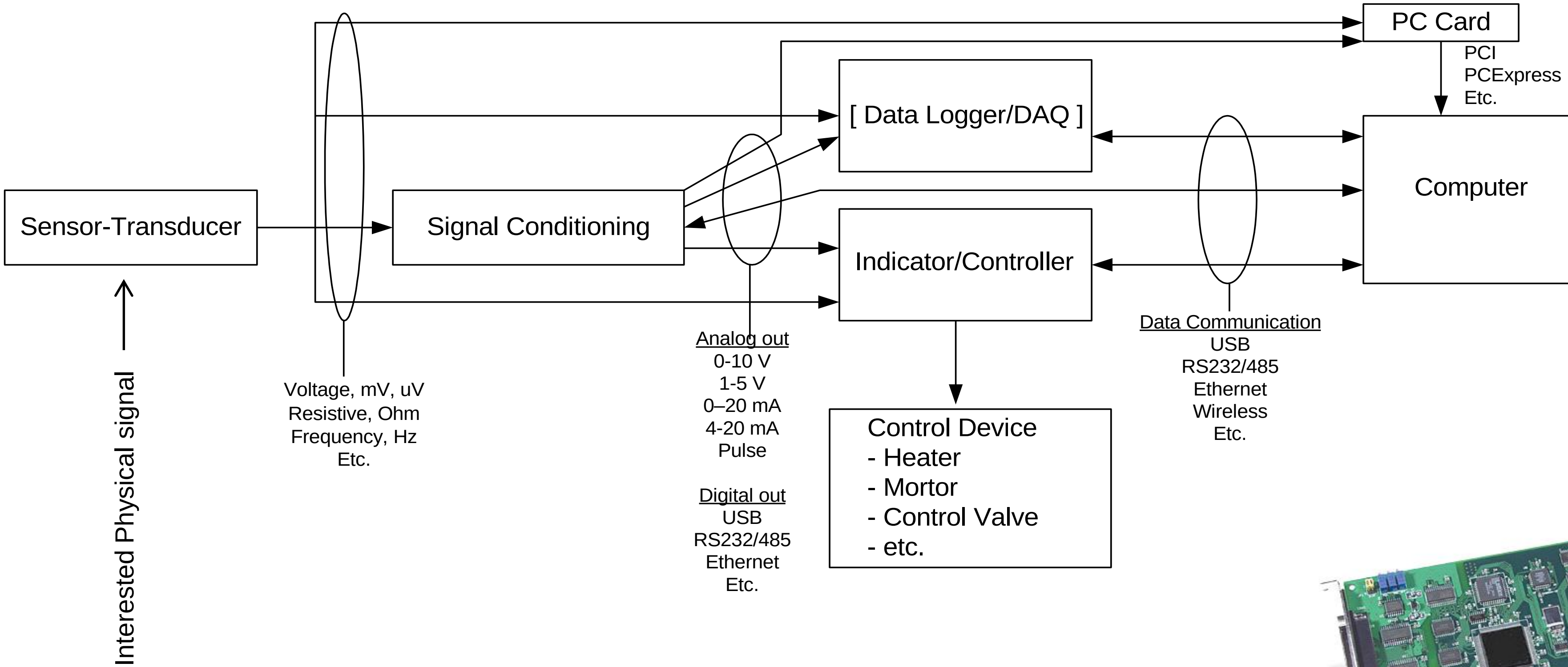
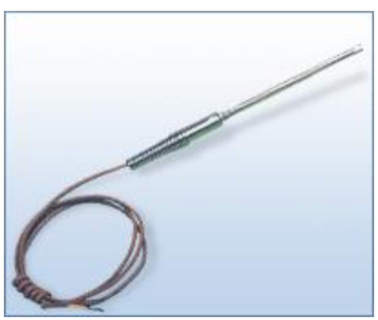
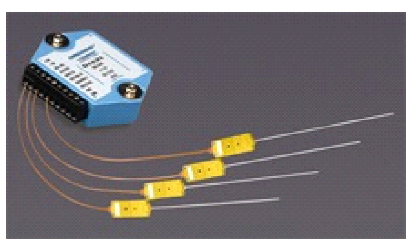
Measurement





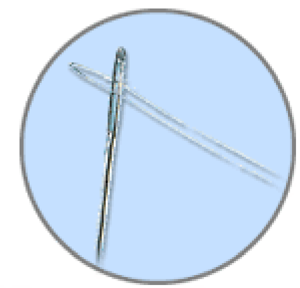


IPTS-68 REFERENCE TEMPERATURES

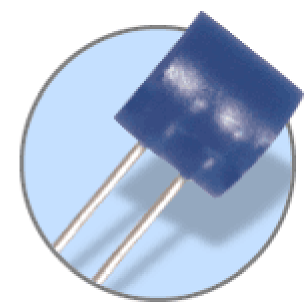
EQUILIBRIUM POINT	K	⁰C
Triple Point of Hydrogen	13.81	-259.34
Liquid/Vapor Phase of Hydrogen at 25/76 Std. Atmosphere	17.042	-256.108
Boiling Point of Hydrogen	20.28	-252.87
Boiling Point of Neon	27.102	-246.048
Triple Point of Oxygen	54.361	-218.789
Boiling Point of Oxygen	90.188	-182.962
Triple Point of Water	273.16	0.01
Boiling Point of Water	373.15	100
Freezing Point of Zinc	692.73	419.58
Freezing Point of Silver	1235.08	961.93
Freezing Point of Gold	1337.58	1064.43

Temperature Measurement Sensors

Thermocouple Temperature Measurement Sensors
Thermocouples consist essentially of two strips or wires made of different metals and joined at one end. Changes in the temperature at that juncture induce a change in electromotive force (emf) between the other ends. As temperature goes up, this output emf of the thermocouple rises, though not necessarily linearly.


SH Temperature Measurement Sensors

Resistance Temperature Devices(RTD)
Resistive temperature devices capitalize on the fact that the electrical resistance of a material changes as its temperature changes. Two key types are the metallic devices (commonly referred to as RTDs), and thermistors. As their name indicates, RTDs rely on resistance change in a metal, with the resistance rising more or less linearly with temperature. Thermistors are based on resistance change in a ceramic semiconductor; the resistance drops nonlinearly with temperature rise.

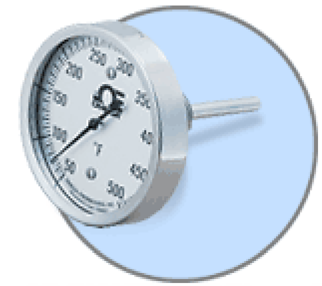

Thin Film Platinum RTD Elements

Infrared Temperature Measurement Devices
Infrared sensors are noncontacting devices. They infer temperature by measuring the thermal radiation emitted by a material.


OS530 Series IR Measurement Device

Bimetallic Temperature Measurement Devices

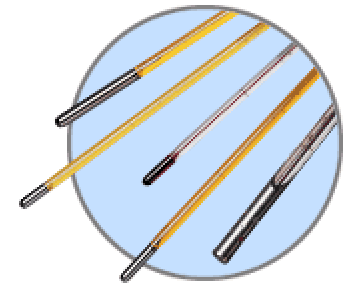
Bimetallic devices take advantage of the difference in rate of thermal expansion between different metals. Strips of two metals are bonded together. When heated, one side will expand more than the other, and the resulting bending is translated into a temperature reading by mechanical linkage to a pointer. These devices are portable and they do not require a power supply, but they are usually not as accurate as thermocouples or RTDs and they do not readily lend themselves to temperature recording.



AR DIALTEMP™ Bimetalic Temperature Measurement

Fluid-Expansion Temperature Measurement Devices

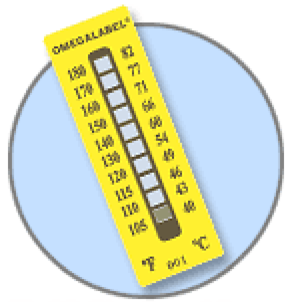
Fluid-expansion devices, typified by the household thermometer, generally come in two main classifications: the mercury type and the organic-liquid type. Versions employing gas instead of liquid are also available. Mercury is considered an environmental hazard, so there are regulations governing the shipment of devices that contain it. Fluid-expansion sensors do not require electric power, do not pose explosion hazards, and are stable even after repeated cycling. On the other hand, they do not generate data that is easily recorded or transmitted, and they cannot make spot or point measurements.



GT-736000 Series Glass-Bulb Thermometers

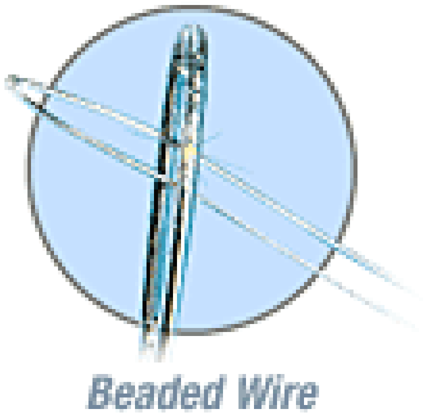
Change-of-State Temperature Measurement Devices

Change-of-state temperature sensors consist of labels, pellets, crayons, lacquers or liquid crystals whose appearance changes once a certain temperature is reached. They are used, for instance, with steam traps - when a trap exceeds a certain temperature, a white dot on a sensor label attached to the trap will turn black. Response time typically takes minutes, so these devices often do not respond to transient temperature changes. And accuracy is lower than with other types of sensors. Furthermore, the change in state is irreversible, except in the case of liquid-crystal displays. Even so, change-of-state sensors can be handy when one needs confirmation that the temperature of a piece of equipment or a material has not exceeded a certain level, for instance for technical or legal reasons during product shipment.

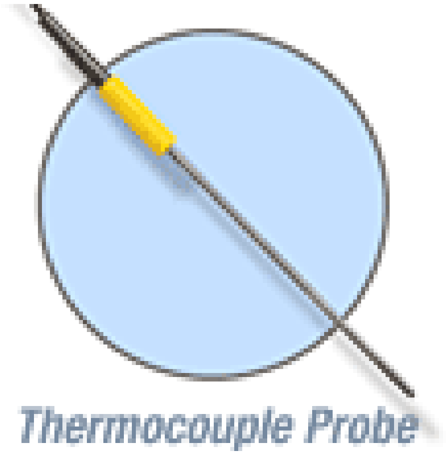


TL-10 Change-of-State Temperature Measurement

Thermocouple

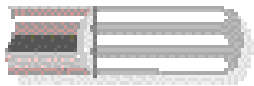


Beaded Wire Thermocouple
A beaded wire thermocouple is the simplest form of thermocouple. It consists of two pieces of thermocouple wire joined together with a welded bead. Because the bead of the thermocouple is exposed, there are several application limitations. The beaded wire thermocouple should not be used with liquids that could corrode or oxidize the thermocouple alloy. Metal surfaces can also be problematic. Often metal surfaces, especially pipes are used to ground electrical systems The indirect connection to an electrical system could impact the thermocouple measurement. In general, beaded wire thermocouples are a good choice for the measurement of gas temperature. Since they can be made very small, they also provide very fast response time.

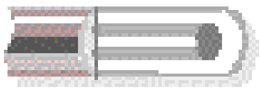


Thermocouple Probe
A thermocouple probe consists of thermocouple wire housed inside a metallic tube. The wall of the tube is referred to as the sheath of the probe. Common sheath materials include stainless steel and Inconel. Inconel supports higher temperature ranges than stainless steel, however, stainless steel is often preferred because of its broad chemical compatibility. For very high temperatures, other exotic sheath materials are also available. View our line of high temperature exotic thermocouple probes.
The tip of the thermocouple probe is available in three different styles. Grounded, ungrounded and exposed. With a grounded tip the thermocouple is in contact with the sheath wall. A grounded junction provides a fast response time but it is most susceptible to electrical ground loops. In ungrounded junctions, the thermocouple is separated from the sheath wall by a layer of insulation. The tip of the thermocouple protrudes outside the sheath wall with an exposed junction. Exposed junction thermocouples are best suited for air measurement.

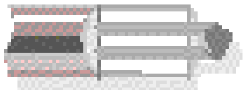
Thermocouple Tip Styles



Grounded Thermocouple

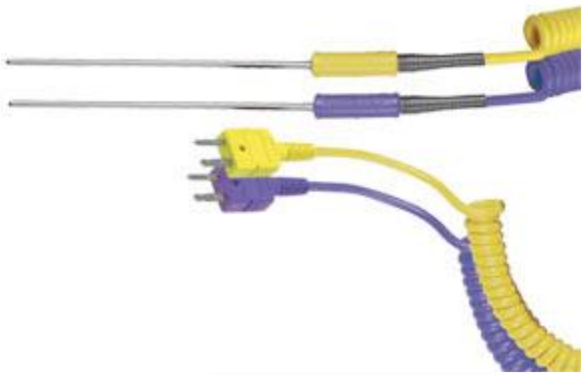


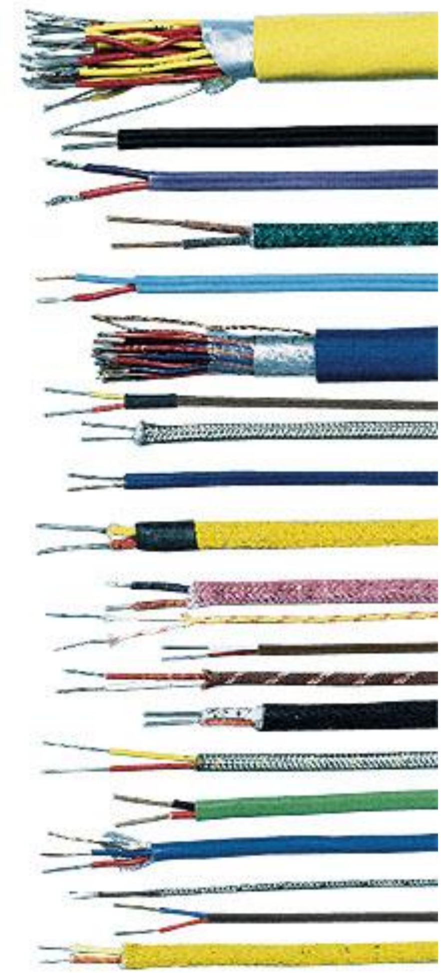
Ungrounded Thermocouple

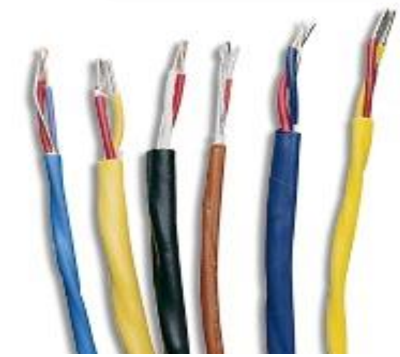


Exposed Thermocouple

Thermocouple แบบ Probe และ แบบสาย ต่างๆ







Common Thermocouple Temperature Ranges

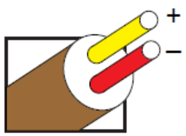
Calibration	Temp Range	Std. Limits of Error	Spec. Limits of Error
J	0°C to 750°C (32°F to 1382°F)	Greater of 2.2°C or 0.75%	Greater of 1.1°C or 0.4%
K	–200°C to 1250°C (–328°F to 2282°F)	Greater of 2.2°C or 0.75%	Greater of 1.1°C or 0.4%
E	–200°C to 900°C (–328°F to 1652°F)	Greater of 1.7°C or 0.5%	Greater of 1.0°C or 0.4%
T	–250°C to 350°C (–328°F to 662°F)	Greater of 1.0°C or 0.75%	Greater of 0.5°C or 0.4%

Thermocouple

Revised Thermocouple Reference Tables

TYPE K

Reference Tables N.I.S.T. Monograph 175 Revised to ITS-90



Thermocouple Grade

Nickel-Chromium vs. Nickel-Aluminum

Extension Grade

MAXIMUM TEMPERATURE RANGE

Thermocouple Grade
– 328 to 2282°F
– 200 to 1250°C

Extension Grade
32 to 392°F
0 to 200°C

LIMITS OF ERROR
(whichever is greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%

COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration

TEMPERATURE IN DEGREES °C
REFERENCE JUNCTION AT 0°C

Thermoelectric Voltage in Millivolts

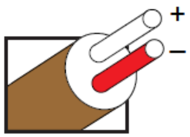
°C	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°C
-90	-3.554	-3.523	-3.492	-3.462	-3.431	-3.400	-3.368	-3.337	-3.306	-3.274	-3.243	-90
-80	-3.243	-3.211	-3.179	-3.147	-3.115	-3.083	-3.050	-3.018	-2.986	-2.953	-2.920	-80
-70	-2.920	-2.887	-2.854	-2.821	-2.788	-2.755	-2.721	-2.688	-2.654	-2.620	-2.587	-70
-60	-2.587	-2.553	-2.519	-2.485	-2.450	-2.416	-2.382	-2.347	-2.312	-2.278	-2.243	-60
-50	-2.243	-2.208	-2.173	-2.138	-2.103	-2.067	-2.032	-1.996	-1.961	-1.925	-1.889	-50
-40	-1.889	-1.854	-1.818	-1.782	-1.745	-1.709	-1.673	-1.637	-1.600	-1.564	-1.527	-40
-30	-1.527	-1.490	-1.453	-1.417	-1.380	-1.343	-1.305	-1.268	-1.231	-1.194	-1.156	-30
-20	-1.156	-1.119	-1.081	-1.043	-1.006	-0.968	-0.930	-0.892	-0.854	-0.816	-0.778	-20
-10	-0.778	-0.739	-0.701	-0.663	-0.624	-0.586	-0.547	-0.508	-0.470	-0.431	-0.392	-10
0	-0.392	-0.353	-0.314	-0.275	-0.236	-0.197	-0.157	-0.118	-0.079	-0.039	0.000	0
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240

Thermocouple

Revised Thermocouple Reference Tables

TYPE J

Reference Tables
N.I.S.T. Monograph 175
Revised to ITS-90



Thermocouple Grade

Iron vs. Copper-Nickel

Extension Grade

MAXIMUM TEMPERATURE RANGE

Thermocouple Grade
32 to 1382°F
0 to 750°C

Extension Grade
32 to 392°F
0 to 200°C

LIMITS OF ERROR
(whichever is greater)
Standard: 2.2°C or 0.75%
Special: 1.1°C or 0.4%

COMMENTS, BARE WIRE ENVIRONMENT:
Reducing, Vacuum, Inert; Limited Use in Oxidizing at High Temperatures;
Not Recommended for Low Temperatures

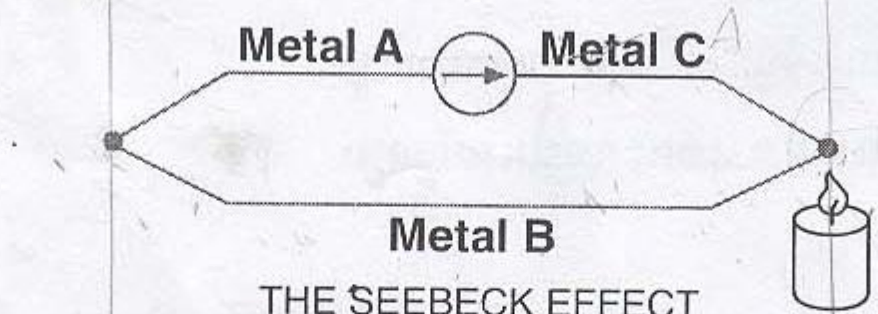
TEMPERATURE IN DEGREES °C
REFERENCE JUNCTION AT 0°C

Thermoelectric Voltage in Millivolts

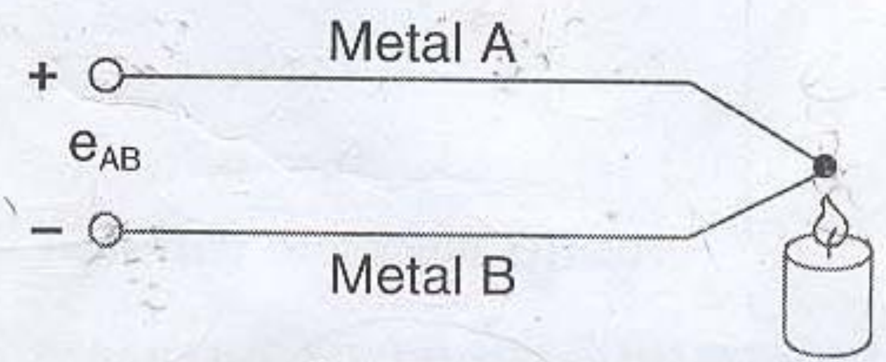
°C	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°C
-200	-8.095	-8.076	-8.057	-8.037	-8.017	-7.996	-7.976	-7.955	-7.934	-7.912	-7.890	-200
-190	-7.890	-7.868	-7.846	-7.824	-7.801	-7.778	-7.755	-7.731	-7.707	-7.683	-7.659	-190
-180	-7.659	-7.634	-7.610	-7.585	-7.559	-7.534	-7.508	-7.482	-7.456	-7.429	-7.403	-180
-170	-7.403	-7.376	-7.348	-7.321	-7.293	-7.265	-7.237	-7.209	-7.181	-7.152	-7.123	-170
-160	-7.123	-7.094	-7.064	-7.035	-7.005	-6.975	-6.944	-6.914	-6.883	-6.853	-6.821	-160
-150	-6.821	-6.790	-6.759	-6.727	-6.695	-6.663	-6.631	-6.598	-6.566	-6.533	-6.500	-150
-140	-6.500	-6.467	-6.433	-6.400	-6.366	-6.332	-6.298	-6.263	-6.229	-6.194	-6.159	-140
-130	-6.159	-6.124	-6.089	-6.054	-6.018	-5.982	-5.946	-5.910	-5.874	-5.838	-5.801	-130
-120	-5.801	-5.764	-5.727	-5.690	-5.653	-5.616	-5.578	-5.541	-5.503	-5.465	-5.426	-120
-110	-5.426	-5.388	-5.350	-5.311	-5.272	-5.233	-5.194	-5.155	-5.116	-5.076	-5.037	-110
-100	-5.037	-4.997	-4.957	-4.917	-4.877	-4.836	-4.796	-4.755	-4.714	-4.674	-4.633	-100
-90	-4.633	-4.591	-4.550	-4.509	-4.467	-4.425	-4.384	-4.342	-4.300	-4.257	-4.215	-90
-80	-4.215	-4.173	-4.130	-4.088	-4.045	-4.002	-3.959	-3.916	-3.872	-3.829	-3.786	-80
-70	-3.786	-3.742	-3.698	-3.654	-3.610	-3.566	-3.522	-3.478	-3.434	-3.389	-3.344	-70
-60	-3.344	-3.300	-3.255	-3.210	-3.165	-3.120	-3.075	-3.029	-2.984	-2.938	-2.893	-60
-50	-2.893	-2.847	-2.801	-2.755	-2.709	-2.663	-2.617	-2.571	-2.524	-2.478	-2.431	-50
-40	-2.431	-2.385	-2.338	-2.291	-2.244	-2.197	-2.150	-2.103	-2.055	-2.008	-1.961	-40
-30	-1.961	-1.913	-1.865	-1.818	-1.770	-1.722	-1.674	-1.626	-1.578	-1.530	-1.482	-30
-20	-1.482	-1.433	-1.385	-1.336	-1.288	-1.239	-1.190	-1.142	-1.093	-1.044	-0.995	-20
-10	-0.995	-0.946	-0.896	-0.847	-0.798	-0.749	-0.699	-0.650	-0.600	-0.550	-0.501	-10
0	-0.501	-0.451	-0.401	-0.351	-0.301	-0.251	-0.201	-0.151	-0.101	-0.050	0.000	0
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507	0
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019	10
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537	20
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059	30
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585	40
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116	50
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650	60
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187	70
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726	80
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269	90
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814	100
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360	110
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909	120
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459	130
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010	140
150	8.010	8.065	8.120	8.175	8.231	8.286	8.341	8.396	8.452	8.507	8.562	150
160	8.562	8.618	8.673	8.728	8.783	8.839	8.894	8.949	9.005	9.060	9.115	160
170	9.115	9.171	9.226	9.282	9.337	9.392	9.448	9.503	9.559	9.614	9.669	170
180	9.669	9.725	9.780	9.836	9.891	9.947	10.002	10.057	10.113	10.168	10.224	180
190	10.224	10.279	10.335	10.390	10.446	10.501	10.557	10.612	10.668	10.723	10.779	190

Thermocouple

When two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, there is a continuous current which flows in the *thermoelectric* circuit. Thomas Seebeck made this discovery in 1821.



THE SEEBECK EFFECT



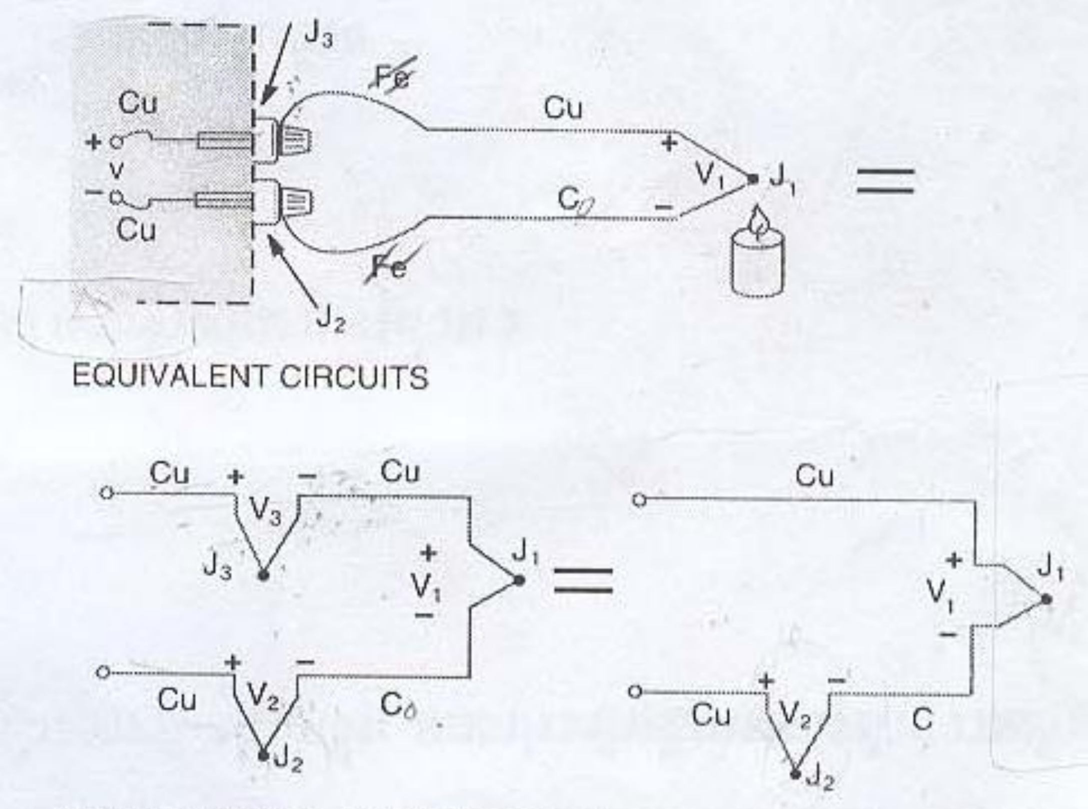
e_{AB} = SEEBECK VOLTAGE

Thermocouple

For small changes in temperature the Seebeck voltage is linearly proportional to temperature:

$$\Delta e_{AB} = \alpha \Delta T$$

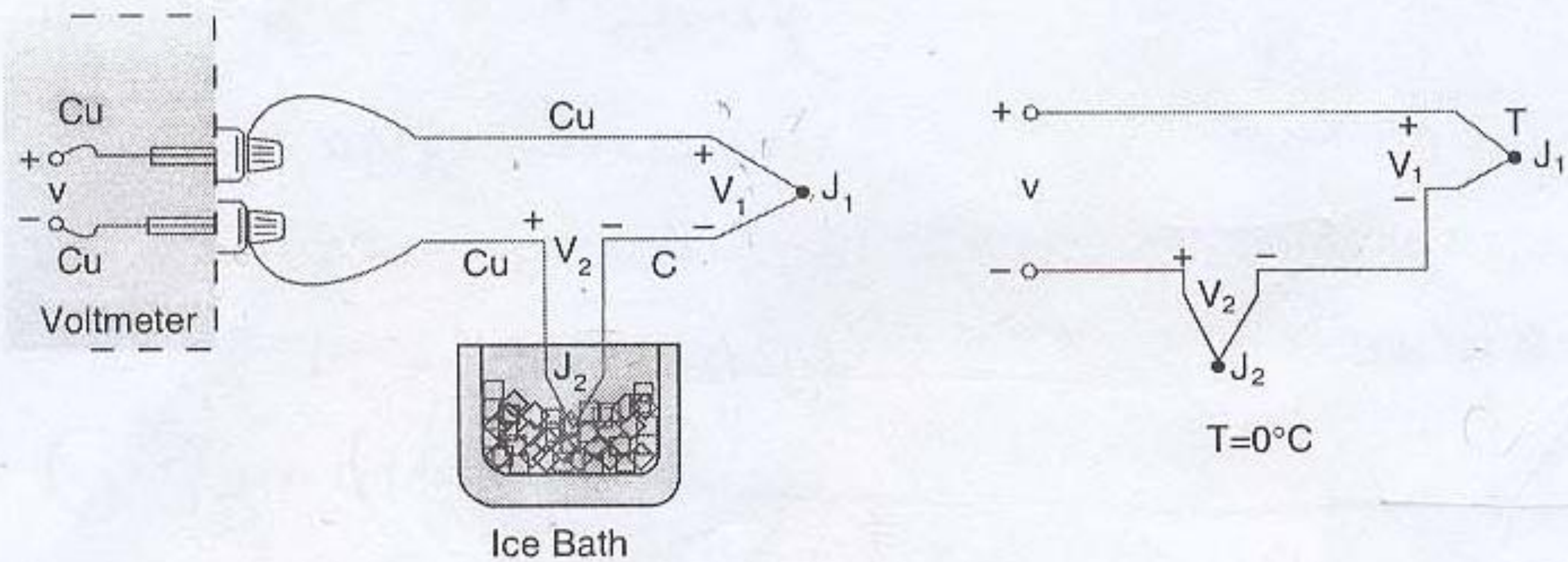
Where α, the Seebeck coefficient, is the constant of proportionality.



MEASURING JUNCTION VOLTAGE WITH A DVM

Thermocouple

The Reference Junction



EXTERNAL REFERENCE JUNCTION

Now the voltmeter reading is (see Figure 5):

$$V = (V_1 - V_2) \cong \alpha(t_{J_1} - t_{J_2})$$

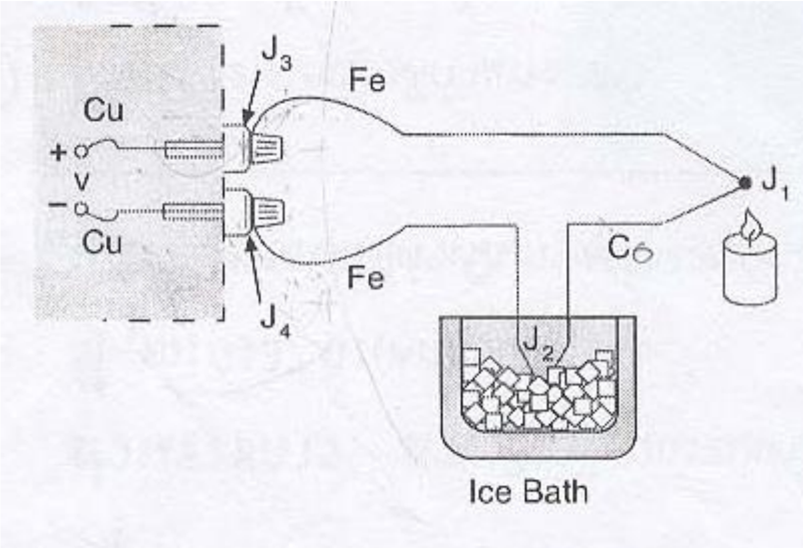
If we specify T_{J_1} in degrees Celsius:

$$T_{J_1}\,(^\circ C) + 273.15 = t_{J_1}$$

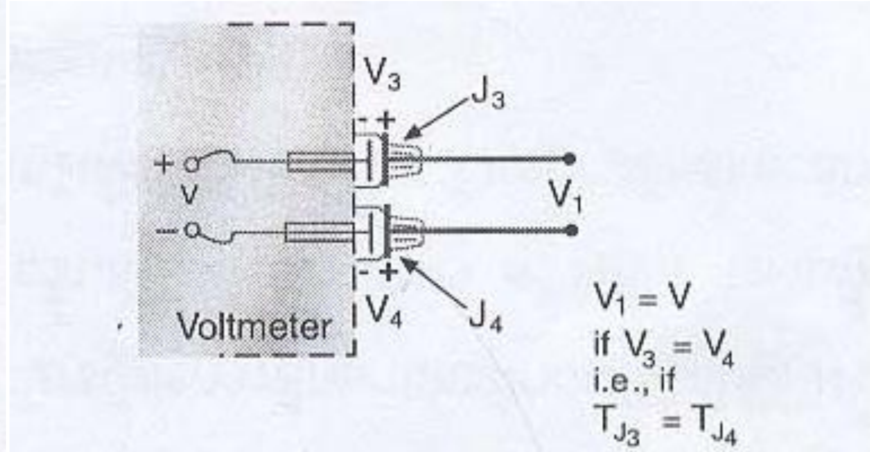
then V becomes:

$$V = V_1 - V_2 = \alpha\,[(T_{J_1} + 273.15) - (T_{J_2} + 273.15)]$$
$$= \alpha\,(T_{J_1} - T_{J_2}) = \alpha\,(T_{J_1} - 0)$$
$$V = \alpha T_{J_1}$$

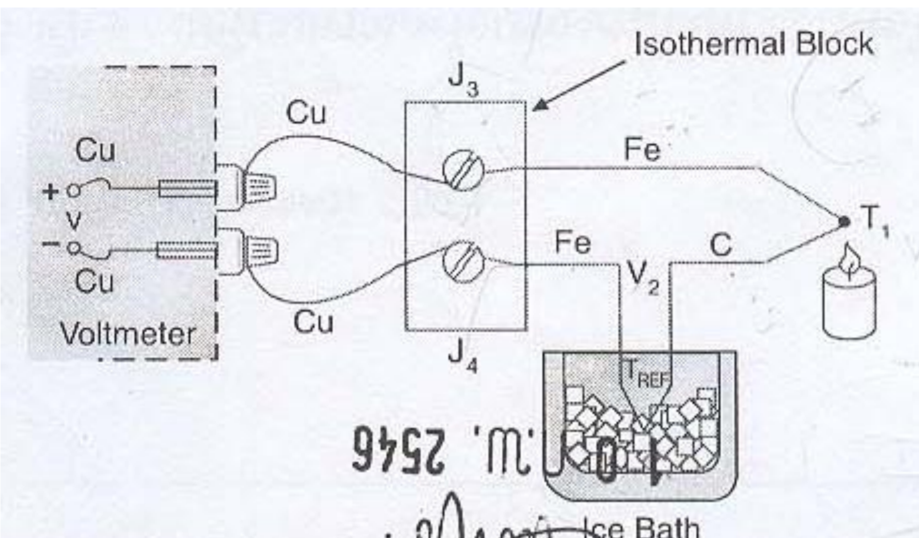
Thermocouple



IRON-CONSTANTAN COUPLE

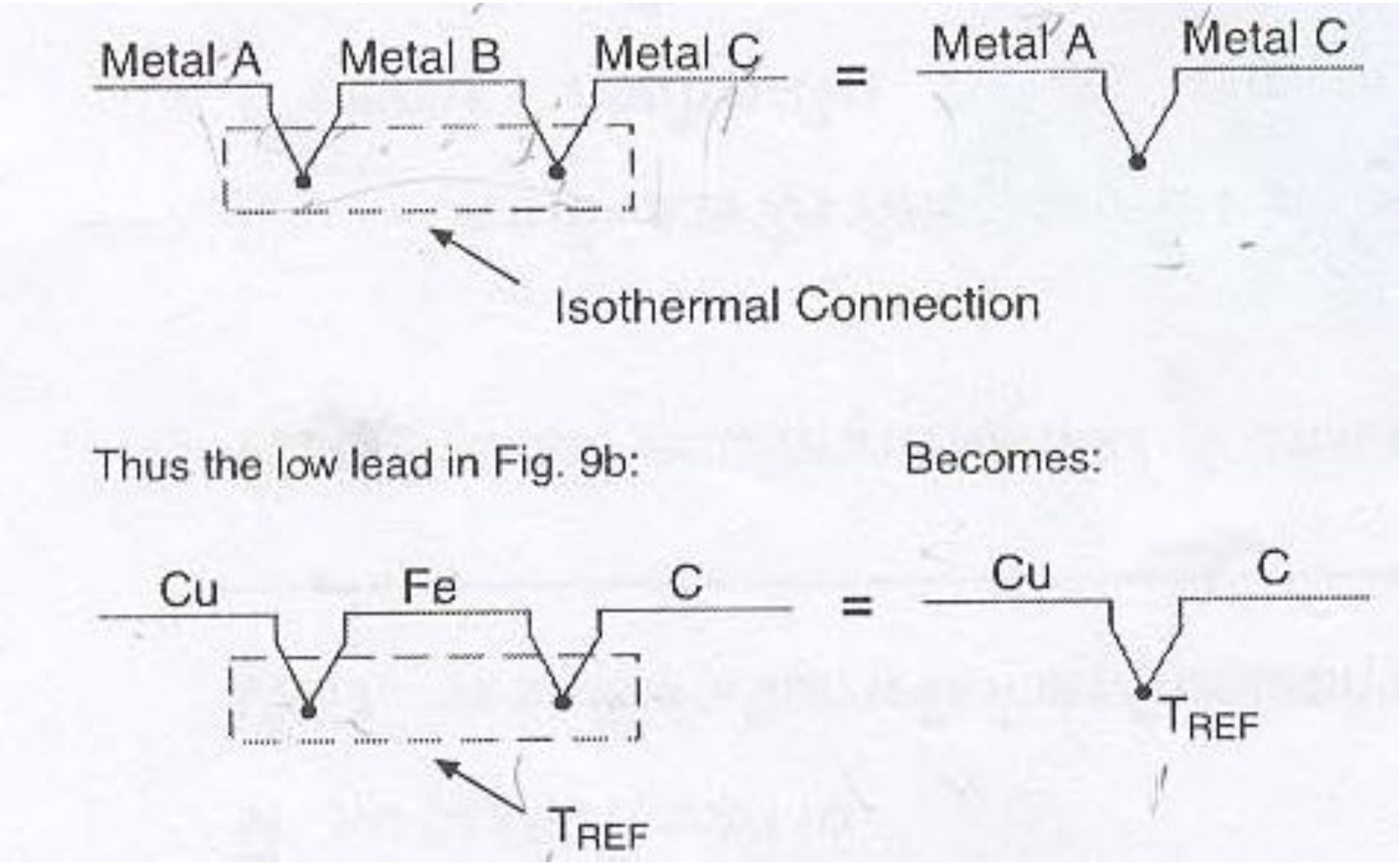


JUNCTION VOLTAGE CANCELLATION



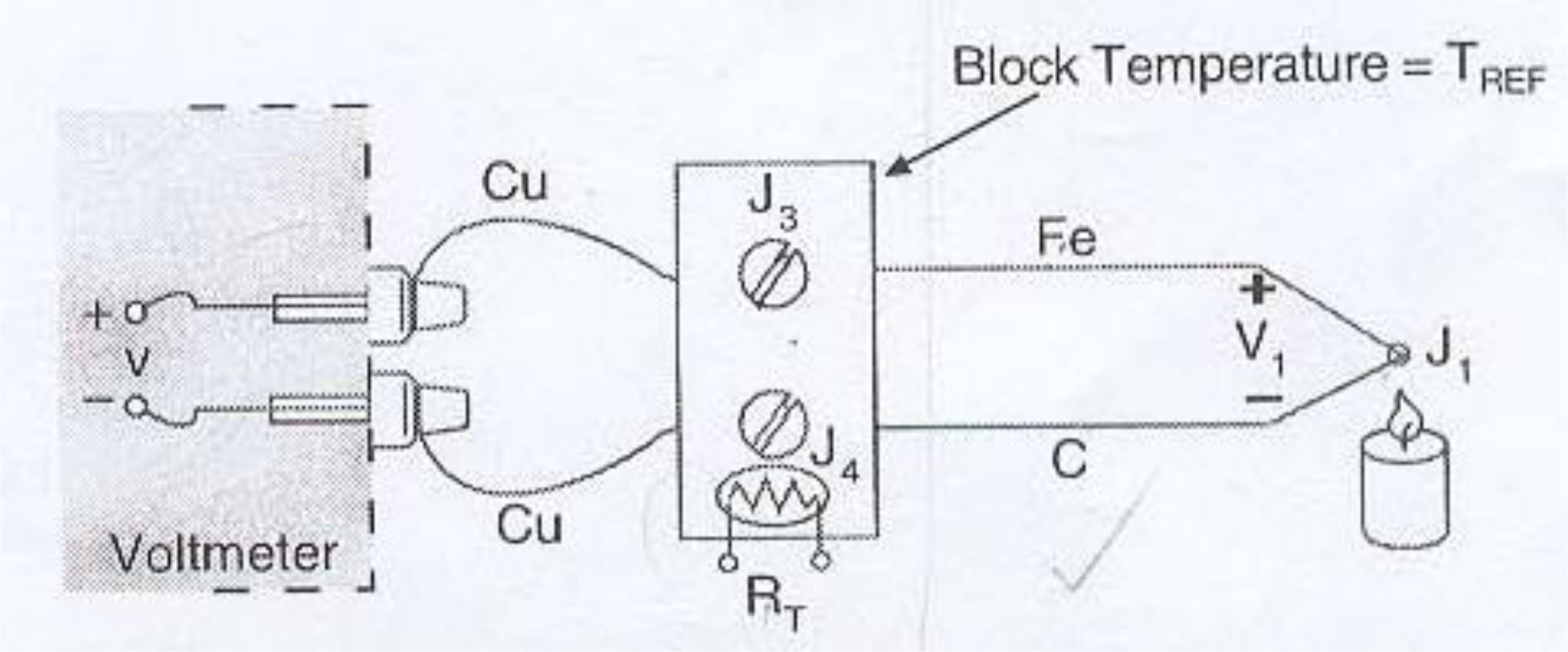
$$V = \alpha\,(T_1 - T_{REF})$$

Thermocouple



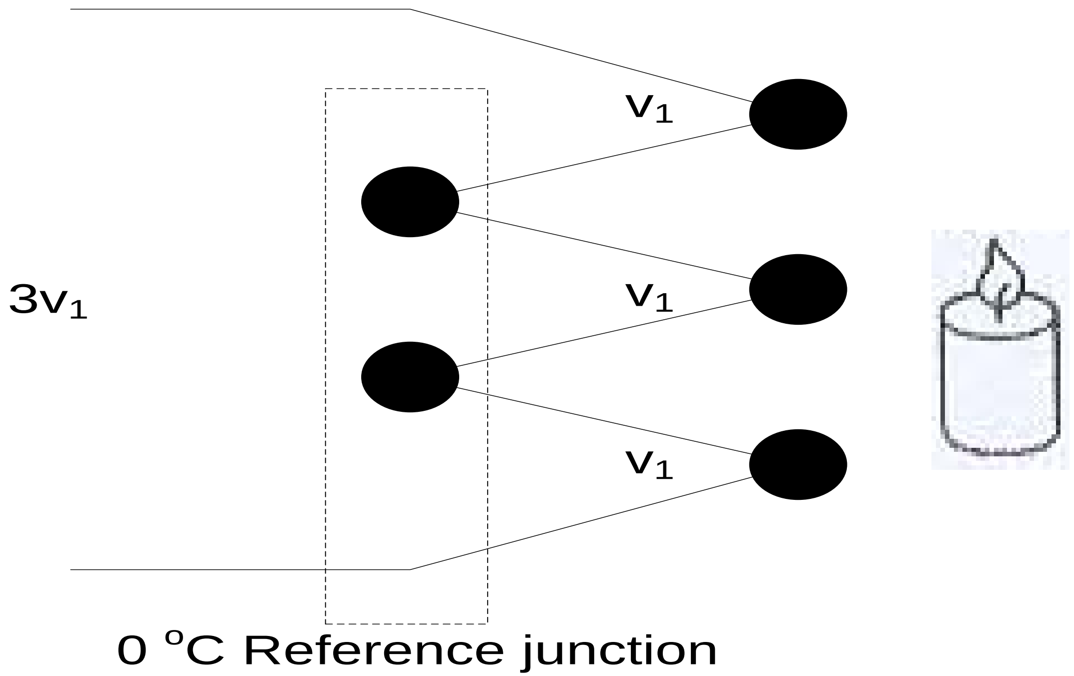
Law of intermediate metal

Thermocouple



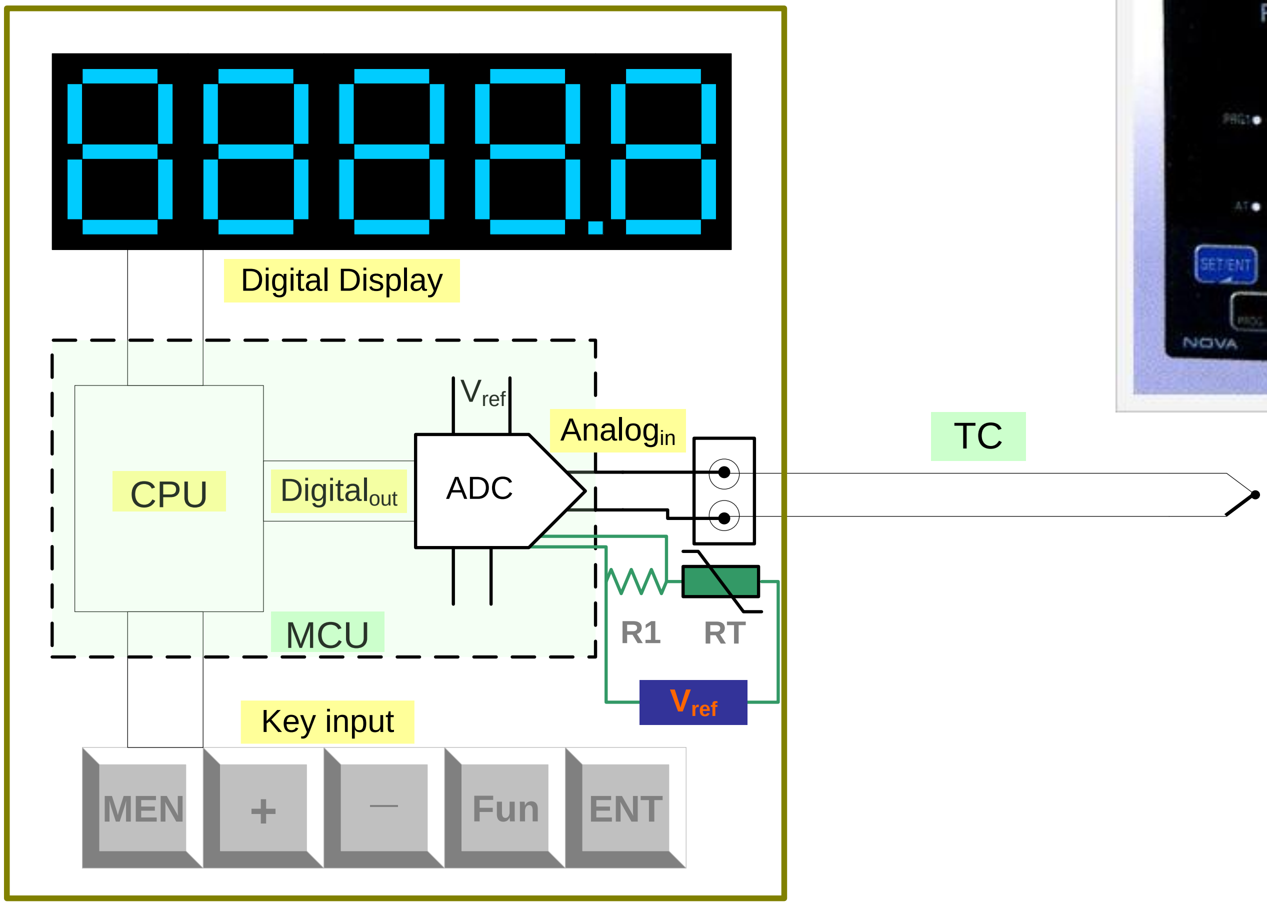
External reference junction no ice-bath

Thermocouple



Thermopile to gain up emf

Thermocouple



TC Digital indicator basic circuit block diagram

PT100 Platinum Resistance Thermometers

Platinum resistance thermometers (PRTs)

Offer excellent accuracy over a wide temperature range (from -200 to +850 °C). Standard Sensors are are available from many manufacturers with various accuracy specifications and numerous packaging options to suit most applications. Unlike thermocouples, it is not necessary to use special cables to connect to the sensor. The principle of operation is to measure the resistance of a platinum element. The most common type (PT100) has a resistance of 100 ohms at 0 °C and 138.4 ohms at 100 °C. There are also PT1000 sensors that have a resistance of 1000 ohms at 0 °C.

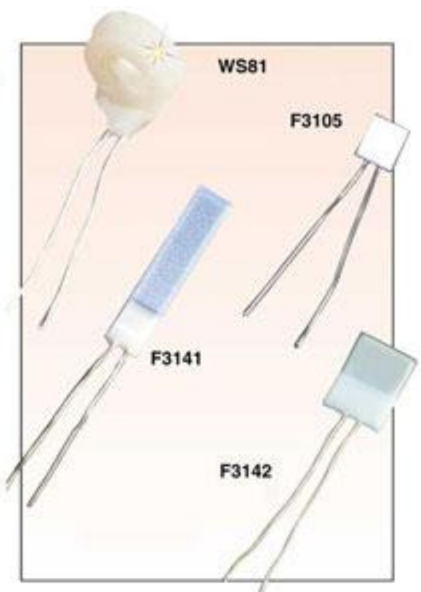
The relationship between temperature and resistance is approximately linear over a small temperature range: for example, if you assume that it is linear over the 0 to 100 °C range, the error at 50 °C is 0.4 °C. For precision measurement, it is necessary to linearise the resistance to give an accurate temperature. The most recent definition of the relationship between resistance and temperature is International Temperature Standard 90 (ITS-90).

The linearisation equation is:

$$Rt = R0 * (1 + A* t + B*t^2 + C*(t-100)* t^3)$$

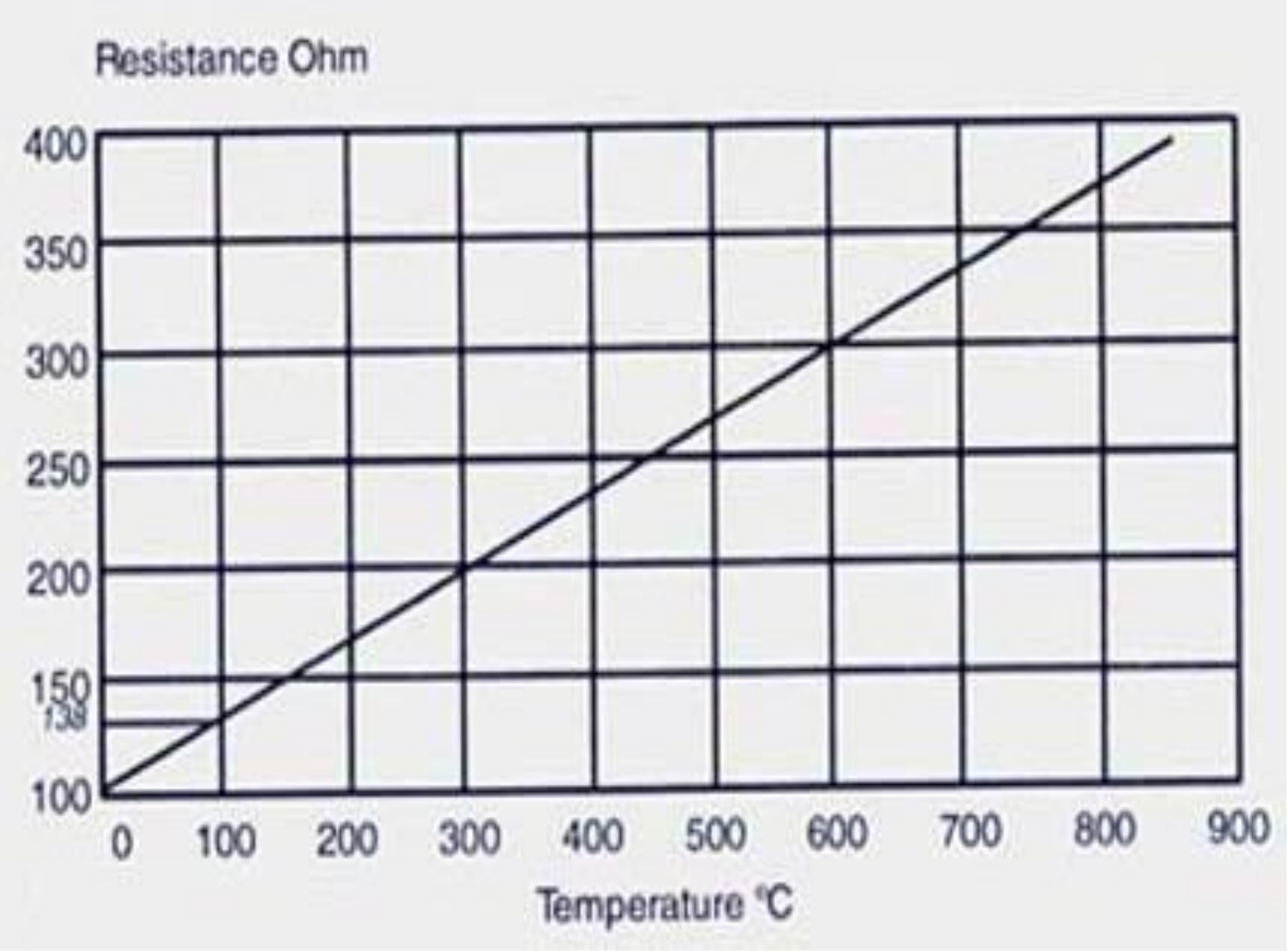
Where:
Rt is the resistance at temperature t, R0 is the resistance at 0 °C, and
A= 3.9083 E-3
B = -5.775 E-7
C = -4.183 E -12 (below 0 °C), or
C = 0 (above 0 °C)

RTD แบบ Probe และ Element ต่างๆ



Ro = 100, 500, or 1000 Ω

PT100 Platinum Resistance Thermometers



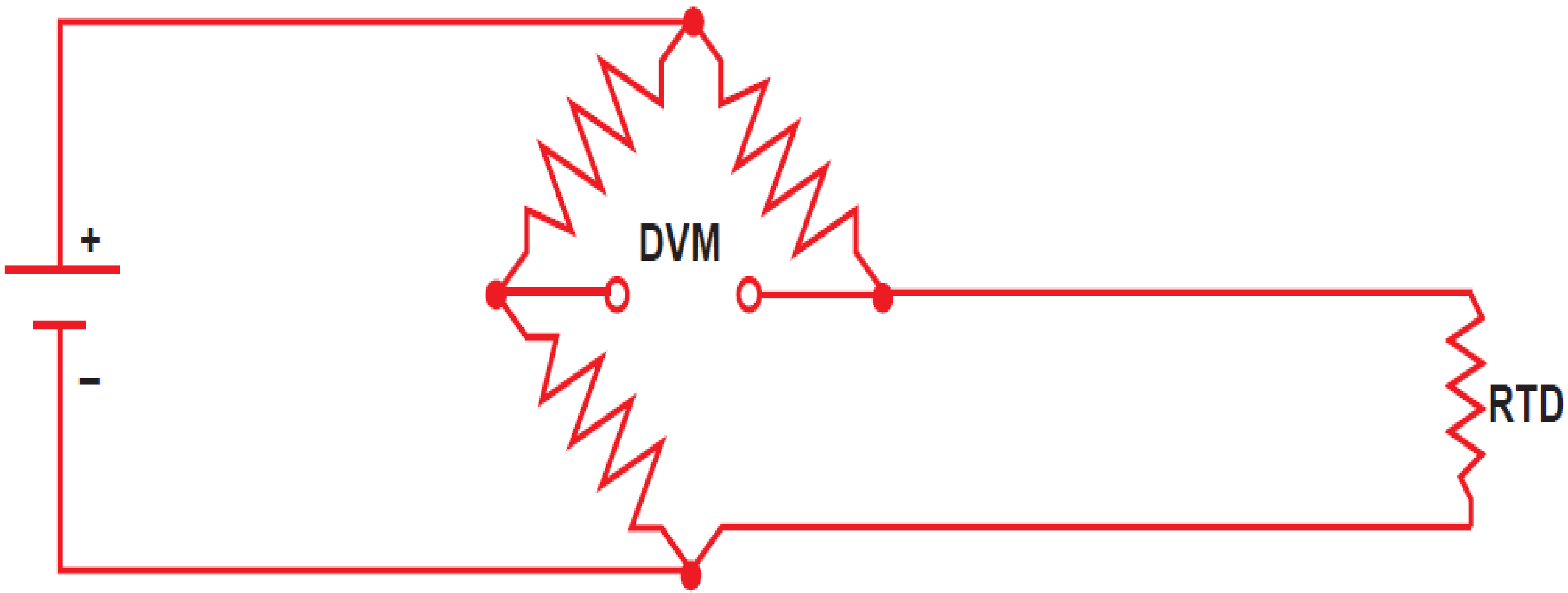
Resistance/Temperature Characteristics of Pt100

PT100 Platinum Resistance Thermometers

RTD measurement circuit:

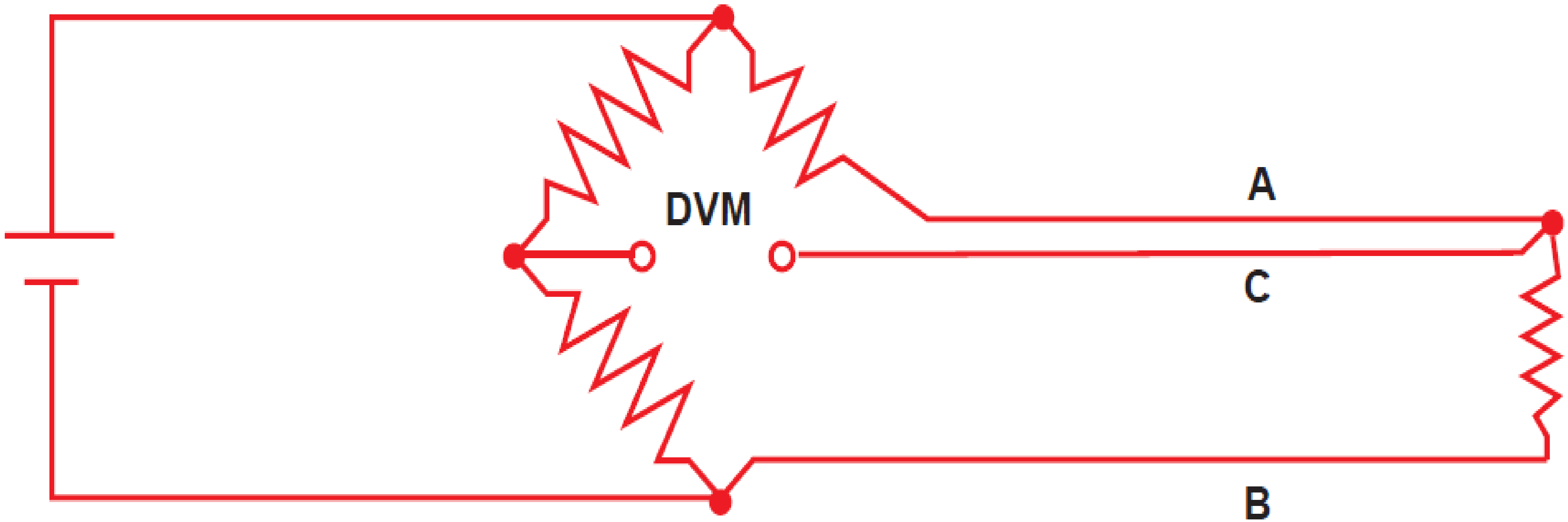
WHEATSTONE BRIDGE

Practical 2 Wire Bridge Circuits for RTD



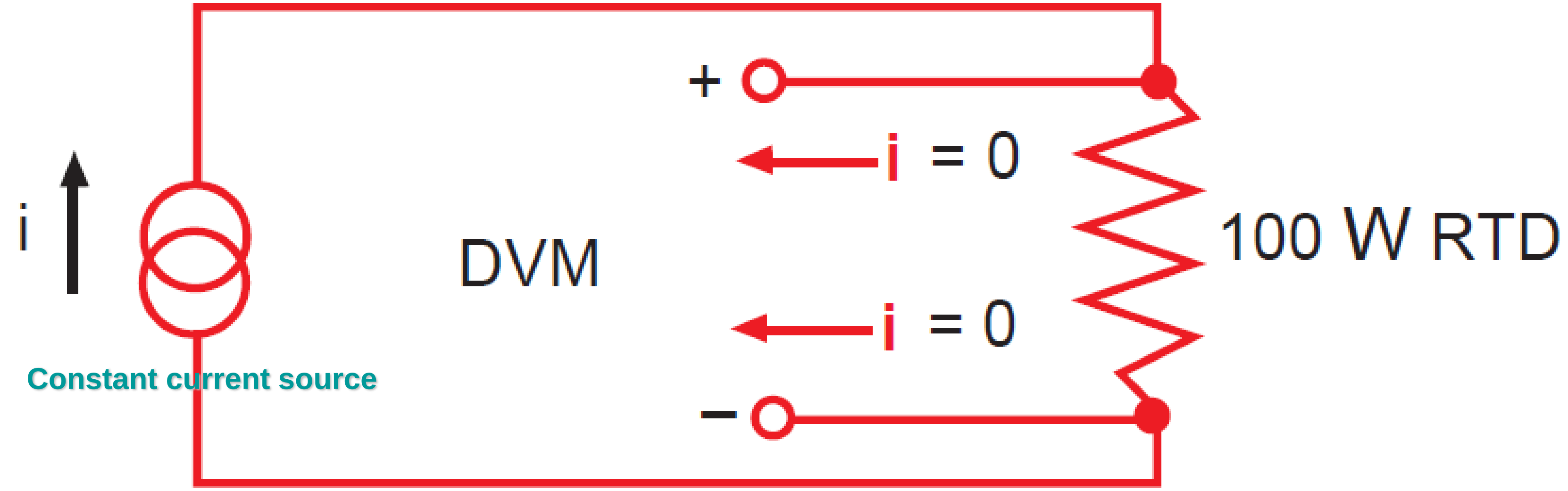
The measuring current should be as small as possible to minimise sensor self-heating; a maximum of around 1mA is regarded as acceptable for practical purposes. This would procedure a 0.1V drop in a Pt100 sensing resistor at 0C. The bridge circuit is applied for resistive sensor (especially small R) due to it can compensate error of extension wires (when apply 3-wire or 4-wire bridge).

Practical 3 Wire Bridge Circuits for RTD



3-WIRE BRIDGE

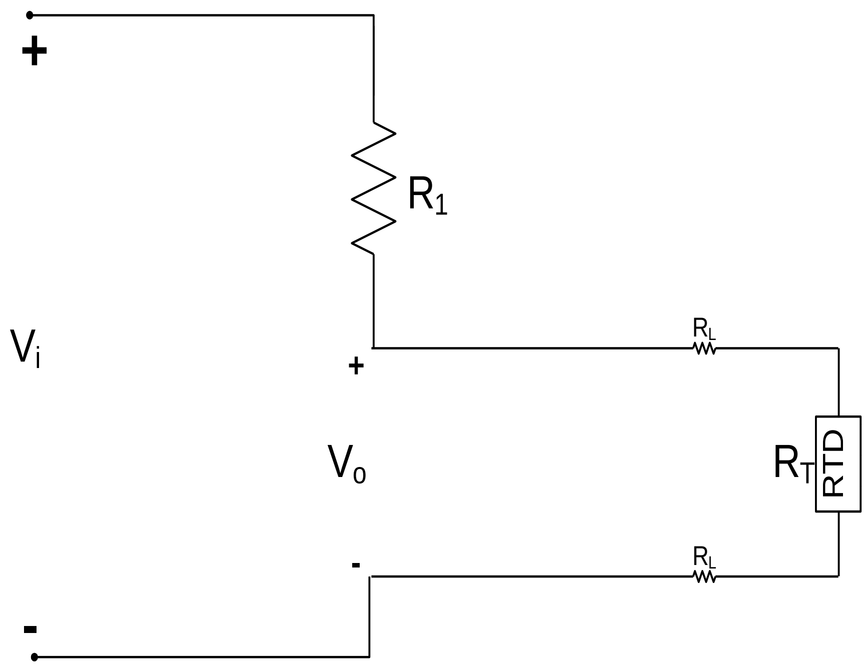
RTD 4 Wire Circuit



4-WIRE OHMS MEASUREMENT

PT100 Platinum Resistance Thermometers

Voltage Divider circuit



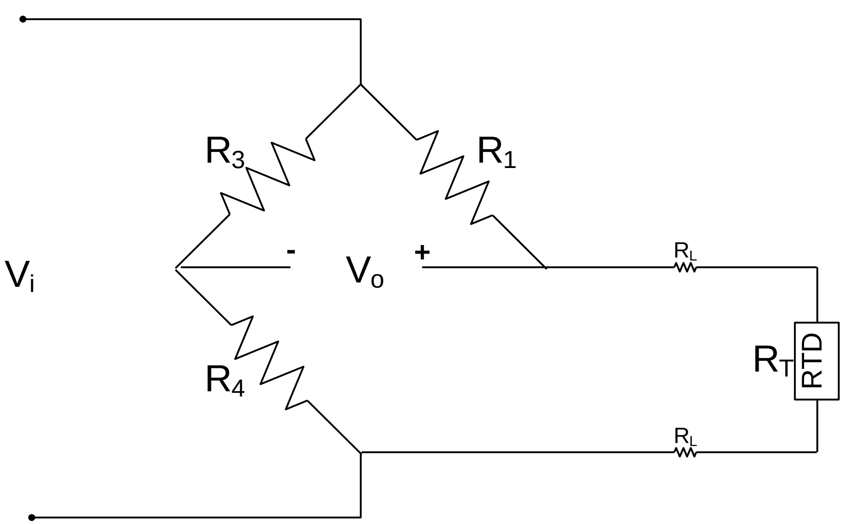
R1=	100.0000	100.0000	100.0000	100.0000	100.0000
R2= R_T =	**100.0000**	**101.0000**	**102.0000**	**103.0000**	**104.0000**
R3=	100.0000	100.0000	100.0000	100.0000	100.0000
R4=	100.0000	100.0000	100.0000	100.0000	100.0000
RL=	5.0000	5.0000	5.0000	5.0000	5.0000
V_i Volt =	10.0000	10.0000	10.0000	10.0000	10.0000
V_o Volt =	5.2381	5.2607	5.2830	5.3052	5.3271

$$V_o = \frac{R_T}{R_1 + R_T} V_i$$

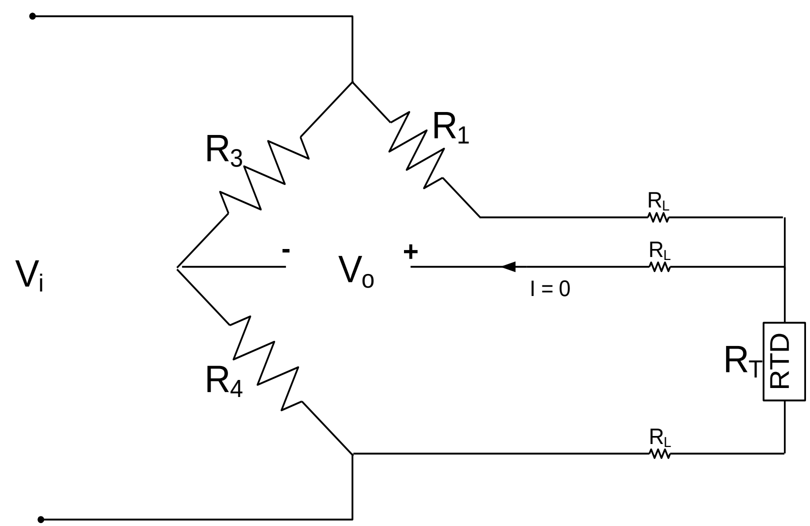
$$R_T = \frac{V_o}{V_i - V_o} R_1$$

RT measure =	**110.0000**	**111.0000**	**112.0000**	**113.0000**	**114.0000**
err =	10.0000	10.0000	10.0000	10.0000	10.0000
%err	10	9.90099	9.803922	9.708738	9.615385

PT100 Platinum Resistance Thermometers



2 wire bridge circuit



3 wire bridge circuit

$$V_o = \left(\frac{R_T}{R_T + R_1} - \frac{R_4}{R_4 + R_3} \right) V_i$$

If $R_3 = R_4$

$$R_T = \frac{0.5V_i + V_o}{0.5V_i - V_o} R_1$$

PT100 Platinum Resistance Thermometers

In case of apply 2 wire bridge circuit to archive RT :

R1=	100.0000	100.0000	100.0000	100.0000	100.0000
R2= R_T =	**100.0000**	**101.0000**	**102.0000**	**103.0000**	**104.0000**
R3=	100.0000	100.0000	100.0000	100.0000	100.0000
R4=	100.0000	100.0000	100.0000	100.0000	100.0000
RL=	5.0000	5.0000	5.0000	5.0000	5.0000
V_i Volt =	10.0000	10.0000	10.0000	10.0000	10.0000
V_o Volt =	0.2381	0.2607	0.2830	0.3052	0.3271

RL mea	**110.0000**	**111.0000**	**112.0000**	**113.0000**	**114.0000**
err =	10.0000	10.0000	10.0000	10.0000	10.0000
%err	10	9.90099	9.803922	9.708738	9.615385

In case of apply 3 wire bridge circuit to archive RT :

R1=	100.0000	100.0000	100.0000	100.0000	100.0000
R2= R_T =	**100.0000**	**101.0000**	**102.0000**	**103.0000**	**104.0000**
R3=	100.0000	100.0000	100.0000	100.0000	100.0000
R4=	100.0000	100.0000	100.0000	100.0000	100.0000
RL=	5.0000	5.0000	5.0000	5.0000	5.0000
V_i Volt =	10.0000	10.0000	10.0000	10.0000	10.0000
V_o Volt =	0.0000	0.0237	0.0472	0.0704	0.0935

RL mea	**100.0000**	**100.9524**	**101.9048**	**102.8571**	**103.8095**
err =	0.0000	0.0476	0.0952	0.1429	0.1905
%err	0	0.047148	0.093371	0.138696	0.18315

PT100 Platinum Resistance Thermometers

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper
OOOO	0.46	11.684	0.049	0.16072	380	302	125 Hz
OOO	0.4096	10.40384	0.0618	0.202704	328	239	160 Hz
OO	0.3648	9.26592	0.0779	0.255512	283	190	200 Hz
0	0.3249	8.25246	0.0983	0.322424	245	150	250 Hz
1	0.2893	7.34822	0.1239	0.406392	211	119	325 Hz
2	0.2576	6.54304	0.1563	0.512664	181	94	410 Hz
3	0.2294	5.82676	0.197	0.64616	158	75	500 Hz
4	0.2043	5.18922	0.2485	0.81508	135	60	650 Hz
5	0.1819	4.62026	0.3133	1.027624	118	47	810 Hz
6	0.162	4.1148	0.3951	1.295928	101	37	1100 Hz
7	0.1443	3.66522	0.4982	1.634096	89	30	1300 Hz
8	0.1285	3.2639	0.6282	2.060496	73	24	1650 Hz
9	0.1144	2.90576	0.7921	2.598088	64	19	2050 Hz
10	0.1019	2.58826	0.9989	3.276392	55	15	2600 Hz
11	0.0907	2.30378	1.26	4.1328	47	12	3200 Hz
12	0.0808	2.05232	1.588	5.20864	41	9.3	4150 Hz
13	0.072	1.8288	2.003	6.56984	35	7.4	5300 Hz
14	0.0641	1.62814	2.525	8.282	32	5.9	6700 Hz
15	0.0571	1.45034	3.184	10.44352	28	4.7	8250 Hz

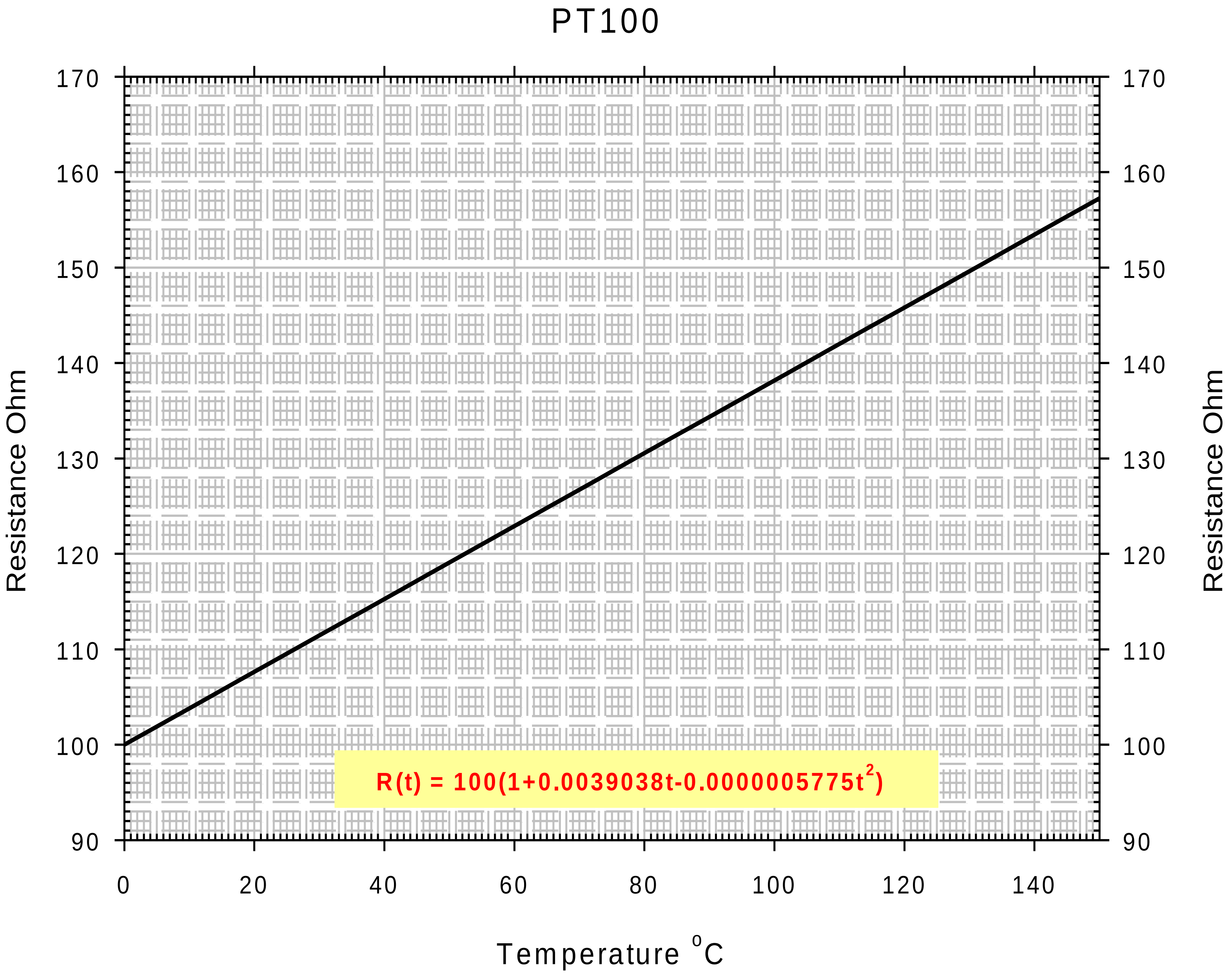
PT100 Platinum Resistance Thermometers

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper
16	0.0508	1.29032	4.016	13.17248	22	3.7	11 k Hz
17	0.0453	1.15062	5.064	16.60992	19	2.9	13 k Hz
18	0.0403	1.02362	6.385	20.9428	16	2.3	17 kHz
19	0.0359	0.91186	8.051	26.40728	14	1.8	21 kHz
20	0.032	0.8128	10.15	33.292	11	1.5	27 kHz
21	0.0285	0.7239	12.8	41.984	9	1.2	33 kHz
22	0.0254	0.64516	16.14	52.9392	7	0.92	42 kHz
23	0.0226	0.57404	20.36	66.7808	4.7	0.729	53 kHz
24	0.0201	0.51054	25.67	84.1976	3.5	0.577	68 kHz
25	0.0179	0.45466	32.37	106.1736	2.7	0.457	85 kHz
26	0.0159	0.40386	40.81	133.8568	2.2	0.361	107 kH
27	0.0142	0.36068	51.47	168.8216	1.7	0.288	130 kHz
28	0.0126	0.32004	64.9	212.872	1.4	0.226	170 kHz
29	0.0113	0.28702	81.83	268.4024	1.2	0.182	210 kHz
30	0.01	0.254	103.2	338.496	0.86	0.142	270 kHz

PT100 Platinum Resistance Thermometers

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper
32	0.008	0.2032	164.1	538.248	0.53	0.091	430 kHz
Metric 2.0	0.00787	0.200	169.39	555.61	0.51	0.088	440 kHz
33	0.0071	0.18034	206.9	678.632	0.43	0.072	540 kHz
Metric 1.8	0.00709	0.180	207.5	680.55	0.43	0.072	540 kHz
34	0.0063	0.16002	260.9	855.752	0.33	0.056	690 kHz
Metric 1.6	0.0063	0.16002	260.9	855.752	0.33	0.056	690 kHz
35	0.0056	0.14224	329	1079.12	0.27	0.044	870 kHz
Metric 1.4	.00551	.140	339	1114	0.26	0.043	900 kHz
36	0.005	0.127	414.8	1360	0.21	0.035	1100 kHz
Metric 1.25	.00492	0.125	428.2	1404	0.20	0.034	1150 kHz
37	0.0045	0.1143	523.1	1715	0.17	0.0289	1350 kHz
Metric 1.12	.00441	0.112	533.8	1750	0.163	0.0277	1400 kHz
38	0.004	0.1016	659.6	2163	0.13	0.0228	1750 kHz
Metric 1	.00394	0.1000	670.2	2198	0.126	0.0225	1750 kHz
39	0.0035	0.0889	831.8	2728	0.11	0.0175	2250 kHz
40	0.0031	0.07874	1049	3440	0.09	0.0137	2900 kHz

PT100 Platinum Resistance Thermometers

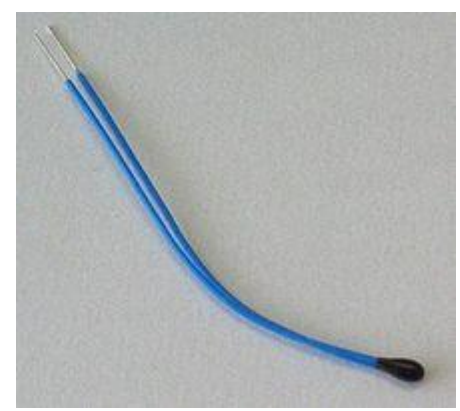


Thermistors

What is a thermistor?

A thermistor is a temperature-sensing element composed of sintered semiconductor material which exhibits a large change in resistance proportional to a small change in temperature. Thermistors usually have negative temperature coefficients which means the resistance of the thermistor decreases as the temperature increases.

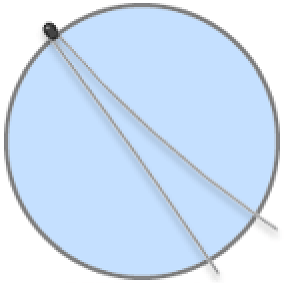
Accuracy
Thermistors are one of the most accurate types of temperature sensors. OMEGA thermistors have an accuracy of ±0.1°C or ±0.2°C depending on the particular thermistor model. However thermistors are fairly limited in their temperature range, working only over a nominal range of 0°C to 100°C .



Low cost, Easy use
Type NTC or PTC 1k,3k, 5k, 10k, 20k, etc. (@25 ^{o}C)

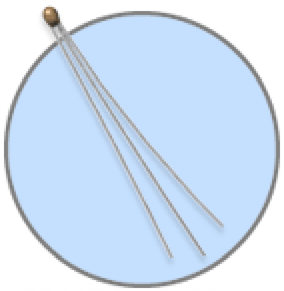
Types of Thermistors

Thermistor Elements
The thermistor element is the simplest form of thermistor. Because of their compact size, thermistor elements are commonly used when space is very limited. OMEGA offers a wide variety of thermistor elements which vary not only in form factor but also in their resistance versus temperature characteristics. Since thermistors are non-linear, the instrument used to read the temperature must linearize the reading.



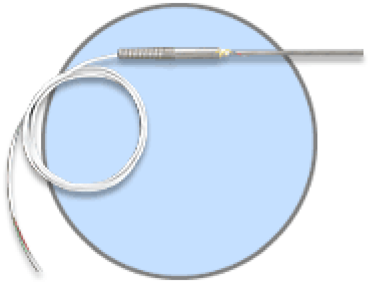
44000 Series
Thermistor Element

Linear Response Thermistor Elements
For applications requiring thermistors with linear response to temperature change, OMEGA offers linear components. These unique devices consist of a thermistor composite for temperature sensing and an external resistor composite for linearizing.



44000 Series Linear
ResponseThermistor Element

Thermistor Probes
The standalone thermistor element is relatively fragile and can not be placed in a rugged environment. OMEGA offers thermistor probes which are thermistor elements embedded in metal tubes. Thermistor probes are much more suitable for industrial environments than thermistor elements.



TJ36 Thermistor Probe

Thermistors

Thermistors typically achieve a higher precision within a limited temperature range [usually −90 °C to 130 °C].

_B_ parameter equation

NTC thermistors can also be characterised with the *B* (thermistor material constant) parameter equation, which is essentially the Steinhart Hart equation as follows,

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

where the temperatures are in kelvins and R_0 is the resistance at temperature T_0 (usually 25 °C = 298.15 K). Solving for *R* yields:

$$R = R_0 e^{B(1/T - 1/T_0)}$$ **or** $$T = \frac{B}{\ln\left(R/r_\infty\right)}$$ **where** $$r_\infty = R_0 e^{-B/T_0}$$

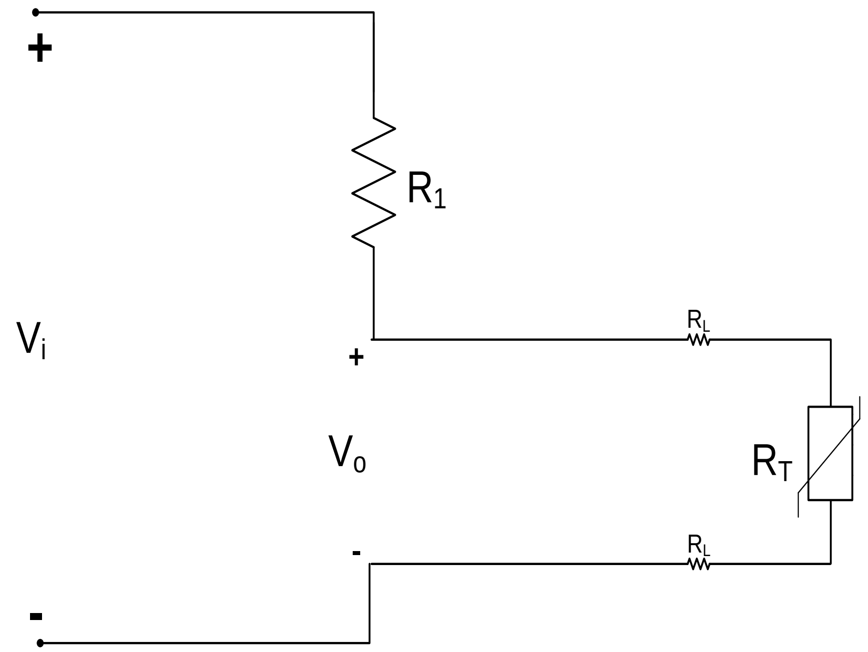
(Note : T- R function, normally adopt from manufacturer)

Thermistors can be classified into two types, depending on the sign of *k*. If *k* is positive, the resistance increases with increasing temperature, and the device is called a positive temperature coefficient (**PTC**) thermistor, or **posistor**. If *k* is negative, the resistance decreases with increasing temperature, and the device is called a negative temperature coefficient (**NTC**) thermistor. Resistors that are not thermistors are designed to have a *k* as close to zero as possible(smallest possible k), so that their resistance remains nearly constant over a wide temperature range.

Thermistors

Voltage Divider circuit

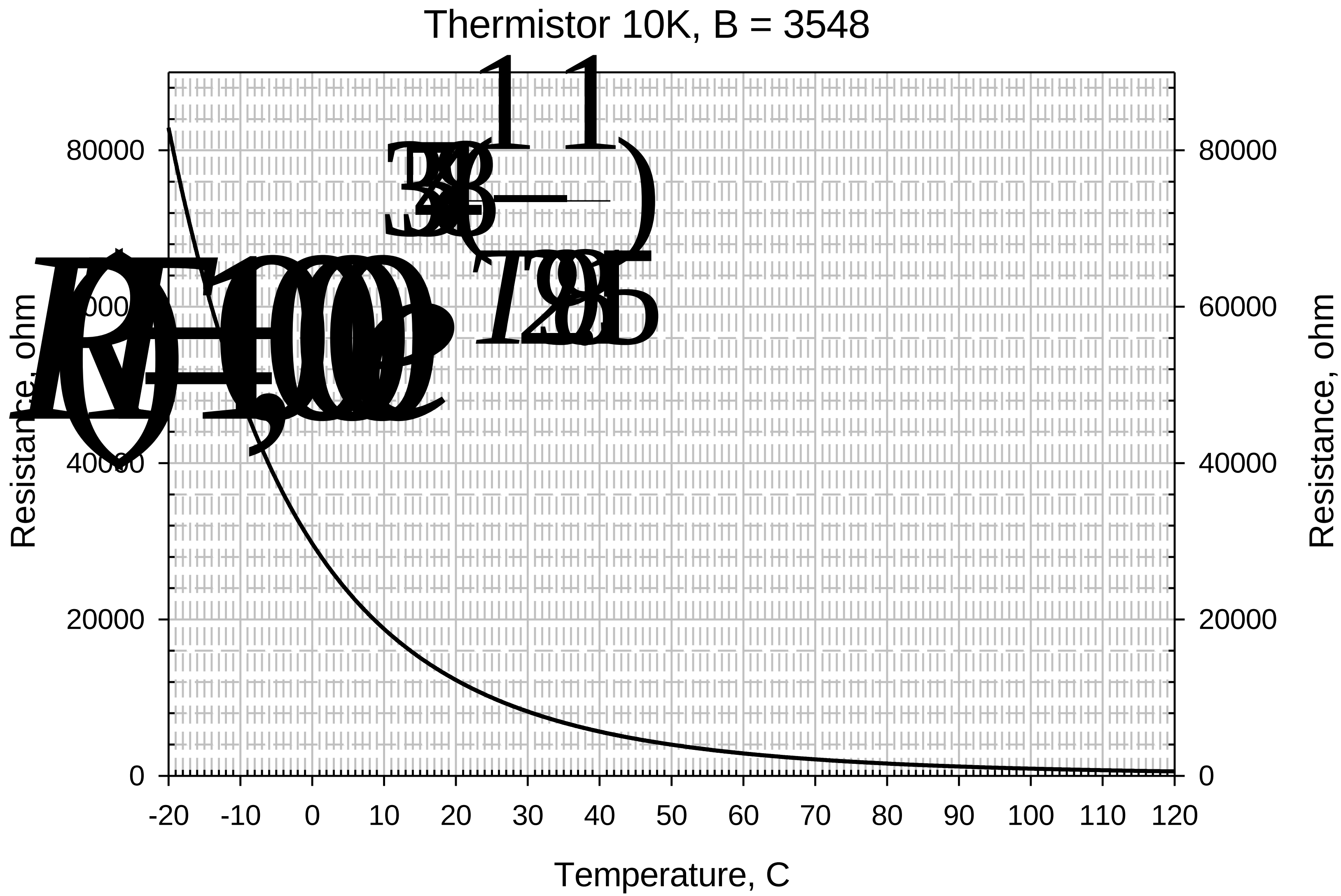
R1 =	10000.00	10000.00	10000.00	10000.00	10000.00
R2 = R_T =	**10000.00**	**9000.00**	**8000.00**	**7000.00**	**6000.00**
R3 =	100.00	100.00	100.00	100.00	100.00
R4 =	100.00	100.00	100.00	100.00	100.00
R_L =	5.00	5.00	5.00	5.00	5.00
V_i =	10.00	10.00	10.00	10.00	10.00
V_o =	5.00	4.74	4.45	4.12	3.75
R_{Tcal} =	**10010.00**	**9010.00**	**8010.00**	**7010.00**	**6010.00**
err =	10.00	10.00	10.00	10.00	10.00
%err	0.10	0.11	0.12	0.14	0.17



$$V_o = \frac{R_T}{R_1 + R_T} V_i$$

$$R_T = \frac{V_o}{V_i - V_o} R_1$$

Thermistors

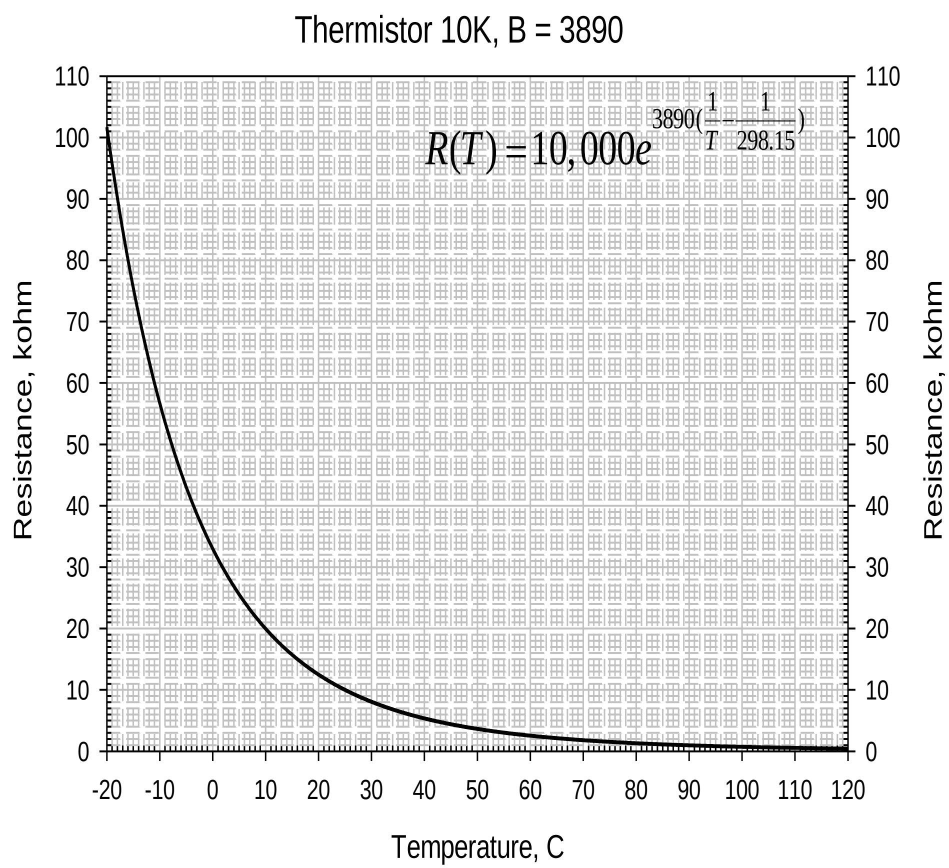


$$R(T) = 10{,}000 \cdot e^{3548\left(\frac{1}{T} - \frac{1}{298.15}\right)}$$

Thermistors

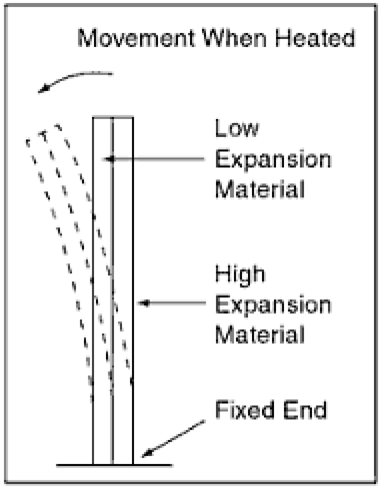
R_T = 10,000 ohms @ 25°C	pull-up resistor (ohms)	10000
alpha @25C = -4.39%	full-scale volts	5.0
beta (0/50C) = 3890K	resolution in bits	10

DegC	DegF	OHMS	Volts	10-bit Val
-50	**-58**	667828	4.926	**1009**
-40	**-40**	335,671	4.855	**994**
-30	**-22**	176,683	4.732	**969**
-20	**-4**	96,974	4.533	**928**
-10	**14**	55,298	4.234	**867**
0	**32**	32,650	3.828	**784**
10	**50**	19,903	3.328	**682**
20	**68**	12,493	2.777	**569**
25	**77**	10,000	2.500	**512**
30	**86**	8,056	2.231	**457**
40	**104**	5,324	1.737	**356**
50	**122**	3,601	1.324	**271**
60	**140**	2,487	0.996	**204**
70	**158**	1,751	0.745	**153**
80	**176**	1,256	0.558	**114**
90	**194**	916	0.420	**86**
100	**212**	679	0.318	**65**
110	**230**	510	0.243	**50**
120	**248**	389	0.187	**38**
130	**266**	300	0.146	**30**
140	**284**	234	0.114	**23**
150	**302**	185	0.091	**19**

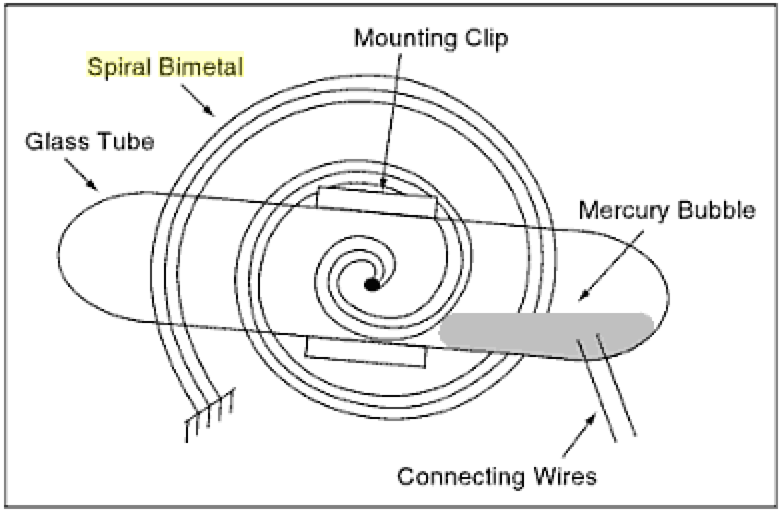


Thermistor 10k Table Beta = 3890

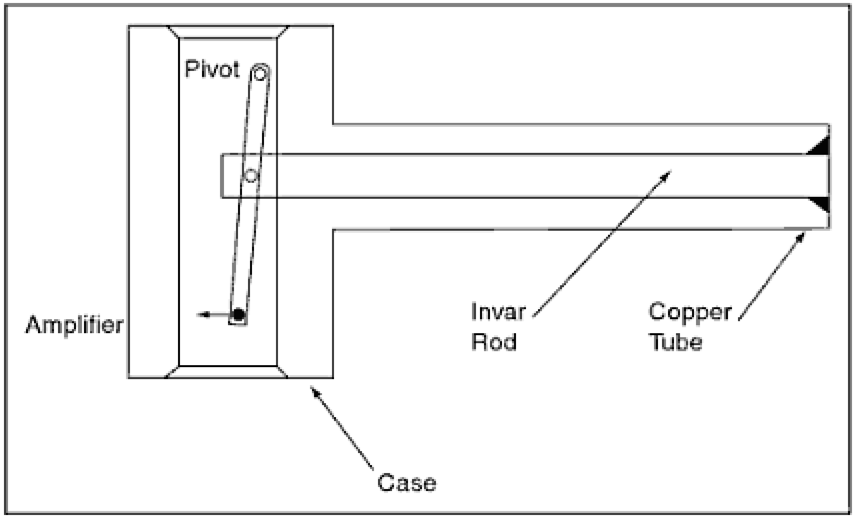
Bimetallic Temperature Measurement Devices



Bimetallic Temperature Sensor



Mercury Switch

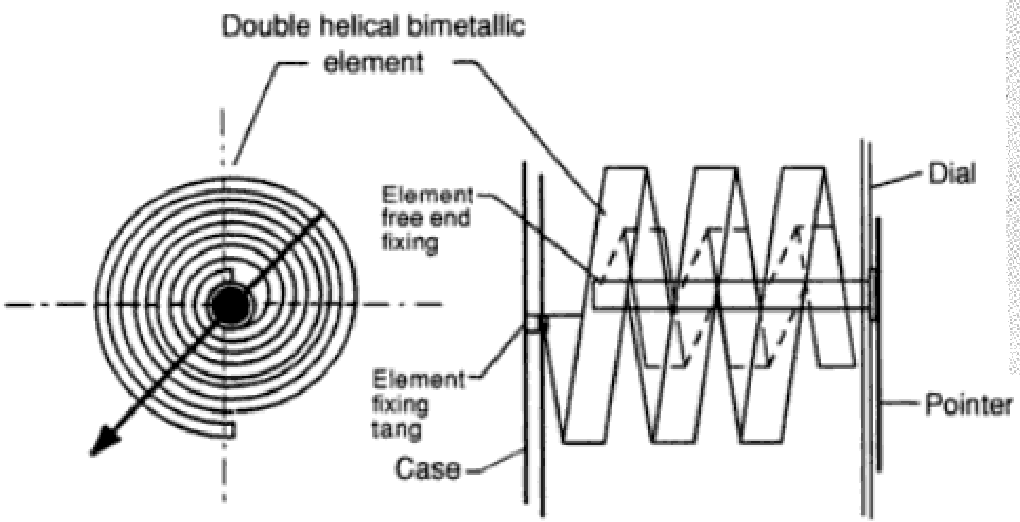


Rod-and-Tube Sensors

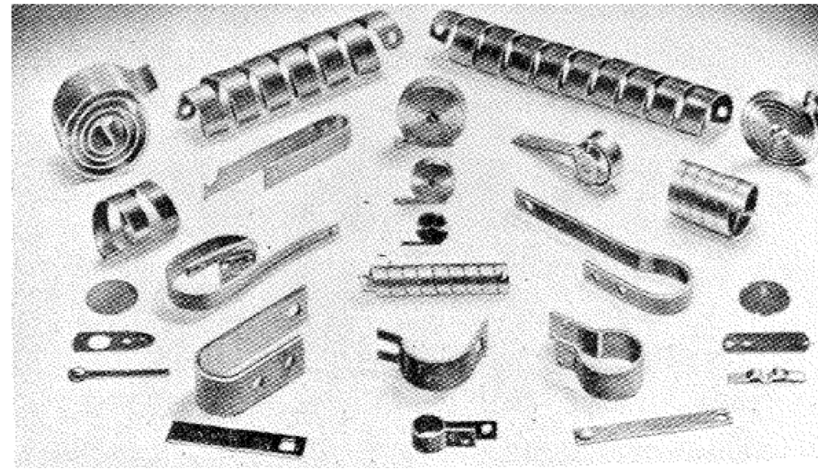
Bimetallic Temperature Control

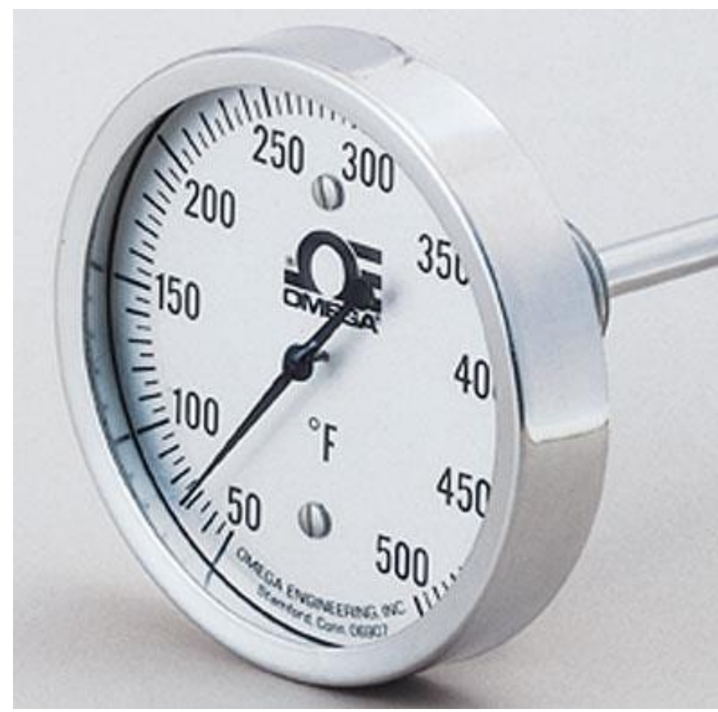
Bimetallic Temperature Measurement Devices

Dial Gauge



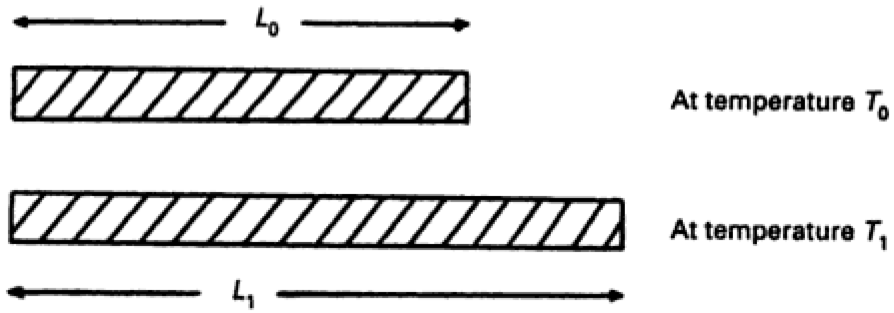
Bimetallic thermometer.





Bimetallic Temperature Measurement Devices

Thermal expansion of metal



$$L_1 = L_0(1 + \gamma(T_1 - T_0))$$

where γ is defined as the coefficient of linear thermal expansion. (The relationship does, in reality, include terms in $(T_1 - T_0)^2$ and higher terms, but the above equation is accurate for all practical purposes).
Typical values of γ are, per degree Celsius:

Steel	6.7×10^{-6}
Copper	16.6×10^{-6}
Aluminium	25×10^{-6}

Ex: How much will a 4 m-long copper rod expand when the temperature is changed from 0 to 100°C?

Bimetallic Temperature Measurement Devices

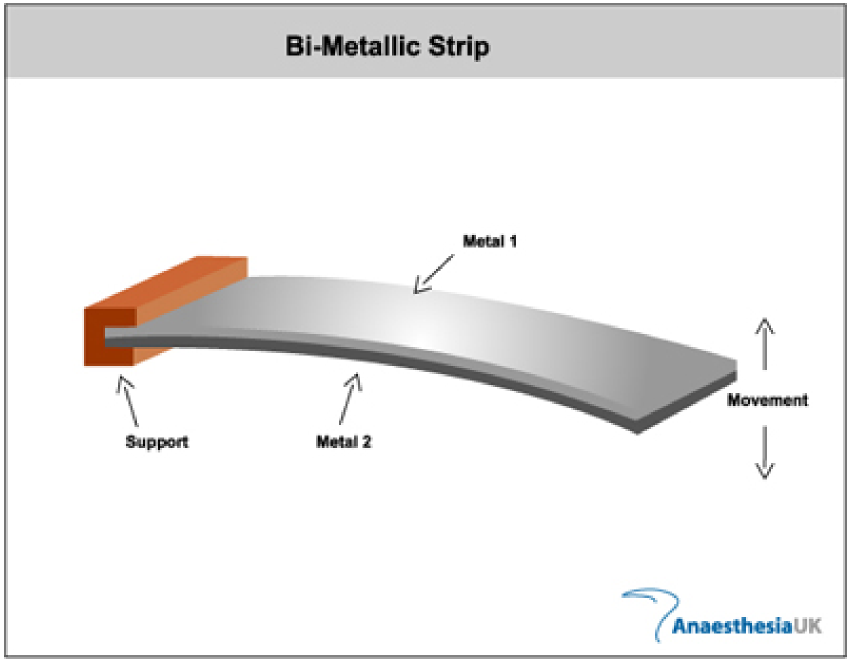
The deflection of the free end of a spiral or helix clamped at the other end is given by

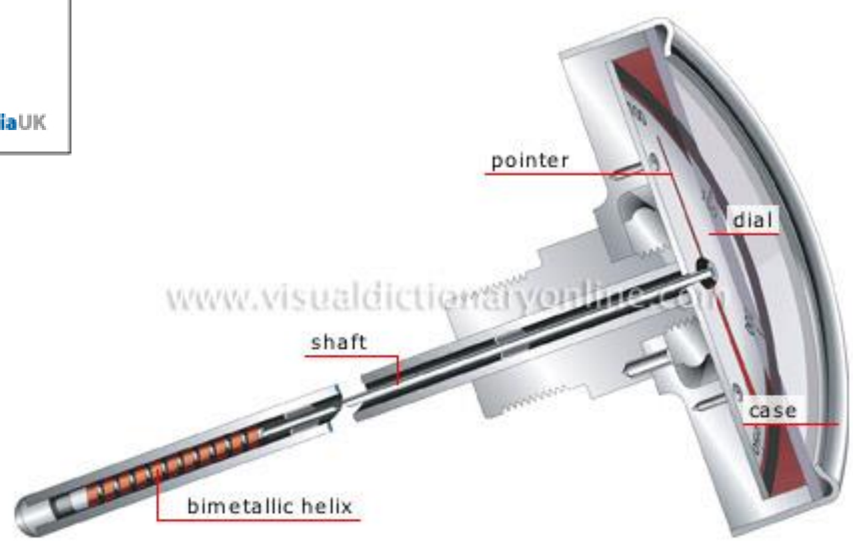
$$R = \frac{FTL}{t}$$

where R is the angular rotation in radians
F is the Flexivity
L is the developed length of the coiled strip in inches
t is the thickness in inches.
T is temperature change in degrees F.

For most bimetals F is equal to 1½ times the difference in thermal coefficient of linear expansion of the high and low expanding components.

Bimetallic Temperature Measurement Devices (Dial Gauge)





Bimetallic Temperature Measurement Devices (Dial Gauge)

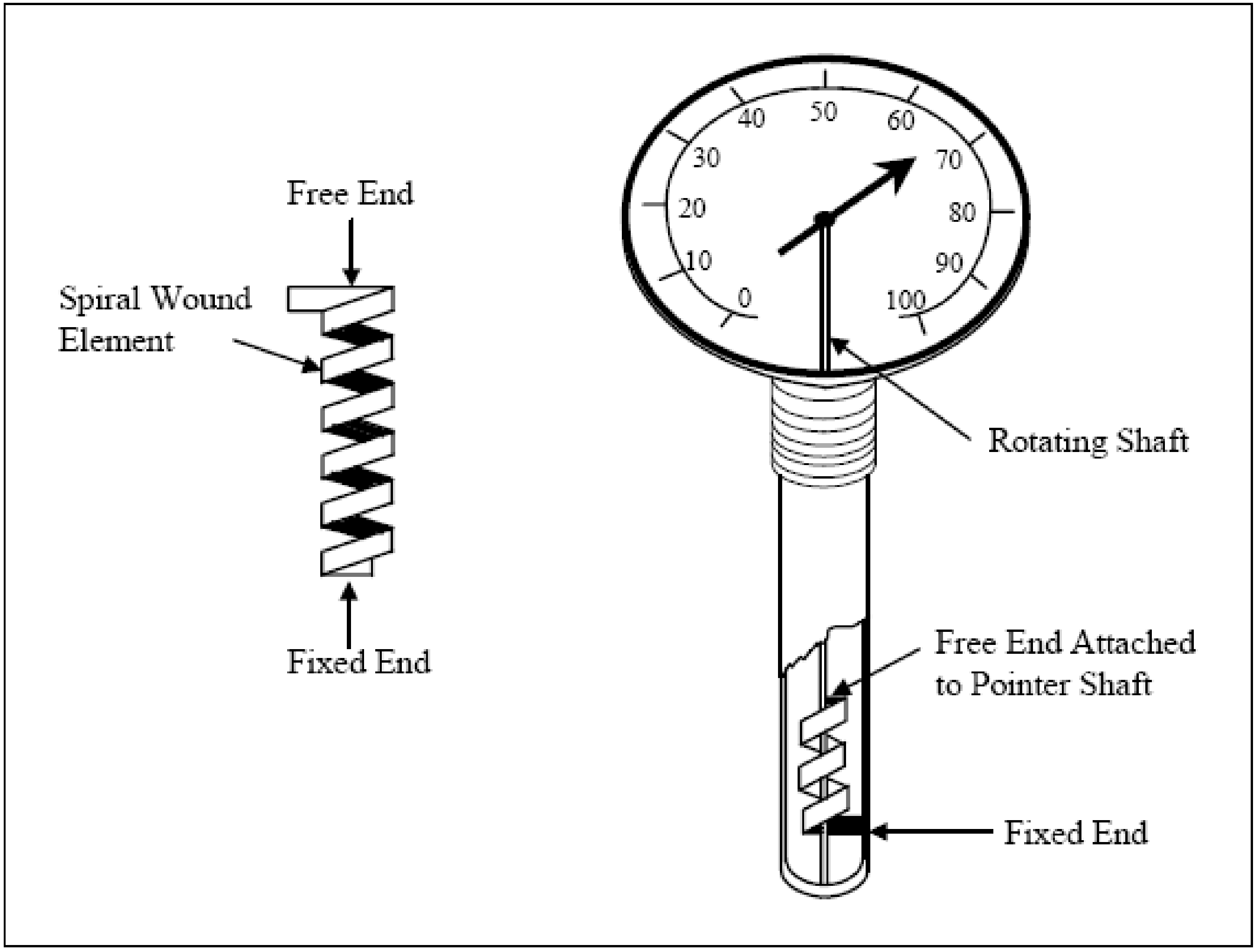
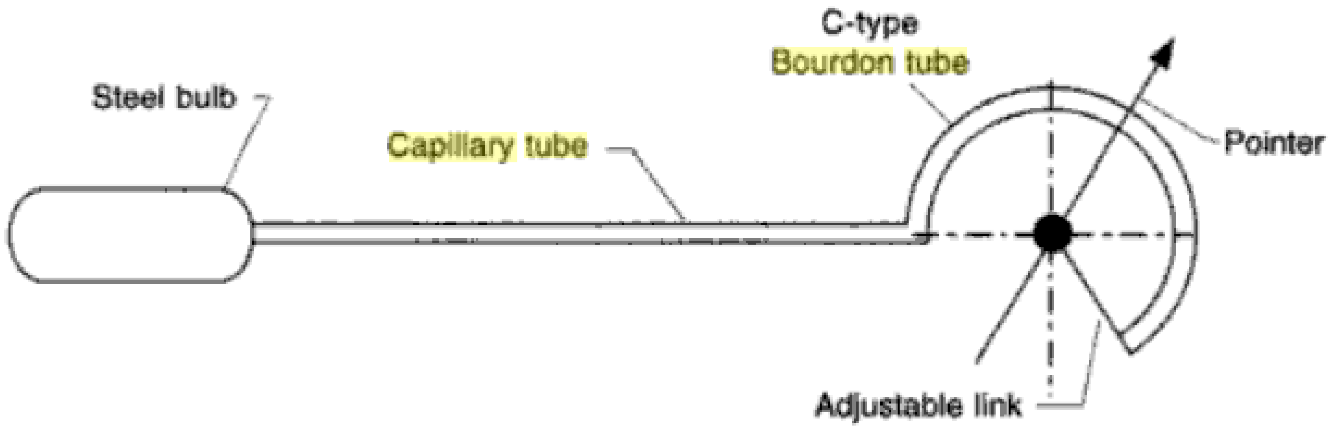


Figure 7-3. Bimetallic dial thermometer

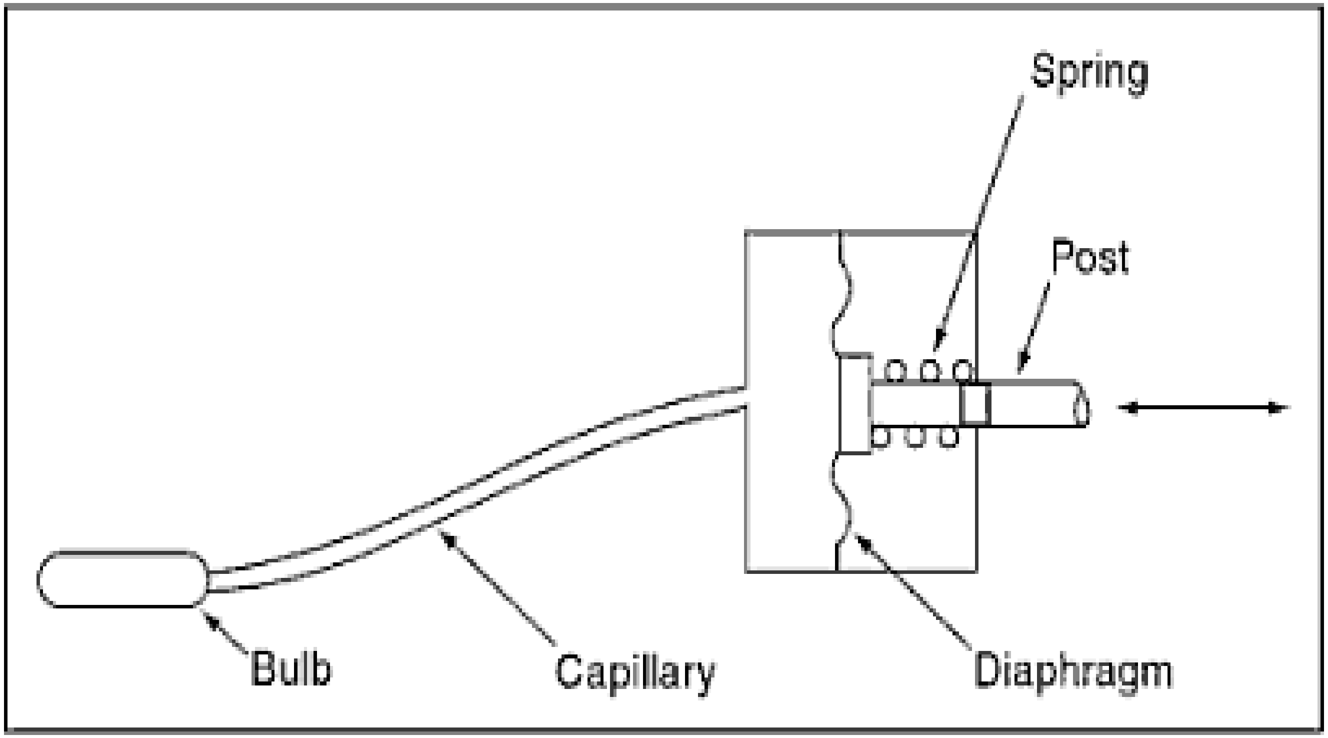
Fluid Expansion (Bourdon tube thermometer)



Typical liquid-filled thermometer.

Dial Gauge (Bourdon tube thermometer)

Fluid Expansion



Capillary Sensors

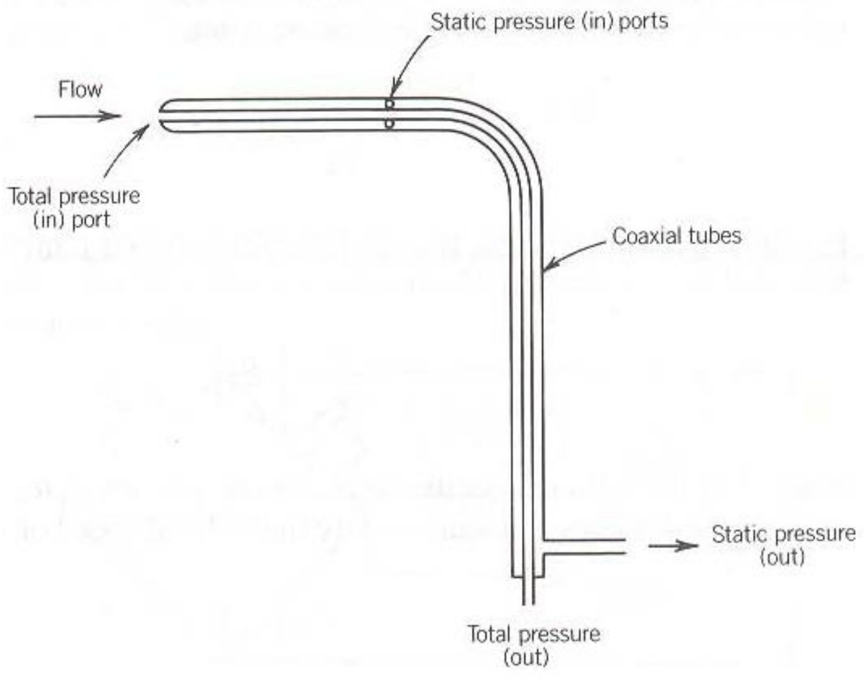
Flow Measurement

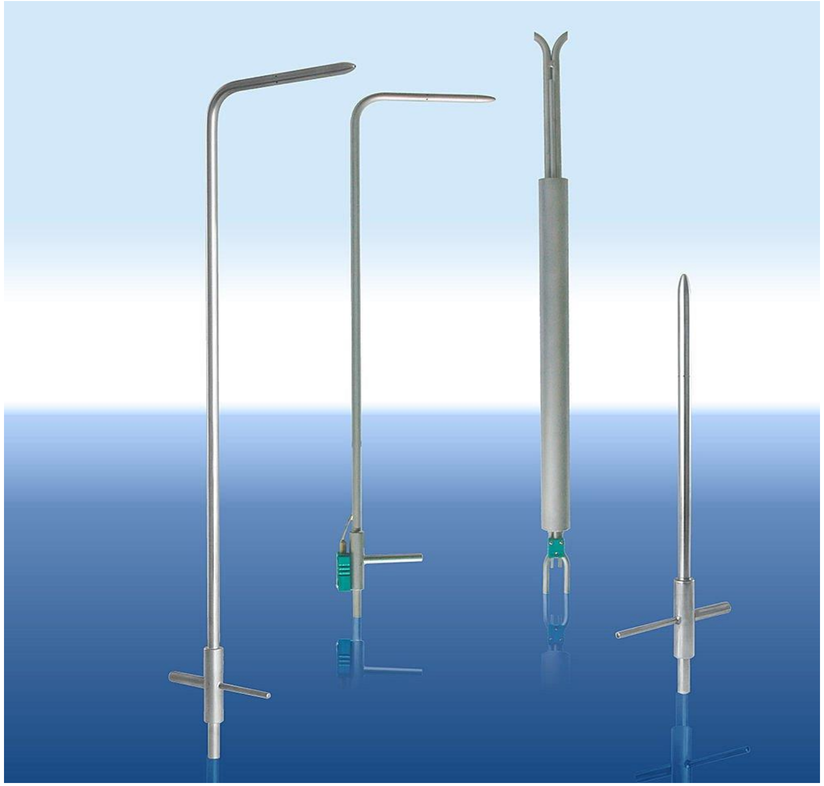
Example often use flow measurement

No	Applied principle	Measurement Devices	Category
1	Fluid velocity	Pitot tube Ultrasonic, Laser Doppler Hot wire	Insertion Non-Invasive Insertion
2	Pressure different	Orifice plate Flow nozzle	Obstruction Obstruction
3	Fluid momentum (force)	Turbine Paddle wheel, Rotametor Positive Displacement Vortex	Insertion Insertion Insertion Insertion Insertion
4			

Flow Measurement

Pitot tube





Industrial Standard Pitot tube

<< Apply to measure air-craft velocity

Pitot tube

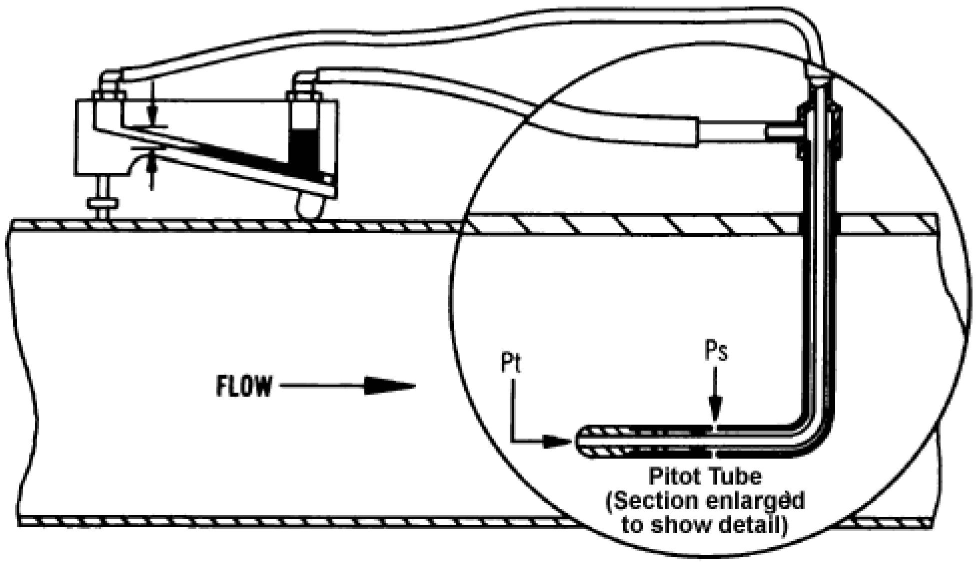


Fig.3 – Pitot Tube senses total and static pressure.
Manometer measures velocity pressure –
(Difference between total and static pressures).

Pitot–Static Pressure Probe

For a steady, incompressible, isentropic flow, equation 9.16 can be written at any arbitrary point x in the flow field as

$$p_t = p_x + \frac{1}{2g_c}\rho U_x^2$$

Pitot tube

$$p_v = p_t - p_x = \frac{1}{2g_c}\rho U_x^2$$

Here p_v, the difference between the total and static pressures at any point in the flow, is called the *dynamic pressure*. The determination of the dynamic pressure of a moving fluid at point x would provide a method for the estimation of the local velocity existing at point x. From (9.30),

$$U_x = \sqrt{\frac{2g_c p_v}{\rho}} = \sqrt{\frac{2g_c(p_t - p_x)}{\rho}} \qquad \text{(P1)}$$

The pitot–static pressure probe is relatively insensitive to misalignment over the yaw angle range of ±15°. When possible, the probe can be rotated until a maximum signal is measured, a condition that is indicative of alignment with the mean flow direction. However, the probes have a lower velocity limit of use which is brought about by strong viscous effects in the entry regions of the pressure ports. In general, viscous effects should not be a concern, provided that the Reynolds number based on the probe radius, $Re_r = Ur/\nu > 500$ where ν is the kinematic vis-

Flow Measurement

Pitot tube

cosity of the fluid. For $10 < Re_r < 500$, a correction to the dynamic pressure should be applied, $p_v = C_v p_i$, where

$$C_v = 1 + \frac{4}{Re_r}$$

and p_i is the dynamic pressure indicated by the probe. However, even with this correction the uncertainty (bias limit) in measured dynamic pressure will be on the order of 40% at $Re_r \approx 10$ but decreases to 1% at $Re_r \approx 500$.

In high-speed gas flows, compressibility effects near the probe leading edge necessitate a closer inspection of the governing equation for a pitot–static pressure probe. which states the energy balance for a perfect gas between the freestream and a stagnation point,

$$\frac{U^2}{2g_c} = c_p(T_t - T)$$

Pitot tube

For an isentropic process, the relationship between temperature and pressure can be stated as

$$\frac{T}{T_1} = \left(\frac{p}{p_1}\right)^{(k-1)/k}$$

where k is the ratio of specific heats for the gas, $k = c_p/c_v$. The Mach number of a moving fluid relates its local velocity to the local speed of sound,

$$M = \frac{U}{a}$$

where the acoustic wave speed, or speed of sound, is defined for a perfect gas as

$$a = \sqrt{kRTg_c}$$

Pitot tube

where T is the absolute temperature of the gas. Combining equations and using a binomial expansion yields the relationship between total pressure and static pressure in a moving compressible flow,

$$p_v = p_t - p = \frac{1}{2g_c}\rho U^2[1 + M^2/4 + (2-k)M^4/24) + \cdots] \quad \text{(P2)}$$

It is apparent that equation 9.37 reduces to equation 9.31 when $M \ll 1$. The error in the estimate of p_v based on use of equation 9.31 relative to the true dynamic pressure becomes significant for $M > 0.2$ as shown in Figure 9.24.

For $M > 1$, the local velocity can be estimated by the Rayleigh relation

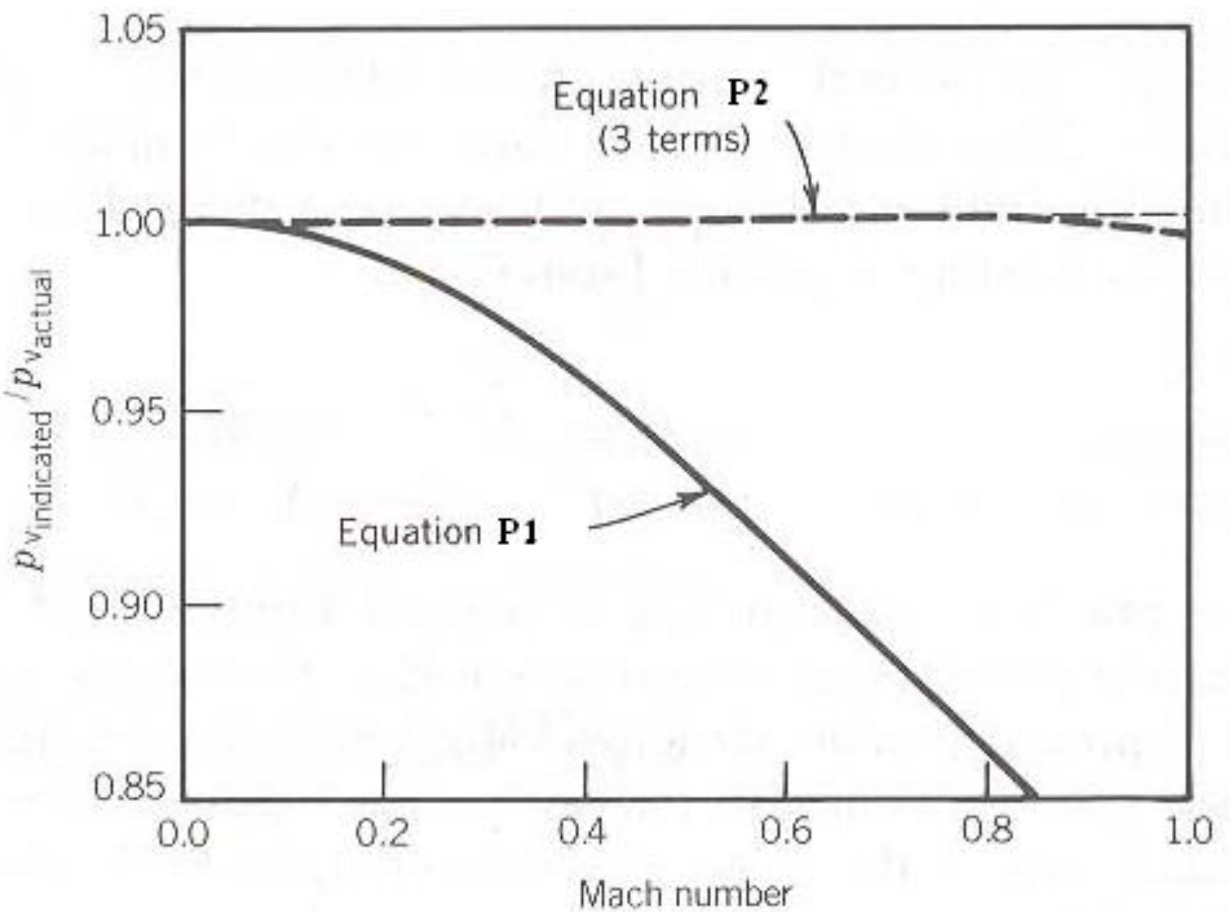
$$U = \sqrt{2g_c[k/(k-1)](p/\rho)[(p_t/p)^{(k-1)/k} - 1]}$$

where p and p_t must be measured by independent means.

Flow Measurement

Pitot tube

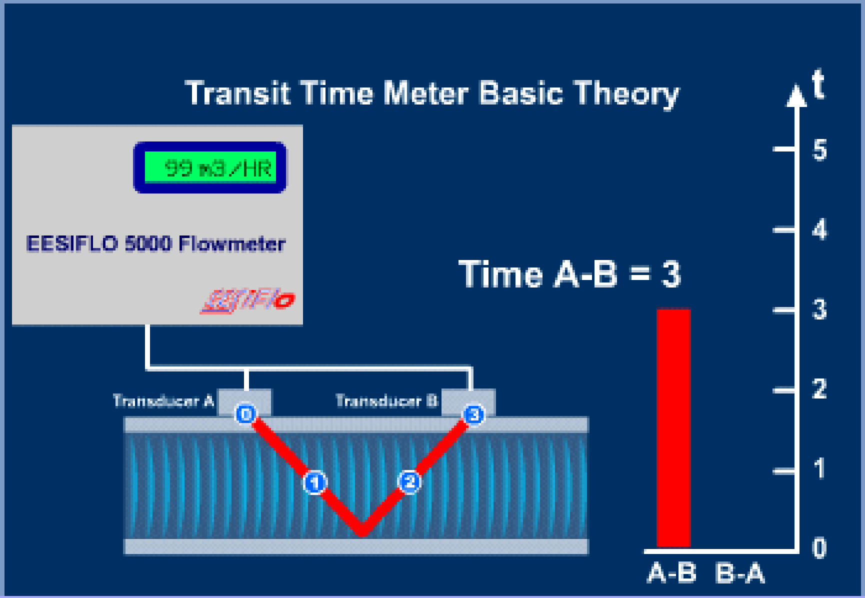
Relative error in the dynamic pressure between using equations P1 and P2 at increasing flow speeds.

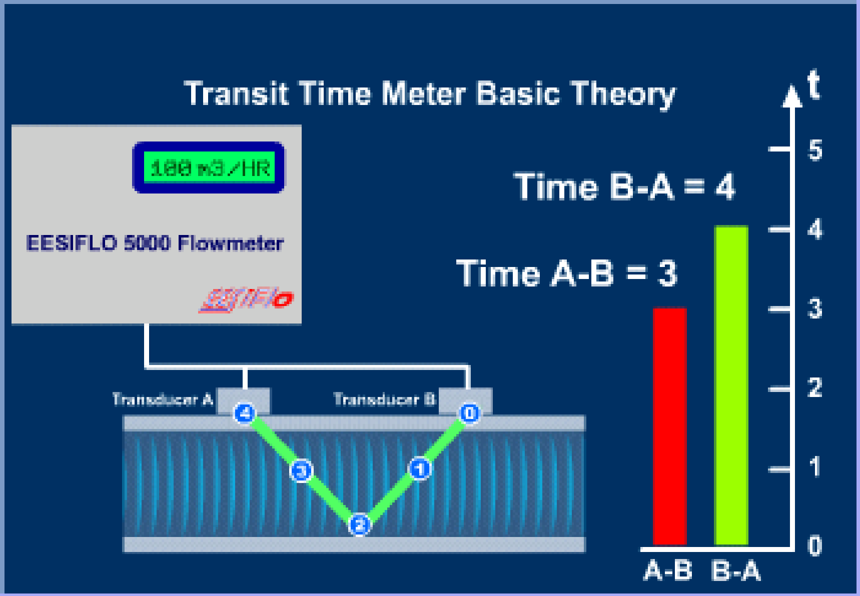


Flow Measurement

Ultrasonic

Transit Time Meter Basic Theory



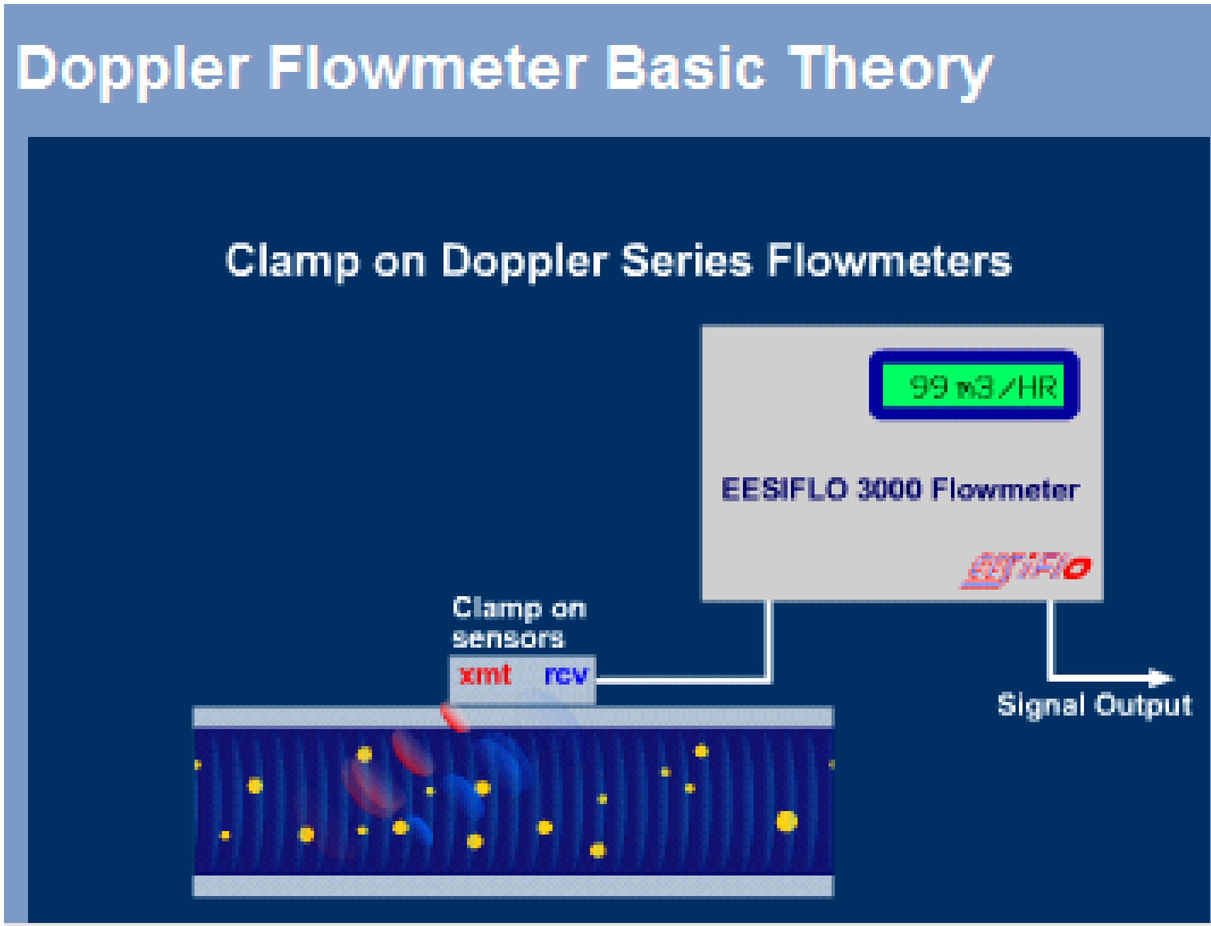


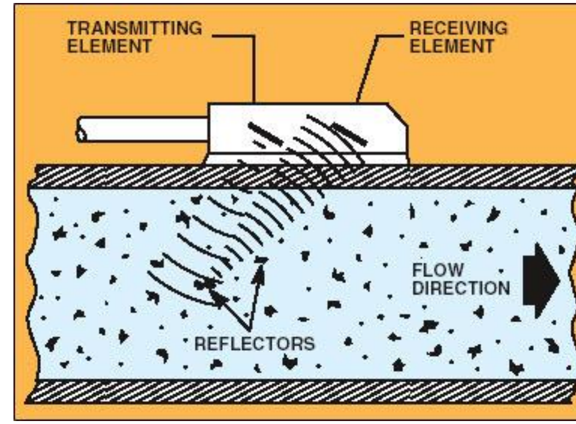
Measurements are made by sending bursts of signals through a pipe . The measurement of flow is based on the principle that sound waves travelling in the direction of flow of the fluid require less time than when travelling in the opposite direction. At zero velocity , the transit time or delta T is zero. If we know the diameter of the pipe , the pipe wall thickness and the pipe wall material the angle of refraction can be calculated automatically and we will know how far apart to space our transducers.

The difference in transit times of the ultrasonic signals is an indication for the flow rate of the fluid. Since ultrasonic signals can also penetrate solid materials, the transducers can be mounted onto the outside of the pipe. Fast Digital Signal Processors and signal analysis guarantee reliable measuring results even under difficult conditions where previously ultrasonic flowmeters have failed.

Flow Measurement

Ultrasonic

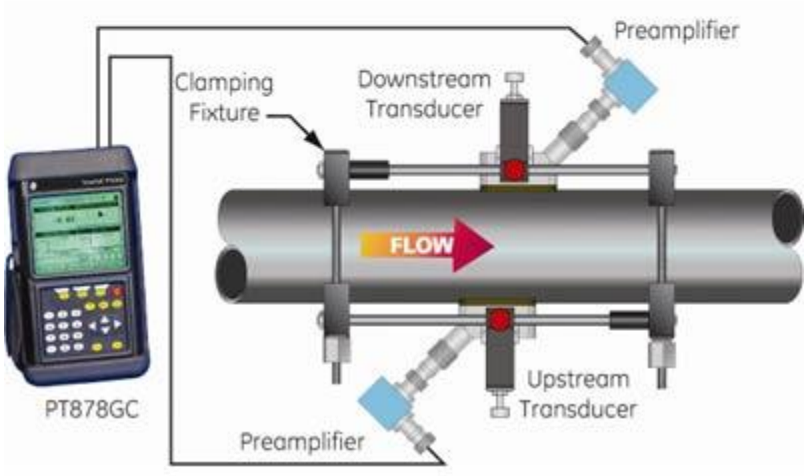




Doppler ultrasonic flowmeters operate on the Doppler shift principal , whereby the transmitted frequency is altered linearly by being reflected from particles and bubbles in the fluid. The net result is a frequency shift between transmitter and receiver frequencies that can be directly related to the flow velocity. If the pipe internal diameter is known, the volumetric flow rate can be calculated. Doppler meters require a minimum amount of solid particles or air in the line to achieve measurements.

Flow Measurement

Ultrasonic



Flow Measurement

Pressure Differential Meter

The operating principle of a pressure differential meter is based on the relationship between volume flow rate and the pressure drop $\Delta p = p_1 - p_2$, along the flow path,

$$Q \approx (p_1 - p_2)^n$$

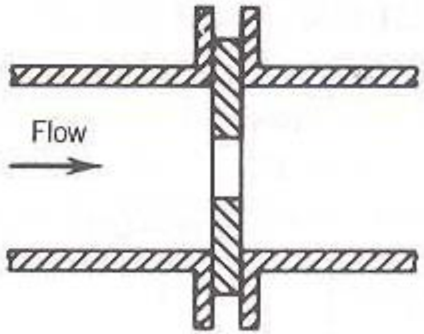
where the value of n equals one for laminar flow occurring between the pressure measurement locations and n equals one-half in fully turbulent flow.

An intentional reduction in flow area will cause a measurable local pressure drop across the flow path. The reduced flow area causes a local increase in velocity. So the pressure drop is in part due to the so-called Bernoulli effect, the inverse relationship between local velocity and pressure, as well as flow energy losses. The class of pressure differential meters that use such methods is commonly called *obstruction meters*. A special class of pressure differential meters alter the flow in such a manner as to force the flow to become laminar ($Re_{d_1} < 2000$) between two locations of pressure measurement. This class is known as *laminar flow meters*.

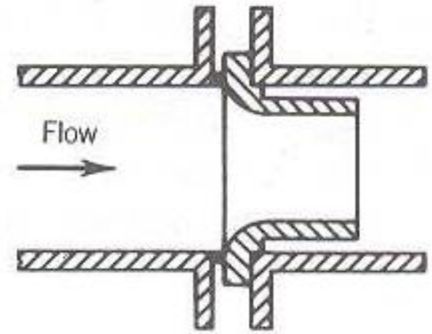
Flow Measurement

Pressure Differential Meter

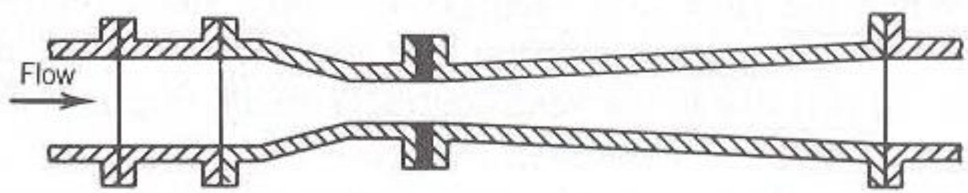
Flow area profiles of common obstruction meters.
(*a*) Square edged orifice plate meter. (*b*) ASME long radius nozzle.
(*c*) ASME Herschel venturi meter.



(*a*) Square edged orifice plate meter.



(*b*) ASME long radius nozzle.

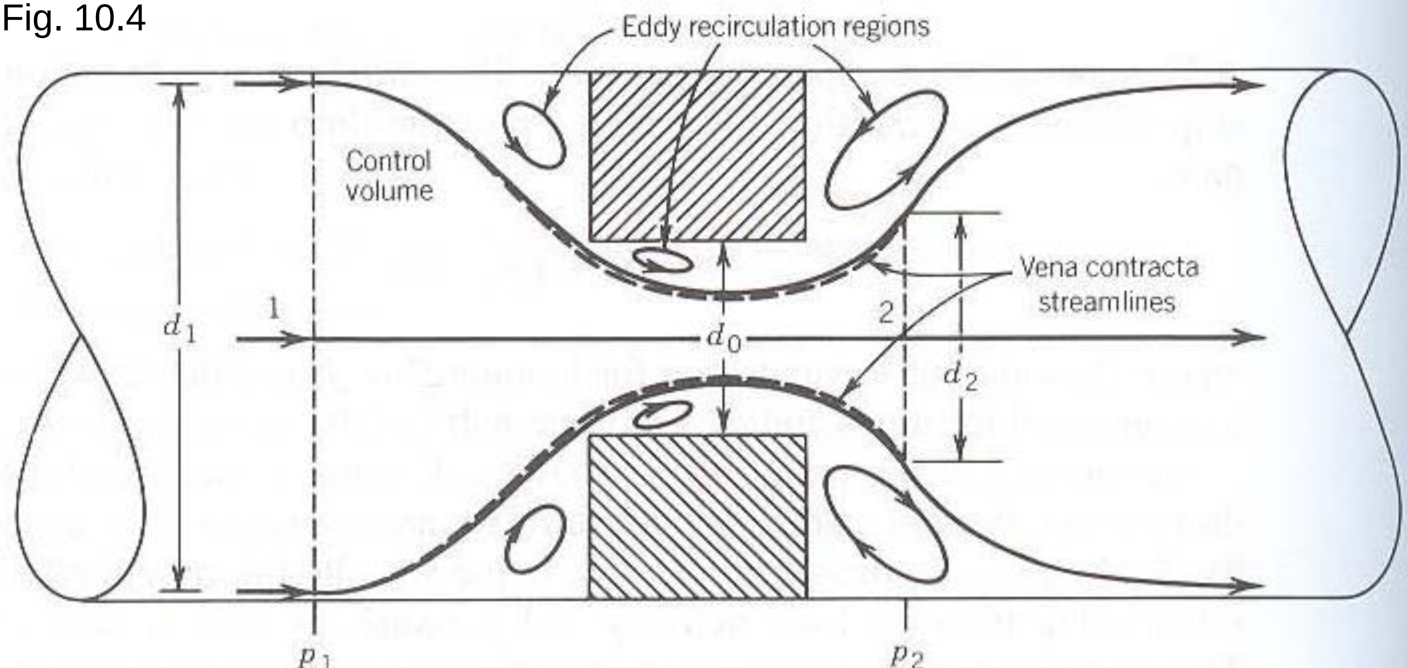


(*c*) ASME Herschel venturi meter.

Flow Measurement

Control volume concept as applied between two streamlines for flow through an obstruction meter.

Fig. 10.4



consider the energy equation written between two control surfaces for an incompressible fluid flow through the arbitrary control volume shown. It can be assumed that (1) no external energy in the form of heat is added to the flow, (2) there is no shaft work done within the control volume, and that the flow is (3) steady and (4) one-dimensional. This yields

$$\frac{p_1}{\gamma} + \frac{\overline{U}_1^2}{2g} = \frac{p_2}{\gamma} + \frac{\overline{U}_2^2}{2g} + h_{L_{1-2}} \qquad \textbf{(10.8)}$$

Pressure Differential Meter

Pressure Differential Meter

where $h_{L_{1-2}}$ denotes the head losses occurring due to frictional effects between control surfaces 1 and 2. From conservation of mass (equations 10.4 and 10.6),

$$\overline{U}_1 = \frac{\overline{U}_2 A_2}{A_1}$$

Substituting $\overline{U}_1$ into (10.8) and rearranging yields the incompressible volume flow rate,

$$Q_I = \overline{U}_2 A_2 = \frac{A_2}{\left[1-\left(A_2/A_1\right)^2\right]^{1/2}} \sqrt{\frac{2(p_1 - p_2)}{\rho} + 2gh_{L_{1-2}}} \tag{10.9}$$

where the subscript I is used only to emphasize that (10.9) yields an incompressible flow rate. Later we drop the subscript.

When the flow area changes abruptly, the effective flow area immediately downstream of the alteration will not necessarily be the same as the pipe flow area. This is due to the vena contracta effect, originally investigated by Jean Borda (1733–1799) and illustrated in Figure 10.4. This effect is brought about by an inability of a fluid to expand immediately upon encountering an area expansion due to the inertia of each fluid particle. This forms a central core flow bounded by regions of slower moving recirculating eddies. As a consequence, the pressure sensed

Flow Measurement

Pressure Differential Meter

with pipe wall taps located within the vena contracta region will correspond to the higher moving velocity within the vena contracta of unknown flow area, A_2. The unknown vena contracta area will be accounted for by introducing a contraction coefficient C_c, where $C_c = A_2/A_0$, into (10.9). This yields

$$Q_I = \frac{C_c A_0}{\left[1-\left(C_c A_0 / A_1\right)^2\right]^{1/2}} \sqrt{\frac{2\Delta p}{\rho} + 2gh_{L_{1-2}}} \qquad (10.10)$$

The frictional head losses can be incorporated into a friction coefficient, C_f, such that (10.10) becomes

$$Q_I = \frac{C_f C_c A_0}{\left[1-\left(C_c A_0 / A_1\right)^2\right]^{1/2}} \sqrt{\frac{2\Delta p}{\rho}} \qquad (10.11)$$

For convenience, the coefficients are factored out of (10.11) and replaced by a single coefficient known as the discharge coefficient, C, and (10.11) becomes

$$Q_I = CEA \sqrt{\frac{2\Delta p}{\rho}} \qquad (10.12)$$

Pressure Differential Meter

where E, known as the velocity of approach factor, is defined by

$$E \equiv \frac{1}{\left[1-\left(A_0/A_1\right)^2\right]^{1/2}} = \frac{1}{(1-\beta^4)^{1/2}} \tag{10.13}$$

with $\beta \equiv d_0/d_1$. In engineering handbooks, the product CE is often represented by the flow coefficient, K_0.

The discharge coefficient can be defined as the ratio of the actual flow rate through a meter to the ideal flow rate possible for the pressure drop measured. As shown, it is derived from frictional effects and vena contracta effects. Both effects alter the flow rate from ideal flow concepts. Due to its nature, C will depend on the flow Reynolds number and the β ratio, d_0/d_1, for each particular obstruction flow meter design. Because the magnitude of the vena contracta and head loss effects must vary along the length of a meter, the flow rate estimate based on pressure drop is very sensitive to pressure tap location, and consistency in tap placement is imperative for correct operation [2].

Pressure Differential Meter

Compressibility Effects

In compressible gas flows, compressibility effects change the value of the discharge coefficient. Rather than modify C, it is customary to introduce the compressible adiabatic expansion factor, Y, defined as the ratio of the actual compressible volume flow rate, Q, divided by the incompressible flow rate Q_I. Combining with (10.12) yields

$$Q = YQ_I = CEAY\sqrt{\frac{2\Delta p}{\rho_1}} \tag{10.14}$$

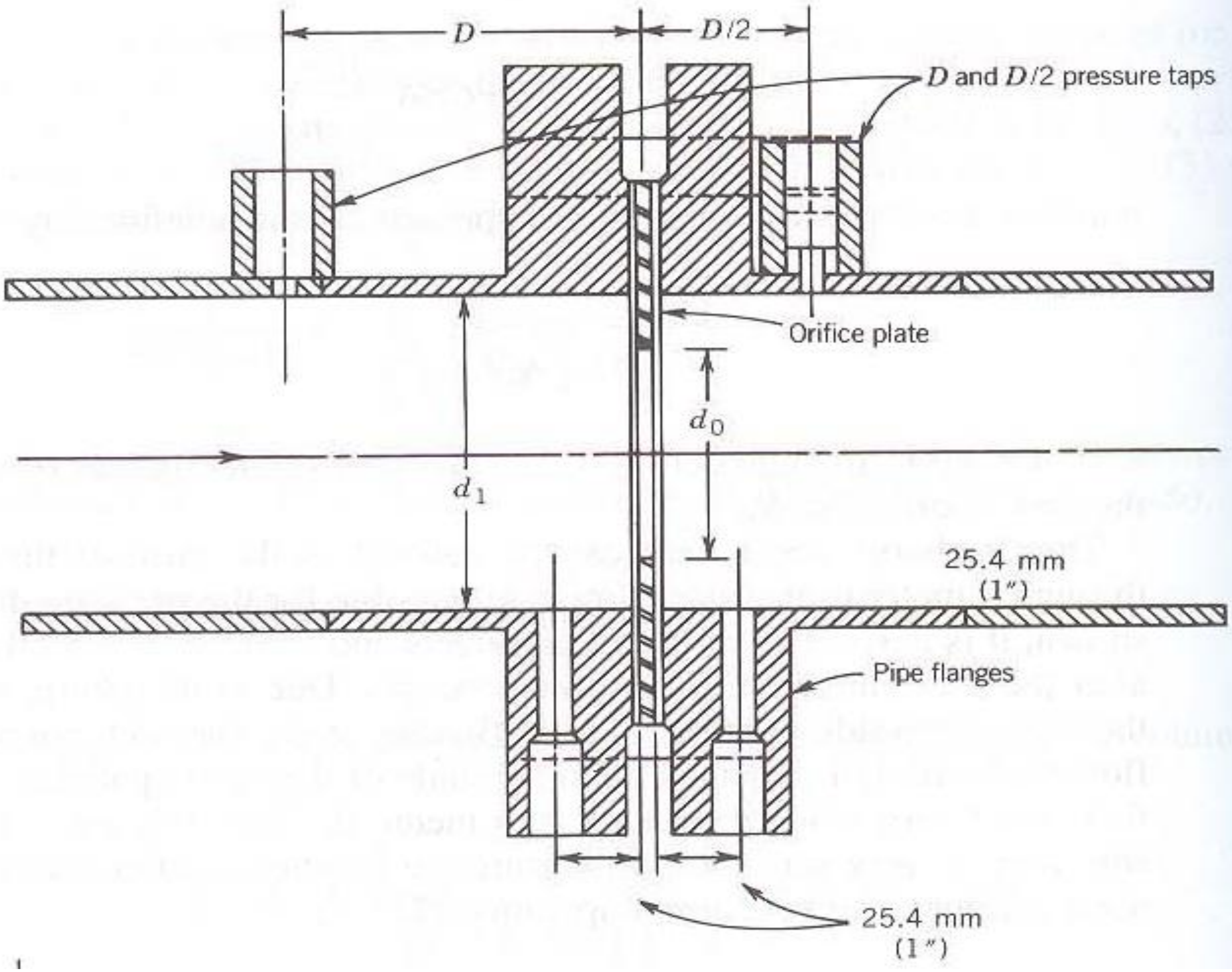
Equation 10.14 represents a general form of the working equation for obstruction meter volume flow rate determination.

The value for the expansion factor, Y, depends on several values: the β ratio, the particular gas specific heat ratio, k, and the relative pressure ratio across the meter, $(p_1 - p_2)/p_1$, for a particular meter type. As a general rule, compressibility effects become important when $(p_1 - p_2)/p_1 \geq 0.1$. Note that when $Y \approx 1$, equations 10.12 and 10.14 become identical.

Flow Measurement

Square-edged orifice Meter

FIGURE 10.5 Square-edged orifice meter installed in a pipeline with optional 1D and $\frac{1}{2}$D, and flange pressure taps shown. Relative flow pressure drop along pipe axis is shown.



Flow Measurement

Square-edged orifice Meter

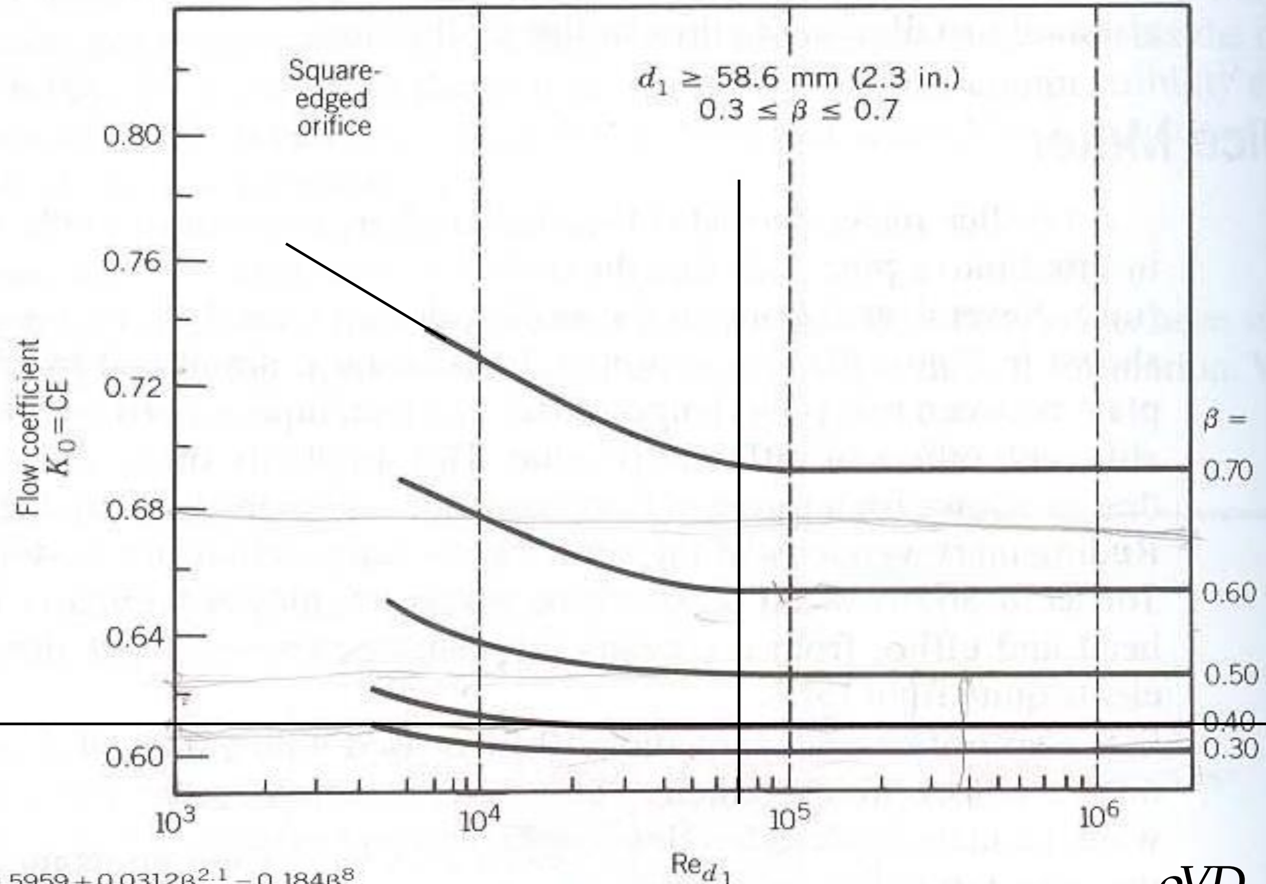
For an orifice plate, equation 10.14 is used with values of A and β being based on the orifice hole diameter. The exact location of the pressure taps is crucial when tabulated values for flow coefficient and expansion factor are used. Standard pressure tap locations include (1) flange taps where pressure tap centers are located 25.4 mm (1 in.) upstream and 25.4 mm (1 in.) downstream of the nearest orifice face, and (2) taps located one pipe diameter upstream and one-half diameter downstream of the upstream orifice face. Nonstandard tap locations require on-site meter calibration.

Values for the flow coefficient as functions of β and Re_{d_1} and for the expansion factor as functions of k and $(p_1 - p_2)/p_1$ for a square-edged orifice plate are given in Figures 10.6 and 10.7 based on the use of flange taps. Uncertainty bias limits for discharge coefficient [12] are about 0.6% of C for $0.2 \le \beta \le 0.6$ and β% of C for all $\beta > 0.6$. Bias limits for the expansion factor are about $(4(p_1 - p_2)/p_1)$% of Y. While the orifice plate represents a relatively inexpensive flow meter choice that provides an easily measurable pressure drop, it introduces a large permanent pressure loss, $(\Delta p)_{loss}$ into the flow system. The magnitude of pressure drop is illustrated in Figure 10.5 with the pressure loss estimated from Figure 10.8.

Flow Measurement

Square-edged orifice Meter

FIGURE 10.6 Flow coefficients for a square-edged orifice meter having flange pressure taps. (Compiled from data in [2]).



$$K_0 = \frac{1}{(1-\beta^4)^{1/2}}(0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + B_1 d_1^{-1}\beta^4(1-\beta^4)^{-1} - B_2 d_1^{-1}\beta^3 + 91.71\beta^{2.5}Re_{d_1}^{-0.75})$$

where $B_1 = 0.09$ (US) $= 2.286$ (SI) $\quad B_2 = 0.0337$ (US) $= 0.8560$ (SI)

$$Re = \frac{\rho V D}{\mu}$$

Flow Measurement

Square-edged orifice Meter

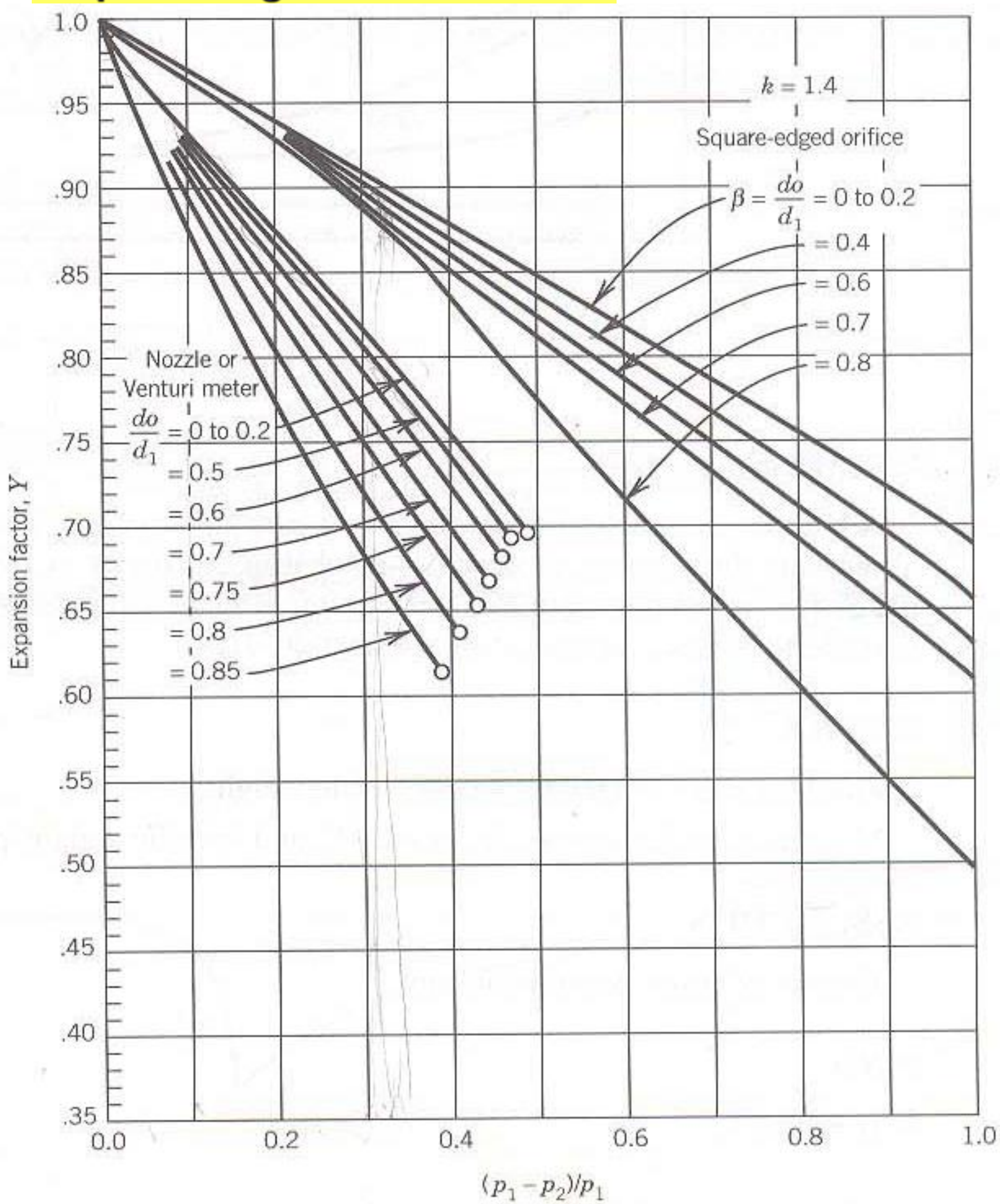


FIGURE 10.7 Expansion factors for common obstruction meters with $k = c_p/c_v = 1.4$. (Courtesy of American Society of Mechanical Engineers, New York, NY; compiled and reprinted from [2].)

Flow Measurement

Square-edged orifice Meter

Common properties for air are indicated the table below

Temperature - *t* - (^{o}C)	Density - *ρ* - (kg/m^3)	Specific heat capacity - c_p - (kJ/kg K)	Thermal conductivity - *l* - (W/m K)	Kinematic viscosity - *ν* - (m^2/s) x 10^{-6}	Expansion coefficient - *b* - (1/K) x 10^{-3}	Prandtl's number - P_r -
-150	2.793	1.026	0.0116	3.08	8.21	0.76
-100	1.980	1.009	0.0160	5.95	5.82	0.74
-50	1.534	1.005	0.0204	9.55	4.51	0.725
0	1.293	1.005	0.0243	13.30	3.67	0.715
20	1.205	1.005	0.0257	15.11	3.43	0.713
40	1.127	1.005	0.0271	16.97	3.20	0.711
60	1.067	1.009	0.0285	18.90	3.00	0.709
80	1.000	1.009	0.0299	20.94	2.83	0.708
100	0.946	1.009	0.0314	23.06	2.68	0.703
120	0.898	1.013	0.0328	25.23	2.55	0.70
140	0.854	1.013	0.0343	27.55	2.43	0.695
160	0.815	1.017	0.0358	29.85	2.32	0.69
180	0.779	1.022	0.0372	32.29	2.21	0.69
200	0.746	1.026	0.0386	34.63	2.11	0.685
250	0.675	1.034	0.0421	41.17	1.91	0.68
300	0.616	1.047	0.0454	47.85	1.75	0.68
350	0.566	1.055	0.0485	55.05	1.61	0.68
400	0.524	1.068	0.0515	62.53	1.49	0.68

Flow Measurement

Square-edged orifice Meter

In the SI system the dynamic viscosity units are **N s/m^2**, **Pa s** or **kg/m s** where

- *1 Pa s = 1 N s/m^2 = 1 kg/m s*

The dynamic viscosity is also often expressed in the metric CGS (centimeter-gram-second) system as ***g/cm.s***, ***dyne.s/cm^2*** or ***poise (p)*** where

- *1 poise = dyne s/cm^2 = g/cm s = 1/10 Pa s*

For practical use the *Poise* is to large and it's usual divided by *100* into the smaller unit called the ***centiPoise (cP)*** where

- *1 p = 100 cP*

Water at *68.4^{o}F (20.2^{o}C)* has an absolute viscosity of one - *1 - centiPoise*.

Kinematic Viscosity

is the ratio of absolute or dynamic viscosity to density - a quantity in which no force is involved. Kinematic viscosity can be obtained by dividing the absolute viscosity of a fluid with it's mass density

$$v = \mu / \rho \qquad (2)$$

where

v = kinematic viscosity

μ = absolute or dynamic viscosity

ρ = density

In the SI-system the theoretical unit is m^2/s or commonly used ***Stoke (St)*** where

- *1 St = 10^{-4} m^2/s*

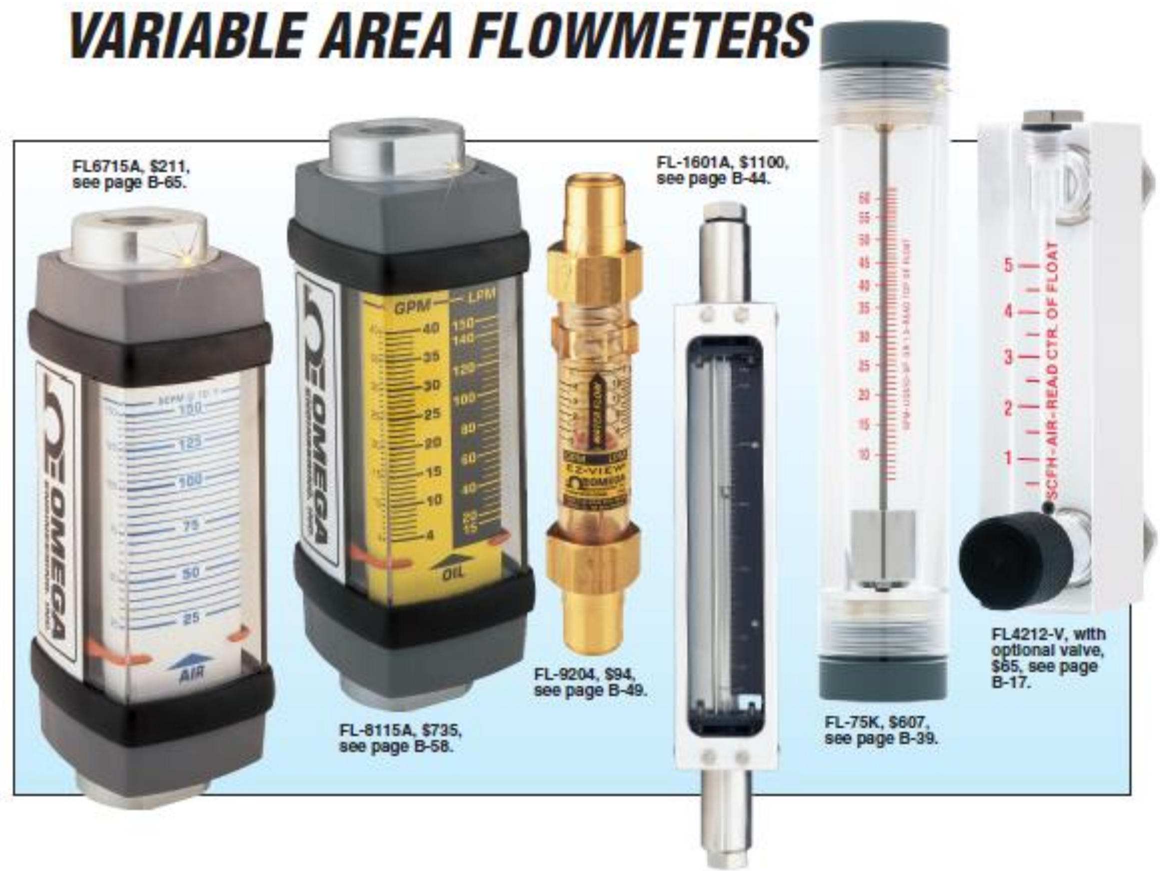
Since the *Stoke* is an unpractical large unit, it is usual divided by *100* to give the unit called ***Centistokes (cSt)*** where

- *1 St = 100 cSt*
- *1 cSt = 10^{-6} m^2/s*

Since the specific gravity of water at *68.4^{o}F (20.2^{o}C)* is almost *one (1)*, the kinematic viscosity of water at *68.4^{o}F* is for all practical purposes *1.0 cSt*.

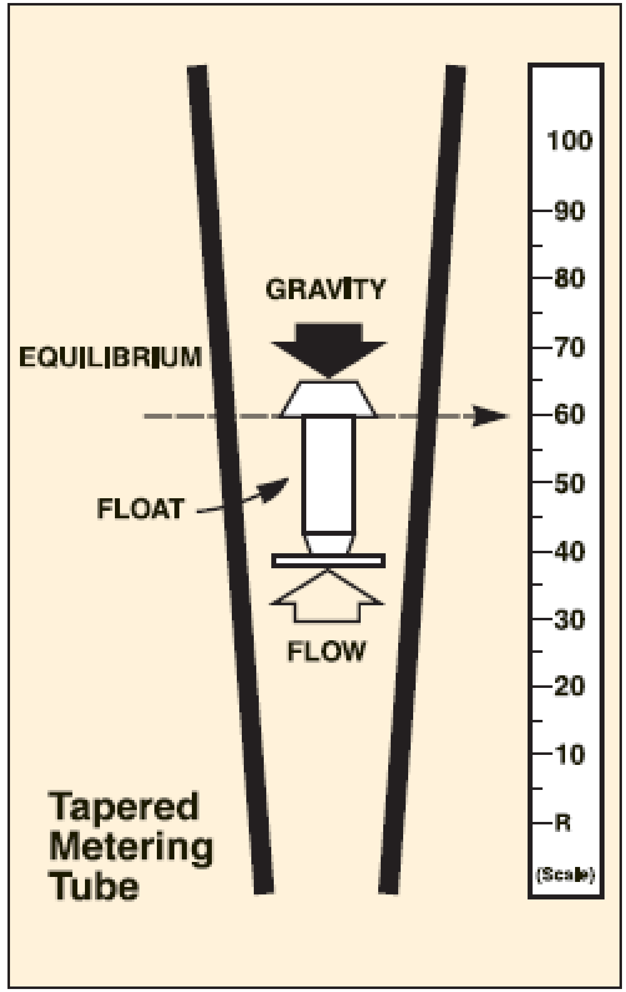
Flow Measurement

Rotameter



Flow Measurement

Rotameter



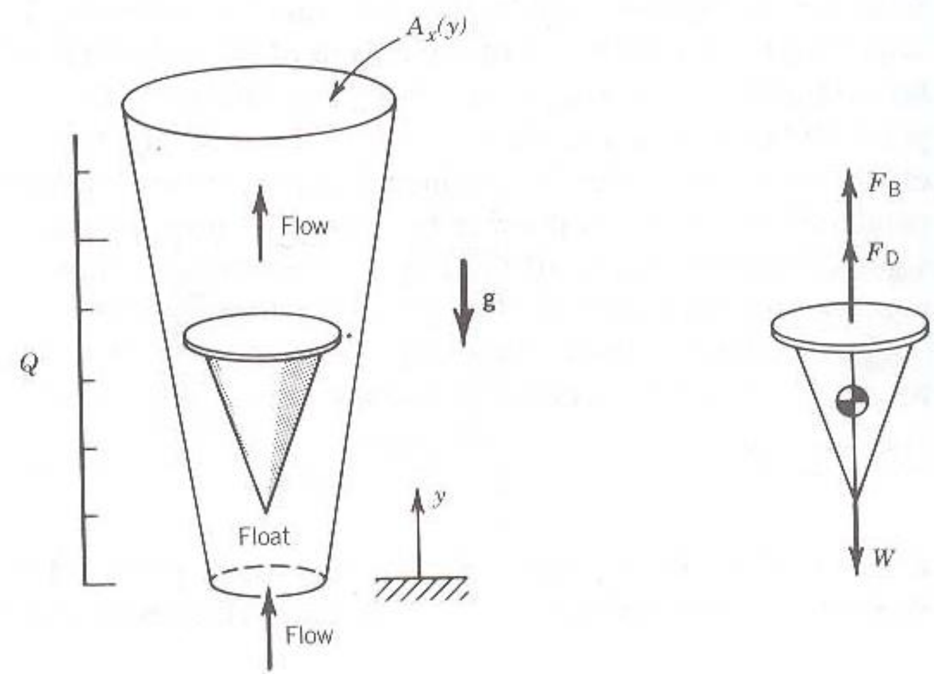
Variable area flowmeter, also called a rotameter, has a float that moves up or down in a tapered tube. The distance it moves is proportional to the liquid flowrate and the annular area between the float and the tube well.

Flow Measurement

Rotameter

The rotameter remains a widely used insertion meter for flow rate indication. As depicted in Figure 10.18, the meter consists of a float within a vertical tube, tapered to an increasing cross-sectional area at its outlet. Flow entering through the bottom passes over the float, which is free to move. The basic principle of the device is based on the simple balance between the drag force, F_D, and the weight, W, and buoyancy forces, F_B, acting on the float in the moving fluid. It is the drag force on the float that varies with the average velocity over the float.

FIGURE 10.18 Rotameter.



Rotameter

The force balance in the vertical direction y yields

$$\Sigma F_y = 0 = -F_D + W - F_B \tag{10.29}$$

or with $F_D = C_D \frac{1}{2} \rho A_X \overline{U}^2$, $W = \rho_b V_b$, and $F_B = \rho V_b$,

$$C_D \frac{1}{2} \rho A_x \overline{U}^2 = g(\rho_b - \rho) V_b \tag{10.30}$$

where

ρ_b = density of float
ρ = density of fluid
C_D = drag coefficient of the float; $C_D = f(\mathrm{Re})$
A_x = tube cross-sectional area
$\overline{U}$ = average velocity past the float
V_b = volume of float

In operation, the float will rise to some position within the tube at which such a force balance exists. The height of this position increases with flow velocity and, hence, flow rate. This flow rate is found by

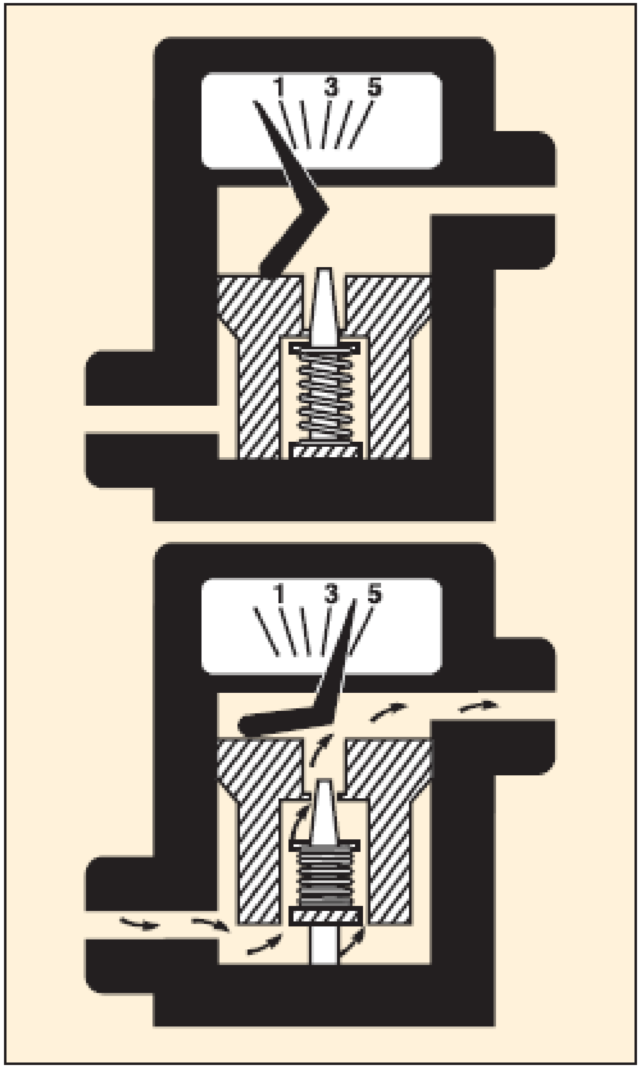
$$Q = \overline{U} A_a(y) = \left| C_D K_1 \right|^{1/2} A_a(y) \tag{10.31}$$

Flow Measurement

Rotameter

where $A_a(y)$ is the annular area between the float and the tube, which depends on the height of the float in the tube, and K_1 is a constant depending on the meter design and fluid in use. Since annular area is a function of float position within the vertical tube, the float's vertical position gives a direct measure of flow rate which can be read from a graduated scale, electronically sensed with an optical cell, or detected magnetically. Floats with sharp edges are less sensitive to fluid viscosity changes with temperature. Rotameters are used in noncritical applications where accuracy is not of prime concern. Uncertainty bias limits of ±2% of flow rate

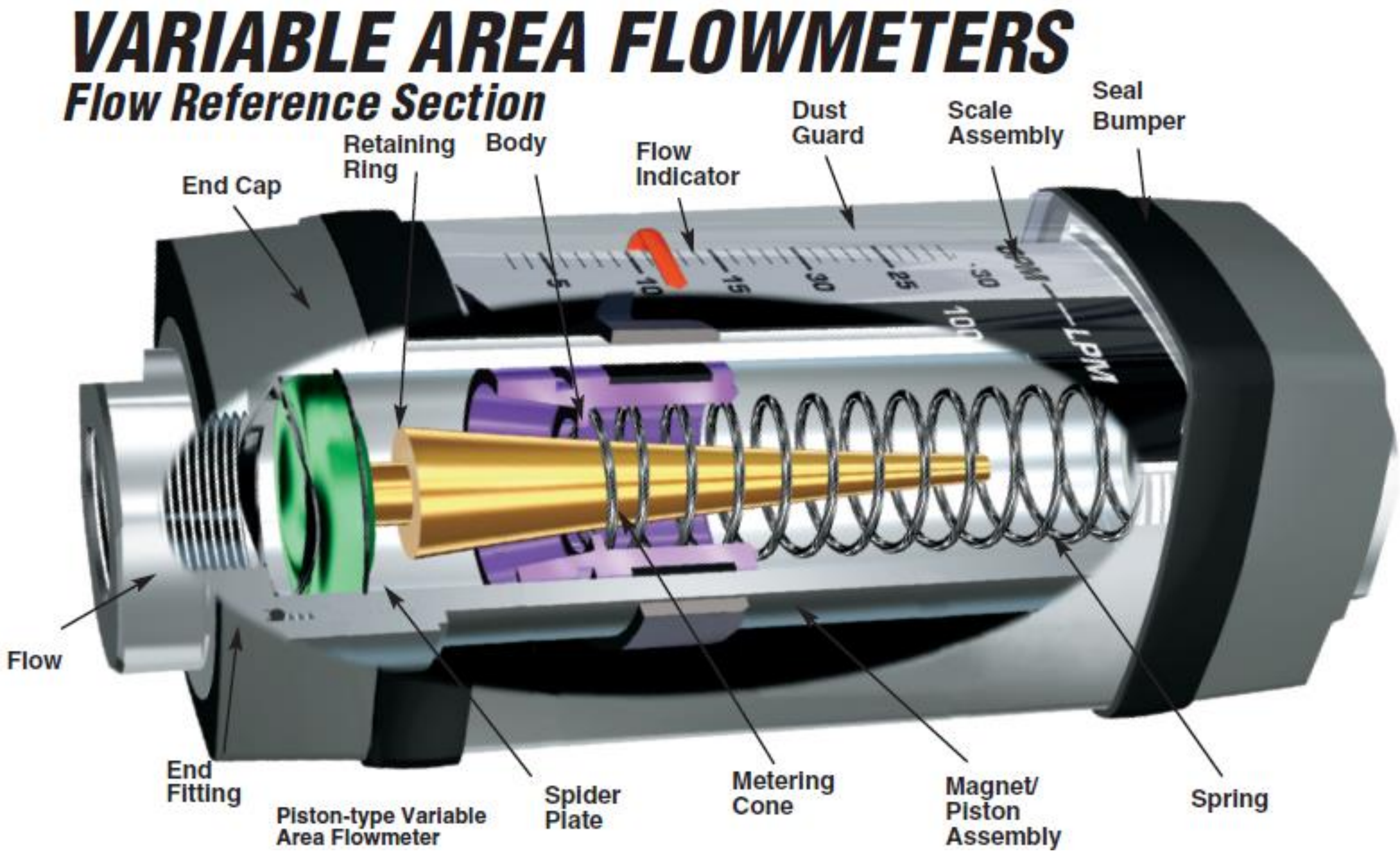
Rotameter



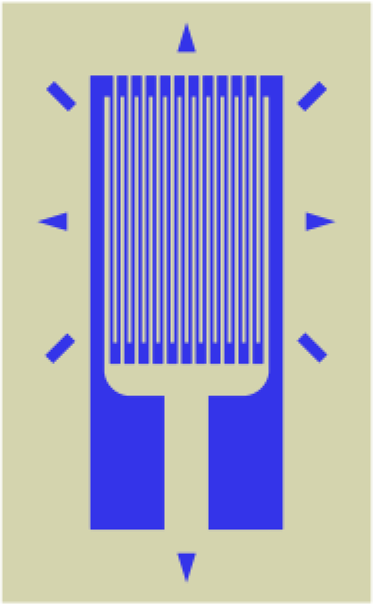
Flowmeters Operating Principle of FL-O Series

Flow Measurement

Rotameter



Strain Measurement

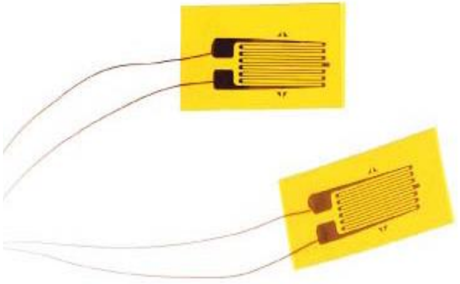


When external forces are applied to a stationary object, stress and strain are the result. Stress is defined as the object's internal resisting forces, and strain is defined as the displacement and deformation that occur. For a uniform distribution of internal resisting forces, stress can be calculated (Figure 2-1) by dividing the force (F) applied by the unit area (A):

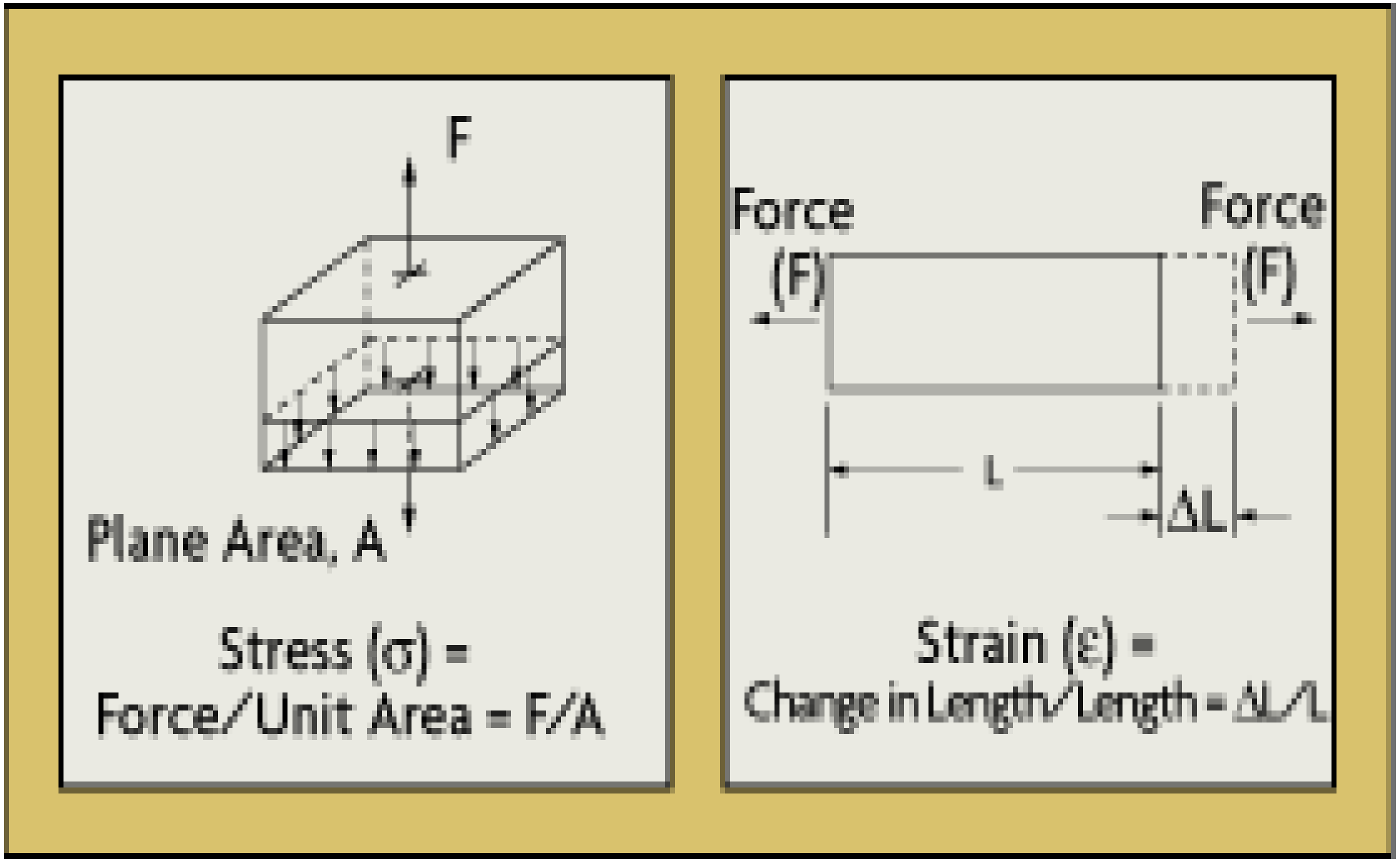
$$\text{Stress } (\sigma) = F/A$$

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain is calculated by dividing the total deformation of the original length by the original length (L):

$$\text{Strain } (\varepsilon) = (\Delta L)/L$$

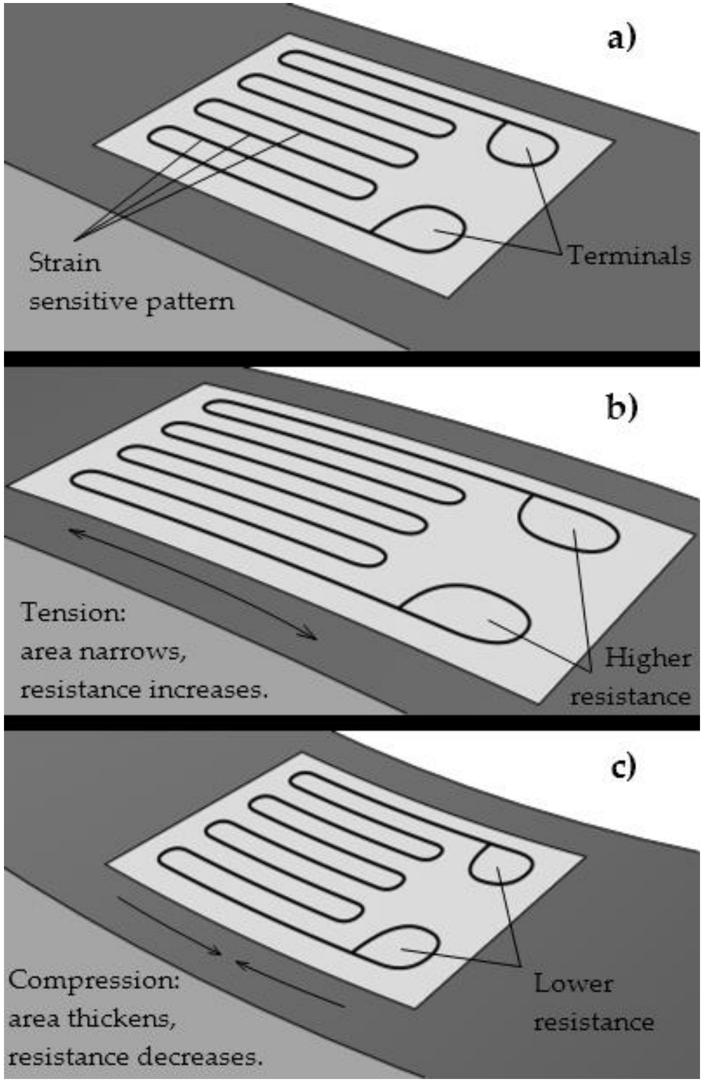


Strain Measurement



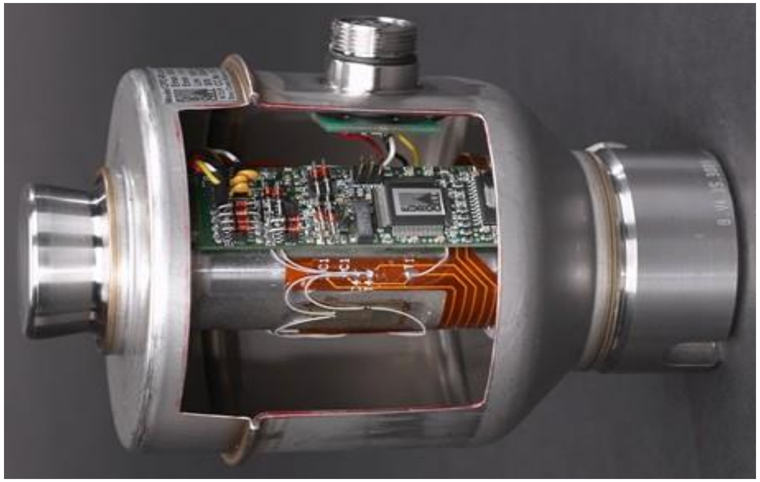
Definitions of Stress & Strain

Strain Measurement



Foil strain gauges are used in many situations. Different applications place different requirements on the gauge. In most cases the orientation of the strain gauge is significant.

Strain gauge based technology is utilized commonly in the manufacture of pressure sensors. The gauges used in pressure sensors themselves are commonly made from silicon, polysilicon, metal film, thick film, and bonded foil.



Digital Load Cell

Strain Measurement

Strain gauge is a resistive elastic unit whose change in resistance is a function of applied strain.

$$\frac{dR}{R} = \varepsilon . GF \qquad 4.1$$

where *R* is the resistance,

ε is the strain,

and *GF* is the strain sensitivity factor of the gage material
(GF, gage factor value normally is suppied by manufacturer)

A wire strain gage is made by a resistor, usually in metal foil form, bonded on an elastic backing. Its principle is based on fact that the resistance of a wire increases with increasing strain and decreases with decreasing strain, as first reported by Lord Kelvin in 1856.

Strain Measurement

Consider a wire strain gage, as illustrated above. The wire is composed of a uniform conductor of electric resistivity ρ with length *l* and cross-section area *A*. Its resistance *R* is a function of the geometry given by

$$R = \rho \frac{l}{A} \qquad 4.2$$

The resistance change rate is a combination effect of changes in length, cross-section area, and resistivity.

$$dR = \frac{\rho}{A} dl - \frac{\rho l}{A^2} dA + \frac{l}{A} d\rho \qquad 4.3$$

$$\frac{dR}{R} = \frac{dl}{l} - \frac{dA}{A} + \frac{d\rho}{\rho} \qquad 4.4$$

Ex4.1 Determine the total resistance of a copper wire having a diameter of 1 mm and a length of 5 cm. The resistivity of copper is 1.7×10^{-8} Ω-m.

Ex4.2 A very common material for the construction of strain gauges is the alloy Constantan (55% copper with 45% nickle), having resistivity of 49 x10^{-8} Ω-m. A typical strain gauge might have a resistance of 120 Ω. What length of con-Stantan wire of diameter 0.025 mm would yield a resistance of 120 Ω.

Strain Measurement

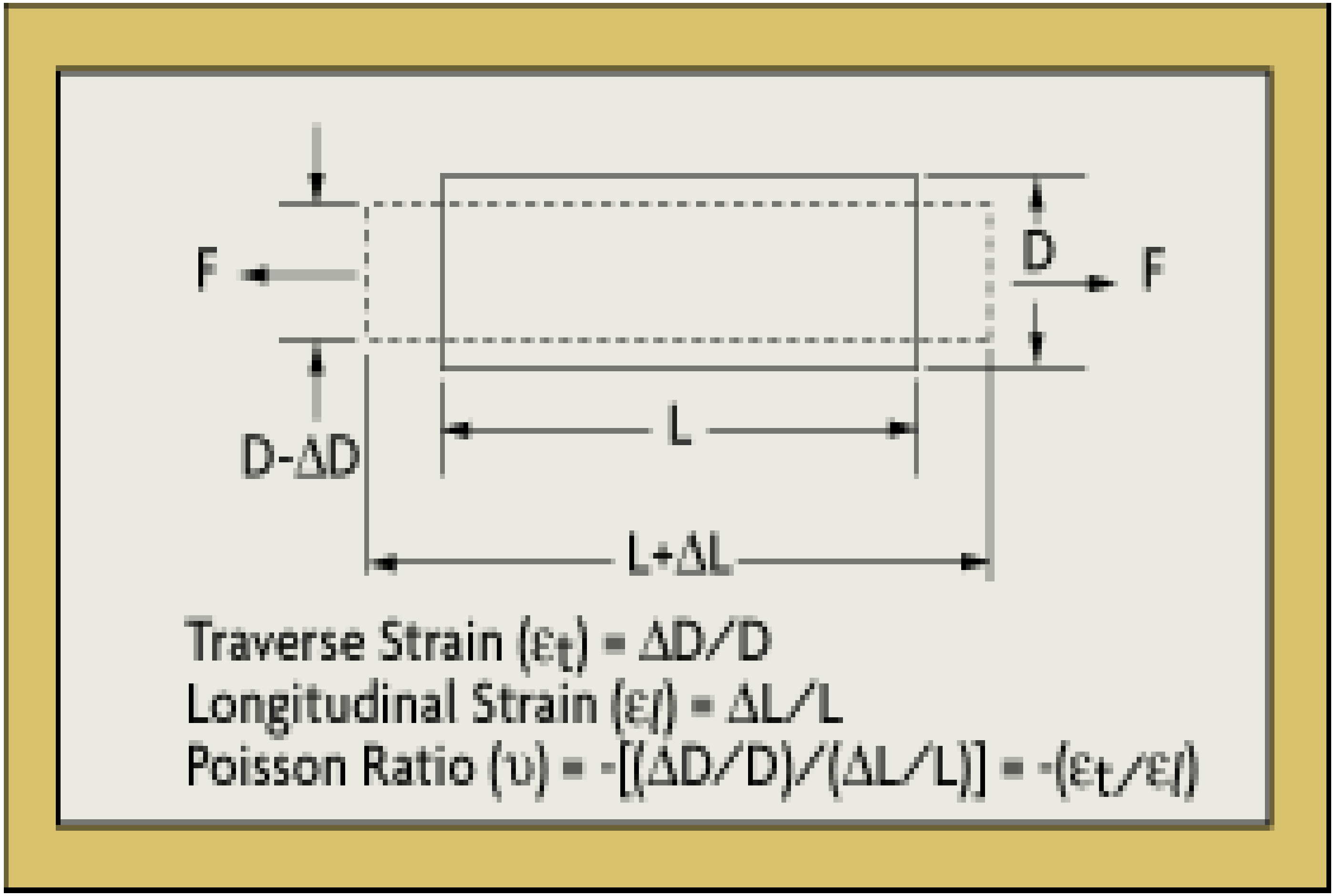
When the strain gage is attached and bonded well to the surface of an object, the two are considered to deform together. The strain of the strain gage wire along the longitudinal direction is the same as the strain on the surface in the same direction.

$$\varepsilon_l = \frac{dl}{l} \qquad 4.5$$

However, its cross-sectional area will also change due to the Poisson's ratio. Suppose that the wire is cylindrical with initial radius *r*. The normal strain along the radial direction is,

$$\varepsilon_\gamma = \frac{dr}{r} = -\nu \cdot \varepsilon_l = -\nu \frac{dl}{l} \qquad 4.6$$

Strain Measurement



Poisson Strain

Strain Measurement

The change rate of cross-section area is twice as the radial strain, when the strain is small.

$$\frac{dA}{A} = -2\nu\frac{dl}{l} \qquad 4.7$$

The resistance change rate becomes

$$\frac{dR}{R} = \frac{dl}{l} - \frac{dA}{A} + \frac{d\rho}{\rho} = (1+2\nu)\frac{dl}{l} + \frac{d\rho}{\rho}$$

$$= (1+2\nu)\varepsilon_l + \frac{d\rho}{\rho} \qquad 4.8$$

Strain Measurement

For a given material, the sensitivity of resistance versus strain can be calibrated by the following equation.

$$\mathrm{GF} = S = \frac{dR/R}{\varepsilon_l} = 1 + 2\nu + \frac{d\rho/\rho}{\varepsilon_l} \qquad 4.9$$

When the sensitivity factor *S* or Gauge Factor *GF* is given, (usually provided by strain gage vendors) the average strain at the point of attachment of the strain gage can be obtained by measuring the change in electric resistance of the strain gage.

$$\varepsilon_l = \frac{dR/R}{S} \approx \frac{\Delta R}{SR} \qquad 4.10$$

Measuring Circuits

In order to measure strain with a bonded resistance strain gage, it must be connected to an electric circuit that is capable of measuring the minute changes in resistance corresponding to strain. Strain gage transducers usually employ four strain gage elements electrically connected to form a Wheatstone bridge circuit (Figure 4.1). A Wheatstone bridge is a divided bridge circuit used for the measurement of static or dynamic electrical resistance. The output voltage of the Wheatstone bridge is expressed in millivolts output per volt input. The Wheatstone circuit is also well suited for temperature compensation.

In Figure 4.1, if R1, R2, R3, and R4 are equal, and a voltage, VIN, is applied between points A and C, then the output between points B and D will show no potential difference. However, if R4 is changed to some value which does not equal R1, R2, and R3, the bridge will become unbalanced and a voltage will exist at the output terminals. In a so-called G-bridge configuration, the variable strain sensor has resistance Rg, while the other arms are fixed value resistors. The sensor, however, can occupy one, two, or four arms of the bridge, depending on the application. The total strain, or output voltage of the circuit (VOUT) is equivalent to the difference between the voltage drop across R1 and R4, or Rg. This can also be written as:

Strain Measurement

$$V_{OUT} = V_{CD} - V_{CB}$$

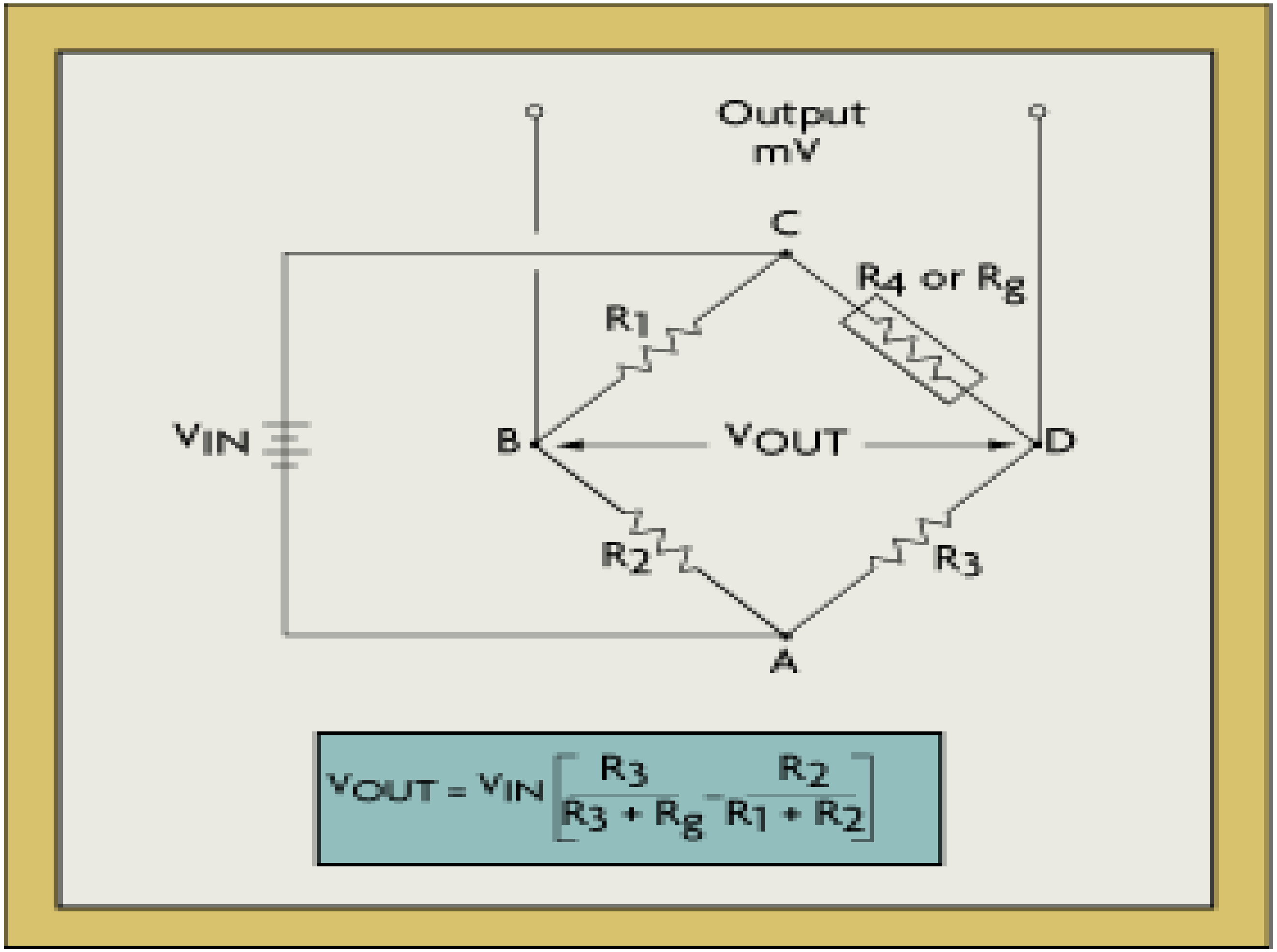


Figure 4.1: Wheatstone Bridge Circuit Schematic

Strain Measurement

A strain gauge, having a gauge factor of 2, is mounted on a rectangular steel bar (E_m = 200 x 10^6 kN/m2), as show on Fig 1. The bar is 3 cm. wide and 1 cm high, and is subjected to a tensile force of 30 kN. Determine the resistance change of the strain gauge, if the resistance of the gauge was 120 Ω in the absence of the axial load.

Apparent Strain

Apparent strain is any change in gage resistance that is not caused by the strain on the force element. Apparent strain is the result of the interaction of the thermal coefficient of the strain gage and the difference in expansion between the gage and the test specimen. The variation in the apparent strain of various strain-gage materials as a function of operating temperature is shown in Figure 4.2.

In addition to the temperature effects, apparent strain also can change because of aging and instability of the metal and the bonding agent. Compensation for apparent strain is necessary if the temperature varies while the strain is being measured. In most applications, the amount of error depends on the alloy used, the accuracy required, and the amount of the temperature variation. If the operating temperature of the gage and the apparent strain characteristics are known, compensation is possible.

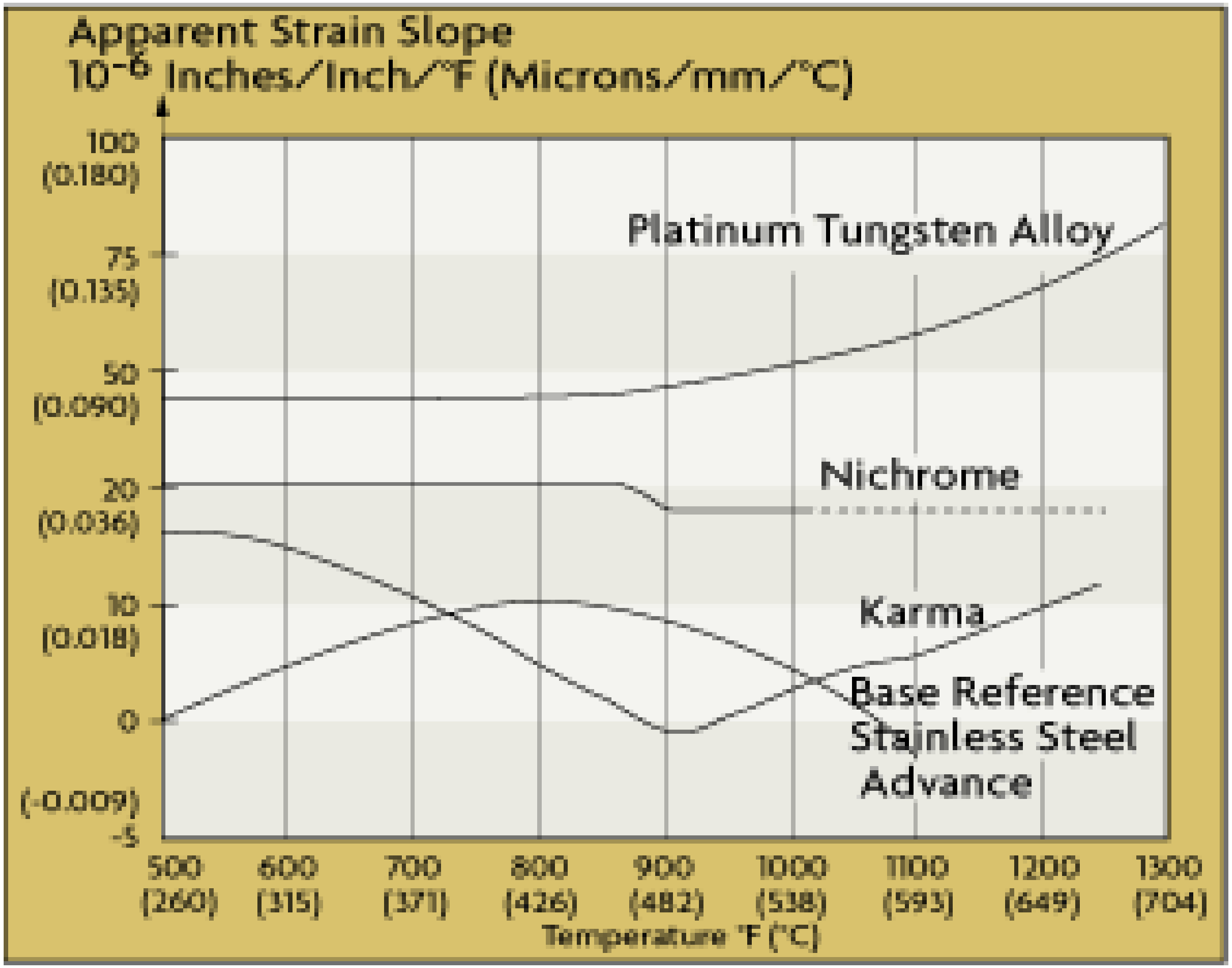


Figure 4.2: Apparent Strain Variation with Temperature

Strain Measurement

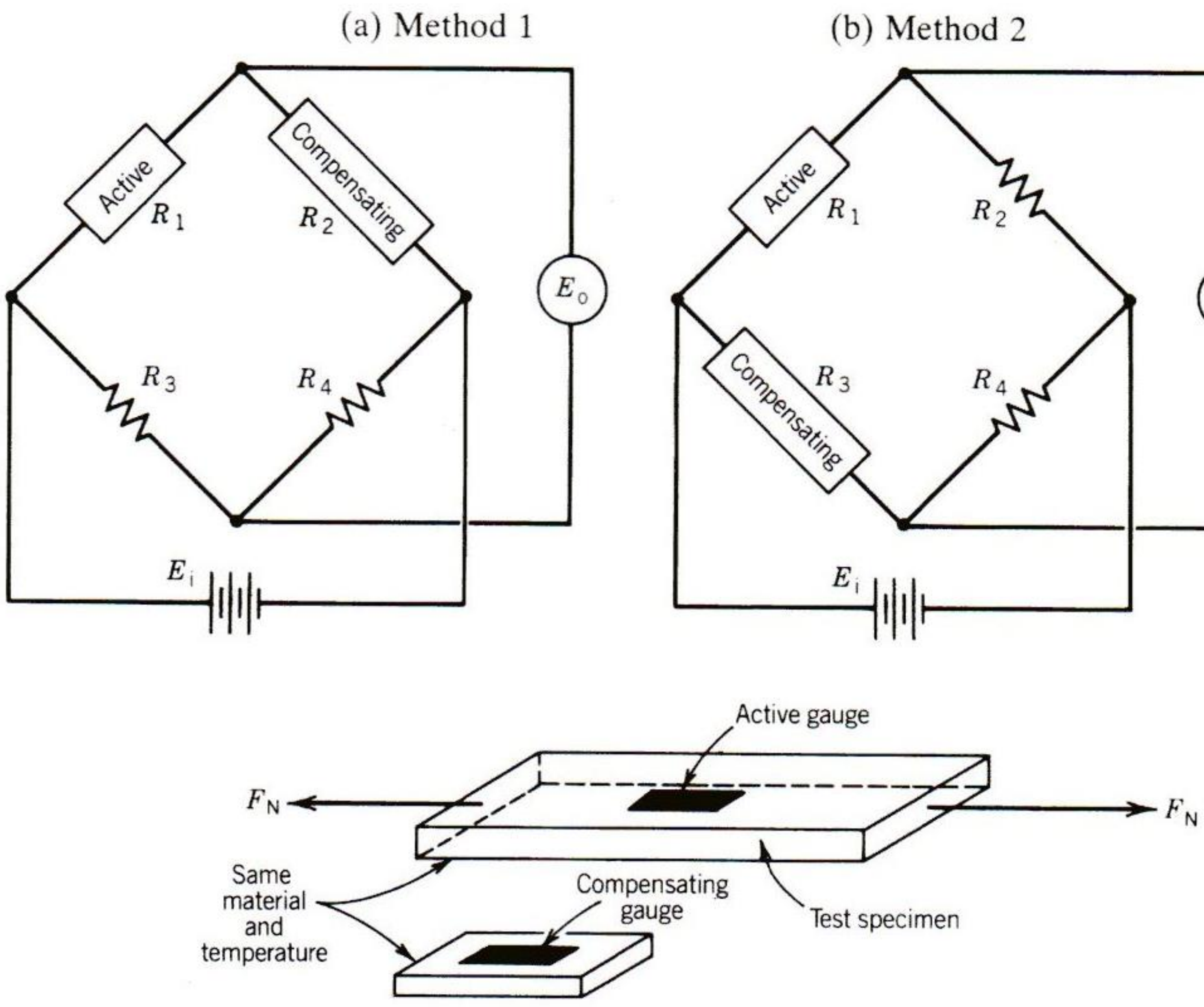


Fig 4.3 Bridge arrangements for temperature compensation

Strain Measurement

Calculate the change in length of a steel rod ($E_m = 20 \times 10^{10}$ Pa) which has a length of 0.3 m and a diameter of 5 mm. The rod supports a mass of 50 kg in a standard gravitation field in such a way that a state of uniaxial tension is created in the rod.

Strain Measurement

Compare the resistance of a volume of $\pi \times 10^{-5}$ m^3 of aluminum wire having a diameter of 2 mm, with the same volume of aluminum formed into 1-mm-diameter wire. (The resistivity of aluminum is 2.66×10^{-8} Ω-m.)

Strain Measurement

A conductor made of nickel ($\rho_c = 6.8 \times 10^{-8}$ Ω-m) has a rectangular cross section 5×2 mm and is 5 m long. Determine the total resistance of this conductor. Calculate the diameter of a 5-m-long copper wire having a circular cross-section which yields the same total resistance.

Strain Measurement

Consider a Wheatstone bridge circuit having all resistances equal to 100 Ω. The resistance R_1 is a strain gauge that cannot sustain a power dissipation of more than 0.25 W. What is the maximum applied voltage that can be used for this bridge circuit? At this level of bridge excitation, what is the bridge sensitivity?

Strain Measurement

A resistance strain gauge with $R = 120\ \Omega$ and a gauge factor of 2 is placed in an equal-arm Wheatstone bridge in which all the resistances are equal to $120\ \Omega$. If the maximum gauge current is to be 0.05 A, what is the maximum allowable bridge excitation voltage?

Strain Measurement

A strain gauge having a nominal resistance of 350 Ω and a gauge factor of 1.8 is mounted in an equal-arm bridge, which is balanced at a zero applied strain condition. The gauge is mounted on a 1-cm^2 aluminum rod, having $E_m = 70$ GPa. The gauge senses axial strain. The bridge output is 1 mV for a bridge input of 5 V. What is the applied load, assuming the rod is in uniaxial tension?

Strain Measurement

Material	Resistivity [Ω·m] at 20 °C	Temperature coefficient* [K^{-1}]	Reference
Silver	1.59×10^{-8}	0.0038	[1][2]
Copper	1.68×10^{-8}	0.0039	[2]
Gold	2.44×10^{-8}	0.0034	[1]
Aluminium	2.82×10^{-8}	0.0039	[1]
Calcium	3.36×10^{-8}	0.0041	
Tungsten	5.60×10^{-8}	0.0045	[1]
Zinc	5.90×10^{-8}	0.0037	[3]
Nickel	6.99×10^{-8}	0.006	
Iron	1.0×10^{-7}	0.005	[1]
Platinum	1.06×10^{-7}	0.00392	[1]
Tin	1.09×10^{-7}	0.0045	
Lead	2.2×10^{-7}	0.0039	[1]
Manganin	4.82×10^{-7}	0.000002	[4]
Constantan	4.9×10^{-7}	0.000008	[5]
Mercury	9.8×10^{-7}	0.0009	[4]
Nichrome[6]	1.10×10^{-6}	0.0004	[1]
Carbon (amorphous)	$5\text{-}8 \times 10^{-4}$	−0.0005	[1][7]

Strain Measurement

Carbon (graphite)[8]	$2.5\text{-}5.0\times10^{-6}$ ⊥ basal plane 3.0×10^{-3} // basal plane		[9]
Carbon (diamond)[10]	$\sim10^{12}$		[11]
Germanium[10]	4.6×10^{-1}	−0.048	[1][2]
seawater	2×10^{-1}	?	
Silicon[10]	6.40×10^{2}	−0.075	[1]
Glass	10^{10} to 10^{14}	?	[1][2]
Hard rubber	approx. 10^{13}	?	[1]
Sulfur	10^{15}	?	[1]
Paraffin	10^{17}	?	
Quartz (fused)	7.5×10^{17}	?	[1]
PET	10^{20}	?	
Teflon	10^{22} to 10^{24}	?	

*The numbers in this column increase or decrease the significand portion of the resistivity. For example, at 30 °C (303 K), the resistivity of silver is 1.65×10^{-8}. This is calculated as $\Delta\rho = \alpha \Delta T \rho_o$ where ρ_o is the resistivity at 20 °C (in this case) and α is the temperature coefficient.

Strain Measurement

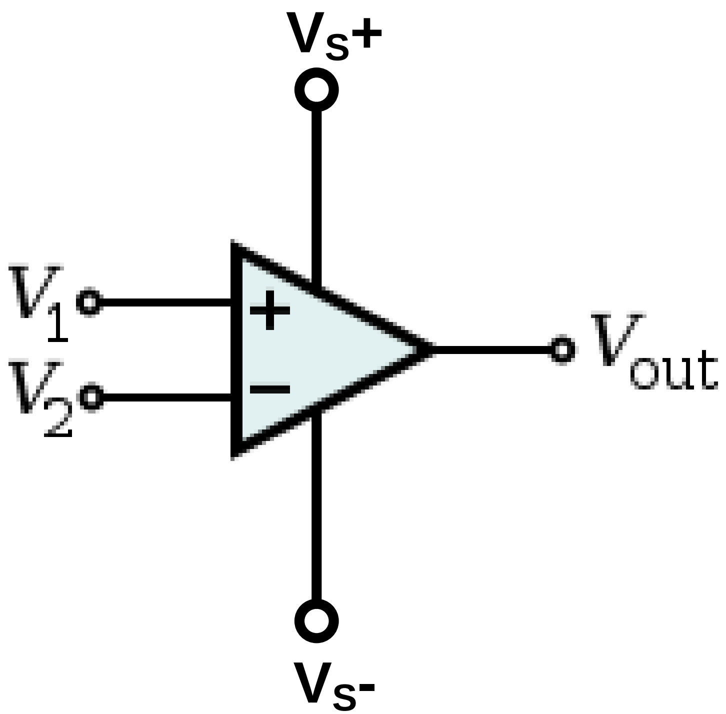
$$\varepsilon_l = \frac{dR/R}{S} \approx \frac{\Delta R}{S\,R}$$

To convert the change in resistance to strain, the sensitivity factor *S* of the strain gage material must first be determined. The sensitivity factors of common strain gage materials are listed in the following table. Platinum and Nickel which are not used in the pure form are listed for comparison purposes only.

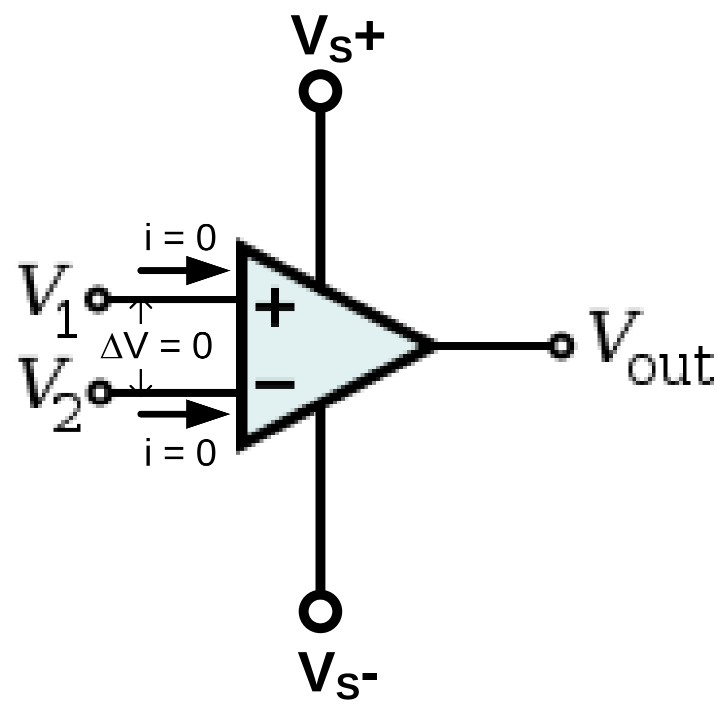
Material	Sensitivity (*S*)
Platinum (Pt 100%)	6.1
Platinum-Iridium (Pt 95%, Ir 5%)	5.1
Platinum-Tungsten (Pt 92%, W 8%)	4.0
Isoelastic (Fe 55.5%, Ni 36% Cr 8%, Mn 0.5%) *	3.6
Constantan / Advance / Copel (Ni 45%, Cu 55%) *	2.1
Nichrome V (Ni 80%, Cr 20%) *	2.1
Karma (Ni 74%, Cr 20%, Al 3%, Fe 3%) *	2.0
Armour D (Fe 70%, Cr 20%, Al 10%) *	2.0
Monel (Ni 67%, Cu 33%) *	1.9
Manganin (Cu 84%, Mn 12%, Ni 4%) *	0.47
Nickel (Ni 100%)	-12.1

* Isoelastic, Constantan, Advance, Copel, Nichrome V, Karma, Armour D, Monel, and Manganin are all trade names owned by the respective owners.

Basic Op-Amp circuit



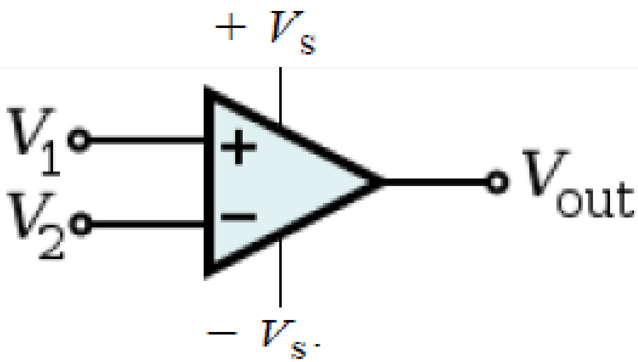
Operating Amplifier - Symbol



Ideal Op-Amp

Basic Op-Amp circuit

Comparator



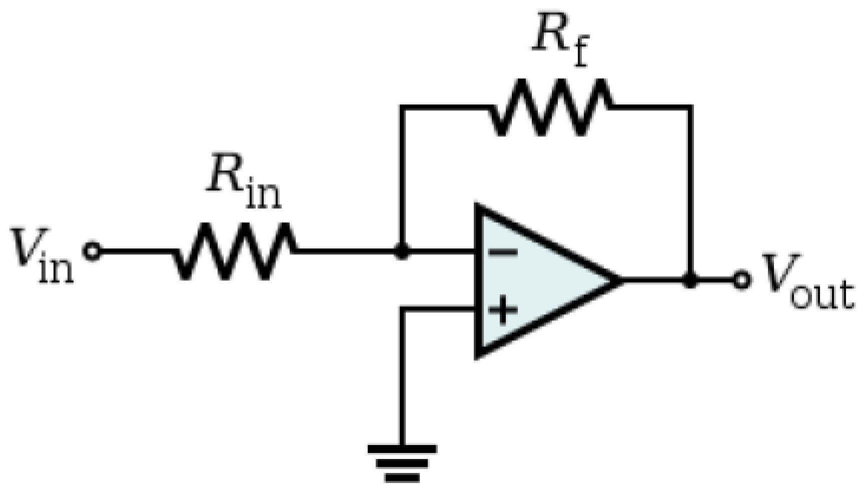
Compares two voltages and switches its output to indicate which voltage is larger.

- $$V_{out} = \begin{cases} V_{S+} & V_1 > V_2 \\ V_{S-} & V_1 < V_2 \end{cases}$$

(where V_s is the supply voltage and the opamp is powered by $+V_s$ and $-V_s$.)

Basic Op-Amp circuit

Inverting amplifier



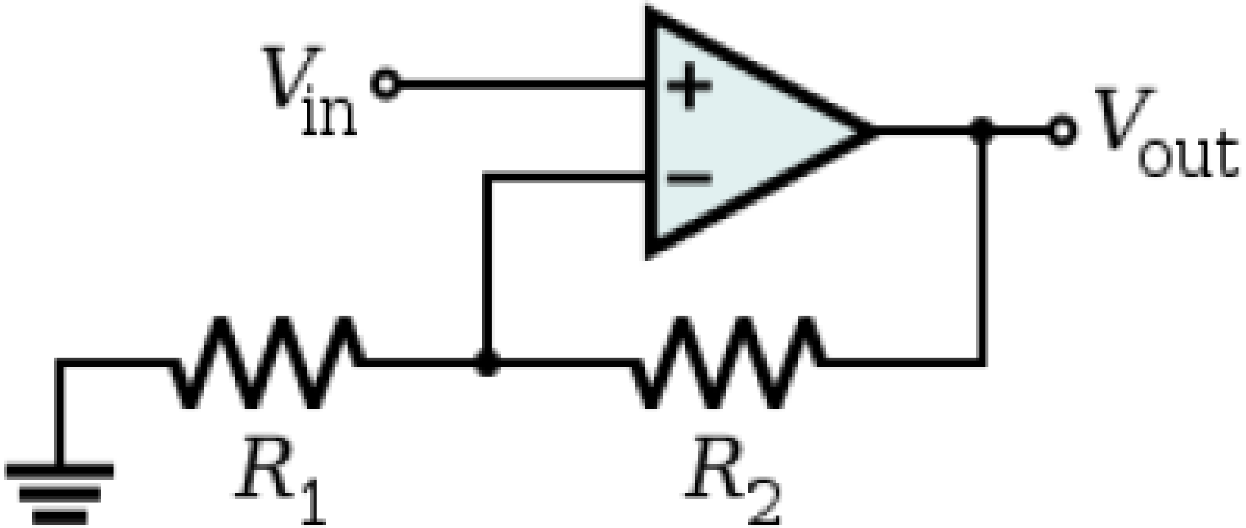
An inverting amplifier uses negative feedback to invert and amplify a voltage. The R_f resistor allows some of the output signal to be returned to the input. Since the output is 180° out of phase, this amount is effectively subtracted from the input, thereby reducing the input into the operational amplifier. This reduces the overall gain of the amplifier and is dubbed negative feedback.[2]

$$V_{\mathrm{out}} = -\frac{R_{\mathrm{f}}}{R_{\mathrm{in}}} V_{\mathrm{in}}$$

The gain of the amplifier is determined by the ratio of R_f to R_{in}. That is:

$$A = -\frac{R_f}{R_{in}}$$

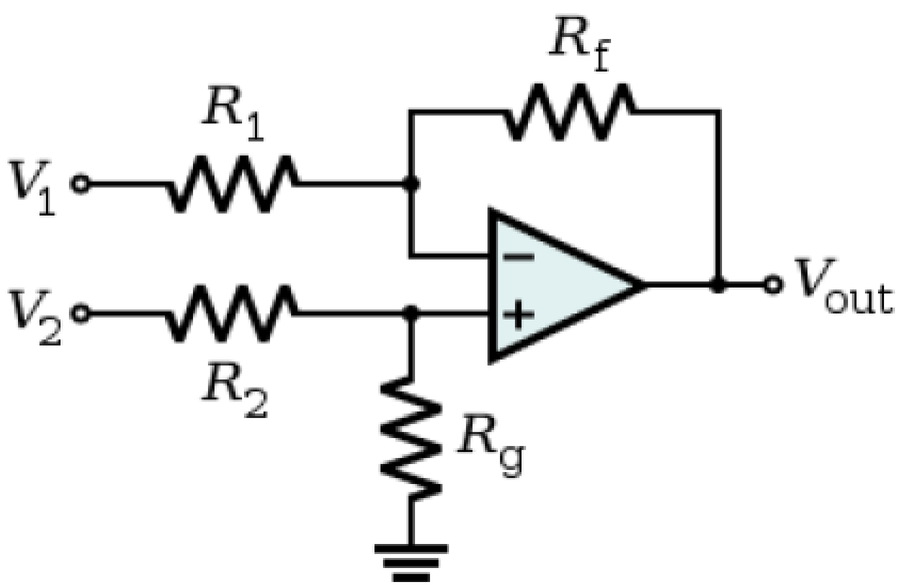
Non-inverting amplifier



$$V_{out} = V_{in}\left(1 + \frac{R_2}{R_1}\right)$$

Basic Op-Amp circuit

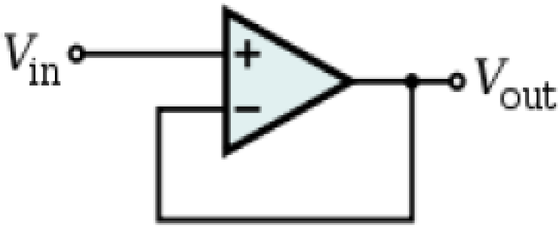
Differential amplifier



$$V_{out} = \frac{(R_f + R_1)\,R_g}{(R_g + R_2)\,R_1} V_2 - \frac{R_f}{R_1} V_1$$

Basic Op-Amp circuit

Voltage follower

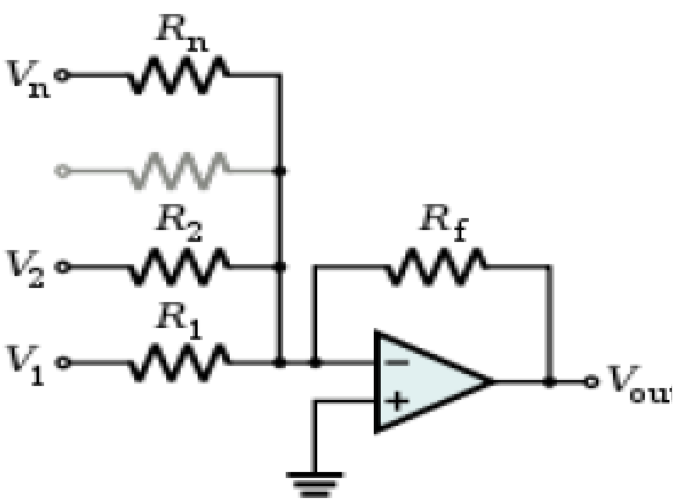


Used as a buffer amplifier to eliminate loading effects (e.g., connecting a device with a high source impedance to a device with a low input impedance).

$$V_{out} = V_{in}$$

$Z_{in} = \infty$ (realistically, the differential input impedance of the op-amp itself, 1 MΩ to 1 TΩ)

Summing amplifier

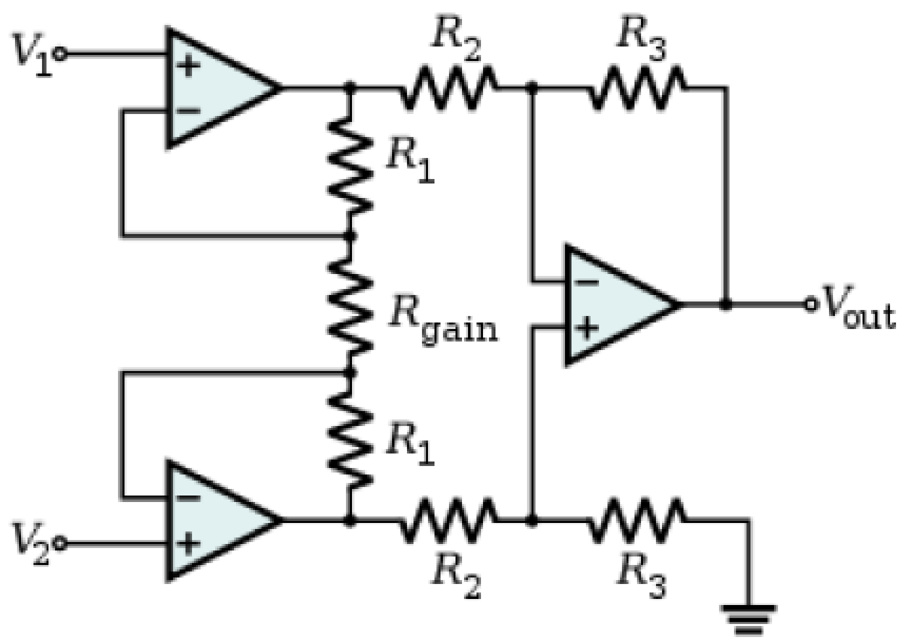


A summing amplifer sums several (weighted) voltages:

$$V_{out} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right)$$

Basic Op-Amp circuit

Instrumentation amplifier



The most commonly used instrumentation amplifier circuit is shown in the figure. The gain of the circuit is

$$\frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2}$$

Analog to Digital Converter
(ADC , Ex Successive-Approximation method)

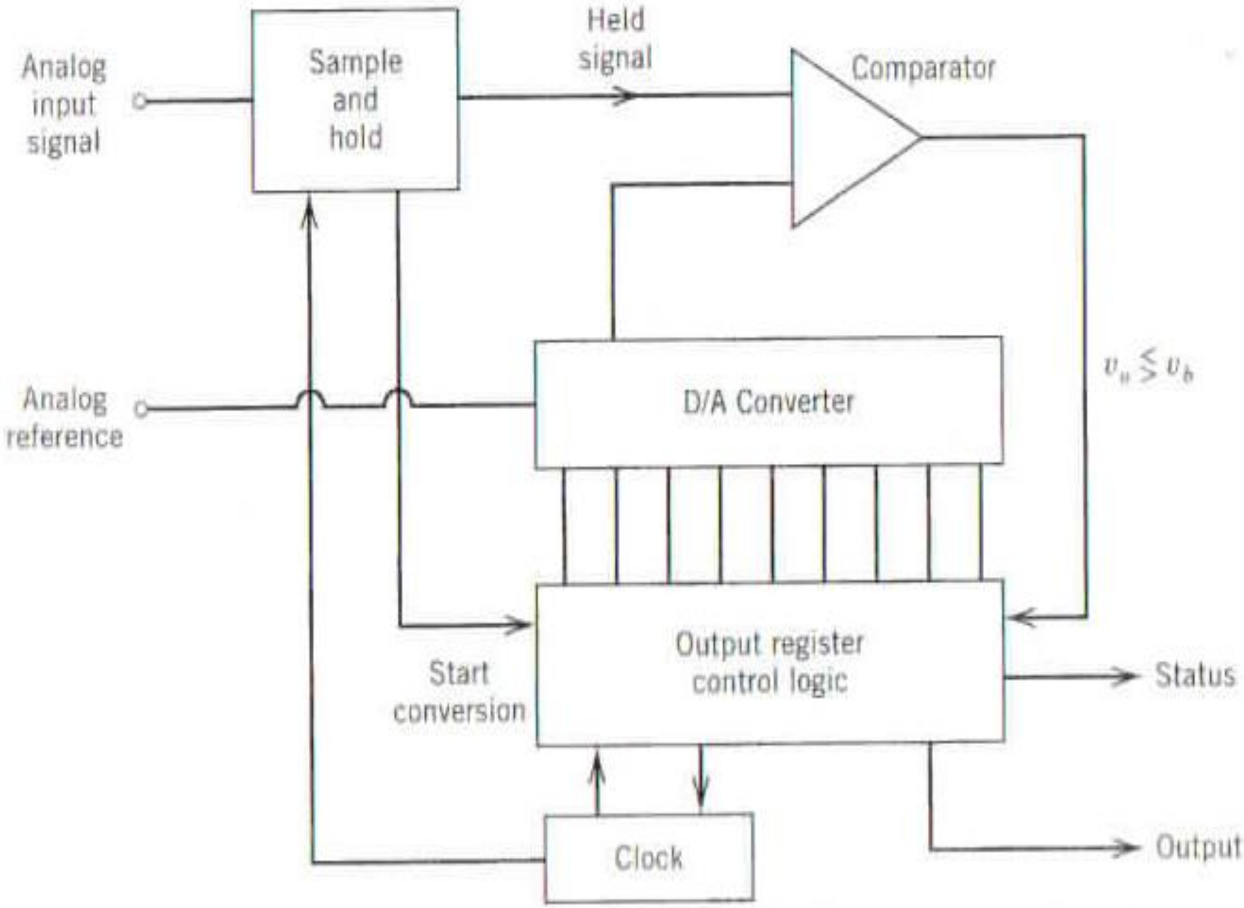
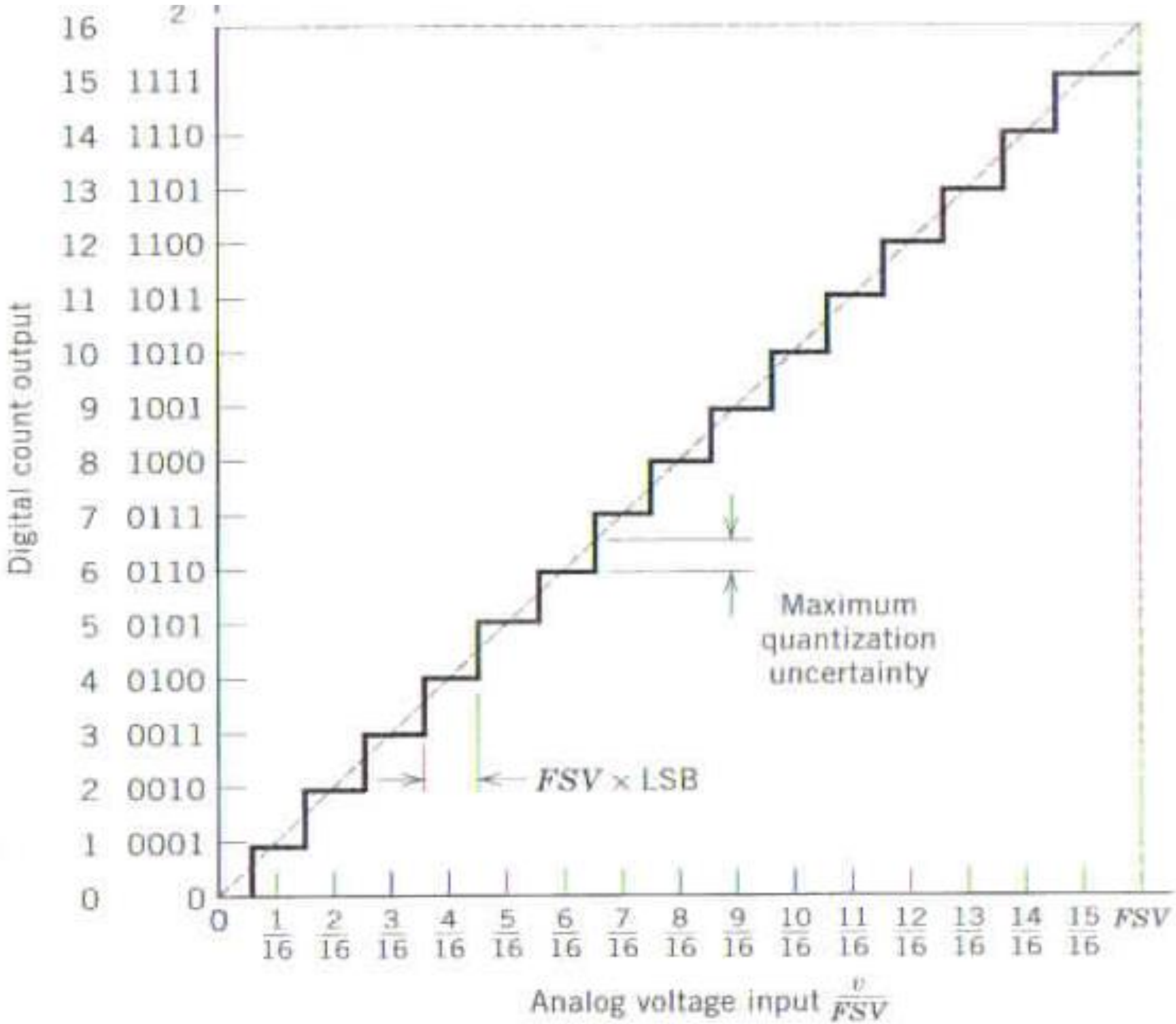


Figure 4.8 Successive-approximation converter with a sample-and-hold device and control logic.

$$Digital \quad Out = D_O = INT\left[\frac{V_i}{V_{ref}/(2^n - 1)}\right]$$

(Unipolar)

Analog to Digital Converter (ADC)



DAC : Digital to Analog Converter

(Applied for Successive-Approximation ADC)

$$R_n = 2^n R_f$$

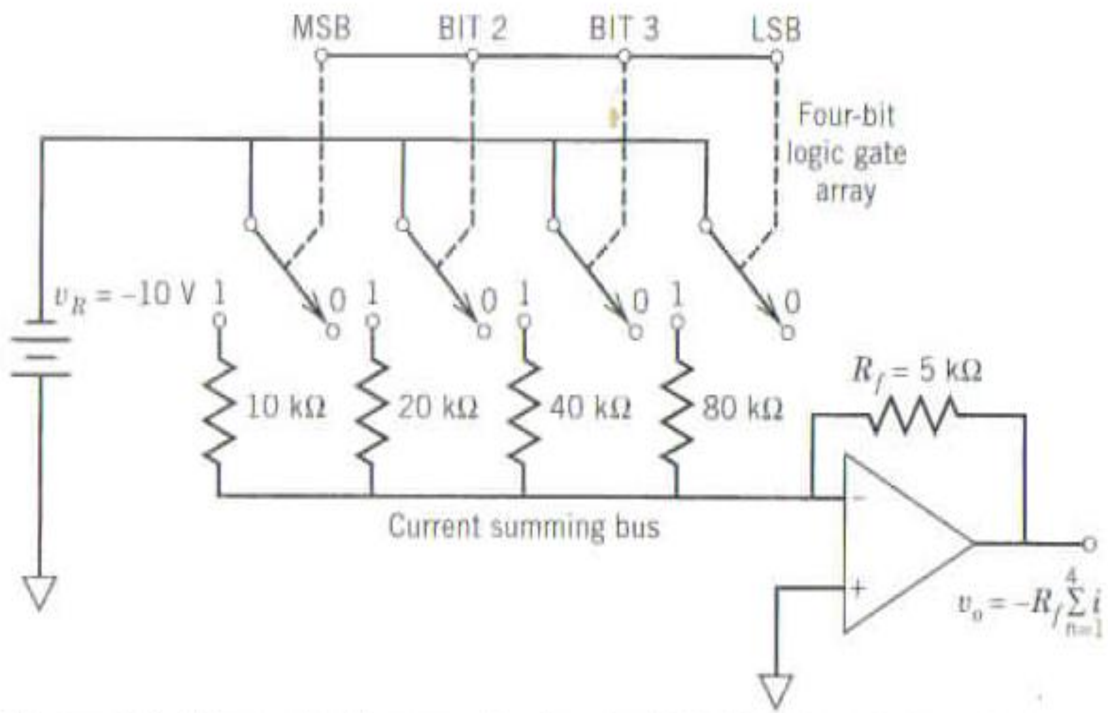
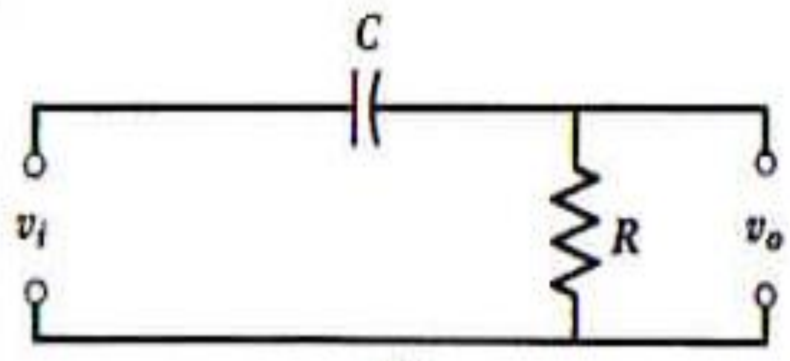


Figure 4.5 Schematic diagram of a simple 4-bit digital-to-analog converter.

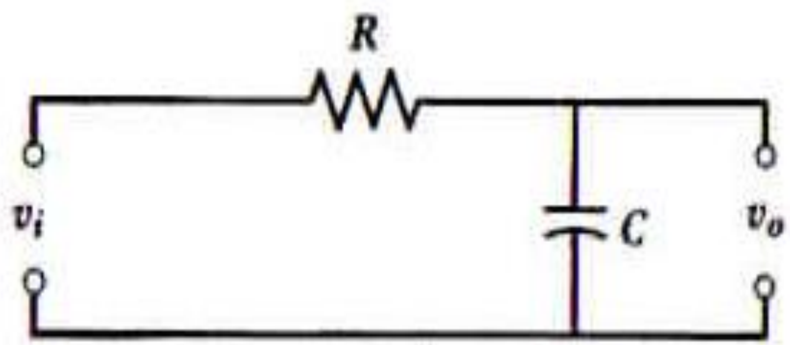
R_n is the resistance of the n_{th} bit

R_f is the feedback resistance on the operational amplifier

Passive Filter (1st order) Low Pass and High Pass



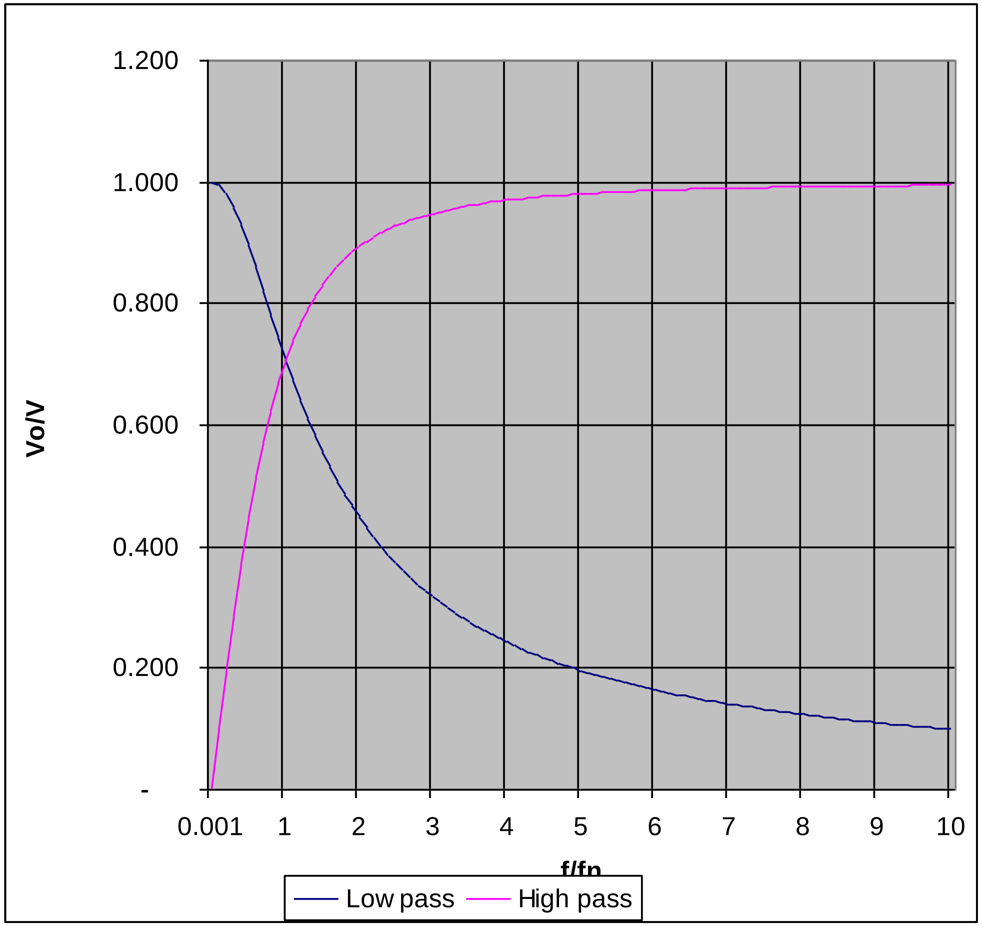
(a)



(b)

a – RC High-Pass filter
b – RC Low-Pass filter

Passive Filter (1st order) Low Pass and High Pass



Low pass

$$\frac{V_o}{V_i} = \frac{1}{\sqrt{\left(\frac{f}{f_n}\right)^2 + 1^2}}$$

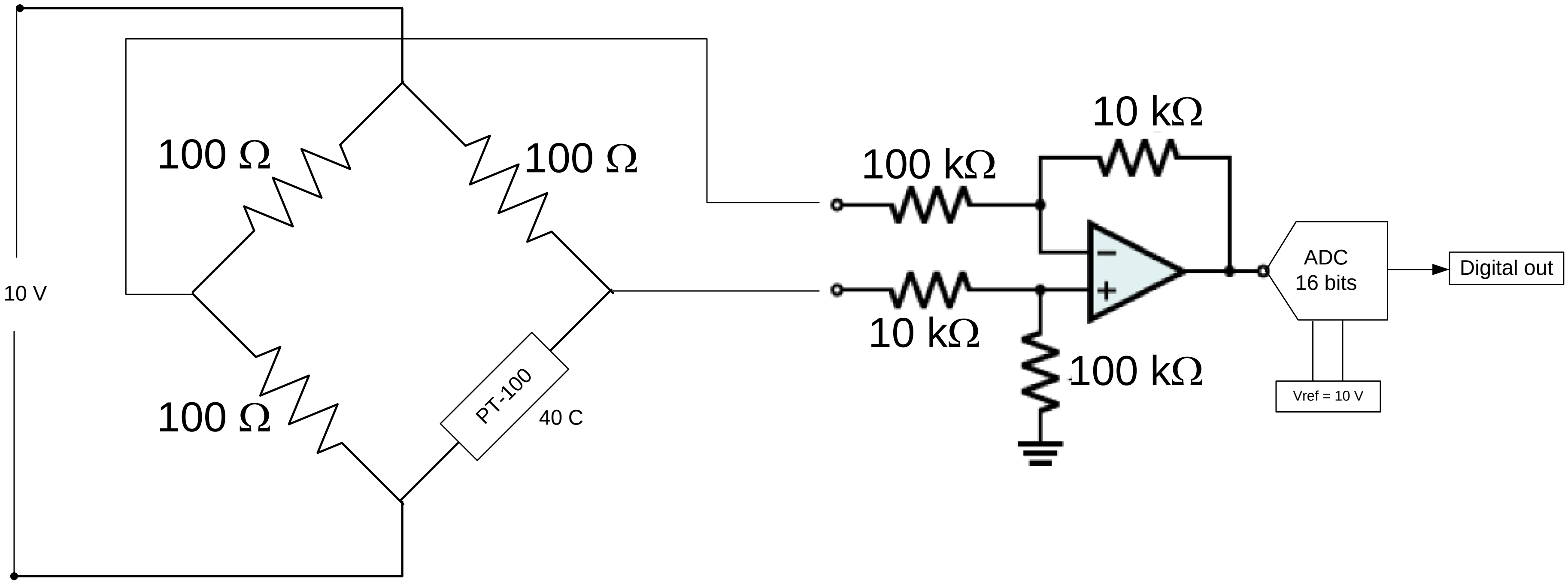
High pass

$$\frac{V_o}{V_i} = \frac{1}{\sqrt{\left(\frac{f_n}{f}\right)^2 + 1^2}}$$

$$f_n = \frac{1}{2\pi RC}$$

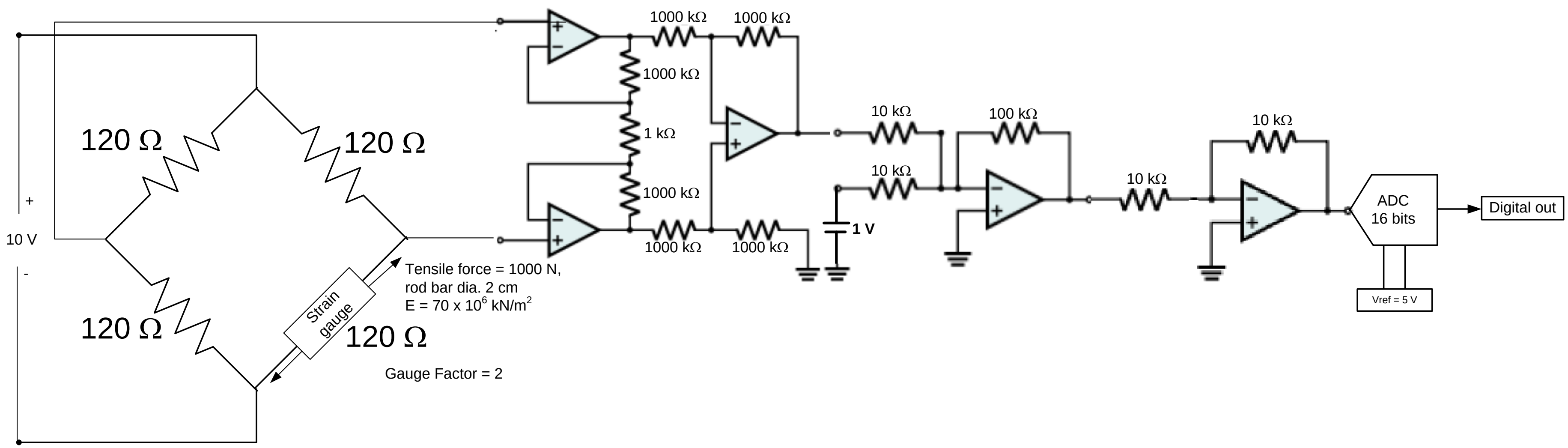
Signal Conditioning
(Use Op-Amp circuits to rearrange the input signal)

Ex SC1



Signal Conditioning

Ex SC2



Signal Conditioning (Op-Amp basic circuit)

Ex SC3 From Ex SC2, if the load is varied on the range 1kN – 100kN. Find signal conditioning circuit to obtain output range within 1-5 V.