Temperature Measurement and Control

- What is the definition of temperature?
  - Correlates to molecular kinetic energy
  - Measure of the “quality of heat”

- Reference material
  http://www.omega.com/temperature/Z/zsection.asp

Temperature Measurement and Control

- Applications for physicists
  - Necessary for some other process of interest
    - Purification by vacuum sublimation
    - Device fabrication
    - Crystal growth
    - Cold traps for numerous applications
    - Process needs to be done under predetermined thermal conditions
  - Inherent to an experiment
    - Measurement of temperature dependence of some property
    - Determination of temperature at which some physical phenomenon occurs
    - Temperature dependence of experiment needs to be controlled with high precision

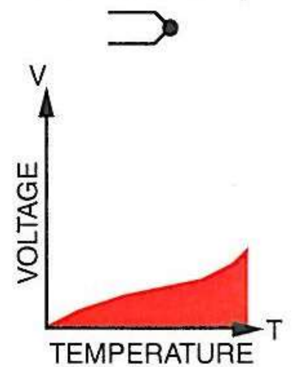
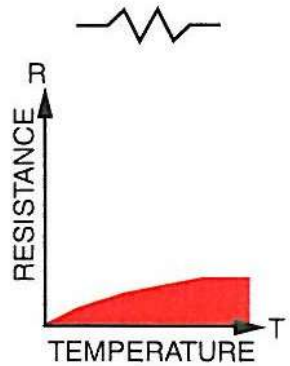
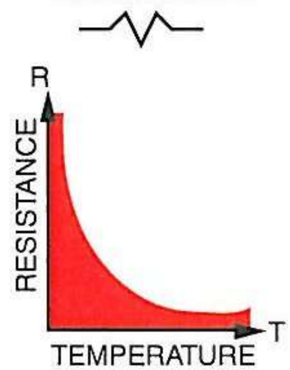
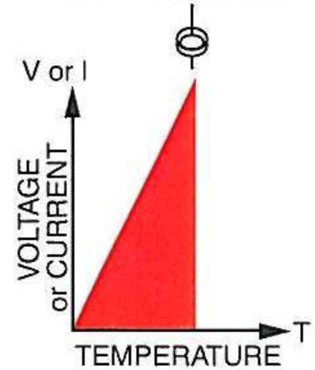
Devices and Techniques for Temperature Measurement

- Requires material parameter proportional to temperature
- Uncertainty principle applies! How much does the act of measuring the temperature and getting the result out change the system temperature?
- Under what circumstances is the act of taking the measurement insignificant?

Devices for Temperature Measurement

- Expansion thermometers
  - Familiar
  - Convenient
- Thermocouples
- RTDs (Resistive Temperature Devices)
- Thermistors
- Integrated Circuits
- Optical pyrometers
- Infrared thermometers

Practical Temperature Measurements*

	Thermocouple	RTD	Thermistor	I. C. Sensor
				
Advantages	☐ Self-powered ☐ Simple ☐ Rugged ☐ Inexpensive ☐ Wide variety ☐ Wide temperature range	☐ Most stable ☐ Most accurate ☐ More linear than thermocouple	☐ High output ☐ Fast ☐ Two-wire ohms measurement	☐ Most linear ☐ Highest output ☐ Inexpensive
Disadvantages	☐ Non-linear ☐ Low voltage ☐ Reference required ☐ Least stable ☐ Least sensitive	☐ Expensive ☐ Current source required ☐ Small Δ R ☐ Low absolute resistance ☐ Self-heating	☐ Non-linear ☐ Limited temperature range ☐ Fragile ☐ Current source required ☐ Self-heating	☐ T<200°C ☐ Power supply required ☐ Slow ☐ Self-heating ☐ Limited configurations

* Stolen from Omega who stole it from HP

Non-Electronic Thermometry

- Expansion thermometers
  - Common
  - Inexpensive
  - Absolute or differential
  - Huge thermal mass
  - Very slow to respond
- Bimetallic strip thermometers
  - Dial
  - Convenient
  - Inexpensive
  - Poor accuracy and precision
  - Great for food preparation

Radiative Methods

- Optical pyrometer
  - Body of interest must emit in the visible
  - Ancient technology
  - Temperature measured must be at least 650 C
  - Essentially no upper limit to capability
- Infrared Thermometers
  - "Quantum detectors"
    - Basically solar cells in the IR
    - Fit blackbody spectrum
  - "Thermal detectors"
    - Bolometers, pyroelectric detectors
    - Radiation causes temperature of detector to rise

Thermal Expansion Coefficient

- Classic mercury-in-glass
- When are they useful?
- What are some applications?
- Why do they have the shape they do?
- Alcohol thermometers
  - Why use them?
  - (Hint: $T_m(Hg)$ = 234.32 K = -38.84 C)

LANGE'S HANDBOOK OF CHEMISTRY

Editor: JOHN A. DEAN

Professor of Chemistry
University of Tennessee (Knoxville)

Formerly Compiled and Edited by
NORBERT ADOLPH LANGE, Ph.D.

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- $V(T) = V_0(1 + aT + bT^2 + cT^3)$

$dV/dT = a + 2bT + 3cT^2$

$0.81 < a < 1.57 \times 10^{-3}$

Table 10-42
COEFFICIENTS OF CUBICAL EXPANSION FOR VARIOUS LIQUIDS AND AQUEOUS SOLUTIONS

See also the table *Coefficients of Cubical Expansion For Various Solids.*

If V_0 is the volume at 0°C, then the volume at t°C = $V_t = V_0(1 + at + bt^2 + ct^3)$. Where the compound is marked with * the basic volume is not that at 0°C, but at some other temperature, t_0. The equation then reads $V_t = Vt_0(1 + a(t - t_0) + b(t - t_0)^2 + c(t - t_0)^3]$. In the case of aqueous solutions, the concentrations in percent are given after the name.

Liquid	Coef. at 20°C. ×10³	Range °C.	a×10³	b×10⁶	c×10⁸
Acetic acid	1.071	16 to 107	1.063	−0.12636	1.0876
Acetone	1.487	0 to 54	1.324	3.809	−0.87983
Allyl alcohol	1.049	0 to 94	0.97019	1.6725	0.36452
Allyl bromide	1.241	0 to 69	1.2275	−0.44365	2.5843
Allyl chloride	1.475	9 to 44	1.3218	5.078	−4.1915
Allyl ether	1.346	0 to 88	1.2519	2.2401	0.35775
Allyl iodide	1.091	0 to 101	1.0539	0.63572	1.0036
Amyl acetate	1.162	0 to 124	1.1501	−0.09046	1.3015
Amyl alcohol	0.902	−15 to 80	0.89001	0.65729	1.18458
Amyl benzoate	0.848	0 to 198	0.81711	0.7377	0.10593
Amyl bromide	1.102	0 to 80	1.02321	1.90086	0.19756
Amyl chloride	1.208	0 to 100	1.17155	0.50077	1.35368
Amyl iodide	0.986	20 to 142	0.92658	1.4647	0.05962
Aniline	0.858	0 to 141	0.82349	0.8408	0.10741
Arsenous chloride	1.020	−15 to 130	0.97907	0.96695	0.17772
Benzene	1.237	11 to 81	1.17626	1.27755	0.80648
Benzoyl chloride	0.880	12 to 146	0.85893	0.44219	0.27139
Bromine	1.113	−7 to 60	1.03819	1.711138	0.54471
n-Butyl alcohol	0.950	6 to 108	0.83751	2.8634	−0.12415
n-Butyric acid	1.063	0 to 100	1.02573	0.83760	0.34694
iso-Butyric acid	1.068	16 to 118	0.97625	2.3976	−0.32145
Calcium chloride, 40.9%	0.458	17 to 24	0.42383	0.8571	....
Cane sugar, 43.2%	0.343	0 to 35	0.2536	2.247	....
n-Caproic acid	0.975	15 to 155	0.94413	0.68358	0.26586
Carbon disulfide	1.218	−34 to 68	1.1398	1.37065	1.91225
Carbon tetrachloride	1.236	0 to 76	1.18384	0.89881	1.35135
Chloral	0.934	13 to 51	0.9545	−2.2139	5.6392
Chloroform	1.273	0 to 63	1.10715	4.66473	−1.74328
o-Cresol	......	66 to 186	0.71072	1.1464	0.2242
m-Cresol	......	65 to 194	0.77526	0.27102	0.3868
p-Cresol	......	66 to 186	0.86476	0.53912	0.64418
Cymene	0.946	0 to 100	0.895	1.277	....
Diallyl	1.375	0 to 60	1.3423	−0.34339	3.8693
Diethyl ketone	1.233	0 to 95	1.15342	1.88396	0.32021
Dipropyl	1.381	0 to 66	1.2948	1.7471	1.2363
Ethyl acetate	1.389	−36 to 72	1.2585	2.95688	0.14922
Ethyl alcohol	......	0–80	1.04139	0.7836	1.7618
Ethyl alchol 50%	......	0–39	0.7450	1.85	0.730
Ethyl benzoate	0.900	0 to 159	0.86606	0.8229	0.12084
Ethyl benzene	0.961	24 to 131	0.86172	2.5344	−0.18319
Ethyl bromide	1.418	−32 to 54	1.33763	1.50135	1.6900
Ethyl chloride	1.706	−32 to 26	1.57458	2.81366	1.56987
Ethyl ether	1.656	−15 to 38	1.51324	2.35918	4.00512
Ethyl formate	1.417	0 to 63	1.36446	0.13538	3.9248
Ethyl iodide	1.179	10 to 65	1.1520	0.26032	1.4181
Ethyl nitrate	1.299	9 to 72	1.1290	4.7915	−1.8413
Ethyl oxalate	1.136	0 to 141	1.06031	1.0983	2.6657

- Mercury
  - a = 0.181690×10^{-3}
  - b = 0.00295×10^{-6}
  - C = 0.0115×10^{-8}

Note: "Coefficient at 20 C" = $a + bT + CT^2$ where T = 20

Table 10-42 (*Continued*)

COEFFICIENTS OF CUBICAL EXPANSION FOR VARIOUS LIQUIDS AND AQUEOUS SOLUTIONS

Liquid	Coef. at 20°C. $\times 10^3$	Range °C.	$a \times 10^3$	$b \times 10^6$	$c \times 10^8$
Ethyl sulfide	1.278	0 to 90	1.19643	1.80653	0.78821
Ethylene chloride	1.161	−28 to 84	1.11893	1.0469	0.10342
Ethylene glycol	0.6375	11 to 136	0.5657	1.7074	0.293
Formic acid	1.025	5 to 104	0.99269	0.62514	0.5965
Glycerol	0.505	....	0.4853	0.4895	....
iso-Hexane	1.445	0 to 55	1.37022	0.97649	2.9819
Hydrochloric acid, 33.2%	0.455	0 to 33	0.4460	0.215	....
4.2%	0.239	0 to 33	0.0652	4.355	....
1.0%	0.211	0 to 32	0.0153	4.899	....
*3.4%, to =110°	......	110 to 140	0.620	4.5	....
Isoprene	1.567	0 to 33	1.4603	0.99793	5.60149
Mercury	......	0 to 100	0.18169041	0.002951266	0.0114562
	......	24 to 299	0.181163	0.01155	0.0021187
Methyl acetate	1.427	0 to 58	1.34982	0.87098	3.5562
Methyl alcohol	1.259	−38 to 70	1.18557	1.56493	0.91113
Methyl benzoate	0.895	0 to 162	0.8633	0.7414	0.15896
Methyl bromide	1.684	−35 to 28	1.41521	3.31528	11.3809
Methyl cyanide	1.301	6 to 66	1.2118	1.7780	1.5322
Methyl ethyl ketone	1.315	0 to 76	1.18654	3.37043	−0.53365
Methyl formate	1.563	0 to 10	1.35824	10.538	−1.8085
Methyl iodide	1.273	5 to 39	1.1440	4.0465	−2.7393
Methyl propionate	1.304	0 to 74	1.3049	−1.3275	4.6943
Methyl sulfide	1.082	0 to 111	1.01705	1.57606	0.19072
Nitrobenzene	......	144 to 164	0.8263	0.52249	0.13779
Olive oil	0.721	....	0.68215	1.14053	−0.539
n-Pentane	1.656	−190 to 30	1.50697	3.435	0.975
iso-Pentane	1.680	0 to 27	1.46834	5.09626	0.6979
Petroleum, sp. gr. 0.8467	0.955	24 to 120	0.8994	1.396	....
Petroleum ether	2.26	−190 to 0	1.46	1.60	....
Phenol	1.090	36 to 157	0.834	0.10732	0.4446
Phosphorus tribromide	0.868	0 to 100	0.8472	0.43672	0.25276
Phosphorus trichloride	1.154	−36 to 75	1.12862	0.87288	1.79236
Phosphorus oxychloride	1.116	0 to 107	1.06431	1.12666	0.5299
Potassium chloride, 24.3%	0.353	16 to 25	0.2695	2.080	....
Propionic acid	1.102	0 to 133	1.0396	1.5487	0.04301
n-Propyl alcohol	0.956	0 to 94,	0.7743	4.9689	−1.4069
iso-Propyl alcohol	1.094	0 to 83	1.04345	0.44303	2.7274
n-Propyl chloride	1.447	0 to 42	1.3306	3.8313	−1.3859
iso-Propyl chloride	1.591	0 to 34	1.3696	5.5287	....
n-Propyl ether	1.354	0 to 88	1.2132	3.9318	−1.3644
iso-Propyl ether	1.452	0 to 67	1.2872	4.2923	−0.58573
Propyl iodide	1.102	10 to 98	1.0276	1.8658	−0.0051
Silicon tetrachloride	1.430	−32 to 59	1.29412	2.18414	4.08642
Sodium acid sulfate, 21%	0.555	0 to 34	0.5364	4.75	....
Sodium chloride, 20.6%	0.414	0 to 29	0.3640	1.237	....
Sodium sulfate,1.9%	0.235	0 to 40	0.0449	4.749	....
24%	0.410	11 to 40	0.3599	1.258	....
Stannic chloride	1.178	−19 to 113	1.1328	0.91171	0.75798
Sulfur chloride	0.968	12 to 111	0.9591	−0.03819	0.73186
Sulfuric acid, conc.	......	0–30	0.5758	−0.864	....
Sulfuric acid 10.9%	0.387	0 to 30	0.2835	2.580	....
5.4%	0.311	0 to 30	0.1450	4.143	....
1.4%	0.234	0 to 30	0.03335	5.025	....
*2.3%, to =100°	......	110 to 140	0.729	2.8	....

Misc

- Water, etc.

Table 10-42 (*Continued*)

COEFFICIENTS OF CUBICAL EXPANSION FOR VARIOUS LIQUIDS AND AQUEOUS SOLUTIONS

Liquid	Coef. at 20°C. $\times 10^3$	Range °C.	$a \times 10^3$	$b \times 10^6$	$c \times 10^8$
*4.5%, to=110°	......	110 to 140	0.648	4.2	....
Thymol	......	62 to 157	0.84369	0.26625	0.35997
Titanium tetrachloride	0.998	−22 to 134	0.94257	1.34579	0.0888
Toluene	1.099	0 to 100	1.028	1.779	....
o-Toluidine	0.847	0 to 141	0.82136	0.6046	0.14696
Trimethyl carbinol	1.023	20 to 77	1.31261	−8.8155	3.61209
n-Valeric acid	1.004	8 to 144	0.97557	0.61852	0.30378
Water (see also below)		−13 to 0	−0.09417	1.449	−59.85
o-Xylene	0.973	16 to 131	0.91734	1.3245	0.19586
m-Xylene	1.009	0 to 141	0.96396	1.0251	0.32753
p-Xylene	1.011	19 to 131	0.97013	0.8714	0.5287

WATER

To find the cubical expansion of water, substitute in the following formulas:

0° to 33°: $Vt = Vo(1 - 0.0_4 64268t + 0.0_5 850526t^2 - 0.0_7 678977t^3 + 0.0_9 401209t^4$

0° to 80°: $Vt = Vo(1 - 0.0_4 53255t + 0.0_5 761532t^2 - 0.0_7 437217t^3 + 0.0_9 164322t^4$

Table 10-43

CUBICAL EXPANSION OF SOLIDS

The coefficient of cubical expansion is the increase in volume per unit volume per degree C. rise in temperature. For ordinary work the assumption may be made that the coefficient of cubical expansion is about three times the coefficient of linear expansion.

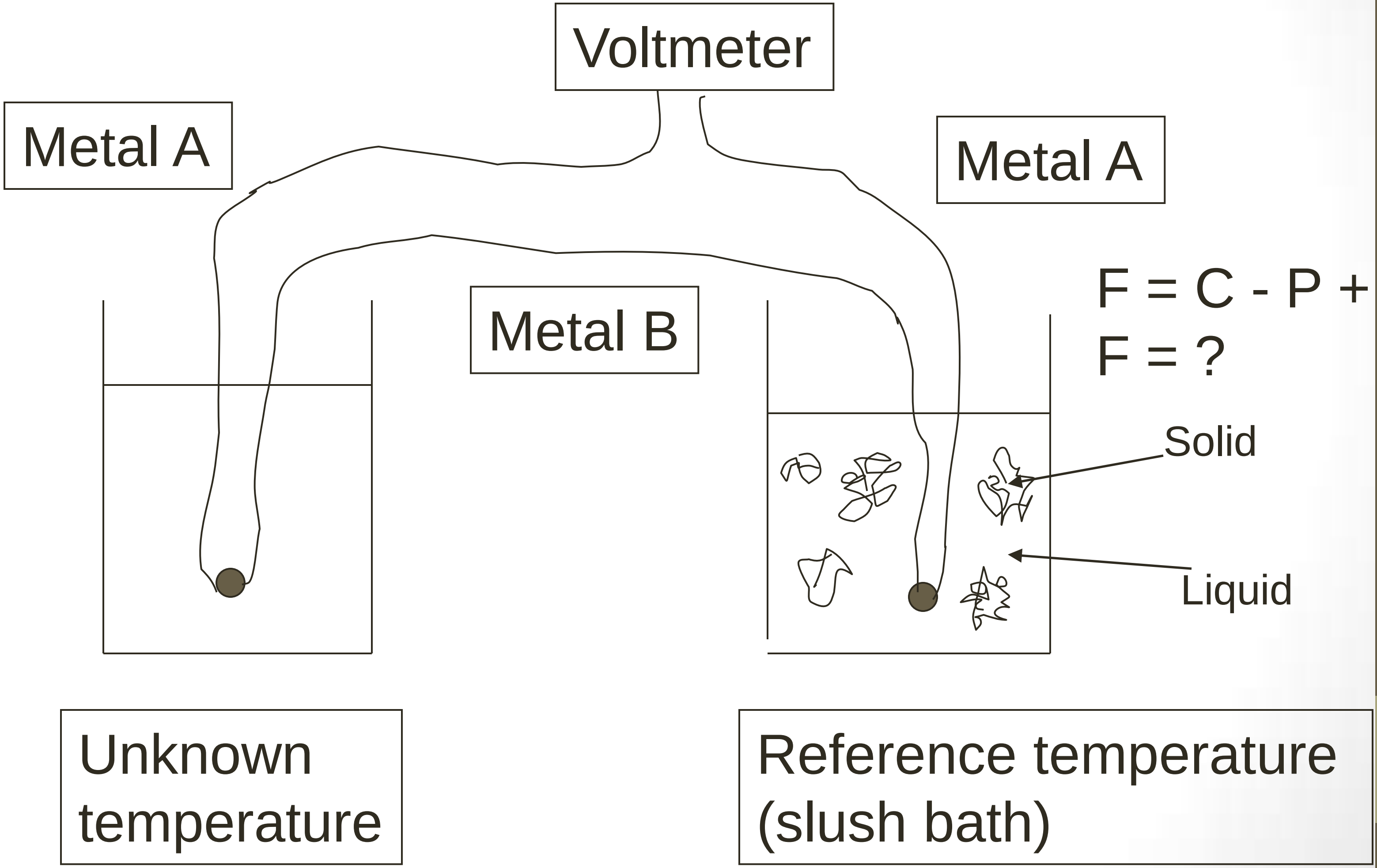
Substance	Temp. °C.	Coef. $\times 10^7$
Antimony	0 to 100	316.7
Beryl	0 to 100	10.5
Bismuth	0 to 100	394.8
Copper	0 to 100	499.8
Diamond	40	35.4
Emerald	40	16.8
Galena	0 to 100	558
Glass, Corning 790	0 to 350	24
" , Corning 774	0 to 350	96
" , Corning 8800	0 to 350	183
" , Jena 59 III	20 to 100	156
" , soda lime tubing	0 to 300	276
Gold	0 to 100	441.1
Ice	−20 to −1	1125.0
Iceland spar	50 to 60	144.7
Iron	0 to 100	355.0
Lead	0 to 100	839.9

Substance	Temp. °C.	Coef. $\times 10^7$
Paraffin	20	5880
Platinum	0 to 100	265
Porcelain	0 to 100	108.0
" , Berlin	20	81.4
Potassium chloride	0 to 100	1094
" nitrate	0 to 100	1967
" sulfate	20	1075.4
Quartz	0 to 100	384
Rock salt	50 to 60	1212.0
Rubber	20	4870
Silver	0 to 100	583.1
Sodium	20	2136.4
Stearic acid	33.8 to 45.5	8100
Sulfur, native	13.2 to 50.3	2230
Tin	0 to 100	688.9
Zinc	0 to 100	892.8

Thermocouples

- Seebeck Effect
  - Any conductor subjected to a temperature gradient generates a potential difference
  - Measuring potential difference requires attaching leads and a voltmeter
  - Completing circuit means no net potential difference around the circuit
  - How to get useful information?

Typical Thermocouple Configuration



$F = C - P + 2$

$F = ?$

Thermocouple types

Type K (chromel–alumel) is the most common general purpose thermocouple. It is inexpensive available in a wide variety of probes. They are available in the −200 °C to +1350 °C range. The type K was specified at a time when metallurgy was less advanced than it is today and, consequently, characteristics vary considerably between examples. Another potential problem arises in some situations since one of the constituent metals, nickel, is magnetic. One characteristic of thermocouples made with magnetic material is that they undergo a step change when the magnetic material reaches its Curie point. This occurs for this thermocouple at 354 °C. Sensitivity is approximately 41 µV/°

Thermocouple types

- Type E (chromel–constantan)[4] has a high output (68 µV/°C) which makes it well suited to cryogenic use. Additionally, it is non-magnetic.

- Type J (iron–constantan) is less popular than type K due to its limited range (−40 to +750 °C). The Curie point of the iron (770 °C) causes an abrupt change to the characteristic and it is this that provides the upper temperature limit. Type J thermocouples have a sensitivity of about 50 µV/°C.[3]

Thermocouple types

- **B, R, and S**
- Types B, R, and S thermocouples use platinum or a platinum–rhodium alloy for each conductor. These are among the most stable thermocouples, but have lower sensitivity, approximately 10 µV/°C, than other types. The high cost of these makes them unsuitable for general use. Generally, type B, R, and S thermocouples are used only for high temperature measurements.
- Type S thermocouples use a platinum–rhodium alloy containing 10% rhodium for one conductor and pure platinum for the other conductor. Like type R, type S thermocouples are used up to 1600 °C. In particular, type S is used as the standard of calibration for the melting point of gold (1064.43 °C)

Thermocouple types

- **Chromel-gold/iron**
- In chromel-gold/iron thermocouples, the positive wire is chromel and the negative wire is gold with a small fraction (0.03–0.15 atom percent) of iron. It can be used for cryogenic applications (1.2–300 K and even up to 600 K). Both the sensitivity and the temperature range depends on the iron concentration. The sensitivity is typically around 15 µV/K at low temperatures and the lowest usable temperature varies between 1.2 and 4.2 K

Resistive Temperature Detectors

- What is a platinum RTD?
- Basically nothing but a coil of very thin platinum wire whose resistance is 100 ohms at room temperature
- $R = R_0(1 + AT + BT^2)$ $T > 0$ C
  - R_0 = 100 ohms
  - $A = 3.9083 \times 10^{-3}\ C^{-1}$
  - $B = -5.775 \times 10^{-7}\ C^{-2}$

Resistive Temperature Detectors

- **Why use an RTD instead of a thermocouple or thermistor sensor?**
  Each type of temperature sensor has a particular set of conditions for which it is best suited. RTDs offer several advantages:
  - A wide temperature range (approximately -200 to 850°C)
  - Good accuracy (better than thermocouples)
  - Good interchangeability
  - Long-term stability

RTD standards

- Two standards for platinum RTDs:
  - European standard (also known as the DIN or IEC standard)
  - American standard.
- The **European standard** is considered the world-wide standard for platinum RTDs.

  -Requires the RTD to have an electrical resistance of 100.00 Ω at 0°C

  -Requires a temperature coefficient of resistance (TCR) of 0.00385 Ω/Ω/°C between 0 and 100°C.
- Two resistance tolerances specified
  - Class A = ±(0.15 + 0.002*t)°C or 100.00 ±0.06 Ω at 0ºC
  - Class B = ±(0.3 + 0.005*t)°C or 100.00 ±0.12 Ω at 0ºC

Thin Film

Thin-film RTD elements are produced by depositing a thin layer of platinum onto a substrate.

- A pattern is then created that provides an electrical circuit that is trimmed to provide a specific resistance.
- Lead wires are then attached and the element coated to protect the platinum film and wire connections.

OMEGA's F2020, 100 Ω, Class "A" thin-film element, see page C-85.

Wire wound RTDs

- Two types of wire-wound elements:
  - those with coils of wire packaged inside a ceramic or glass tube (the most commonly used wire-wound construction),
  - those wound around a glass or ceramic core and covered with additional glass or ceramic material (used in more specialized applications).


Typical wire-wound RTD element

Thermistors

- Thermistors differ from resistance temperature detectors in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals.
- The temperature response is also different; RTDs are useful over larger temperature ranges.

Steinhart-Hart Equation

$$\frac{1}{T} = a + b\,\ln(R) + c\,\ln^3(R)$$

- *a*, *b* and *c* are called the Steinhart-Hart parameters, and must be specified for each device.
- *T* is the temperature in Kelvin .
- *R* is the resistance in Ohms.
- The error in the Steinhart-Hart equation is generally less than 0.02°C in the measurement of temperature.

B Parameter Equation

- NTC thermistors can also be characterised with the *B* parameter equation, which is essentially the Steinhart Hart equation with *c=0*

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B} \ln\left(\frac{R}{R_0}\right)$$

Thermistors

- Many NTC thermistors are made from a pressed disc or cast chip of a semiconductor such as a sintered metal oxide.
- Most PTC thermistors are of the "switching" type, which means that their resistance rises suddenly at a certain critical temperature. The devices are made of a doped polycrystalline ceramic containing barium titanate (BaTiO3) and other compounds.

Self-heating in Thermistors

- $P_{in} = IV = V^2/R = I^2R$
- $P_{out} = K(T_R - T_{amb})$ Newton's Law of Cooling
- In thermal equilibrium $P_{in} = P_{out}$
- $V^2/R = K(T_R - T_{amb})$
- $T_R = T_{amb} + V^2/KR = T_{amb} + I^2R/K$
- Hence temperature read by device depends on how much current you feed into it to read its resistance.
- Uncertainty principle!

Terms Characterizing Thermistor Performance

- **DISSIPATION CONSTANT**
  The ratio, (expressed in milliwatts per degree C) at a specified ambient temperature, of a change in power dissipation in a thermistor to the resultant body temperature change.
- Why is this relevant?
- When is it important?

Terms Characterizing Thermistor Performance

- **THERMAL TIME CONSTANT**
  The time required for a thermistor to change 63.2% of the total difference between its initial and final body temperature when subjected to a step function change in temperature under zero-power conditions.
- Why is this relevant?
- When is it important?

Terms Characterizing Thermistor Performance

- **RESISTANCE RATIO CHARACTERISTIC**
  The resistance ratio characteristic identifies the ratio of the zero-power resistance of a thermistor measured at 25°C to that resistance measured at 125°C

Thermistors: Applications

- Thermometry!
- PTC thermistors can be used as current-limiting devices for circuit protection, as fuses.
- Current through the device causes a small amount of resistive heating.
- If the current is large enough to generate more heat than the device can lose to its surroundings, the device heats up, causing its resistance to increase, and therefore causing even more heating. This positive feedback drives the resistance upwards, reducing the current and voltage available to the device.

Thermistors: Applications

- NTC thermistors are used as resistance thermometers in low-temperature measurements of the order of 10 K.
- NTC thermistors can be used as inrush-current limiting devices in power supply circuits.

143-502LAG-RC1 NTC Thermistor

- **Manufacturer:** HONEYWELL S&C / FENWALL
- **Newark Part Number:** 30F1712
- **Manufacturer Part No:** 143-502LAG-RC1.
- RoHS Compliance : **No**
- **Description**
- NTC Thermistor
- Resistance: 5 kohm (at “room temperature”)
- Thermistor Tolerance: ± 10%
- Dissipation Constant: 7mW/°C
- Leaded Process Compatible: No
- Mounting Type: Through Hole
- Peak Reflow Compatible (260 C): No
- Resistance Ratio: 9
- RoHS Compliant: No

Temperature Control
(A Wholly Owned Subsidiary of "Process Control")

- Why is this important?
- Good science requires that to correlate cause and effect, all other parameters must remain constant as only one parameter is changed and another observed.
- "Process controls" are required to keep parameters constant.
- "Process controls" also allow one parameter to be changed in a defined controlled manner.

Terminology

- Controller (temperature): A device that makes continuous operator attention and input unnecessary.
- Examples
  - Cruise control on car
  - Fill valve in your toilet tank
  - Thermostat in your house
    - This is an example of one simple type of temperature controller: “On-off”
    - Contrast with “temperature controller” on your [gas] barbeque!

Terminology

- Set Point: the desired temperature that you want in your system
- Error: difference between set point and actual temperature in your system
  - Error = Set Point - Measurement

Specific Example

- You want to control the temperature of a furnace.
- n.b.: you actually control the current fed into the heating coils or windings
- Example works for any general process control with feedback

PID Control

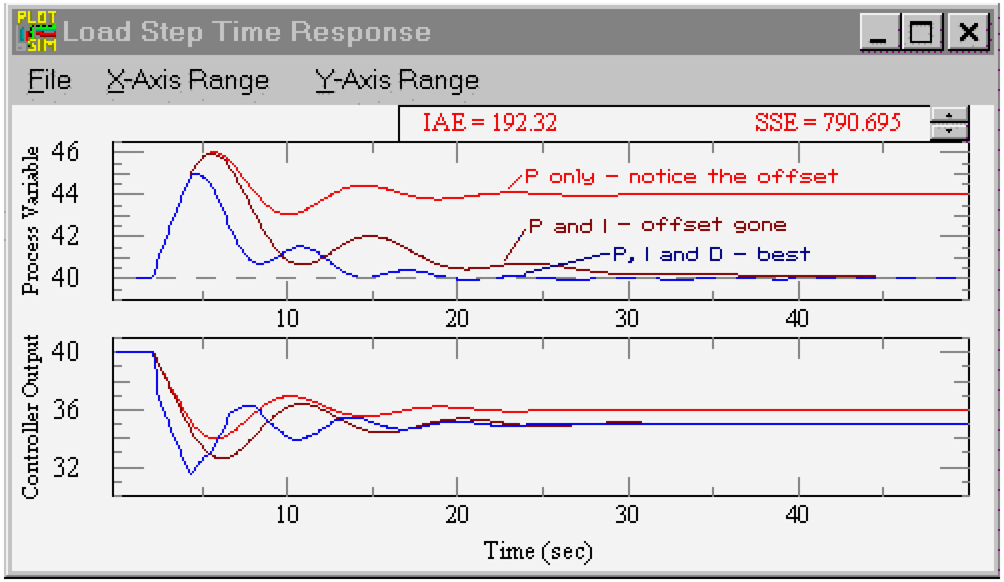
- P = Proportional
  - Power output is proportional to error signal
    = 100/Gain

  Gain? Gain = ratio of output change to error
- I = Integral
  - If output is proportional to error, what is output when there is no error?
  - Corrects for “droop”
  - Also known as reset
  - Basically an offset to confuse the controller
- D = Derivative
  - Related to slope of error signal
  - Also known as rate

PID Control

- Proportional band: Size of error within which output is proportional to error signal
  - If signal is below proportional band, supply gives full output
  - If signal is above proportional band, supply shuts off completely
  - If proportional band is too wide, control is poor
  - If proportional band is too narrow, system will oscillate
  - Various schemes for proportioning power input to furnace

Effects of Tuning Parameters



Adjusting PID Parameters

- http://www.omega.com/temperature/Z/pdf/z115-117.pdf
- http://www.expertune.com/tutor.html
- Old-fashioned
  - plot TC output on a chart recorder.
  - Balance TC approximate output with precisely adjusted voltage
  - Observe change in system temperature when set point has changed
- Modern old-fashioned
  - Use $130 Omega A/D converter to enter TC data into computer
- Truly modern solution
  - But auto-tuning controller