

Appendix A. 2-Drop Calorimeter Student Handout

CHEMISTRY 356-358, Physical Chemistry Laboratory

The Cutting Edge of Experimental Thermodynamics: Isothermal Heat Conduction Calorimetry

A physical chemistry laboratory experiment under development at Drexel University, with the cooperation of scientists and engineers at Dow Chemical Company and Lund University, Lund, Sweden.

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Objective: To explore the use of isothermal heat conduction calorimetry as a means of measuring a variety of heat changes such as determining the enthalpies of vaporization and reaction, evaluating the radiant power of a light source, measuring the heat of water adsorption of zeolites and identifying the heat of metabolism from small insects.

Introduction: Calorimetry is the measurement of heat. All chemical reactions and processes and all biological processes, which are ultimately chemically based, are accompanied by the generation or absorption of heat. Thermodynamics, the science underlying the interpretation of calorimetric measurements, is extremely well understood and allows for the determination of many useful chemical properties of substances.

Types of Calorimetry

Because of the central importance of energy changes in chemical reactions, calorimetry is usually a part of any experimental chemistry curriculum. Most general chemistry texts and physical chemistry lab manuals mention one type of calorimeter, the *bomb*

calorimeter. By measuring the heat change in reactions in which the standard enthalpies of formation are known for all but one of the reactants or products, the unknown enthalpy of formation can be determined. Bomb calorimeters are used for determining enthalpies of combustion of organic compounds but are limited in the type of heat changes that could be measured.

Calorimetry as practiced in both academic and industrial research labs, however, is much more diverse. In current literature, forty-four researchers in thermodynamics identifying important areas for development in the 21st century hardly mention combustion calorimetry, but describe dozens of applications of heat conduction calorimeters (Letcher, 1999). Common types of calorimetry are:

Solution calorimetry: a method of measuring the total heat evolved in a chemical process in solution, the process being carried out inside an adiabatic container such as a dewar flask.

With the proper kind of solution calorimeter, one can measure the heat evolved or consumed in fast reactions carried out when one reactant is incrementally added to another. Such experiments are called *thermal titrations*, and they have been widely used in biochemical systems to determine both enthalpy change and binding constant for the formation of enzyme-substrate complexes.

Differential scanning calorimetry (DSC): a method of comparing the heat capacities and heat generation or absorption within a sample and a reference as the temperature of both is raised at a constant rate.

Thermal gravimetric analysis (TGA): the loss of mass of a sample is continuously monitored as the temperature is raised at a constant rate. Although

not strictly a calorimetric measurement, thermal gravimetric analysis is often combined with differential scanning calorimetry; the acronym is *DSC/TGA*.

If the molar enthalpy change for a reaction is already known, measuring the rate of heat evolution in slow reactions determines the time dependence of the extent of the reaction and thus the rate of reaction. With calorimeters of high sensitivity it is possible to measure the heat given off by an unconnected dry cell battery as it slowly loses its chemical energy, an explosive as it slowly decomposes on the shelf, or even the heat generated by an exercising insect or a germinating seed.

Comparison of Adiabatic and Heat Conduction Calorimetry

Both the bomb calorimeter and the solution calorimeter are examples of **adiabatic calorimetry**. When a chemical process occurs in an adiabatically isolated system of known heat capacity, C , the temperature change, ΔT , is measured and the heat change is calculated from the equation:

$$Q = C\Delta T \qquad \text{Equation A-1}$$

In **heat conduction calorimetry**, the reaction vessel is isolated adiabatically from its surrounds except for contact with a heat flow sensor, which in turn is connected to a large heat sink such as a constant temperature bath. The heat flow sensor generates an output voltage proportional to the flow of heat, dQ/dt , through the sensor from the reaction vessel to the heat sink. This heat flow sensor signal is recorded as a function of time, and the total heat generated in the process is obtained by **integrating the heat flow signal over the duration of the experiment**:

$$Q = \int \frac{dQ}{dt} * dt \quad \text{Equation A -2}$$

Heat Flow Sensors – Thermocouple Plates (TCP)

The key to making heat conduction calorimetry practical is the availability of sensitive and relatively inexpensive heat flow sensors. Ingemar Wadsö (Wadsö, 1997) has pioneered the use of thermopiles as heat flow sensors. They are commercially available in the form of thermoelectric heat pump (Melcor, 1995) devices that operate on the inverse Peltier effect. The Peltier effect is responsible for the generation of a thermocouple voltage signal. Two dissimilar conducting materials (such as copper and constantan wire), connected at two points of differing temperature, generate a voltage difference proportional to the temperature difference. In the inverse Peltier effect, a flow of current through two dissimilar conductors causes a temperature difference to develop across the two connection points of the dissimilar materials. In a thermoelectric heat pump, when a voltage is applied to a thin array of dissimilar conducting pairs of materials, heat is pumped from one side of the array to the other side. In the commercial devices, the dissimilar materials are small rectangular pieces of n- and p- doped BiTe semiconductors. Thermoelectric heat pumps are used, for example, in cooling the integrated circuits used in computers. **Figure A-1** depicts the structure of the type of thermocouples used (Tellurex, 2002). The two-drop calorimeter was constructed using TCP, CP1.4-71-045L from Melcor (Trenton).

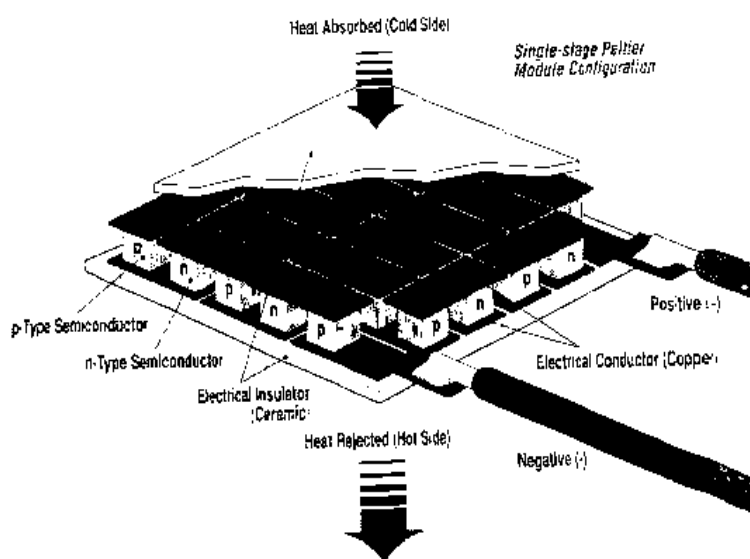


Figure A-1. Thermocouple Plate (TCP) (Tellurex, 2002)

One TCP is comprised of a large number of thermocouples connected in series electrically to give a high output voltage. They are connected in parallel thermally to give a high ratio of output voltage with a temperature difference.

The Working Equations for a Heat Conduction Calorimeter

The Tian equation is employed to calculate the thermal power from the measured signal. The output voltage, U (V), from the heat flow sensors recorded as a function of time may be converted into the heat flow rate, P (W), by multiplication with the calibration coefficient, ϵ (W/V). If we are interested in the kinetics of rapidly changing processes the Tian equation takes into account the heat capacity and the rate of temperature change of the reaction vessel (Bäckman *et al.*, 1994).

$$dQ/dt = P = \varepsilon(U + \tau^* dU/dt) \quad \text{Equation A-3}$$

Here τ , the time constant, of the calorimeter is given by

$$\tau = C / k \quad \text{Equation A-4}$$

Where C (J/K), is the heat capacity of the sample and its holder cup and k (W/K), is the heat conductance of the TCP. The calibration coefficient, ε (W/V), takes into account the thermal conductance of each thermocouple divided by the material constant of the thermocouple (Bäckman et al., 1994). The calibration coefficient is usually found from electrical calibrations, as discussed below. Using **Equation A-3**, when the signal, $U(t)$, is numerically differentiated to give, dU/dt , the actual thermal power produced in the sample from the measured voltage may be calculated.

When the thermal power changes slowly, at steady state conditions, $dU/dt = 0$. The Tian equation may be reduced to:

$$P = \varepsilon^* U \quad \text{Equation A-5}$$

For the experiments described here, the reduced form of the Tian equation, **Equation A-5**, may be used.

Design and Construction of a Simple Heat Conduction 2-Drop Calorimeter

Thomas C. Hofelich, a chemist in the Analytical Sciences Laboratory at Dow Chemical Company, has developed a sensitive and inexpensive heat conduction calorimeter, which he has used extensively at Dow for measuring heat production when small quantities of reagents are mixed (Hofelich *et al.*, 1994). Hofelich calls his device “The

2-Drop Calorimeter,” because the heat evolved when one drop of reactant A is added to one drop of reactant B can be measured.

Dr. Lars Wadsö, an engineer at the Division of Building Materials, Lund University, Sweden, has also developed a similar, inexpensive, isothermal heat conduction calorimeter(Wadsö, 1998). Experimental applications he has developed include:

Polymer science:	Curing reaction of a standard epoxy
Food science:	Microbiological growth in food
Material science:	Steel corrosion
Coatings technology:	Oxidation of linseed oils
Biotechnology:	Heat production in waste compost

Commercial versions of the type of calorimeter described here have recently been introduced. Typical industrial uses include the determination of the heat evolved upon mixing materials of both known and unknown origin (hazardous evaluation), and the study of the effect of concrete additives on the hydration of cement paste (Hofelich *et al.*, 1997; Wadsö, 1998).

In this experiment, a 2-drop calorimeter constructed at Drexel from Hofelich’s and Wadsö’s plans will be used (Hofelich, 1997). The sample chamber of the 2-drop calorimeter is a small glass vial of 2 cm³ volume. Inside the insulated box housing the calorimeter, the sample vial rests in an aluminum cup in good thermal contact with a Melcor thermopile resting on a large aluminum block functioning as a heat sink. There are two identical thermopile – aluminum cup – sample vial combinations, one serving as the **reference** and one serving as the **sample chamber**. **Figure A-2** is a schematic picture (Wadsö, 1999) of an isothermal heat conduction calorimeter.

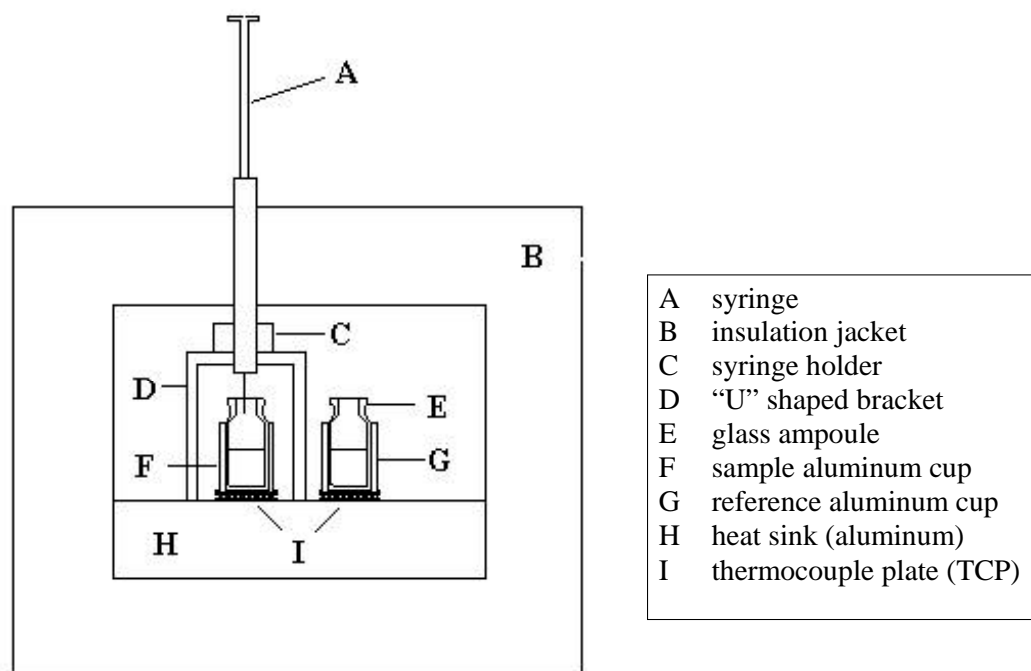


Figure A-2. Isothermal Heat Conduction 2-Drop Calorimeter

Calibration of the instrument

Thermal calibration of the 2-drop calorimeter is achieved by applying a known voltage, V , across a resistor of resistance, R , attached to the side of the aluminum cup where:

$$V = I * R \quad \text{Equation A-6}$$

$$P = I * V \quad \text{Equation A-7}$$

thereby leading to:

$$P = V^2/R \quad \text{Equation A-8}$$

The thermal power generated in the resistor is:

$$dQ/dt = P = V^2/R \quad (\text{W}) \quad \text{Equation A-9}$$

When a steady state output voltage is obtained, the calibration coefficient may be found from

$$\varepsilon = P/U \quad (\text{W/V}) \quad \text{Equation A-10}$$

where U , is the total measured voltage output. Typical values of ε , for commercially available thermopiles are 2.4 – 2.5 W/V. **Figure A-3** depicts a typical steady state output voltage used during the calibration.

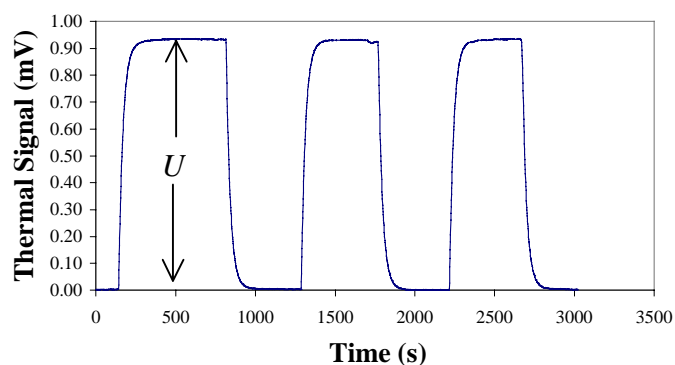


Figure A-3. Calibration thermal signal for 2-Drop Calorimeter

Enthalpy of Vaporization of Organic Solvents

The 2-drop calorimeter provides an easy method for determining the enthalpies of vaporization of volatile organic solvents. As only one drop of the solvent is released into the aluminum cup, the thermopile reads the endothermic event as the solvent evaporates and the thermal signal is gathered. By measuring the mass of 20 drops of

solvent and using the solvent's molecular weight calculating the mass of one drop, we can compute the molar enthalpy of vaporization of the solvent.

The calibration coefficient from the calibration is used to convert the voltage (U) to a thermal signal (W). Integration of the area under each thermal signal curve, U , gives the heat signal, Q , in Joules. Using the measured heats and the amount of solvent in each drop, the molar enthalpy of vaporization is found:

$$\Delta_{\text{vap}}H = \frac{\epsilon \int U dt}{n} \quad \text{Equation A-11}$$

Here, n , is the moles of solvent.

Laser Power Meter

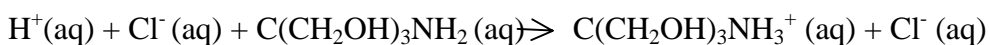
The TCP used in the 2-drop calorimeter are sensitive enough to be used as a laser power meter. In this experiment, the radiant power of a light source, a helium-neon laser, is measured. The 5 mW laser will be directed on the top surface of the sample aluminum cup blackened with graphite. After leaving the laser on for a few minutes, a steady-state output voltage will be reached. The output voltage, U , multiplied by the calibration coefficient, ϵ , gives the thermal power (W). The percentage of light absorbed and reflected can then be found

$$\{\text{Power}_{\text{(measured)}} / \text{Power}_{\text{(radiated)}}\} * 100 = \% \text{ absorbed} \quad \text{Equation A-12}$$

Thermal Titration of Tris(hydroxymethyl)aminomethane, (THAM), $C(CH_2OH)_3NH_2$, with 3M HCl

Using heat conduction calorimeters, thermal titrations carried out when one reactant is incrementally added to another enable the measurement of the heat evolved in fast reactions. This method has been widely used in biochemical systems to determine both the enthalpy change and the binding constant for the formation of enzyme-substrate complexes. Performing a thermal titration in this calorimeter requires only microliters of the titrating solution. In this experiment, a small sample of reagent A, either solution or solid, is placed in the vial, and the titrating reagent B is held in a 1000 μ l syringe mounted above the vial. Single drops of B are added to the vial, and the thermal signal generated from each addition is recorded.

As the first drops of titrant are delivered, a large exothermic signal is seen. Two or three drops at a time are delivered after the signal returns to the baseline. Releasing the drops of titrant is repeated until the expected equivalent molar volume is achieved indicating that the endpoint is reached. The titration proceeds according to:



Equation A-13

The volume of HCl required to neutralize all of the THAM is used to determine the enthalpy of reaction for this titration. At any intermediate point in the titration, the ratio of the added volume to the total volume of HCl equals the ratio of the added number of drops to the total number of drops.

The number of moles, n_i , in each drop of titrant is, $n_{i(HCl)} = V_{i(HCl)} * M_{HCl}$, where V_i , is the volume of titrant used and M , is the molarity of the titrant. Each peak,

corresponding to the i^{th} drop of the titrant, is integrated to give the heat, Q_i (J), Equation A-2. The total heat in all peaks before the endpoint, $\Sigma_i Q_i$, divided by the moles of titrant added before the endpoint, $\Sigma_i n_i$, gives the enthalpy of the process.

$$\Delta_r H = \Sigma_i Q_i / \Sigma_i n_i \quad \text{Equation A-14}$$

Another method of calculating the enthalpy of reaction is to employ the moles of THAM used. Because of difficulty in seeing the syringe gradients, we will be using Equation A-15, the moles of THAM for our calculations.

$$\Delta_r H = \Sigma_i Q_i / \Sigma_i n_{\text{THAM}} \quad \text{Equation A-15}$$

Using the literature value (Eatough *et al.*, 1974) for the enthalpies of formation of all reactants and products, Hess's Law is used to calculate the $\Delta_r H$. We assumed no concentration dependence for the $\Delta_f H$ (s).

Insect Metabolism

Isothermal calorimeters have been explored as a means of measuring the heat of metabolism of small insects. The rates of heat exchange between small insects and their environments are believed to be controlled by several factors: radiative heat gain, convective heat loss, metabolism, and evaporation. These properties vary with the size, shape, orientation, and surface properties of the insect (Casey, 1988).

Isothermal microcalorimeters offer a non-damaging route to monitor the metabolism of insects. To simplify the multiple sources of possible heat exchange, the heat measured from an insect scurrying in the vial is taken as the heat of metabolism. The heat

measured is the sum of the heats from all of the insect processes that takes place in the calorimeter.

The integration of the peaks, Equation A-2, corresponding to the activity events, gives the heat, Q , in Joules. If we assumed that the heat evolved from the bug is all the heat of metabolism, it is interesting to try to calculate how much sugar is needed to generate the same amount of heat. An approximate value can be found by using the “burning” of glucose in oxygen as a model of metabolism.



From the $\Delta_f H$ of the products and reactants, the $\Delta_r H$ can be found from Hess's Law. We can use this to determine the amount of glucose that would produce this amount of heat.

$$\text{mass}_{\text{glucose}}(\text{g}) = (\sum_i Q_i * 180 \text{ g/mole}_{\text{glucose}}) / \Delta_r H_{\text{m, glucose}} \quad \text{Equation A-17}$$

Heat of Water Adsorption on Zeolites

Zeolites, or "molecular sieves" have a porous structure. The internal surface area of these pores is quite large (several hundred square meters per gram of zeolite). Zeolites used as molecular sieves usually come as spherical pellets with diameters of ca. 1-2 mm. When even a few milligrams of dry zeolites are exposed to water vapor, large exothermic heat flows are observed. Carefully keeping the zeolites in a dry environment is essential prior to the experiment or during the prep time. In this lab period, the exothermic event will not reach completion. We will therefore only use a ten-minute period of the water adsorption event to calculate the $\Delta_{\text{absorption}}H$ of the

zeolites. The enthalpy of the adsorption process for this time period and mass of zeolites is found:

$$\Delta_{adsorption}H = \frac{\epsilon \int U dt}{mass_{zeolites}} \quad \text{Equation A-18}$$

which then yields the ΔH in Joules/gram.

Procedure

Data Acquisition Setup:

1. Put the top part of the insulating box on the calorimeter. This will allow the instrument to reach thermal equilibrium while setting up the computer interface and preparing for data acquisition.
2. Make the necessary connections from the calorimeter leads to the A/D computer interface terminal board. A single-ended setup is used. One lead is connected to pin 1 and the other to pin 18. The polarity (-/+) is arbitrary. If it is reversed, the magnitude of the signal remains the same, but the sign of the signal will change.
3. On the computer, open the **Agilent VEE Pro 6** software. There should be a shortcut on the desktop, if not, the software can be opened through Programs and Agilent VEE.
4. Close the “Tip of the Day”. Open a new file. In the folder VEE Programs, open **two_drop**. You will see the following control panel open:

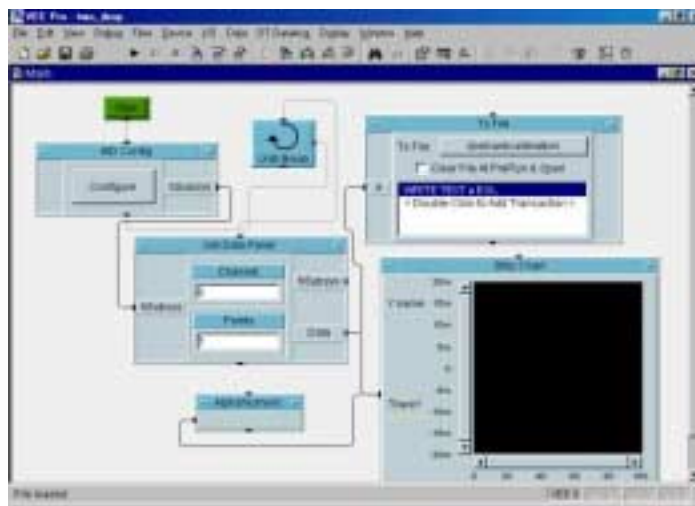



Figure A-4. VEE control panel for data acquisition of 2-Drop Calorimeter experiments.

5. On the A/D config icon, double click in the “Configure” box. The **channel** should read **0**, the **gain** is **8**, and the **sample rate** is **1 Hz**. Click on the “Hardware” tab on the right hand side. Make sure the “**channel type**” is “single-ended.”
6. In the “Get Data Panel,” the **channel** should read **0**, and **points** are **1**.
7. Right click on a plain light blue part of the “strip chart.” A submenu will appear for the “y plot.” Select the “properties” option. Go to the “**scales**” tab. (Do **not** use the auto scale option because the graph constant updates, it will be difficult to see any changes unless you are following the “AlphaNumeric” display.)
8. Change the **X Name** to “**Time (s)**” and the **Y Name** to “**Volts**”. For the X, or Time axis the **maximum** should be **100** and the **minimum** should be **0**. For the Y, or Volts axis, change the scale to **5m** for the **maximum** (meaning 5 mV) and **-5m** for the **minimum**. (N.B. Your *data is still recorded in volts*, this is just scaling or magnifying the axis of the chart so that we will be able to see the signal.) The Y scale may be changed for any of the experiments.
9. It is crucial to **save the data** to a file for later data analysis. In the light blue section of the “**To File**” look for the raised light blue box, next to the words “To file:” Double click in there and at the bottom type in a name for your file. It will put the correct file extension, you just need to type in a name for the particular part of the experiment (e.g. calibration). You may want to further distinguish the file with your initials or the date. This will save the data in the file “VEE Programs.” Afterwards, you can move the file to your own folder under “My Documents.”
10. You can start the data collection in one of two ways – click on the green “start” button or click on the  on the toolbar at the top.
11. Start the data collection to record the thermal baseline. You want to collect about 5 minutes of a stable baseline before starting the calibration.
12. In between each experiment, be sure to change the file name according to the experiment being performed.

Calibration of the Calorimeter

1. While data for the baseline is being recorded, use a **voltmeter** to **measure the voltage of the battery** that you will use as your potential source.
2. Also **measure the resistance** of the resistor attached to the side of the sample aluminum cup and record its value. A $1\text{ k}\Omega$ chip-resistor is used as the heating element. However the thin copper wire leads on the resistor also impose some resistance. Measuring the resistance using an ohmmeter will account for this

extra resistance. **The resistor is used only for the calibration and does not play a part in any of the other experiments.**

3. Close the electrical circuit (turn on the switch, if one available) by connecting the battery to the leads from the calorimeter. After a few seconds (depending on the time constant) you will see a decrease (or increase depending on the polarity of the leads in the terminal board) in the signal indicating an exothermic process from the heating of the sample cup. Since the thermopiles are heat flux sensors, the signal will decrease in magnitude and eventually reach a steady state and level off. After a few minutes (e.g. 5 min.) disconnect the battery and the signal will return to the base line. Wait a short while to establish a baseline after the **heating event**. Repeat the calibration **two more times** and then stop logging data by clicking on the stop program (■) on the toolbar.

Experiment 1: Enthalpies of Vaporization

1. Weigh a clean glass vial and a lid. Fill a syringe with the organic solvent. Release 20 drops in a glass vial, cover to prevent any evaporation and find the mass. After finding the mass of 20 drops, divide to find the mass of one drop. Use the molecular weight to determine the amount of moles in one drop.
2. Fill a 1 ml syringe to the 0.5 ml mark with the organic solvent. Mount the syringe on the sliding top and align the syringe exactly above the aluminum sample cup (the one you calibrated that had the resistor attached to the side). You may lower the syringe a few mm into the cup, but the syringe should not touch the sides or the bottom of the aluminum cup.
3. Tighten all screws and put the insulating box on the calorimeter so that the syringe extends through the hole in the top part of the insulating box. Allow for thermal equilibrium to be reached.
4. Prepare for data acquisition in the same manner as described in the calibration procedure. Remember to **change "To file" name. Start logs** and keep recording the signal for a few minutes (e.g. 5min). This will provide for a **baseline** before the actual event.
5. Start pushing down the plunger on the syringe very slowly until you observe a change in the signal. This will indicate that a drop has disengaged from the syringe tip and has fallen into the aluminum cup. It is difficult to see the actual event. An **endothermic signal** will be observed until all of the liquid is vaporized. The signal will eventually return to the baseline.
6. Record a **few minutes of baseline before starting the next drop. Repeat** the measurement **twice more** after which time you can "stop" the data acquisition.

Experiment 2: Laser Power Meter

1. Use a ring stand to secure the He-Ne laser above one of the aluminum cups, the one that has a blackened graphite mark on the bottom.
2. Turn the laser on to get the system set-up. Remember to change the file name. Once you are ready to start the data acquisition, leave the laser on but cover over the opening so that no light is directed into the calorimeter.
3. Start the data acquisition and allow the system to reach thermal equilibrium and a baseline to be established (about 5 min). Remove the covering over the opening and allow for a steady-state thermal signal to be reached (about 8-10 min.).
4. Cover over the calorimeter top so that the light is not reaching the inside of the calorimeter. Allow for a baseline to be established (about 5 min). **Repeat** the above **twice more**.

Experiment 3: Thermal Titration of a Saturated Solution of Tris (hydroxymethyl) aminomethane (THAM), $C(CH_2OH)_3NH_2$, with 3M Hydrochloric Acid

1. In a vial prepare 10-12 mg of dried $C(CH_2OH)_3NH_2$ (THAM) in a saturated solution, and position the vial in the sample aluminum cup.
2. Fill a 1 ml syringe with the titrant, 3M HCl. Secure the syringe in the sliding top in the usual manner. Lower the tip of the syringe into the vial. Tighten all screws and put the insulating box on the calorimeter.
3. Allow the system to reach thermal equilibrium. Start logs and record the signal for a few minutes. Deliver one drop of the titrant. This will produce an exothermic signal.
4. Wait for the signal to return to the baseline and deliver another drop. Repeat this until the endpoint of the titration is reached. Once the endpoint is passed small peaks are still observed and may be due to the heat of dilution of the HCl.

Experiment 4: Insect Metabolism

1. Remove the insulating top of the calorimeter. **Gently** place a small size insect into the sample aluminum cup. A small glass vial or watch glass may be used as a lid to keep the insect in the aluminum cup.
2. Put the insulating box on the calorimeter and allow the system to reach thermal equilibrium before you begin recording the data. Sometimes, it is a challenging task to keep the insect awake. Since the environment inside the calorimeter is

cold and dark, the insect may fall asleep. Find a way to wake up the insect (use of chemicals and other torture methods are not allowed).

3. Once the log is started, the recorded thermal signal will show a baseline metabolism of the insect and peaks corresponding to activity events.
4. Record the thermal signal for about 15 min. to accumulate thermal signals from the base metabolism and activity peaks.

Experiment 5: Heat of Water Adsorption on Zeolites

1. Place a few of these spheres (5-8 or more) in a special 2-drop calorimeter vial and put the vial in an oven for a day or longer. This drying procedure should drive off all water molecules.
2. Remove the zeolites from the oven immediately covering the container with a piece of aluminum foil. It is essential to have a tight seal so that no water is absorbed prematurely.
3. Measure the mass of the vial, containing the dry spheres, and sealed with Al foil. Place the vial containing the zeolites on a heat sink and leave it there until the vial reaches room temperature. To speed up the cooling you may use some ice, but keep in mind the zeolites should be **at** and **not below** room temperature when they are placed in the aluminum cup.
4. Mount a glass tube in the sliding top. Align the tube above the sample aluminum cup. Lower the glass tube into the aluminum cup. Make sure the tube does not touch the bottom or the sides of the aluminum cup.
5. Place a small beaker of water on the heat sink before putting the insulating box on the calorimeter. Wait a while to ensure thermal equilibrium as well as a water saturated atmosphere inside the insulating box.
6. Start logs and wait a few minutes before removing the Al foil on the vial. Remove the Al foil and immediately, using a paper funnel, slide the zeolites through the glass tube into the aluminum cup. Raise the glass tube carefully without moving it sideways. If you leave the glass tube in place, it may obstruct the flow of water vapors into the aluminum cup.
7. Place the aluminum foil back on the empty vial and measure its mass one more time. Use this and the previous mass measurement to obtain the mass of the dry zeolite spheres.

Data Analysis

1. Preparation of Data.

- a. Open a file (e.g. calibration) in Excel. The format is an ACSII file. We want the default options so when the dialogue box comes up, you can click on finished.
- b. Column A is the recorded voltage signal. Click on A to highlight it and then right click. Insert a column. The voltage data moves to column B.
- c. In column A insert the time, 1 second intervals.
- d. Repeat for each of the files that you will be using when you work on that data.

2. Calibration. Open the data in GRAMS 32. There should be a shortcut on the desktop, if not, go to Programs - Galatica – GRAMS 32. Follow the additional instructions about opening the file in GRAMS. Use the “Applications” and “Integration” functions. For the calibration, the **height** (depth) information will be shown on the right hand side. Determine the calibration coefficient, ϵ , in W/V, using Eqn. 10. For your lab write-up prepare a graph from the calibration by plotting the thermal signal (V) vs. time (s). The graphs for the lab report can be finished on your own. It is more crucial to get the GRAMS information while in the lab period. In a data table, show the battery voltage, the resistor’s resistance, and the three height values (volts), their average and standard deviation.

3. Enthalpy of Vaporization. Determine the mass and then the moles of the organic solvent used in each drop. Open the data in Excel, insert a time column and again follow the instructions for opening the file in GRAMS. **Integrate** and **record the area** under each curve to get the total heat, Q , in Joules. Show the area for each peak in a table (v*s). Take the average, to get the mean value for one drop. Using the sensitivity factor, ϵ (W/V), from the calibration experiment convert the thermal signal (U_{volts}) to thermal power (W). This integrated signal now multiplied by ϵ is the heat of the evaporation (Q). Use, Q / mol , to determine the $\Delta_{\text{vap}}H$. Finally, compare the enthalpy to the literature value (e.g. from the CRC online). In the lab report, include a graph of the volts versus time (or power versus time).

4. Heat of Laser Light Absorption. Open the data in Excel and follow the attached procedure for opening the data in GRAMS. Integrate and record the **height (volts)** (depth) of each heating event. Take and average to get the mean light absorbed in the aluminum cup. Show the height of each peak in a table. Using the sensitivity factor, ϵ , from the calibration experiment, once again, convert the average thermal signal to thermal power (W). Compare this with the stated power output from the laser. Calculate the percent absorbed in the aluminum cup and the remaining amount that was reflected.

5. Thermal Titration. Determine the moles of THAM used in the titration. Open the data in Excel and follow the attached procedure for opening the data in GRAMS. Integrate and record the **area** of each exothermic peak. Show these values in a table (v*s) and add the values to get the **total** thermal signal from the reaction. Convert the

thermal signal (V) to thermal power (W) by using ϵ . These integrated values are now the heat of the reaction (Q). Determine the ΔH of the reaction. Compare this experimental value with a literature value for the reaction. You may have to use Hess's Law and the heats of formation to calculate a literature value for the heat of reaction. In your report show a plot of the thermal signal versus the time as you prepared in the preceding parts.

6. Insect Metabolism. Follow the above procedure for opening the data in Excel and then in GRAMS to integrate the peaks. Because the thermal signals are much smaller in magnitude, work with a small portion of the data, one that has a substantial peak(s). Record the **areas** under the peaks chosen. These are due to heat given off by the insect's metabolism. Show these values in a table (v*s) and sum them. Use ϵ to convert the values to power (W). These integrated values multiplied by ϵ are now the heat given off by the insect (Q). Use Hess's Law to calculate the $\Delta_r H$ of glucose ($C_6H_{12}O_6$) combustion. Using the calculated $\Delta_r H$ and the heat measured from the peaks, find the mass equivalent that would be used to evolve the experimental amount of heat, Q . Convert to this value of glucose to milligrams.

7. Heat of Water Adsorption on Zeolites. Follow the above procedure for opening the data in Excel and then in GRAMS. Convert the thermal signal (V) to thermal power (W) and graph the data. Integrate to get the total heat, Q . Use the mass of zeolites used to find the moles. Determine the $\Delta_{\text{adsorption}} H$ for the selected time period.

Questions and Further Thoughts

1. When analyzing the vaporization graphs, because the volume of organic solvent released in one drop is highly reproducible, the area under the peaks should be the same. However, you may notice that the peaks have broadened. In analyzing the environment of the calorimeter, what may be some reasons accounting for this peak broadening?

A large percentage of the $\Delta_{\text{vap}} H$ is used in breaking the intramolecular bonds. What fraction of the $\Delta_{\text{vap}} H$ of the organic solvent is spent on expanding the gas vapor? (Assume ideal behavior.)

$$\Delta_{\text{vap}} H = \Delta_{\text{vap}} U + \Delta_{\text{vap}} (PV) \quad \text{where volume}_{\text{liquid}} \ll \text{volume}_{\text{vapor}}$$

2. The experimental value of the $\Delta_{\text{vap}} H$ of each of the organic solvents is compared with the literature value and assumes that the experimental value is measured at room temperature, 25°C. Many times however, the lab temperature fluctuates according to the outside temperature. If the temperature in the lab is 18°C, how will this affect the evaporation process. What steps should be included in the calculation to account for this temperature change? Calculate the $\Delta_{\text{vap}} H$ of one of the organic solvents at 18°C. What is the percent difference?

3. The time constant, τ , is the thermal response time of the calorimeter. The Tian equation takes into account the heat content of the sample and holder cup:

$$P = \epsilon(U + \tau * dU/dt)$$

Because the reactions performed in these experiments are slower reactions, the time constant is considered negligible and we calculated the heat flow rate as:

$$P = \epsilon * U$$

If we had taken the time constant into account, how would this have changed the results of the integrated peaks? Why does the time constant need to be accounted for in a fast reaction taking only milliseconds?

4. If you were constructing a calorimeter for long-term studies on insects, what factors would have to be taken into consideration?

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Appendix B. Nomenclature and Abbreviations Used

α	Wave phase shift in quartz
α	Transition region in glassy materials, gradual main chain relaxation
α	Linear coefficients of thermal expansion, (length/(length * °C))
α_0	Coefficient of expansion of an ideal material
α_G	Coefficient of expansion of a glass
$a_{\text{adsorbate}}$	Vapor activity of gaseous adsorbate
ac	Alternating current
a_c	Shift factor used to describe the diluent concentration effect on the polymer modulus
a_t	Temperature shift factor for WLF equation
a_w	Water vapor activity
A	Area
Å	Angstrom
AFM	Atomic force microscope
A_{SAW}	kHz change in frequency due to a 1°C change per kHz of coating on resonator surface
AT	Temperature compensated cut of quartz, 35°15' off of Y axis
β	Transition region in glassy materials, relaxation of side groups
β'	Plasticizing parameter relating the diluent volume fraction to the free volume
B	Constant in WLF equation, close to unity
BT	Temperature compensated cut of quartz
BET	Sorption isotherm model by S. Brunauer, P.H. Emmett, and E. Teller
BVD	Butterworth Van Dyke equivalent electrical circuit
δc	Concentration gradient
c_m	Elasticity
c_q	Complex shear modulus of quartz
c_q^0	Storage shear modulus of quartz
C	Sensitivity constant for a 5 MHz QCM, 56.6 Hz $\mu\text{g}^{-1}\text{cm}^2$
C	Capacitance
C	D'Arcy and Watt constant proportional to the number and affinity of weak binding sites
C_p	Heat capacity
C_0	Shunt capacitance or static capacitance, gold electrodes of the QCM, wires and clamping

C1	Capacitance of the resonating QCM
C1	Universal constant for the WLF equation
C2	Capacitance of the added mass to the QCM
C2	Universal constant for the WLF equation
CS	Conformation substate
C_s	Concentration of analyte in the sorbent phase, thin film
C_v	Concentration of analyte in the vapor phase
δ	Transition region of glassy materials, characterized by local motions
δ	Angle of phase shift between the applied stress and the resulting strain
δ	Acoustic wave decay length
$\tan \delta$	Tangent of the phase angle, ratio of the storage and loss components
D	Diffusion coefficient
D	D'Arcy and Watt constant proportional number of multilayer binding sites
DAQ	Data acquisition board
dc	Direct current
dq/dt	Heat flux
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimetry
DTA	Differential thermal analysis
e	Piezoelectric constant of quartz
$e(T)$	Seebeck coefficient
ϵ_q	Permittivity of quartz
ϵ	Calibration coefficient of the thermopile
E_s	Seebeck voltage
E	Internal energy
EF	Equilibrium fluctuations
Endo	Endothermic
Exo	Exothermic
dE_s	Change in Seebeck voltage
ΔE_2	Energy change in the thin film adsorbent
f	Oscillation frequency
f	Fractional free volume
f_h	Fraction of heat flow that does not pass through the thermopile
f_g	Fractional free volume at T_g

f_o	Series resonant oscillation frequency
f_2	Polymer free volume
f_r	Resonant frequency
Δf_s	Frequency shift of the sorbent phase before vapor sorption
Δf_v	Frequency shift of the sorbent phase due to vapor sorption
F	Force
FIMS	Functionally Important Motions
γ	Strain in an elastic deformation
γ	Transitions characterized by bending and stretching motions
γ	D'Arcy and Watt constant proportional to water affinity of the multilayer binding sites
γ_o	Maximum strain in an elastic deformation
γ'	Elastic deformation in-phase strain
γ''	Elastic deformation out-of- phase strain
γ^*	Elastic deformation complex strain
ΔG	Gibbs free energy
$\Delta_{\text{mixing}}G$	Free energy of mixing
$\Delta_{\text{sorption}}G$	Free energy of sorption
G	Conductance
G	Complex shear modulus (of a thin film)
G'	Storage shear modulus
G''	Loss shear modulus
G_c	Thermal conductance per thermocouple plate
G_c	Crystal conductance
GC	Gas chromatography
GPIB	General purpose interphase board
G_q	Complex shear modulus of quartz
G_s	Source conductance
G_t	Total conductance
η	Viscosity
η_f	Viscosity of the thin film
η_q	Viscosity of quartz
h	g H ₂ O/ g lysozyme
h	$g_{\text{adsorbate}}/g_{\text{adsorbent}}$
h_f	Thickness of the thin film

h_q	Thickness of quartz
$h'p$	Constant in the D'Arcy Watt sorption isotherm
H	Enthalpy
ΔH	Enthalpy change
$\Delta_{\text{adsorption}}H$	Enthalpy of adsorption
$\Delta_{\text{condensation}}H$	Enthalpy of condensation
$\Delta_{\text{crystallization}}H$	Enthalpy of crystallization
$\Delta_{\text{dehydration}}H$	Enthalpy of dehydration
$\Delta_{\text{denaturation}}H$	Enthalpy of denaturation
$\Delta_{\text{fusion}}H$	Enthalpy of fusion
$\Delta_{\text{hydration}}H$	Enthalpy of hydration
$\Delta_{\text{mixing}}H$	Enthalpy of mixing
$\Delta_{\text{reaction}}H$	Enthalpy of reaction
$\Delta_{\text{sorption}}H$	Enthalpy of sorption
$\Delta_{\text{vaporization}}H$	Enthalpy of vaporization
HCC	Heat conduction calorimeter
HEW	Hen egg white
HPLC	High performance liquid chromatography
I	Current amplitude
i	Square root of -1
i.d.	Internal diameter
IGC	Inverse gas chromatography
ϕ	Acoustic wave phase shift
j	Square root of -1
J	Current density across the quarts of the QCM
J	Flux
κ	Electromechanical coupling coefficient
k	Thermal conductivity
k_1	Proportionality constant used for rate of evaporation in Langmuir isotherm
k_2	Proportionality constant used for rate of condensation in Langmuir isotherm
k_a	Rate constant for adsorption
k_d	Rate constant for desorption
k_q	Wave vector for shear wave in quartz
K	Partition coefficient/ equilibrium constant

K^2	Quartz electromagnetic coupling coefficient
K_q^{o2}	Electromechanical coupling factor for lossless quartz
K_q^2	Electromechanical coupling factor for lossy quartz
K_c	Equilibrium constant
K_D	Dissociation constant
K_{eq}	Equilibrium constant
λ_q	Wavelength of the propagating acoustic wave in QCM
l and l_f	Thickness of the thin film
Δl_q	Change in the thickness of the resonating quartz
l_q	Thickness of resonating quartz
L	Inductance
L_1	Inductance of the resonating QCM
L_2	Inductance of the added mass to QCM
LCR	Simple circuit consisting of an inductor, capacitor, and resistor
LEM	Lumped element model
LF	Low frequency
Δm	Change in the mass
m	Mass
M	Mass factor in determining Z_L
M_b	myoglobin
metMb	metmyoglobin
MFC	Mass flow controller
m_p^∞	Mass of the film and the sorbed solvent vapor at time infinity
m_p^i	Initial mass of the film and the sorbed solvent vapor
m_p^t	Mass of the film and the sorbed solvent vapor at time t
ΔM_q	Change in the mass of resonating quartz
M_q	Mass of resonating quartz
ν	Frequency
n	Number of moles
n	Number of the overtone frequency
n_a	Gas molecules adsorbed per gram of solid
n_q	The ratio of the overtone frequency over the quartz resonant frequency
n_1^s	Moles of thin film adsorbent
n_2^g	Moles of gaseous adsorbate

N	Odd integer for the resonator harmonic number
NMR	Nuclear magnetic resonance
OCN	Oscillating capillary nebulizer
o.d.	Outer diameter
p	Instantaneous power
p_i	Partial pressure
p/p^0	Vapor activity
p^0	Saturation vapor pressure
P	Pressure
P	Heat flux, thermal power
PBS	Phosphate buffer solution
P_{crystal}	Power generate in quartz crystal
PDMS	Polydimethylsiloxane
PIB	Polyisobutylene
PLO	Phase lock oscillator
PVA	Polyvinylalcohol
θ	Fraction of monolayer, fraction of surface coverage
q	Charge
q_i	Integral calorimetric heat
Q	Quality factor
Q	Heat
Q_i	Integral heat of adsorption
QCM	Quartz crystal microbalance
ρ_f	Density of thin film
ρ_L	Density of vapor when in liquid phase
ρ_q	Density of quartz
ρ_s	Density of sorbent phase
ρ	Electrical resistivity
r	Acoustic wave reflectance coefficient
r	Dissipation factor
rf	Radio frequency
r_m	Rate of mass uptake
rpm	Rotations per minutes
R	Resistance
R	Motional Resistance
R	Ideal gas law constant

ΔR	Change in motional resistnace
RH	Relative humidity
R1	Resistance of the resonating QCM
R2	Resistance of the added mass to the QCM
σ	stress in an elastic deformation
sub- T_g	Sub-glass transition, β , δ , γ relaxations
ΔS	Entropy
$\Delta_{\text{mixing}} S$	Entropy of mixing
$\Delta_{\text{sorption}} S$	Entropy of sorption
$\Delta_{\text{vaporization}} S$	Entropy of vaporization
S	Sensitivity constant of a thermopile
SAW	Surface acoustic wave device
S_{exp}	Experimental thermopile sensitivity
S_{id}	Ideal thermopile sensitivity
τ	Time constant in Tian equation
τ	Average time of stay of vapor molecule on the film surface
t	Time
T	Temperature
TA	Thermal analysis
T_c	Critical temperature
TCP	Thermocouple Plate
T_d	Temperature of denaturation
T_g	Glass transition temperature
TG	Thermogravimetry
TGA	Thermogravimetric analysis
TLM	Transmission line model
T_m	Temperature of melt
TSM	Thickness shear mode resonantor
U	Voltage
v	Acoustic factor in determining Z_L
v_1	Volume fraction of diluent
V	Voltage
V	Volume
V^0	Specific volume at absolute zero
V_L^0	Specific volume extrapolated from the liquid state to absolute zero
V_G^0	Specific volume extrapolated from the glassy state to absolute zero

V_f	Free volume
VI	Virtual instrument
V_q	Speed of the propagating acoustic wave in QCM
V_s	Volume of the adsorbent polymer phase
V_t	Specific volume (cc/g)
V_v	Volume of the adsorbate liquid vapor
VCO	Voltage controlled oscillator
ω	Angular frequency = $2\pi\nu$
W	Uptake of adsorbate in D'Arcy and Watt isotherm
WLF	Williams-Landel-Ferry equation
W_m	Proportionality constant proportional to the energy of adsorption
x	Displacement
δx	Diffusion direction
X_1	Thin film adsorbate
X_2	Gaseous adsorbent
X_C	Capacitive reactance
X_f	Reactance of the thin film
X_L	Inductive reactance
Y	Admittance
Y_{EL}	Electrical admittance
z	Ratio of acoustic impedance in quartz over that in the thin film
Z	Thermoelectric material property, figure of merit
Z_{AB}	Complex electrical input impedance
Z_{eq}	Acoustic impedance of QCM
Z_L	Complex acoustic impedance due to the mass loading
Z_Lp, Z_L'	Real part of acoustic load impedance
Z_Lpp, Z_L''	Imaginary part of acoustic load impedance
Z_m	Total motional impedance in an equivalent electrical circuit
Z_q	Acoustic impedance of quartz
Z_1	Motional impedance of the unperturbed quartz crystal
Z_2	Complex motional impedance created by an acoustically thick film

Appendix C. Quartz Constants

(Lucklum *et al.*, 1997; Lucklum & Hauptmann, 1997; Lucklum & Hauptmann, 2000)

$\rho_q = 2.651 \times 10^3 \text{ kg m}^{-3}$	density
$\epsilon_q = 3.982 \times 10^{-11} \text{ A}^2 \text{ s}^4 \text{ kg}^{-1} \text{ m}^{-3}$	permittivity
$e_q = 9.53 \times 10^{-2} \text{ A s m}^{-2}$	piezoelectric constant
$\eta_q = 3.5 \times 10^{-4} \text{ kg m}^{-1} \text{ s}^{-1}$	viscosity
$c_q = 2.947 \times 10^{10} \text{ N m}^{-2}$	piezoelectric stiffened elastic constant
$v_q = 3347 \text{ m s}^{-1}$	shear sound velocity
$K_q^{02} = e_q^2 / (\epsilon_q c_q)$	electromechanical coupling facto for lossless quartz
$K_q^2 = e_q^2 / [\epsilon_q (c_q + j\omega\eta_q)]$	electromechanical coupling factor for lossy quartz
$L_q = (\rho_q h_q^3) / (8Ae_q^2)$	motional inductance of quartz crystal
$C_o = \epsilon_q (A/h_q)$	static quartz capacitance
$\omega = 2\pi f$	angular frequency
$\alpha = \omega (h_q / v_q)$	wave phase shift in quartz
$Z_q = \rho_q v_q = \text{sqrt}(\rho_q c_q)$	specific quartz impedance

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Appendix D. “Fast Three Step Method” Equations Used in TK Solver Model

Adapted equations as entered in TK Solver 4.0, File 3_Step
Original Equations in (Behling *et al.*, 1999; Lucklum & Hauptmann, 2001)

Rule
;Fast Three-Step Method for Shear Moduli Calculation from Quartz Crystal Resonator Measurements
;Carsten Behling, Ralf Lucklum, Peter Hauptmann, IEEE 46(6), Nov. 1999, 1431-1438
$Lq=(q*hq^3)/(8*Aq*eq)$; motional inductance of quartz crystal
$Zq=sqrt(\rho q*cq)$; specific quartz impedance
$\omega=2*pi()*f$
$ZLpp=(f/f)*-1*pi()*Zq$
$ZLp=(R/(2*\omega*Lq))*(pi()*Zq)$
;M= $\omega*\rho*hf$; mass factor
;Using the ZLp,ZLpp from above to get first approx. for G',G'' values for approximations
;($G0p,G0pp$)= $power((,0),-1)*((1/M^2,0)+(1/ZLp,0))*(1/3*M^3,0)*(M,ZLpp)$
;($G1p,G1pp$)= $power((,0),-1)*(power((-2*M,-ZLpp),2)/power((1-pi()/2,0),2))$
;($G2p,G2pp$)= $power((,0),-1)*(-pi()^2/8*ZLp^2,0)+(0,M*ZLpp)+((pi()/4*ZLp,0)*csqrt(pi()^2/4*ZLp^2,-4*M*ZLpp))$
;($G2bp,G2bpp$)= $power((,0),-1)*((4*M^2,0)/(pi(),-8*M*1/ZLpp))$
;($G3p,G3pp$)= $power((,0),-1)*(power((-2*M,-ZLpp),2)/power((1+3/2*pi(),0),2))$
;($G4p,G4pp$)= $power((,0),-1)*(power((-M,-ZLpp),2)/power((pi(),0),2))$
;Using the G',G'' values to recalculate the ZL values
;($sqG0p,sqG0pp$)= $csqrt(0,/G0pp)$
;($ZL0p,ZL0pp$)= $csqrt(\rho*G0p,\rho*G0pp)*ctan(0,\omega*hf*sqG0pp)$
; ($sqG1p,sqG1pp$)= $csqrt(0,/G1pp)$
;($ZL1p,ZL1pp$)= $csqrt(\rho*G1p,\rho*G1pp)*ctan(0,\omega*hf*sqG1pp)$
; ($sqG2p,sqG2pp$)= $csqrt(0,/G2pp)$
;($ZL2p,ZL2pp$)= $csqrt(\rho*G2p,\rho*G2pp)*ctan(0,\omega*hf*sqG2pp)$

Rules (continued)
; (sqG2bp,sqG2bpp)=csqrt(0,/G2bpp)
;(ZL2bp,ZL2bpp)=csqrt(ρ^*G2bp,ρ^*G2bpp)*ctan(0, $\omega^*hf^*sqG2bpp$)
;(sqG3p,sqG3pp)=csqrt(0,/G3pp)
;(ZL3p,ZL3pp)=csqrt(ρ^*G3p,ρ^*G3pp)*ctan(0, $\omega^*hf^*sqG3pp$)
;(sqG4p,sqG4pp)=csqrt(0,/G4pp)
;(ZL4p,ZL4pp)=csqrt(ρ^*G4p,ρ^*G4pp)*ctan(0, $\omega^*hf^*sqG4pp$)
;Iteration process, solving for
;(0,0)=(ZL0p* $\varphi0,0$)-ctan(0, $M^*(\varphi0+((1/3)^*(\varphi0^3))))$; $\varphi\sim 0$
;(0,0)=(ZL1p* $\varphi1,0$)-ctan(0, $M^*(1-(\pi()/2)+(2^*1))$) ; $\varphi\sim \pi/4$
;(0,0)=(ZL2p* $\varphi2,0$)-ctan(0, $M^*(1/((\pi()/2)-\varphi2))$) ; $\varphi\sim \pi/2$
;(0,0)=(ZL2bp* $\varphi2b,0$)-ctan(0, $M^*(8*\varphi2b/((\pi()^2)-(4*\varphi2b^2))$)) ; $\varphi\sim \pi/2$
;(0,0)=(ZL3p* $\varphi3,0$)-ctan(0, $M^*(-1-((3/2)^*\pi()+2*\varphi3))$) ; $\varphi\sim 3/4\pi$
;(0,0)=(ZL4p* $\varphi4,0$)-ctan(0, $M^*(-\pi()+\varphi4)$) ; $\varphi\sim \pi$

Variables					
Status	Input	Name	Output	Unit	Comment
		ZLp		Pa*s*m-1	real part of acoustic load impedance
		ZLpp		Pa*s*m-1	imaginary part of acoustic load impedance
Guess	.001	ϕ_0			$\phi \sim 0$
Guess	.77018	ϕ_1			$\phi \sim \pi/4$
	1.4503	ϕ_2			$\phi \sim \pi/2$
	1.4503	ϕ_{2b}			$\phi \sim \pi/2$
	2.2566	ϕ_3			$\phi \sim 3/4\pi$
	3.0001	ϕ_4			$\phi \sim \pi$
	1090			kg*m ⁻³	film density
	4999000	f		s ⁻¹	series resonant frequency
	8.5	hf		micron	height of film
	.002651	q		kg*m ⁻³	quartz density - Lucklum, Faraday D., 107, 1997
	2.947E10	cq		N*m ⁻²	piezoelectric stiffened elastic constant, effective shear modulus of quartz - Lucklum, Faraday D., 107, 1997
	.0033	hq		cm	effective quartz thickness
	1.9793	Aq		cm ²	effective quartz area
	.0953	eq		A*s*m ²	piezoelectric constant- Lucklum, Faraday D., 107, 1997
	8838.833	Zq		Pa*s*m-1	specific quartz impedance
	55	f		kHz	change in frequency from resonant frequency
	250	R		Ohm	change in resistance
		Lq		henry	motional inductance of quartz
				s ⁻¹	angular frequency
		M			Mass factor in equation for ZL

Variables					
Status	Input	Name	Output	Unit	Comment
		G0p		Pa	First approximations for
		G0pp		Pa	shear storage, Gp, and shear
		G1p		Pa	loss, Gpp, moduli
		G1pp		Pa	
		G2p		Pa	
		G2pp		Pa	
		G2bp		Pa	
		G2bpp		Pa	
		G3p		Pa	
		G3pp		Pa	
		G4p		Pa	
		G4pp		Pa	
		ZL0p		Pa*s*m-1	Acoustic load impedance
		ZL0pp		Pa*s*m-1	real ZLp and imaginary ZLpp
		ZL1p		Pa*s*m-1	as calculated from the first
		ZL1pp		Pa*s*m-1	approximations of Gp and Gpp
		ZL2p		Pa*s*m-1	
		ZL2pp		Pa*s*m-1	
		ZL2bp		Pa*s*m-1	
		ZL2bpp		Pa*s*m-1	
		ZL3p		Pa*s*m-1	
		ZL3pp		Pa*s*m-1	
		ZL4p		Pa*s*m-1	
		ZL4pp		Pa*s*m-1	
		sqG0p			square root terms of Gp and Gpp
		sqG0pp			used to calculate the acoustic
		sqG1pp			load impedance
		sqG1p			
		sqG2p			
		sqG2pp			
		sqG2bpp			
		sqG2bp			
		sqG3pp			
		sqG3p			
		sqG4pp			
		sqG4p			

Functions			
Name	Type	Arguments	Comment
ctan	Rule	2;2	Tangent of complex argument
ctanh	Rule	2;2	Hyperbolic tangent of complex argument
cabs	Rule	2;1	Absolute value or modulus of complex argument
csqrt	Rule	2;2	Square root of complex argument
csin	Rule	2;2	Sine of complex argument
ccos	Rule	2;2	Cosine of complex argument

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1989 – 1994 St. Monica, 7 th grade	Philadelphia, PA
1994 – 1996 St. Teresa, 7 th – 8 th grade	Runnemede, NJ
1996 – 1999 St. Cecilia, 8 th grade	Philadelphia, PA
1999 – 2002 Drexel University teaching assistant	Philadelphia, PA

Publications

Wadsö, L.; Smith, A.L.; Shirazi, H.M.; Mulligan, R.; Hofelich, T. “The Isothermal Heat Conduction Calorimeter: A Versatile Instrument for Studying Processes in Physics, Chemistry and Biology.” *Journal of Chemical Education*. **2001**, 78(8), 1080-1087.

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Presentations

57 th Annual Calorimetry Conference Rutgers University, New Brunswick, N.J.	2002
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“*Applications of the Quartz Crystal Microbalance/Heat Conduction Calorimeter: Measuring the Thermodynamic and Mechanical Hydration Effects on a Myoglobin Thin Film.*”

Smith, A. L.; Mulligan, R.