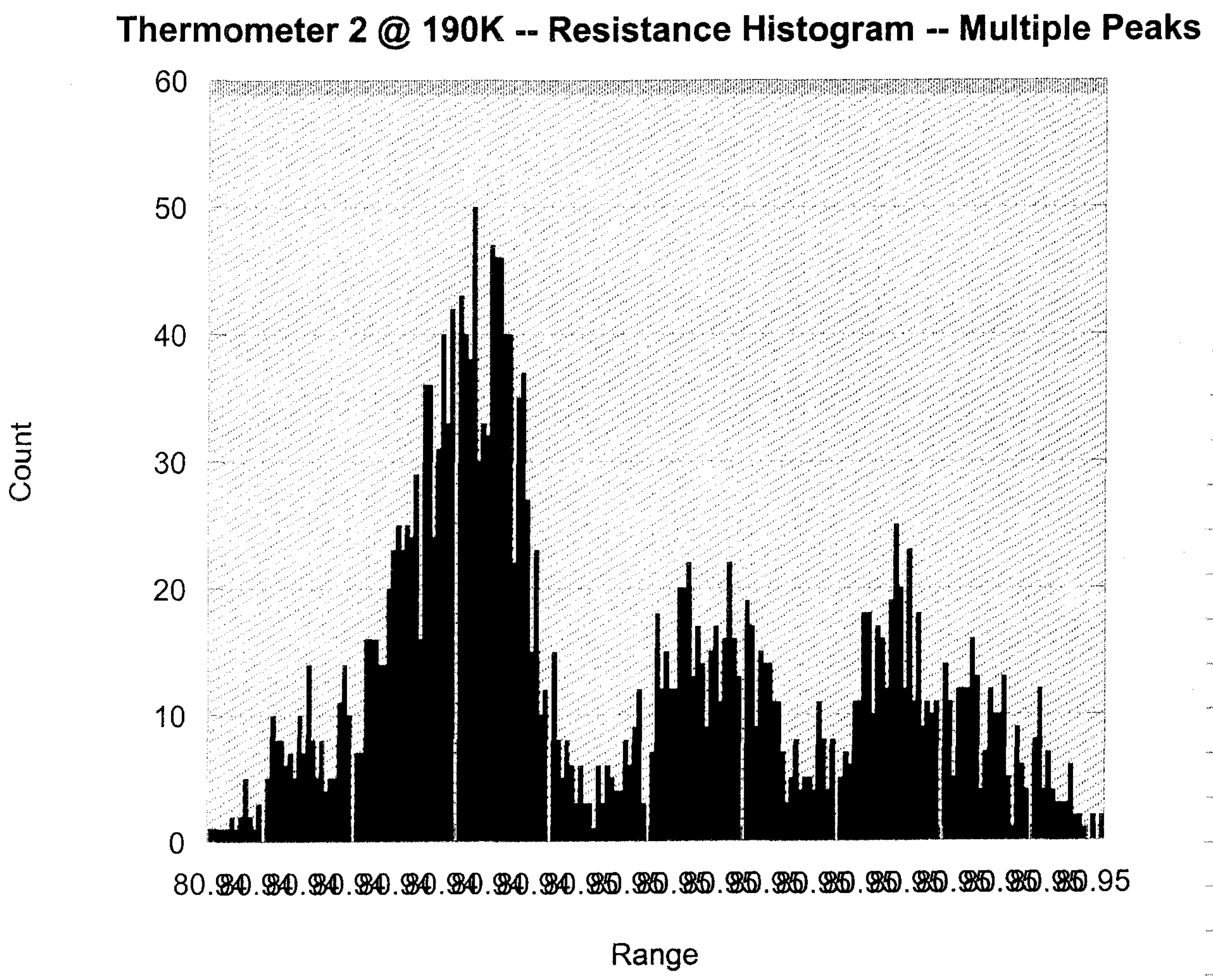
A histogram was made for each axis. The mean was taken for the X and Y points and a plot of R vs. T was constructed.

The errors in R and T are the σ's from the fits.

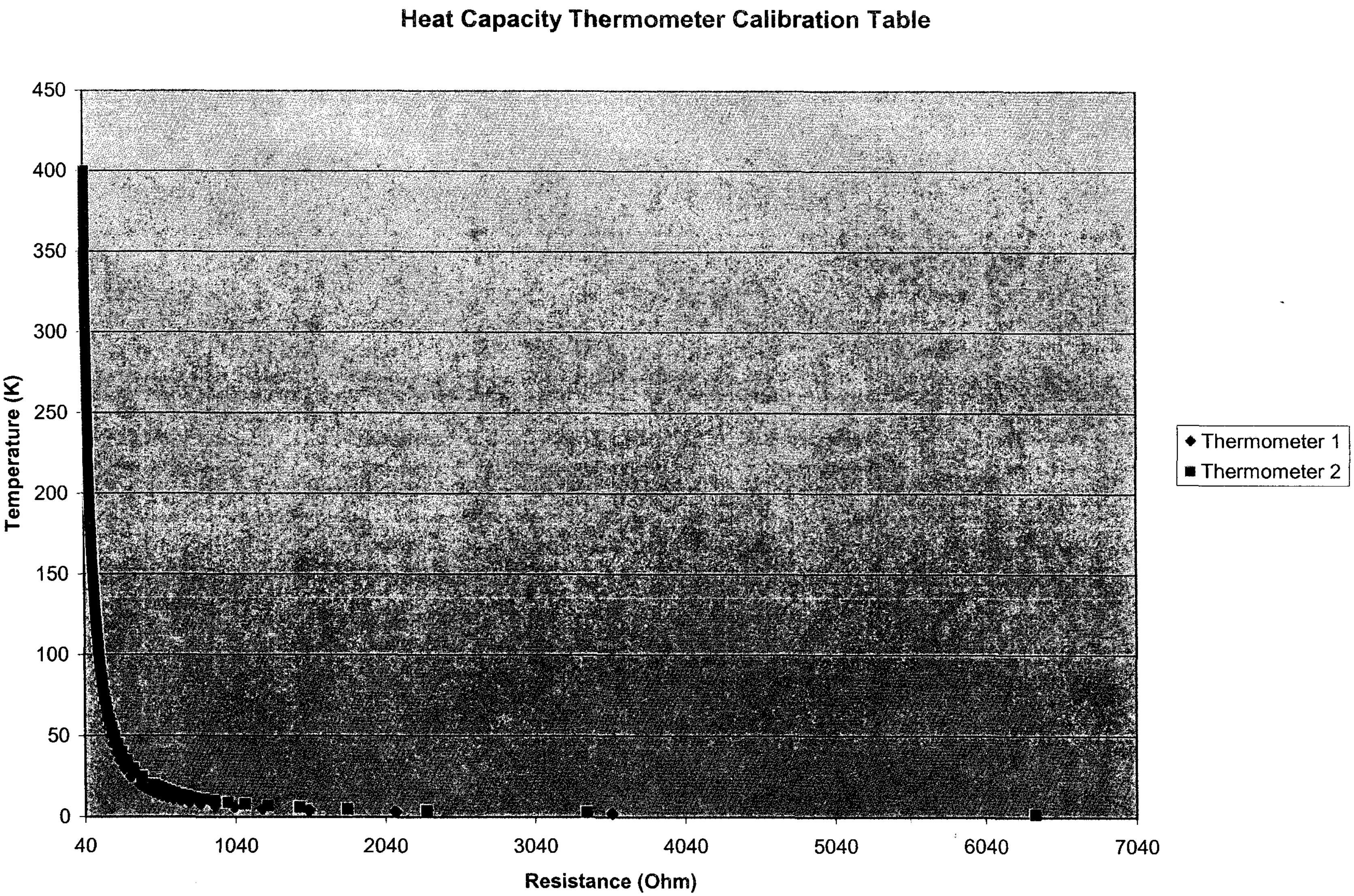
Sometimes the system took a long time to reach equilibrium and finding the Gaussians were difficult. Great care had to be taken to remove the bad data. An example of a histogram of the temperature of thermometer 2 at 400K is on the next page.



The plot above is fairly decent. It shows the remnants of some non-Gaussian tails which can be removed by ~~[illegible]~~ removing more of the transient behavior.


Thermometer 2 @ 190K -- Resistance Histogram -- Multiple Peaks

Above is an example of a difficult to locate equilibrium point. Eventually the real equilibrium point can be located by a careful analysis of the transient behavior.



Here is the calibration plot for the 2 thermometers.
The data for the fits follow on the next pages

Because the entire plot cannot be fit well enough all at once, I decided to fit small pieces. The equation that was used is the same suggested in the NTC article I pasted into the book on page 9. The results are below:

$$\boxed{T = \frac{1}{m_1 + m_2 \ln(R) + m_3 \left(\ln(R)\right)^3}}$$

Thermometer 1
(Chip Thermometer) →

Temperature (K)	m1	m2	m3
400 to 385.01	0.9942	-0.277122	0.0031572
380.01 to 355.01	1.0116	-0.27434	0.0031688
350.01 to 325.01	1.1499	-0.30773	0.0034571
320.01 to 295.01	0.52782	-0.15379	0.0020588
290 to 265	0.21042	-0.067428	0.001111
260 to 235	0.10097	-0.035665	0.00071519
230 to 205	0.082639	-0.029097	0.00059723
200 to 175	0.057128	-0.020962	0.0004747
170 to 165	0.040273	-0.015396	0.00038476
160 to 135	0.040315	-0.015429	0.00038598
130 to 105	0.035815	-0.013937	0.00036183
100 to 75	0.025429	-0.010323	0.00029703
70 to 45	0.023829	-0.0098036	0.00028925
40 to 19.002	0.0074325	-0.003785	0.00016912
18.001 to 13.001	0.019689	-0.0083897	0.00026543
12.001 to 7.0005	0.020535	-0.008767	0.00027593
6.001 to 2	-0.0019079	-0.000097272	0.000084243

Thermometer 2
(Puck Thermometer) ↓

Temperature (K)	m1	m1 error	m2	m2 error	m3	m3 error	Chisq	R
400 to 380.01	0.0036798	0.006599	-2.24E-03	0.0025656	0.00013309	5.79E-05	1.85E-03	1.00E+00
375.01 to 355.01	0.0036624	0.0015591	-2.24E-03	0.00059902	0.00013324	1.32E-05	1.10E-04	1.00E+00
350.01 to 330.01	0.0036286	0.0039189	-2.23E-03	0.0014864	0.00013352	3.19E-05	7.30E-04	1
325.01 to 305	0.0035785	0.0036185	-0.0022262	0.0013533	0.00013379	2.82E-05	6.56E-04	1
300 to 280	0.0035139	0.0034881	-0.0022271	0.0012846	0.00013484	2.60E-05	6.28E-04	1
275 to 255	0.0034255	0.0045306	-0.0022262	0.0016404	0.00013608	3.20E-05	1.09E-03	1
250 to 230	0.0043177	0.0073898	-0.0026028	0.0026233	0.00014545	4.93E-05	0.0028804	0.99999
225 to 205	0.011338	0.0069093	-0.0051465	0.0023882	0.00019484	4.27E-05	0.0023129	1
200 to 180	0.015582	0.0063796	-0.0066822	0.0021487	0.00022445	3.66E-05	0.0018071	1
175 to 155	0.023152	0.0058232	-0.0092865	0.0019032	0.00027006	3.06E-05	0.0013631	1
150 to 130	0.015582	0.0063796	-0.0066822	0.0021487	0.00022445	3.66E-05	0.0018071	1
125 to 105	0.050724	0.0049042	-0.018295	0.0014878	0.00041262	2.07E-05	0.00065912	1
100 to 80	0.14577	0.089195	-0.047818	0.025013	8.34E-04	3.04E-04	0.086222	0.99983
75 to 55	0.13041	0.0079176	-0.042356	0.0021625	0.00073973	2.46E-05	0.00079303	1
50 to 30	0.26581	0.01819	-0.079467	4.57E-03	1.15E-03	4.42E-05	0.0024187	1
25 to 17.001	0.59221	1.82E-02	-0.16179	4.11E-03	1.93E-03	3.25E-05	2.00E-05	1
16.001 to 12.001	0.71554	4.21E-02	-0.19113	9.15E-03	2.18E-03	6.62E-05	9.84E-06	1
11.001 to 7.0005	8.18E-01	3.79E-02	-0.21445	7.91E-03	2.35E-03	5.22E-05	1.24E-05	1
6.001 to 2	0.4346	0.044703	-0.13662	0.0085885	0.0018792	4.72E-05	5.87E-05	1

Temperature	# Points	Temp Std.	Temp. Error	Bridge 1 Resistance	Bridge 1 Res. Std.	Bridge 1 Error	Eqn Fit	Residual
2	2054	0.00075145	1.66E-05	3550.9	1.6839	0.037154	1.992562	-0.007438
2.9999	1711	0.0082274	1.99E-05	2103.9	0.46909	0.011341	3.000527	0.000627
3.9999	1617	0.00067164	1.67E-05	1526.6	0.15771	0.003922	4.003904	0.004004
5	2513	0.00073214	1.46E-05	1219.9	0.090718	0.0018097	5.002926	0.002926
6.0001	1458	0.00053897	1.41E-05	1030	0.055802	0.0014614	5.997075	-0.003025
7.0005	1570	0.0019615	4.95E-05	899.8	0.2637	0.0066552	7.00185	0.00135
8.0007	1501	0.00080466	2.08E-05	804.06	0.1203	0.0031051	7.999177	-0.001523
9.0008	1458	0.00068684	1.80E-05	731.06	0.077539	0.0020307	8.992326	-0.008474
10.001	1233	0.00061025	1.74E-05	672.73	0.033901	0.00096545	9.992624	-0.008376
11.001	1873	0.00086954	2.01E-05	625.11	0.052244	0.0012072	10.99422	-0.006779
12.001	1786	0.00083909	1.99E-05	585.37	0.035513	0.00084032	11.99622	-0.004783
13.001	1051	0.00074648	2.30E-05	551.56	0.020423	0.00062995	12.9914	-0.009599
14.001	1248	0.0007738	2.19E-05	522.35	0.018266	0.00051705	14.00116	0.000158
15.001	2168	0.0013417	2.88E-05	496.87	0.022953	0.00049296	15.00159	0.00059
16.002	2441	0.0022192	4.49E-05	474.26	0.051474	0.0010418	15.99653	-0.005466
17.001	1672	0.0010834	2.65E-05	454.08	0.012556	0.00030731	16.97998	-0.021021
18.001	2225	0.0030025	6.37E-05	435.02	0.049152	0.001042	17.99944	-0.001556
19.002	1557	0.0020276	5.14E-05	419.59	0.017396	0.00044087	19.03637	0.034373
20.001	4832	0.0030016	4.32E-05	404.64	0.038406	0.0005525	20.00534	0.004337
25	1513	0.001165	3.00E-05	345.8	0.0076259	0.00019605	24.94645	-0.053553
30	1389	0.0013404	3.60E-05	304.23	0.0044506	0.00011942	29.99649	-0.003507
35	1477	0.0015111	3.93E-05	272.91	0.0033844	8.81E-05	35.06078	0.060779
40	1643	0.0017339	4.28E-05	248.38	0.0034098	8.41E-05	39.98429	-0.015711
45	1863	0.0018696	4.33E-05	228.5	0.0028081	6.51E-05	45.02917	0.029167
50	1913	0.0021148	4.84E-05	212.1	0.0022696	5.19E-05	49.98413	-0.015868
55	1937	0.0023157	5.26E-05	198.24	0.0022214	5.05E-05	55.00466	0.004659
60	1730	0.0025214	6.06E-05	186.41	0.0019262	4.63E-05	60.03201	0.032011
65	1677	0.0027715	6.77E-05	176.19	0.0023016	5.62E-05	65.02601	0.02601
70	1282	0.0028432	7.94E-05	167.16	0.0019696	5.50E-05	70.01016	0.010159
75	1353	0.0031635	8.60E-05	159.16	0.0020725	5.63E-05	74.88951	-0.110492
80	2202	0.0034237	7.30E-05	152.01	0.0031996	6.82E-05	80.1261	0.126097
85.001	1980	0.0033979	7.64E-05	145.87	0.0031871	7.16E-05	85.20587	0.204868
90	1938	0.0026324	5.98E-05	140.72	0.0032249	7.33E-05	89.94986	-0.050141
95	1836	0.0014009	3.27E-05	135.98	0.0022952	5.36E-05	94.76171	-0.238286
100	1533	0.0013285	3.39E-05	131.15	0.0015782	4.03E-05	100.1625	0.162502

Above is the information gathered from fitting the Dawson Bath thermometer data is presented, starting with Bridge I (Chip thermometer).

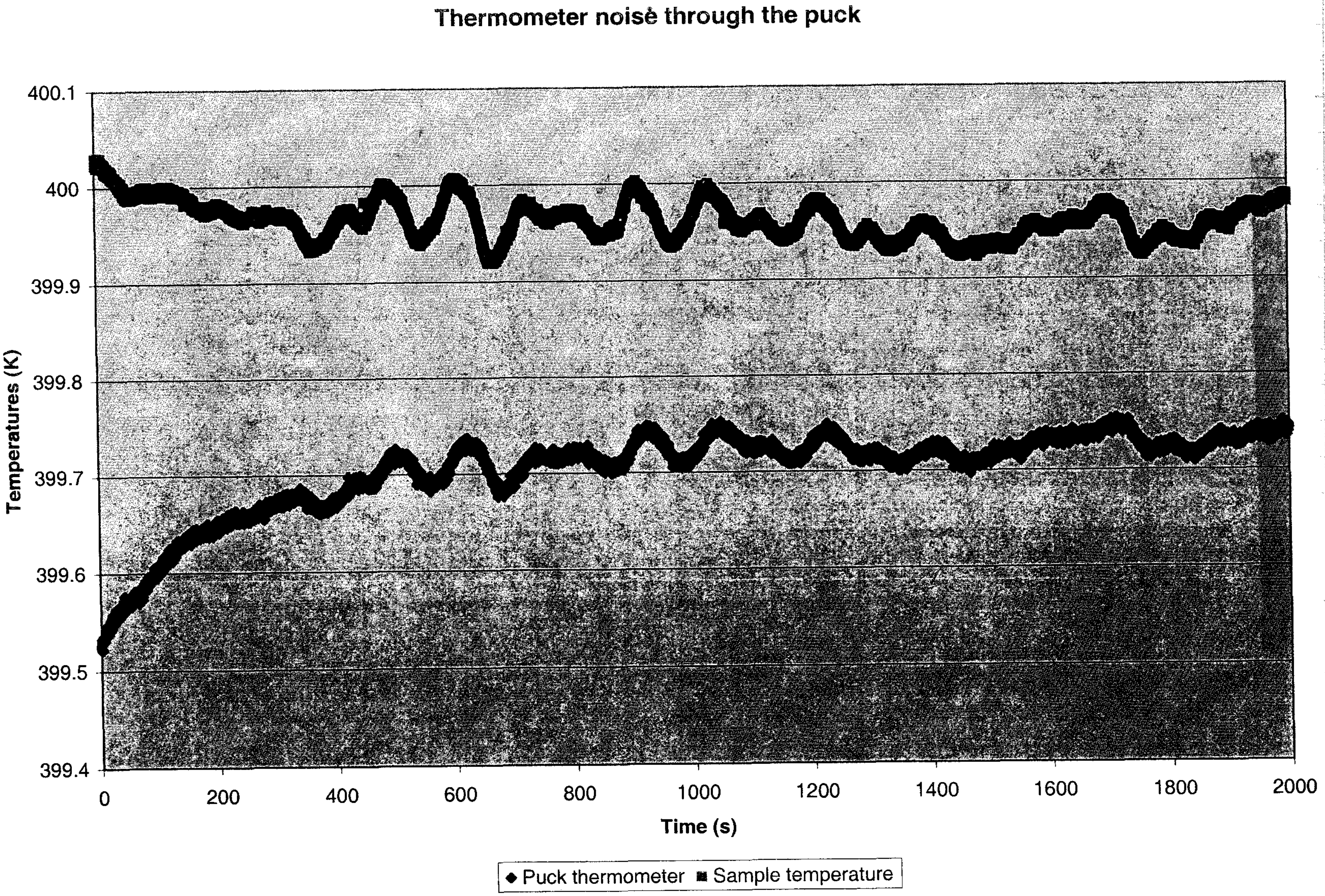
105	2178	0.0015297	3.28E-05	126.49	0.0019872	4.26E-05	104.9813	-0.018657
110	2189	0.0013936	2.98E-05	122.2	0.0019562	4.18E-05	109.9931	-0.006943
115	1855	0.0015891	3.69E-05	118.23	0.0021137	4.91E-05	115.0053	0.005332
120	1854	0.0015086	3.50E-05	114.54	0.0021045	4.89E-05	120.0135	0.013474
125	1683	0.0014622	3.56E-05	111.11	0.0011881	2.90E-05	124.992	-0.008048
130	1859	0.0014316	3.32E-05	107.88	0.0016226	3.76E-05	129.9816	-0.018408
135	1776	0.001599	3.80E-05	104.87	0.0016063	3.81E-05	134.9521	-0.047897
140	1614	0.0015196	3.78E-05	102.03	0.0013461	3.35E-05	139.9749	-0.025057
145	1602	0.0017354	4.34E-05	99.368	0.0016518	4.13E-05	144.9805	-0.019476
150	1709	1.63E-03	3.94E-05	96.858	0.0014731	3.56E-05	149.9814	-0.018578
155	1605	0.0014313	3.57E-05	94.485	0.0015841	3.95E-05	154.975	-0.02497
160	1268	0.0014825	4.16E-05	92.243	0.00088519	2.49E-05	159.9424	-0.057603
165	1344	0.0014963	4.08E-05	90.109	0.0010977	2.99E-05	165.0057	0.00565
170	938	0.0011956	3.90E-05	88.078	0.00066289	2.16E-05	170.0399	0.039917
175	1392	0.0023045	6.18E-05	86.161	0.0014694	3.94E-05	174.9542	-0.04576
180	1169	0.0013407	3.92E-05	84.332	0.00084345	2.47E-05	179.9911	-0.00891
185	878	0.0012685	4.28E-05	82.596	0.00064503	2.18E-05	185.0041	0.004096
190	1389	0.0022938	6.15E-05	80.943	0.0014013	3.76E-05	189.9982	-0.001756
195	1021	0.0015645	4.90E-05	79.364	0.00071799	2.25E-05	194.9792	-0.020821
200	917	0.0017138	5.66E-05	77.849	0.00070755	2.34E-05	199.9594	-0.040581
205	861	0.0020551	7.00E-05	76.394	0.001034	3.52E-05	204.9106	-0.089413
210	889	0.0023501	7.88E-05	75.009	0.0013377	4.49E-06	209.9354	-0.064596
215	1006	0.0020409	6.43E-05	73.68	0.0011678	3.68E-05	214.9488	-0.051195
220	1185	0.00172	5.00E-05	72.404	0.0010943	3.18E-05	219.9454	-0.054552
225	1364	0.0024209	6.56E-05	71.172	0.0010238	2.77E-05	224.9457	-0.054342
230	1265	0.0027043	7.60E-05	69.995	0.0010583	2.98E-05	229.8887	-0.111301
235	1399	0.0023142	6.19E-05	68.864	0.00094713	2.53E-05	234.9613	-0.038699
240	2469	0.0030839	6.21E-05	67.774	0.0010173	2.05E-05	239.9787	-0.02131
245	1950	0.0034953	7.92E-05	66.72	0.0012057	2.73E-05	245.009	0.008972
250	1266	0.0027819	7.82E-05	65.707	0.00097161	2.73E-05	250.0157	0.015746
255	1570	0.0024097	6.08E-05	64.732	0.0010275	2.59E-05	255.0001	0.000125
260	1950	0.0031705	7.18E-05	63.795	0.0017131	3.88E-05	259.9486	-0.051434

265	1620	0.0031277	7.77E-05		62.887	0.0011234	2.79E-05	265.0075	0.007516
270.01	1112	0.0036795	1.10E-04		62.016	0.00072368	2.17E-05	270.0265	0.016496
275	1614	0.0027336	6.81E-05		61.169	0.0010254	2.55E-05	275.0617	0.061668
280	1814	3.38E-03	7.95E-05		60.352	0.0010082	2.37E-05	280.0675	0.067504
285	1040	0.0028919	8.97E-05		59.562	0.00067189	2.08E-05	285.0513	0.05128
290	1028	0.0041023	1.28E-04		58.8	0.00086112	2.69E-05	289.9957	-0.004254
295.01	2580	0.0053287	1.05E-04		58.063	0.00098067	1.93E-05	294.9425	-0.067483
300.01	1724	0.0029197	7.03E-05		5.73E+01	0.001179	2.84E-05	299.9397	-0.070281
305.01	1702	0.0047073	1.14E-04		56.656	0.00094032	2.28E-05	304.946	-0.064041
310	1249	0.0054132	1.53E-04		55.982	0.00082103	2.32E-05	309.9906	-0.009375
315.01	1538	0.0028393	7.24E-05		55.331	0.00081942	2.09E-05	315.029	0.018963
320.01	1861	0.0061941	1.44E-04		54.699	0.00096331	2.23E-05	320.0837	0.073713
325.01	1681	0.0039926	9.74E-05		54.089	0.0011355	2.77E-05	324.9671	-0.042914
330.01	2465	0.0057094	1.15E-04		53.493	0.0011938	2.40E-05	330.0247	0.014677
335.01	1072	0.0047747	1.46E-04		52.914	0.0007206	2.20E-05	335.0628	0.052833
340.01	1331	0.0072719	1.99E-04		52.355	0.00098994	2.71E-05	340.0466	0.036615
345.01	2260	0.006157	1.30E-04		51.811	0.0012193	2.57E-05	345.0122	0.002202
350.01	1132	0.0066313	1.97E-04		51.279	0.00067294	2.00E-05	349.9809	-0.029067
355.01	2465	0.0060539	1.22E-04		50.765	0.0010331	2.08E-05	354.9087	-0.101269
360.01	1525	0.0070967	1.82E-04		50.262	0.0012842	3.29E-05	359.9559	-0.054078
365.01	1162	0.0076695	2.25E-04		49.77	0.0010617	3.12E-05	365.0007	-0.009341
370.02	1151	0.0042393	1.25E-04		49.293	0.00072095	2.13E-05	369.9953	-0.024716
375.01	1625	0.0094141	2.34E-04		48.828	0.0010872	2.70E-05	374.9641	-0.045888
380.01	1316	0.0098416	2.71E-04		48.375	0.0010526	2.90E-05	379.9009	-0.109096
385.01	1099	0.0072132	2.18E-04		47.93	0.00073078	2.21E-05	384.9886	-0.021416
390.01	1214	0.0058283	1.67E-04		47.498	0.00059016	1.69E-05	389.989	-0.020972
395.01	2134	0.0093203	2.02E-04		47.077	0.001044	2.26E-05	395.0101	6E-05
400	2871	0.010399	1.94E-04		46.668	0.0010803	2.02E-05	400.0343	0.034256

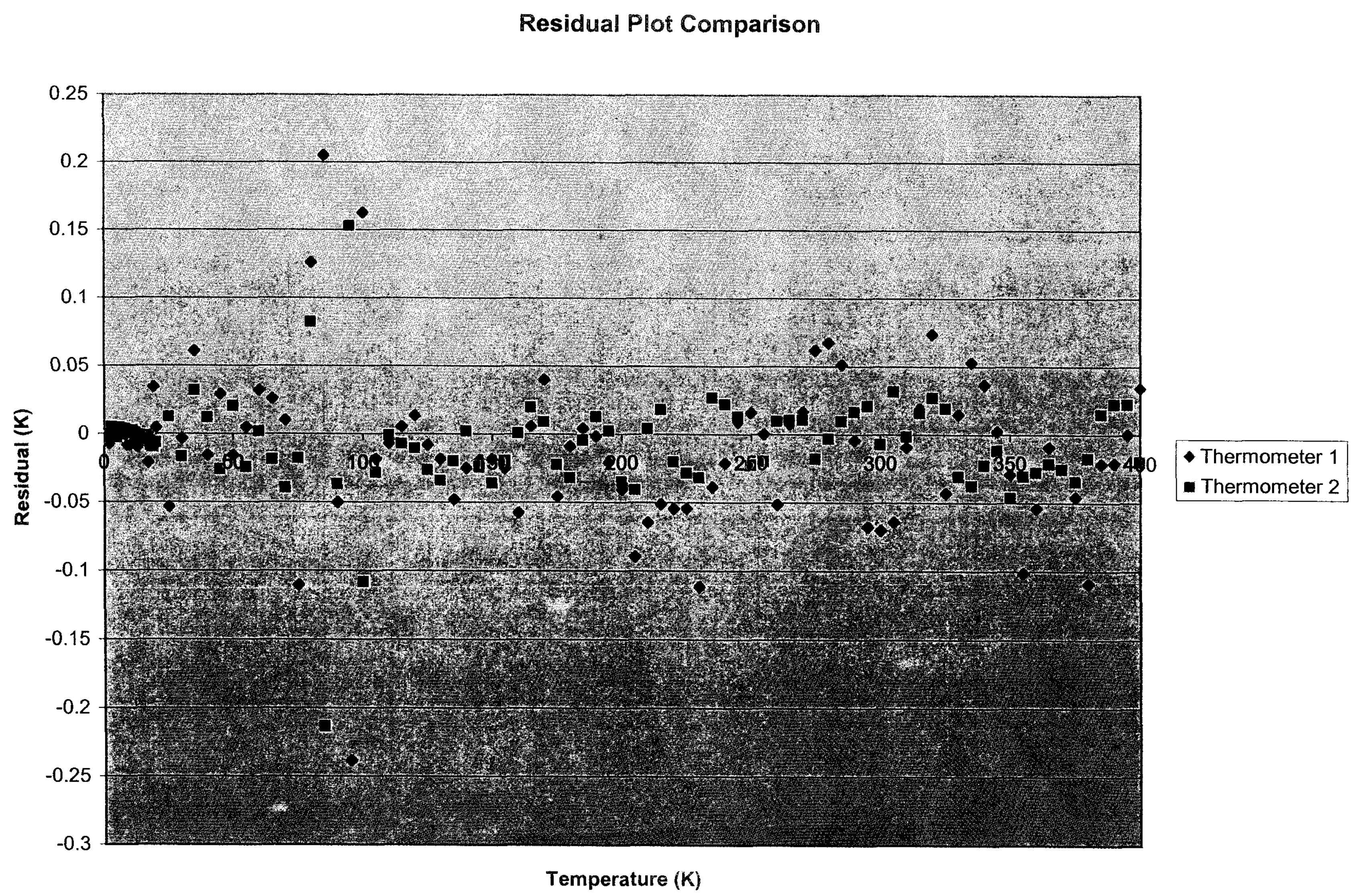
Temperature	# Points	Temp Std.	Temp. Error	Bridge 2 Resistance	Bridge 2 Res. Std.	Bridge 2 Error	Eqn Fit	Residual
2	2158	0.00075028	1.62E-05	6367.9	3.9141	0.084257	1.99750604	-0.00249396
2.9998	2636	0.00098946	1.93E-05	3382.6	1.706	0.033228	3.005308148	0.005508148
3.9999	1734	0.000664	1.59E-05	2314.7	0.37765	0.0090692	4.002532637	0.002632637
5	2706	0.00075321	1.45E-05	1782.6	0.2369	0.0045541	4.997397376	-0.002602624
6.001	1848	0.00060351	1.40E-05	1464.6	0.12635	0.0029392	6.006173688	0.005173688
7.0005	2447	0.0018595	3.76E-05	1252.9	0.38228	0.00774	7.00020229	-0.00029771
8.0007	1563	0.00083691	2.12E-05	1100.6	0.1147	0.0029013	8.004738012	0.004038012
9.0009	1782	0.00080424	1.91E-05	986.6	0.083237	0.0019718	9.001342147	0.000442147
10.001	1905	0.00084034	1.93E-05	896.87	0.058075	0.0013306	10.00162402	0.000624018
11.001	1998	9.01E-04	2.02E-05	824.28	0.042572	0.0095242	11.00377165	0.002771648
12.001	2097	0.00099409	2.17E-05	764.6	0.03548	0.00077479	12.0017472	0.000747198
13.001	2111	0.001068	2.32E-05	714.17	0.02838	0.0006177	12.9985467	-0.002453304
14.001	2166	0.0011553	2.48E-05	670.95	0.023497	0.00050487	13.99859638	-0.002403623
15.002	2241	0.001405	2.97E-05	633.46	0.023267	0.00049151	14.99999	-0.002009999
16.001	2058	0.001146	2.53E-05	600.62	0.018898	0.00041657	16.00010944	-0.000890559
17.001	1863	0.0011411	2.64E-05	571.43	0.014998	0.00034747	16.99764365	-0.003356352
18.002	1614	0.0014903	3.71E-05	545.39	0.00024302	0.00038803	17.993428	-0.008571995
19.003	1747	0.0032371	7.74E-05	521.91	0.048304	0.0011557	18.99353689	-0.009463107
20	3145	0.0021267	3.79E-05	500.67	0.0015468	0.00070131	19.99385171	-0.006148285
25	1496	0.0011579	2.99E-05	418.13	0.0085966	0.00022234	24.98729961	0.012700388
30	1390	0.0013436	3.60E-05	361.1	0.0054168	0.00014529	30.01643697	-0.016436968
35	1532	0.0015121	3.86E-05	318.93	0.0054402	0.00013899	34.96775575	0.032244252
40	1423	0.0017509	4.64E-05	286.39	0.0038657	0.00010248	39.98771332	0.012286679
45	1878	0.0018663	4.31E-05	260.38	0.002913	6.72E-05	45.02558593	-0.025585935
50	1919	0.0021147	4.83E-05	239.18	0.002607	5.95E-05	49.97919604	0.020803959
55	1929	0.0023025	5.24E-05	221.46	0.0020892	4.76E-05	55.02409868	-0.02409868
60	1916	0.0025147	5.75E-05	206.49	0.0025236	5.77E-05	59.99795717	0.002042829
65	1528	0.0027785	7.11E-05	193.58	0.0016832	4.31E-05	65.01838232	-0.018382316
70	1244	0.0028245	8.01E-05	182.37	0.0017657	5.01E-05	70.03906861	-0.039068611
75	2460	0.0033805	6.82E-05	172.57	0.0041297	8.33E-05	75.01748277	-0.017482773
80	1969	0.0033532	7.56E-05	163.8	0.0028239	6.36E-05	79.91735973	0.082640273
85	1838	0.0033354	7.78E-05	156.35	0.0030293	7.07E-05	85.21304413	-0.213044134
90	1910	0.0026412	6.04E-05	150.16	0.0034795	7.96E-05	90.03624536	-0.036245357
95	1804	0.0014277	3.36E-05	144.45	0.002109	4.97E-05	94.84664428	0.153355725
100	1829	0.0014834	3.47E-05	138.64	0.0019826	4.64E-05	100.1078806	-0.107880611

105	2054	0.0014791	3.26E-05	133.13	0.0019518	4.31E-05	105.0279742	-0.027974192
110	2081	0.0013179	2.89E-05	128.06	0.0018611	4.08E-05	110.0007713	-0.000771298
115	1451	0.0018703	4.91E-05	123.38	0.0020472	5.37E-05	115.0068754	-0.006875351
120	1614	0.0013522	3.37E-05	119.07	0.0021718	5.41E-05	120.0102595	-0.010259528
125	1787	0.0014828	3.51E-05	115.07	0.0016702	3.95E-05	125.0259182	-0.025918187
130	1464	0.0013492	3.53E-05	111.35	0.0015011	3.92E-05	130.0337486	-0.033748628
135	1815	0.0016016	3.76E-05	107.88	0.0019753	4.64E-05	135.0195384	-0.019538429
140	1597	0.0014926	3.74E-05	104.65	0.0013808	3.46E-05	139.997651	0.002348973
145	1620	0.001723	4.28E-05	101.6	0.0017134	4.26E-05	145.0238072	-0.023807172
150	1221	0.0016759	4.80E-05	98.747	0.0011816	3.38E-05	150.035592	-0.035592046
155	1440	0.0013854	3.65E-05	96.07	0.0013156	3.47E-05	155.0193442	-0.019344241
160	1403	0.0015017	4.01E-05	93.532	0.00086557	2.31E-05	159.9989787	0.001021286
165	1346	1.46E-03	3.99E-05	91.147	1.03E-03	2.82E-05	164.9799449	0.020055133
170	835	0.0012092	4.18E-05	88.888	0.00090804	3.14E-05	169.9906162	0.009383797
175	1401	0.0023079	6.17E-05	86.748	0.0015981	4.27E-05	175.0219669	-0.021966865
180	1175	0.0013729	1.40E-04	84.721	0.0006568	1.92E-05	180.0315081	-0.03150809
185	1098	0.0013265	1.40E-04	82.803	0.00087171	2.63E-05	185.0041324	-0.00413244
190	1078	0.0017874	5.44E-05	80.985	0.0009164	2.79E-05	189.986921	0.013078954
195	1042	0.0015639	4.84E-05	79.253	0.00072957	2.26E-05	194.9974141	0.002585893
200	1012	0.0019071	6.00E-05	77.601	0.00090386	2.84E-05	200.0345	-0.034499959
205	1121	0.0019272	5.76E-05	76.02	0.0012882	3.85E-05	205.0401308	-0.040130762
210	879	0.0019314	6.51E-05	74.518	0.00073921	2.49E-05	209.9955796	0.004420364
215	854	0.0021381	7.32E-05	73.08	0.00093875	3.21E-05	214.9815462	0.018453791
220	1093	0.0017584	5.32E-05	71.696	0.00080051	2.42E-05	220.0197604	-0.019760387
225	1346	0.002427	6.62E-05	70.384	0.0011124	3.03E-05	225.0280797	-0.028079741
230	1347	0.0027364	7.46E-05	69.123	0.0010665	2.91E-05	230.0314018	-0.031401776
235	1580	0.0024211	6.09E-05	67.917	0.0011661	2.93E-05	234.9728039	0.027196052
240	1255	0.0022334	6.31E-05	66.752	0.00099583	2.81E-05	239.9775995	0.022400488
245	1703	0.0031606	7.66E-05	65.639	0.0010071	2.44E-05	244.9867231	0.013276914
250	1425	0.0027176	7.20E-05	64.57	0.0010388	2.75E-05	250.0221584	-0.022158431

255	984	0.0020292	6.47E-05	63.545	0.00060955	1.94E-05	255.0192761	-0.019276123
260	1156	0.0032122	9.45E-05	62.557	0.0012165	3.58E-05	259.9898279	0.010172098
265	1265	0.0029865	8.40E-05	61.605	0.00087758	2.47E-05	264.9889463	0.011053706
270	1325	0.0029927	8.22E-05	60.692	0.0011652	3.20E-05	269.9891889	0.010811114
275	1698	0.0032848	7.97E-05	59.811	0.00074272	1.80E-05	275.0175426	-0.01754257
280	1603	0.0030403	7.60E-05	58.963	0.00093567	2.34E-05	280.0027908	-0.002790841
285	1084	0.0035142	1.07E-04	58.145	0.00071084	2.16E-05	284.9898242	0.010175788
290	1085	0.0048738	1.48E-04	57.357	0.0011468	3.48E-05	289.9831918	0.016808176
295	1337	0.0044833	1.23E-04	56.598	0.00090587	2.48E-05	294.9786121	0.021387927
300	1525	2.89E-03	7.39E-05	55.862	7.67E-04	1.97E-05	300.0067664	-0.006766358
305.01	1828	0.0047244	1.11E-04	55.154	0.0010153	2.38E-05	304.978054	0.031945952
310	1267	0.0052132	1.47E-04	54.462	0.0010343	2.91E-05	310.0011795	-0.001179507
315.01	1215	0.0033952	9.74E-05	53.798	0.00051134	1.47E-05	314.9938531	0.016146938
320.01	2390	0.0061676	1.26E-04	53.157	0.0014416	2.95E-05	319.9826008	0.02739923
325.01	1147	0.0033017	9.75E-05	52.535	0.00070046	2.07E-05	324.9904131	0.019586895
330.01	1402	0.0059246	1.58E-04	51.935	0.00097724	2.61E-05	330.0403501	-0.030350098
335.01	1073	0.0042841	1.31E-04	51.35	0.00069278	2.12E-05	335.0471629	-0.037162888
340.01	1136	0.0072644	2.16E-04	50.786	0.00089935	2.67E-05	340.0319108	-0.021910771
345.01	1492	0.004566	0.00011821	50.239	0.00084791	2.20E-05	345.0213572	-0.011357166
350.01	942	0.0052905	0.00017238	49.704	0.00064676	2.11E-05	350.0559047	-0.045904693
355.01	2349	0.0054854	1.13E-04	49.189	0.00084538	1.74E-05	355.0400923	-0.030092257
360.01	1285	0.006925	1.93E-04	48.687	0.00077082	2.15E-05	360.0373923	-0.027392276
365.01	1128	0.0077125	2.30E-04	48.2	0.0010426	3.10E-05	365.0309936	-0.020993605
370.01	1089	0.0038435	1.16E-04	47.726	0.00063438	1.92E-05	370.035076	-0.025076025
375.01	1120	0.005507	1.65E-04	47.265	0.00066307	1.98E-05	375.0438598	-0.033859818
380.01	1329	0.0098141	2.69E-04	46.817	0.0010511	2.88E-05	379.9929809	-0.017019107
385.01	1128	0.0083094	2.47E-04	46.378	0.00061096	1.82E-05	385.0251652	0.015165152
390.01	1200	0.0055452	1.60E-04	45.953	0.00052155	1.51E-05	390.0329262	0.022926204
395.01	1722	0.0087632	2.11E-04	45.54	0.00090087	2.17E-05	395.0327443	0.02274433
400	2542	0.0092609	1.84E-04	45.142	0.00096126	1.91E-05	399.9803898	-0.019610187



After calibrating the thermometer and converting it into temperature we see a very good correlation w/ the sample temperature. This is bad because it shows noise getting into the puck thermometers.



Above is the residuals for the thermometer calibration.