Cryogenic Measurements[1]

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1. INTRODUCTION

Cryogenics usually refers to temperatures less than about 120 K, but in this chapter we use such a definition rather loosely. Typically there is a gradual change in the type of sensors used or measurement methodology as temperature is lowered rather than an abrupt change as the temperature is lowered below 120 K. In some cases a sensor appropriate for 100 K may also be the best for a temperature as high as 300 K. In this chapter we will specify the temperature range appropriate for a particular sensor or measurement methodology. Instrumentation for processes or experiments involving cryogenic temperatures often requires the use of sensors that must operate at these low temperatures. Certainly the measurement of temperature can only be done with a thermometer at the temperature of interest. However, certain other parameters, such as pressure, flow, liquid level, and magnetic field have often been made with the active sensor located at room temperature but which could infer the property at cryogenic temperatures. This procedure usually resulted in a loss of accuracy, particularly under dynamic conditions. When cryogenic sensors were required in the early years of cryotechnology, they were usually constructed in the laboratory. The demand for cryogenic sensors has grown sufficiently that commercial sensors are often available for use at cryogenic temperatures. In some cases, simple modifications of commercial sensors suffice to make them adaptable for use at cryogenic temperatures. In this chapter we review the availability and properties of commercial sensors and discuss the necessary modifications to make them useful for cryogenic temperatures.

The temperature range of primary interest here is between 4 and 300 K. Except for the case of some thermometers, a sensor that functions at 4 K will usually continue to function at lower temperatures as long as the power input is not too great. One of the main reasons commercially available sensors or transducers cannot be used at cryogenic temperatures is because of the choice of materials. In some cases, a material (rubber, for example) undergoes a brittle transition at some low temperature that prevents its use at cryogenic temperatures. In other cases the differential contraction of different materials may be great enough at cryogenic temperatures to cause too high stresses or interference with moving components. Sensors with moving parts (such as flow sensors) are particularly difficult to operate at cryogenic temperatures because of the need for dry lubrication. Often electrical power inputs that are satisfactory for operation at room temperature can cause a sensor to self heat or interfere with the overall experiment at cryogenic temperatures. Thus, commercial sensors can often be adapted for use at cryogenic temperatures by reducing the power input and/or changing a few key materials. Calibration of the sensor at the temperature it is to be used is nearly always necessary. Such calibrations often involve a comparison with a standard at room temperature.

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2. TEMPERATURE

2.1 ITS-90 Temperature Scale and Primary Standards

The temperature scale in use today is known as the International Temperature Scale of 1990 (ITS-90), which extends from 0.65 K to 1,358 K (Preston-Thomas 1990). It is a very close approximation to a true thermodynamic temperature scale. The scale is established by use of physical phenomena known so well that temperature can be calculated without any unknown quantities. Examples include equation of state of a gas, the velocity of sound in a gas, the thermal voltage or current noise in a resistor, blackbody radiation, and the angular anisotropy of gamma-ray emission from some radioactive nuclei in a magnetic field. A provisional extension covering the range from 0.9 mK to 1 K was established in 2000 and is known as PLTS-2000. It uses the melting curve of ^{3}He as the defining scale (BIPM, 2000). The ITS-90 is defined through a set of fixed points, interpolating primary thermometers, and interpolating equations [Preston-Thomas 1990, Mangum et al 2001, Tew and Meyer 2003, Strouse 2008]. Fixed points are triple points and superconducting transition points. A standard platinum resistance thermometer (SPRT) is an example of an interpolating primary thermometer for temperatures between the triple point of equilibrium hydrogen at 13.8033 K and the freezing point of silver at 961.78 K. Use of fixed points and primary thermometers is a complex and expensive undertaking, which limits their use mostly to national standards institutions. The primary standards are transferred to secondary standards, such as high-purity platinum or Rh-Fe alloy resistance thermometers. The secondary standards are then used to calibrate commercial (industrial) thermometers for customer use.

2.2 Commercial Thermometers

Thermometry at cryogenic temperatures has become very well developed with a wide range of commercially available thermometers for the measurement of temperatures from the millikelvin temperatures up to room temperature and above. Excellent reviews of cryogenic thermometry have been published (Rubin, et al. 1982, Sparks, 1983, Courts, et al. 1991, Holmes and Courts, 1992, Rubin, 1997, Yeager and Courts, 2001, and Ekin, 2006). A new class of thermometers not discussed in these previous reviews (except Ekin) is the zirconium oxy-nitride ceramic film thermometers which have low magnetoresistive effects. Most commercial thermometers for cryogenic temperatures are resistors, diodes, thermocouples, or capacitors. The change of their electrical characteristic with temperature determines their suitability as a thermometer. A good thermometer should have high sensitivity and be stable over time. For dynamic measurements it should also have a fast response time.

2.2.1 Metallic Resistance Thermometers

The resistance of most pure metals varies roughly linearly with temperature until at some low temperature the scattering of electrons by impurities dominates the resistance, which leads to a lower limit to the resistance. In most case this limit is reached by 4 K, which means it can no longer function as a thermometer. For standard-grade platinum the ratio of resistance at 4.2 K to that at 273.16 K is usually less than 4×10^{-4}. More impurities cause this ratio to increase and the lower limit to be reached at higher temperatures. Platinum is the most widely used metallic resistance thermometer because it is so reproducible over long periods of time. It is often used as a secondary standard to calibrate other commercial thermometers. The platinum wire used in standard thermometers is of very high purity and care is taken in the construction of the thermometer to eliminate strains in the wire, which can affect the resistance. Figure 1 shows the typical construction of a capsule-type of standard platinum resistance thermometer (SPRT). The capsule-type is most commonly used for cryogenics as opposed to the long-stem type in which heat conduction in the stem from ambient temperature to low temperature can cause unacceptable heat leaks. A helix of platinum wire (about 75 μm diameter) is bifilarly wound on a notched mica or ceramic cross and placed inside the sheath, after which it is annealed at about 600 °C to remove all strains. The capsule is filled with helium gas to enhance heat transfer between the platinum element and the sheath. Platinum, Inconel, glass, or quartz are common sheath materials. Dimensions of the capsule including the platinum-glass electrical feedthrough are about 5.8 mm in diameter by 56 mm long, with a resistance of 25.5 ohms at 0 °C. The ITS-90 temperature range for these thermometers is from 13.8 K up to about 523 K. Special high-temperature versions are used for temperatures up to the silver triple point at 1235.08 K. The reproducibility of these standard-grade thermometers is about 1 mK. Miniature capsule-type SPRTs have been developed recently that are about 3.2 mm in diameter and 9.7 mm long that can be used down to 13.8 K with some sacrifice in reproducibility (Courts and Krause, 2013).

Figure 2 shows how resistance varies with temperature for the most common metallic resistance thermometers. These thermometers have a positive temperature coefficient of resistance. A capacitance thermometer characteristic is also shown in Figure 2, but it will be discussed later. Two curves are shown for platinum thermometers, one for laboratory-grade SPRTs and one for PRTs made with lower purity platinum, referred to as an industrial-grade platinum resistance thermometer (IPRT or just PRT). The resistance of the SPRT follows the ITS-90 definition down to 13.8 K, whereas the PRT meets the ITS-90 definition only down to about 70 K through the use of a slightly different resistance vs. temperature curve. Their reproducibility is about 5 mK or higher. The distinction between the two grades is based on the purity of the platinum and how the active element is supported to eliminate strain. The distinction is quantified by use of the resistance ratio given by

$$W(T) = R(T)/R(273.16\ \text{K}). \tag{1}$$

To be suitable for a SPRT, the platinum must be of sufficient purity to satisfy at least one of the two following relations:

$$W(302.9146\ \text{K}) \geq 1.11807 \tag{2a}$$

$$W(234.3156\ \text{K}) \leq 0.844235. \tag{2b}$$

The defining equations that relate temperature to the ratio W are given by Preston-Thomas, 1990. The constants in the equations are determined from calibrations. An alternate specification of platinum purity used in thermometers is the temperature coefficient of resistance α defined by

$$\alpha = \frac{R(100\,°\text{C}) - R(0\,°\text{C})}{100\,R(0\,°\text{C})}, \tag{3}$$

which technically has units of ohms/(ohm·°C) because the 100 in the denominator represents 100 °C temperature change, but conventionally α is considered dimensionless. To meet the ITS-90 conditions given by Eqs. (2a) and (2b), the temperature coefficient α should satisfy

$$\alpha \geq 0.003925. \tag{4}$$

This high value of alpha is achieved only with expensive reference-grade platinum (99.999 % purity) wound in a strain-free manner and used in laboratory grade SPRTs. The resistance at 0 °C is normally 25.5 Ω. With reference-grade platinum in industrial thermometers, the temperature coefficient is 0.003920. Lower purity platinum is used in most industrial-grade thermometers. Different standards organizations have adopted different temperature coefficients as their standard. The most widely used standard is the European standard (also widely used in the U.S and elsewhere), designated by DIN IEC 60751 and ASTM E-1137 in which $\alpha = 0.0038500$ and the resistance at 0 °C is 100 Ω. The resistance of industrial grade PRTs follows a standard curve down to about 70 K. They are usable for lower temperatures but require an individual calibration. There are three tolerance grades (A, B, and C) for the DIN standard and two for the ASTM standard. For the ASTM standard the grade A has a tolerance ranging from ±0.47 K at 73 K to ±0.13 K at 273 K, whereas the grade B tolerance is ±1.1 K at 73 K and ±0.25 K at 273 K. The tolerance indicates the level of interchangeability for the thermometer.

Resistance thermometers made with Rh-5 at.%Fe have a resistance that continues to change even below 1 K. They are useful for the temperature range of 0.65 K to 500 K, with a linear response above 100 K, as shown in Figure 2. RhFe thermometers are not interchangeable like that of Pt thermometers, but their reproducibility of about 0.2 mK in models fabricated like that of the SPRT makes them a candidate for an interpolating standard below 25 K for the ITS-90 temperature scale (Peng, 2012). Other metals and alloys are sometimes used in resistance thermometers for special reasons. Resistance thermometers that use pure metals are not very sensitive for temperatures of 4 K and below. For these lower temperatures, thermometers made with semi-conductors or other negative temperature coefficient materials become a better choice.

2.2.2 Semiconductor-like Resistance Thermometers

Figure 3 shows the resistance response curves for several types of semiconductor-like resistance thermometers. As the figure indicates, their resistance is very sensitive to temperature below about 100 K, unlike that of platinum thermometers. The response curves for these semiconductor-like thermometers have a negative temperature coefficient. The disadvantage with these thermometers is that except for the RuO_2 thermometers they do not follow a standard response curve as do platinum thermometers, so they are not interchangeable and must be individually calibrated. The RuO_2 thermometers are only interchangeable for the same manufacturer. The zirconium oxy-nitride thermometers, sold under the trade name as Cernox thermometers, are a commonly used type and are available in several versions to cover a wide temperature range. They are a thin film resistor deposited on an alumina substrate. Their reproducibility of 3 mK at 4 K and 15 mK at 77 K allows them to be used in most laboratory settings. Germanium resistance thermometers are generally used for precision measurements below about 80 K. Their reproducibility is about ±0.5 mK at 4 K, but they must be individually calibrated. They can yield accuracies of about 5 to 15 mK for temperatures between about 1 and 20 K with commercial calibrations. Selected germanium thermometers are useful as thermometers down to about 50 mK and are available with commercial calibrations down to that temperature. Carbon-glass thermometers have a very steep response curve which gives them high sensitivity. They are made by impregnating porous glass with carbon (Lawless, 1972). They are not interchangeable, but their reproducibility is quite good. Their high sensitivity makes them useful for temperature control. Carbon resistors in the form of electrical circuit resistors have been used often for very low cost thermometers, but only particular brands have been found to be useful. A useful brand may be discontinued or experience a composition change that greatly affects its low temperature resistance behavior. Thermistors usually have the steepest response curves of all thermometers, which limits the temperature range for an individual thermistor. Their use is then limited to special applications, such as in precise temperature control.

2.2.3 Diode Thermometers

The forward voltage of diodes with constant current excitation varies with temperature and makes a good thermometer. Figure 4 shows typical voltage curves for Si and GaAlAs diodes with a 10 µA current excitation. Special Si diodes make excellent thermometers because of their interchangeability for the same manufacturer and their relatively large voltage signal. They follow a standard curve to within 0.25 K for the "A" grade and 0.5 K for the "B" grade. Magnetic fields have a strong effect on Si diodes, but much less effect on GaAlAs diodes. Unfortunately GaAlAs diodes do not follow a standard curve, so they must be individually calibrated.

2.2.4 Thermocouples

Thermocouples make use of the thermopower or the Seebeck coefficient in metals. If an electrical conductor is placed in a temperature gradient, current carriers (electrons or holes) will diffuse from the hot to cold end to build up a voltage that prevents further diffusion. The voltage gradient with zero current flow is known as the absolute Seebeck coefficient, which is given by

$$S = -\frac{dV}{dT}, \tag{5}$$

where S has units of V/K. Note that it is not possible to measure S directly, since any attempt to measure the voltage with a voltmeter will introduce another conductor in the temperature gradient with its own Seebeck coefficient. What is measured is the relative Seebeck coefficient, which is the difference between the absolute values in the two conductors. The measured Seebeck coefficient of the conductor pair is given as

$$S_{AB} = S_A - S_B = \frac{dV_B}{dT} - \frac{dV_A}{dT} = -\frac{dV_{AB}}{dT}. \tag{6}$$

The sign convention is quite complicated and will not be discussed here. Because the entropy of charge carriers in a superconductor is zero, S of a superconductor is zero. Thus, by choosing one leg of a pair to be a superconductor, S of the other leg can be determined from the measurement of the pair. Such a technique is useful only up to about 120 K, above which no superconductors exist. For higher temperatures $S(T)$ is found from the difficult measurements of the Thomson coefficient μ and use of the relation:

$$S(T) = \int_0^T \frac{\mu(T')}{T'} dT'. \tag{7}$$

Figure 5 shows the temperature dependence for the absolute Seebeck coefficient for materials commonly used in thermocouples (Bentley, 1998). For a finite temperature difference, the voltage across the conductor is the integral of S over the given temperature range. Though the absolute Seebeck coefficient has no practical use, it aids in understanding voltages developed in thermocouple measurement systems. It shows that voltages are developed along the length of conductors in temperature gradients and not at the junctions. The junction simply ensures that the electrical potential of both legs is the same at that point. For example, if both legs of a pair are of the identical material and the open ends are at the same temperature, then according to Eq. (6) there will be no measured voltage difference between the pair. Also, if a third material is introduced in an isothermal part of the thermocouple circuit, then it has no effect on the output because no additional voltage is introduced in the isothermal section. Lastly, Figure 5 is useful in understanding the polarity of each leg in a thermocouple.

Several metal combinations are used for thermocouple thermometry, depending on the temperature and other environmental conditions. The most common combinations for use at cryogenic temperatures are given in Table 1. Designations for single-leg materials are:

Constantan: EN or TN, nominally 55 wt.% Cu and 45 wt.% Ni
Chromel[a]: EP or KP, nominally 90 wt.% Ni and 10 wt.% Cr
Alumel[a]: KN, nominally 95 wt% Ni, 2 wt.% Al, 2 wt.% Mn, and 1 wt.% Si
[a]Trademark of Concept Alloys, Inc.

Figure 6 shows the Seebeck coefficient S_{AB} (sensitivity) of common cryogenic thermocouple pairs. The integral of S_{AB} gives the emf of the pair with the junction held at 0 K, as shown in Figure 7. In practice the reference junction is usually held at 0 °C, so thermocouple tables are usually given with respect to a 0 °C reference. The curves in Figure 7 with a 0 K reference are converted to a 0 °C reference simply by subtracting the voltage at 0 °C from the curves. Figure 8(a) shows a schematic of the theoretical wiring arrangement with the reference junction at 0 K and the voltmeter at a temperature T. Figure 8(b) shows the wiring arrangement for the typical scheme of a 0 °C reference temperature.

Thermocouples are inherently a sensor for measuring temperature differences, so they are often used to measure small temperature differences. Figure 9 shows a schematic for such measurements. In this arrangement most of the temperature difference from some low temperature to ambient is spanned by identical materials on both legs, so no additional voltage is developed over most of the temperature gradient, and both legs can come from the same spool to ensure nearly identical Seebeck coefficients. The reference junctions can be at any temperature, but they must be at the same temperature. Often they are anchored at the low temperature T by potting both of them in a copper piece. With such an arrangement the leads extending to room temperature can be copper or phosphor bronze, which have low values of absolute Seebeck coefficients $S(T)$, so any material variation between the legs has only a minimal spurious voltage generation. The reference junctions could also be at the voltmeter connections, but ensuring isothermal conditions there is more difficult and the two leads extending from low T to ambient are thermocouple materials that may have high $S(T)$ and susceptible to larger variations due to material variations. The emf measured at the voltmeter due to a small temperature difference ΔT at the temperature T is given by

$$\Delta V = S_{AB}(T)\Delta T, \tag{8}$$

where the relative Seebeck coefficient $S_{AB}(T)$ is evaluated at the temperature T. The output voltage can be increased in such a measurement by the use of a thermopile, in which the thermocouple legs are crisscrossed between the two temperatures to form multiple junctions in series. For extremely high resolution, the thermocouple emf can be measured with a superconducting quantum interference device (SQUID) operating at 4.2 K (Fagaly, 1987). Voltages of 10^{-13} V are easily resolved with a SQUID system, and their low temperature operation eliminates most of the spurious thermal emfs in the system. The Au-Fe thermocouples should not be used in magnetic fields, since they are orientation dependent. The type E thermocouple has a small magnetic field dependence and can be used in moderate fields for temperatures above about 40 K.

2.2.5 Capacitance Thermometers

The variation of capacitance for typical capacitance thermometers is shown in Figure 2 with capacitance shown on the right axis. The capacitance can shift equivalent to a kelvin or more upon thermal cycling, but after about an hour at temperature the drift is only a few tenths of a mK at 4.2 K but a few mK at 300 K. Their strong point is that they are very insensitive to magnetic fields. Their change in a magnetic field is less than 0.05 % of the reading over the entire temperature range from 2 to 300 K. Thus, capacitance thermometers are best suited for temperature control during the application of magnetic fields, but a different thermometer must be used to measure the temperature in zero field if that temperature must be known with an uncertainty less than about 1 K.

2.3 Thermometer Use and Comparisons

The selection of an appropriate thermometer for cryogenic use makes use of a comparison of such factors as accuracy, reproducibility, temperature range, temperature resolution, size, cost, magnetic field effect, measuring instrument, and other factors. Accuracy involves how close the true thermodynamic temperature is measured, of which the ITS-90 temperature scale is the latest approximation to such a temperature. How close any thermometer follows the ITS-90 temperature scale depends on the uncertainty of calibration, the temperature resolution of the thermometer and temperature measurement system, and the reproducibility of the thermometer. Typical calibration uncertainties for commercial thermometers range from about ±4 mK at 4 K, ±10 mK at 80 K, and ±25 mK at 300 K. Total thermometer uncertainties must also take into account reproducibility, of which typical values for the various thermometer types are given in Table 2. Individual thermometer calibrations over a wide temperature range ensure the lowest uncertainty, but the cost can be quite high. Much lower cost can be achieved by using interchangeable thermometers, such as platinum resistance thermometers, Si diodes, and thermocouples. Their interchangeability is indicated in Table 2. Figure 1 showed the construction details and size of typical SPRTs. The diameter and length of about 5.8 mm by 56 mm makes them too large for most experimental work. Most industrial thermometers are much smaller and are available in a variety of configurations, as shown in Figure 10. For example wire wound PRTs conforming to IEC 60751 down to 70 K are available in capsules as small as 1.8 mm in diameter and 5 mm long. Thin film platinum RTDs are available in sizes as small as 2 mm × 2 mm × 1 mm thick that conform to IEC 60751 class B down to -50 °C and cost about US$1 each in quantities of 100. Quantitative results on the magnetic field effects of many types of thermometers are given by Sample and Rubin (1977) and by Rubin et al. (1986).

2.3.1 Temperature Resolution and Sensitivity

The relative temperature resolution is given by

$$\frac{\Delta T}{T} = \frac{(\Delta V / V)}{S_d}, \tag{9}$$

where ΔV is the voltage resolution of the measurement system, V is the voltage, and S_d is the dimensionless sensitivity of the thermometer. The expression also applies to a resistor or a capacitor by replacing V with either R or C. For sensors with high voltage outputs, such as volt-level signals with diode thermometers, a 5 ½ digit voltmeter can provide a voltage resolution of about 2×10^{-6}. For thermocouples the maximum output voltage may only be about 10 mV, so a voltmeter with 1 µV resolution yields only $\Delta V/V = 1\times10^{-4}$. The dimensionless sensitivity of the thermometer is given by

$$S_d = \left|\frac{T}{V}\frac{dV}{dT}\right|, \tag{10}$$

where the voltage V can be replaced with R or C. A comparison of the dimensionless sensitivity for the various thermometer types discussed earlier is shown in Figure 11. The parameter O in this figure represents V, R, or C. The dimensionless sensitivity for thermocouples is calculated using the 0 K reference temperature, which can be misleading. For thermocouples it is best to determine the temperature resolution by the equation

$$\Delta T = \frac{\Delta V}{S_{AB}}, \tag{11}$$

where S_{AB} is determined from the sensitivity shown in Figure 6. For example, at 100 K the 30 µV/K sensitivity for type E thermocouples results in a temperature resolution of 0.03 K. However, the uncertainty of the absolute temperature is best given by the standard error of 1.5 K shown in Table 1 that takes into account interchangeability, reproducibility, and long-term drift.

2.3.2 Thermometer Electrical Excitation

Except for the case of thermocouples, all other thermometers discussed here require some type of electrical excitation. For most accurate measurements, a four lead measurement should be used right to the thermometer element: two leads for current and two leads for voltage. Such an arrangement eliminates the error caused by voltage drop in a current carrying lead. The standard calibration curves given for diodes are for an excitation of 10 µA, as listed in Table 2. For resistance thermometers, any current or voltage can be used, provided it does not cause self heating of the thermometer. Thermometers with positive temperature coefficients, such as the metallic resistance thermometers, are best excited with a constant current over a wide temperature range to allow for reduced power at lower temperatures. However, thermometers with negative temperature coefficients, such as semiconductor or semiconductor-like thermometers, are best excited with constant voltage. These typical currents and voltages are listed in Table 2. In practice, the maximum excitation can be determined by increasing the current or voltage until a change in resistance is detected. To prevent self heating errors, the power dissipation should usually be less than about 1 to 10 µW at 300 K and decrease to about 0.01 to 0.1 µW at 4.2 K. The excitations listed in Table 2 usually yield these power levels. The power dissipation in the diode thermometers is in the range of 20 to 50 µW at 4.2 K, which will result in self heating if special care is not taken to thermally anchor them very well.

Resistance thermometers can be excited with either alternating current (AC) or direct current (DC). Direct current is most commonly used because of the availability of lower cost instrumentation. However for the most precision work, AC is commonly used to allow for noise reduction with lock-in amplifiers. AC bridge networks with null detectors provide the ultimate in resistance resolution and have the added advantage of eliminating thermal EMFs caused by temperature gradients. A resistance resolution of 1 µΩ is possible, which gives a temperature resolution of 1 µK in a 25 Ω SPRT (Cutkowsky, 1970). A low frequency of about 30 Hz is commonly used to avoid any problems with reactance in the circuit. Precision work using DC excitation must reverse the current and take the average of the resistance from the two current directions to eliminate thermal EMFs.

2.3.3 Thermal Anchoring of Thermometers and Leads

Any of the thermometers discussed here measure the temperature of the thermometer, so the uncertainties apply only to the thermometer itself and not to the sample to be measured. Because of heat leak through the electrical leads and the self heating due to thermometer excitation, the thermometer temperature can be higher than the sample unless special care is taken to ensure good thermal contact between thermometer and sample and to minimize heat conduction through the leads. Thermometer manufacturers are careful to provide good thermal contact between the thermometer element and any package. Examples of packages are shown in Figure 10. Canister packages must be inserted into a close fitting hole in a high thermal conductivity block or spool. Use of a thermal grease or epoxy ensures good thermal contact between the canister and the block, but the hole must not be blind to allow for air escape and easy thermometer disassembly by pushing on the end rather than pulling on the electrical leads. Figure 10 also shows many packages in which the thermometer canister has already been mounted by the manufacturer in a gold-plated copper spool. The gold plating minimizes radiation heating of the spool and provides a high thermal contact conductance when bolted to the sample. For contact areas greater than about 1 cm^2 the use of thermal grease can provide improved thermal contact.

The second consideration in thermal anchoring thermometers is the thermal anchoring of the electrical leads separately from the thermometer. The Weidemann-Franz law can be used to provide a good rule of thumb to relate heat leak in electrical leads to the electrical resistance of the lead between room and low temperature. For a low temperature of 77 K and a high temperature of 300 K the Weidemann-Franz law gives

$$\dot{Q}R \approx 1\,\mathrm{mW}\cdot\Omega, \tag{12}$$

where $\dot{Q}$ is the heat flow, and R is the electrical resistance. For a two-lead measurement circuit the lead resistance must be much smaller than that of the thermometer. For a 100 Ω Pt thermometer the resistance is only about 10 Ω at 80 K, so even a 0.1 Ω resistance in each lead gives a 2 % error in resistance and a heat leak of 20 mW in both leads according to Equation (12). A typical thermal conductance between a thermometer spool and the sample may be about 1 W/K, which then leads to a temperature difference of 20 mK between the spool and the sample. Another temperature difference will occur between the thermometer and the spool. The problem is not so serious with higher-resistance thermometers or with diodes that have a resistance of about 10^5 Ω. To eliminate the lead conduction problem, electrical leads should be thermally anchored to the sample independently of the thermometer. Often the leads are wrapped around a separate spool which is then bolted to the sample near the thermometer. Typical thermal tempering lengths for various wire sizes and materials are shown in Table 3.

Thermocouples are particularly difficult to thermally anchor to a cryogenic sample because of the small tip and the fact that most cryogenic samples will be in a vacuum. A portion of the thermocouple wire can be thermally anchored to the sample by thermal grease, epoxy, or a bolted spool as discussed for resistance thermometers. The tip can also be greased to the surface but care must be taken to ensure electrical isolation unless the measuring instrument has inputs isolated from ground. If that is the case, soldering the tip to the sample provides excellent thermal contact

2.4 Dynamic Temperature Measurements

Most of the thermometers discussed previously have thermal time constants of several seconds. With some exceptions they are not designed for dynamic temperature measurements. Fast response times are achieved with thermometers that have low heat capacity (low mass or low specific heat) and good thermal contact between the sensing element and the object to be measured. The object to be measured can either be a solid object, in which case it can provide support for the thermometer, or a fluid, in which case the thermometer must be supported by some nearby solid and thermally insulated from it. The second case occurs, for example, in the measurement of the instantaneous temperature of the helium working fluid in regenerative cryocoolers. Typical operating frequencies may range from 1 to 60 Hz. To make such measurements at 60 Hz with negligible phase shifts requires a thermal time constant of less than about 300 μs. In the measurement of instantaneous gas temperature, the dominant thermal resistance is often between the sensing element and the gas. As a result, the measurement of dynamic gas temperatures is usually more difficult to measure than that of liquids or solids.

By their nature, thermocouples have a small mass and a potential for fast response times. The use of small diameter thermocouple wire at cryogenic temperatures can often yield response times of a few tenths of seconds. Faster response times are obtained by using commercially available thin foil thermocouples. Foil thicknesses down to 5 μm are available, but considerable care is required in handling the unsupported foil. For measurements of the surface temperatures of solids, a thermocouple film of 3-6 μm thickness can be sputtered on the surface (Krieder, 1992). The internal response time of such a thin film will be about 1 μs or less, but with the thermal resistance at the interface, the response to temperature changes at the surface may be considerably longer. The response time of unsupported 5 μm thick type E thermocouple foil to oscillating helium gas temperatures were measured at NIST and found to be about 10 ms at 80 K.

Thin film platinum or carbon thermometers can also be used for dynamic temperature measurements and have response times comparable to those of the thin film thermocouples. Louie and Steward (1990) used an unsupported 4 μm thick Pt foil in the measurement of transient heat transfer to liquid hydrogen for response times down to 10 μs. The use of carbon films on a quartz substrate have also been used for transient heat transfer experiments to liquid helium (Giarratano and Steward, 1983) and to liquid hydrogen (Louie and Steward, 1990). Giarratano et al. (1982) measured a response time of about 50 μs at 77 K for a 18 nm thick platinum film on a quartz substrate.

For high-speed temperature measurements in the range of 1 to 20 K, a silicon-on-sapphire (SOS) thermometer is the fastest ever reported. The response time of these thermometers in both liquid and gaseous helium was found to be about 300 ns. (Louie, et al., 1986). These thermometers are made with a 1 μm thick silicon layer on a 0.13 mm thick sapphire substrate. The silicon has been ion implanted with phosphorus to give a resistance versus temperature curve similar to germanium resistance thermometers. These thermometers were used to study the temperature oscillations that occur in thermoacoustic oscillations inside small tubes closed at the room temperature end and open to a dewar of liquid helium at the other end (Louie, et al., 1986). The same thermometers were used for the measurement of instantaneous temperature of the helium gas inside a Stirling cryocooler next to the regenerator. Figure 12 shows how these thermometers were suspended from a fiberglass-epoxy support to measure the gas temperatures in a Stirling refrigerator at temperatures of about 10 K. The 38 μm diameter Cu-Ni support wires minimize the thermal contact between the thermometer and the support.

The thermal response times of several carbon, germanium, and diode thermometers at cryogenic temperatures were measured at NIST (Linenberger, et al., 1982). The response times reported there for the SOS thermometer were superseded by the measurements of Louie et al. (1986). At 4 K, 1/8 W carbon resistors showed response times as fast as 6 ms. Commercial Si diode thermometers in their basic sensor package have a response time at 4 K of about 10 ms as reported by their manufacturer. A response time of about 6 μs at 4 K has been reported for a miniature silicon diode thermometer (Rao et al., 1983). The thin film metal oxy-nitride resistance thermometers have a reported time constant at 4 K of 1.5 ms as an unpackaged chip. When packaged inside a copper canister the response time increases to about 0.4 s at 4 K.

For high speed measurements of oscillating gas temperatures, platinum wire of about 5 μm gives a response time in still helium gas at 300 K of about 300 μs. Unfortunately, platinum wire of this small diameter is not strong enough to withstand oscillating mass flows that usually accompany the oscillating temperatures in gas. Instead, 3.8 μm diameter tungsten wire can be used, which is much stronger and has a measured response time of about 260 μs at 300 K in still helium gas (Rawlins et al., 1991, 1992). Thermometers made with 2 mm long segments of the 3.8 μm diameter tungsten wire have been used in oscillating gas flows at cryogenic temperatures for hours with no breakage, providing the gas is very clean. Such wire is commercially available from manufacturers of hot wire anemometers. A description of a small demountable probe using this wire is given in the section on flow. The resistance of the tungsten wire has a linear temperature dependence down to about 77 K. Above that temperature its dimensionless sensitivity is 1.032, which is comparable to that of platinum.

3. STRAIN

The measurement of strain has many applications beyond its direct measurement. For example, strain gages are commonly used to measure force and pressure. In turn, pressure transducers are often used in the measurement of flow. Most measurements of strain, including those at cryogenic temperatures, are performed with bonded resistance strain gages. We restrict our discussion to these devices. An excellent review of resistance strain gages is given by Hannah and Reed (1992), although their book emphasizes temperatures of 300 K and above. The principles are no different at cryogenic temperatures, but a proper materials selection is important. The resistance strain gage is an element whose resistance is a function of the applied strain. The relative resistance change can be expressed as

$$\Delta R / R = F_S \, (\Delta L / L), \tag{13}$$

where F_S is the gage factor or strain sensitivity factor, and $\Delta L/L$ is the strain. Typical gage factors are about 2 for most of the commonly used metallic alloys. Their gage factors are nearly independent of strain for strain levels up to about ±2000 microstrain (2000×10^{-6}). The metal alloy gages are usable at cryogenic temperatures for strain levels up to about 1.5%. Semiconductors can have gage factors of about 100 or more, but they are very temperature sensitive.

3.1 Metal Alloy Strain Gages

Most measurements of strain at temperatures from 4 K to 300 K are made with a nickel-chromium alloy or a modified nickel-chromium alloy (73%Ni+20%Cr+Al+Fe) either in the form of a wire or, more recently, in the form of photoetched foil. The copper-nickel alloy most often used at ambient temperatures has larger temperature and magnetic field effects and is seldom used for cryogenic temperatures. Typical resistance values for these gages are in the range of 60 to 1000 Ω, although 120 and 350 Ω gages are most commonly used at cryogenic temperatures. The alloy grid is bonded to a carrier matrix (backing), and usually has a geometry like that shown in Fig. 13. Gage lengths vary from about 0.20 mm to 100 mm. The large areas in the region of the bends reduce the effects of transverse strain. Typical ratios of gage factors between transverse and longitudinal strain are only a few percent and have negligible effect on most measurements, unless high accuracy is desired. Many other gage geometries are available from gage manufacturers for use in various applications. The most common backing material for use at cryogenic temperatures is glass-fiber reinforced epoxy-phenolic. The polyimide backing commonly used for large strains at room temperature or above is seldom used for cryogenic temperatures. Most gages have a top layer of insulation bonded over the grid and backing. This top layer is known as the overlay or encapsulating layer. It is particularly important for use in liquid cryogens to prevent the formation of bubbles at the surface of the metal caused by self heating. These bubbles can lead to rapid localized temperature rises which cause considerable noise in the signal. For cryogenic use, the gage is usually bonded to the test specimen with an epoxy recommended by the manufacturer of the gage.

3.2 Temperature Effects

Various temperature effects can have a significant impact on the measurement of strain at cryogenic temperatures. There are three different temperature effects that need to be considered. The first is the effect of temperature on the gage factor. The gage factor for the modified nickel-chromium alloy varies linearly with temperature in such a way that the gage factor at 4 K is about 4 to 5% higher than the gage factor at 297 K (Starr, 1992). For the copper-nickel alloy, the gage factor decreases by about 3% when cooled to 4 K from 297 K.

The second temperature effect is caused by the change in resistivity with temperature, or the temperature coefficient of resistivity (TCR). With the cryogenic alloys discussed here, the change in resistance of a strain gage when cooled from ambient temperature to 4 K is usually less than 5%. A 5% resistance change is the same change that would occur with a strain of 2.5% in a gage alloy with a gage factor of 2. The resistance change caused only by a temperature change is referred to as apparent strain or thermal output.

The third temperature effect is caused by the strain induced in the gage due to the difference in the thermal expansion between the specimen and the gage. This difference is a function of the specimen material and the gage material. With most metals, the difference in thermal contraction from ambient to 4 K is only a few tenths of a percent. In practice, the second and third temperature effects are combined into one apparent strain (A.S.) or thermal output that is a function only of temperature and the difference in thermal expansion between the gage and the specimen.. Strain gage manufacturers can minimize this thermal output for a particular specimen thermal expansion by a proper heat treatment of the gage alloy. That technique is known as self-temperature compensation (STC). Figure 14 shows how this apparent strain varies with temperature for the modified nickel-chromium gage bonded to various materials, and with the curves normalized at 280 K (Pavese, 1984). Shown for comparison is the dashed curve for a copper-nickel alloy gage bonded to a 304L stainless steel specimen. When the modified nickel-chromium curves are normalized at 4.2 K, all the curves agree with each other up to 20 K and reach a minimum of -700×10^{-6} at a temperature of 15 K.

In order to correct for the thermal output or apparent strain, the temperature of the specimen must be measured. Often it is submersed in liquid cryogens, in which case the barometric pressure defines the bath temperature. When the specimen is not in a liquid bath, its temperature must be measured with a thermometer in thermal contact with a strain free area of the specimen that is also in good thermal equilibrium with the portion subjected to the strain. Alternatively, the thermal output can be reduced to zero by using a temperature compensating circuit. This circuit is a Wheatstone bridge with two identical resistance strain gages used for the active and the compensating (reference) arm. The compensating gage is mounted on a strain-free region of the sample which is at the same temperature as the strained region. If the specimen can remain strain-free until the test temperature is reached, then the thermal output can simply be canceled out by adjusting the reference resistor in the Wheatstone bridge circuit.

3.3 Magnetic Field Effects

A magnetic field can cause a change in resistance, which is known as the magnetoresistance effect. This resistance change leads to a strain error. The magnetic field can also affect the gage factor. Walstrom (1975) measured the effect of magnetic fields up to 6 T on several strain gage alloys. For the nickel-chromium alloy, a strain error of $+160\times10^{-6}$ was found at 4.2 K in a magnetic field of 6 T. The error varied approximately quadratically with magnetic field. There was no detectable magnetoresistance strain error at 296 K or 77 K with this alloy. The copper-nickel alloy gage showed much larger magnetoresistance effects. It showed a strain error of -250×10^{-6} at 296 K in a field of 6 T. Presumably, the error would be much larger at cryogenic temperatures, but it was not measured. These results indicate that copper-nickel gages should not be used in magnetic fields. The results of Walstrom also showed that the magnetoresistance effect was independent of field direction and independent of strain for strains up to 10^{-3}. There was about a 1% effect on the gage factor for fields above 3 T with the field perpendicular to the gage surface. No effect on the gage factor was seen with other field orientations.

Freynik, et al. (1977) extended the magnetoresistance measurements on nickel-chromium alloy gages up to magnetic fields of 12 T at 4.2 K. The strain error was found to be $+400\text{x}10^{-6}$ at 4.2 K in a magnetic field of 12 T. Their data were in good agreement with those of Walstrom (1975) for fields of 6 T and below.

3.4 Measurement System

The measurement of strain with resistance strain gages entails the detection of resistance changes that are often less than 1% of the resistance. Such small changes are best measured with a Wheatstone bridge adjusted for zero output at some known reference condition. An amplifier is used on the output voltage to significantly increase the resolution. Either DC or AC bridge excitation can be used, although most commercial strain gage systems use DC voltage. The use of AC excitation eliminates any thermal EMFs generated in the circuit and allows the use of lock-in amplifiers for enhanced signal-to noise ratio. Any change in resistance in the electrical leads to the gage can be compensated by a three wire bridge. As a result, most static measurements of strain should be made with three wire bridges. The bridge excitation voltage must be kept sufficiently low to prevent self heating of the gage. Usually, the excitation voltage is determined experimentally. For cryogenic applications, a bridge excitation of 2 V with a 350 Ω gage is typical for use in a liquid cryogen. In vacuum, voltage levels down to 0.5 V may be necessary to prevent self heating (Ferrero and Marinari, 1990).

3.5 Dynamic Measurements

The intrinsic frequency response of the resistance strain gage should be in the tens or hundreds of kilohertz range. The adhesive joint will lower this frequency response some, but the resulting frequency response should be well above the maximum frequency used in most measurements. Few measurements are made at frequencies above 100 Hz because of the limitations in the equipment used to apply the dynamic strain (Hartwig and Wüchner, 1975). In measurements of dynamic strain, the output of the Wheatstone bridge circuit is coupled to the amplifier through a capacitor (AC coupled) to eliminate any DC component. The AC coupling eliminates all effects associated with slow temperature changes of the specimen. Dynamic strain measurements are typically associated with fatigue measurements. The fatigue life of a properly selected gage can be as high as 10^8 cycles at a strain level of $\pm 2000 \times 10^{-6}$.

4. PRESSURE

The easiest and most common method for measuring pressure at cryogenic temperatures is to connect a capillary line between the desired pressure location and a pressure transducer at ambient temperature. In this case, a conventional pressure transducer can be used. This method is limited to measurements of static pressure because of the low frequency response of the capillary line. This method also has limitations in the low pressure range because of the thermomolecular pressure correction that occurs in a temperature gradient. (McConnville, 1969). The correction becomes particular large for pressures below about 130 Pa. In this region, the pressure at the warm end of the capillary is higher than that at the cold end. Most commercial pressure transducers are designed for use at ambient temperature and cannot be used at cryogenic temperatures. We discuss some of the exceptions here. There are three types of pressure sensors or transducers that are commonly used at cryogenic temperatures, (a) capacitance, (b) variable reluctance, (c) strain gage or piezoresistive, and (d) piezoelectric.

4.1 Capacitance Pressure Sensors

The variable capacitance pressure sensors are one of the most common types of pressure sensors used for precision work at cryogenic temperatures. However, we are not aware of any commercial units that have been used at these temperatures. An excellent review of capacitance pressure sensors used at cryogenic temperatures is given by Jacobs (1986). The sensor consists of a thin, stretched membrane, or for high pressures, a machined diaphragm, which deflects with pressure. It forms one electrode of the capacitor. The other electrode is formed by a stationary disk. The two electrodes must be electrically insulated from each other. The diaphragm and other parts of the sensor are usually of BeCu. A well-constructed capacitance sensor has less than a 5% change in sensitivity when cooled from 300 K to 4 K. The capacitance of these sensors is typically in the range of 20 to 50 pF, and can be measured with a capacitance bridge. For better accuracy, a three-lead bridge should be used to eliminate the effects of temperature-dependent lead capacitance. A frequency-to-voltage converter can also be used to measure the capacitance (pressure). Sensitivities of 1 part in

10^8 have been achieved with some capacitance pressure sensors, although a resolution of 1 part in 10^5 would be more common with inexpensive electronics. A disadvantage of the capacitance sensors is the requirement for coaxial cables between the sensor and the electronics.

4.2 Variable Reluctance Pressure Sensors

The variable reluctance pressure sensor utilizes a magnetically permeable stainless steel diaphragm. Deflection of the diaphragm is sensed by a pair of inductance coils on each side of the diaphragm, as shown in Figure 15. The magnetic reluctance of each of the circuits is a function of the gap between the diaphragm and the "E" core. A change in the reluctance on each side of the diaphragm changes the inductance of each of the coils. These two coils are connected in a bridge circuit, with the coils forming one half of the bridge and a center tapped transformer forming the other half of the four-arm bridge. An AC signal of 3 to 5 kHz is commonly used in the bridge circuit. A carrier demodulator amplifies the output signal and converts it to a DC voltage proportional to the pressure. Because the coils are made of copper wire with very low resistance, the power dissipation in the transducer is quite small and acceptable for most cryogenic use. For temperatures of 77 K and below, the power dissipation is about 1 mW with conventional electronics using a 5 V excitation.

Commercial variable reluctance transducers are made with either all-welded construction or with rubber O-ring seals between the diaphragm and the transducer case. For cryogenic applications, the all-welded models must be chosen. We have found that such transducers perform satisfactorily at temperatures down to 2 K. The differential pressure models with relatively low pressure ranges (below about 100 kPa) remain linear at these low temperatures. Their sensitivity decreases by 12 to 13 % from 300 K to 77 K but remains unchanged from 77 K to 4 K. They have a natural frequency of about 20 kHz and an internal volume of about 0.07 cm^3 on each side of the diaphragm. Their external dimensions are relatively large, as shown in Figure 16(a). Unfortunately, we have experienced some large deviations from linearity at 4 K with the high pressure (5 MPa) models.

The calibration and vibration testing of many of these variable reluctance pressure transducers was reported by Kashani et al. (1990) for use at temperatures down to 2.1 K. The full scale range of these transducers varied from 0.86 kPa to 138 kPa. They found that the sensitivity of a 0.86 kPa transducer increased by about 4% from 300 K to 4.2 K and then decreased by about 2% at 2.1 K. A 138 kPa transducer showed a 6% decrease in sensitivity when cooled from 300 K to 4.2 K. There was no significant change in their responses after they were overpressurized. After temperature cycling the transducers two or three times, they exhibited linearity and repeatability to within ±1% of full scale in liquid helium. Daney (1988) reported that a 5.5 kPa transducer showed a sensitivity change of only 0.2% between 300 K and 4 K. Because of the different values of sensitivity changes reported by different authors on different transducers, it is important that each transducer be calibrated at cryogenic temperatures. Once calibrated, it should be repeatable to within ±1%. The zero reading also shifts with temperature, but the transducer is normally rezeroed electronically after it has reached the desired temperature.

4.3 Piezoresistive Pressure Sensors

The piezoresistive pressure sensors use a strain gage to measure the deflection of a diaphragm subjected to a pressure on one side. They are the most common commercial pressure sensor. Some of them can be used at cryogenic temperatures if the materials have been properly selected. One type of sensor uses a metal diaphragm, typically stainless steel, with a thin film strain gage deposited on the diaphragm, or a metal foil stain gage bonded to the diaphragm. Various strain gage materials have been used, but the nickel-chromium alloy discussed in the previous section on strain is particularly good for use at cryogenic temperatures. Cerutti, et al. (1983) reported on tests with several commercial strain-gage pressure sensors at temperatures down to 4.2 K and in magnetic fields up to 6 T. As is expected, their behavior is similar to that discussed for strain gages. For example, the calibration factor changes by about 5% for the nickel-chromium gages when cooled from 300 K to 4 K. Thermal zero shifts of these same sensors were less than 3% of full scale (F.S.) for a temperature change from 293 to 4.2 K. The apparent pressure error at full scale due to a temperature change from 293 to 4 K was about 4% F.S. The combined non-linearity and hysteresis was about ±0.2% F.S. at a fixed temperature of 4.2 K. When the sensor was cycled between 293 K to 4.2 K, the non-linearity and hysteresis increased to ±2.3% F.S. A magnetic field caused a maximum signal variation at 5 K of about 0.5% F.S., which occurred at low pressures and a field of 1.6 T.

Another type of piezoresistive pressure sensor uses a semiconductor strain gage to measure the deflection of a diaphragm. Doped silicon is nearly always used for these gages because the processing of silicon is a very well established technology. In some cases, the diaphragm is also made of silicon with the strain gage grid diffused into the diaphragm. The silicon diaphragm is usually bonded to a stainless steel case by epoxy. The silicon diaphragm is often etched (micromachined) into a particular geometry to concentrate the stress at the region where the strain gage is located. This construction has the advantage of nearly eliminating all mechanical hysteresis in the sensor. The epoxy bond has the disadvantage of limiting the maximum negative pressure differential to about 1 MPa before the epoxy bond will crack. The epoxy bond can occasionally develop leaks after rapid cooldown. The sensors that employ a stainless steel diaphragm welded to the case do not suffer from the limited negative pressure differential, and they are less likely to develop small leaks past the diaphragm. The silicon strain gage elements are bonded directly to the back side of the diaphragm to maintain a high frequency response. The bond does have the disadvantage of slightly higher non-linearity and hysteresis (0.5 to 1%) compared with that of the all-silicon construction (about 0.5%). These silicon pressure sensors, with stainless steel or silicon diaphragms, can be made as small as 1.3 mm diameter. A common configuration available in a wide range of full-scale pressure ratings has a diameter of 3.9 mm at the tip where the diaphragm is located. A 10-32 UNF-2A thread (4.8 mm diameter) allows the sensor to be screwed into a small pressure port. Figure 16(b) shows the geometry of this type of pressure sensor or transducer. A rubber O-ring fits in a groove under the head of these transducers to seal against the pressure port. For use at cryogenic temperatures, the O-ring must be replaced with a Teflon gasket about 0.13 mm thick. The gasket is compressed by a circular tongue on the mating assembly that fits closely within the O-ring groove to prevent extrusion of the Teflon. The geometry of this type of transducer makes it easy to place the diaphragm very close to the location where the pressure is to be measured. Their natural frequency is about 500 kHz, which permits pressure measurements at very high frequencies. These transducers can be used in the differential mode by utilizing the reference port, but the permissible pressure on the backside of the diaphragm is limited to about 1 MPa. We have not used these transducers in the differential mode.

The advantage of the silicon strain gage over the metallic strain gage in these pressure transducers is the greatly enhanced sensitivity. The 5 MPa transducers with silicon strain gages have sensitivities in the range of 3600 to 8700 mV V^{-1} MPa^{-1} compared with 0.65 mV V^{-1} MPa^{-1} for a transducer with a metal strain gage. The silicon transducers can be used with much cheaper readout electronics. The disadvantage of the silicon device is that it is much more temperature sensitive. Manufacturers of these transducers build in a temperature compensation circuit as part of the Wheastone bridge that is good for the region of about 260 K to 360 K. The zero shift and the sensitivity shift within this temperature range is less than 4%.

The sensitivity (V/Pa) and the zero reading of these silicon-based pressure sensors will change considerably when used at cryogenic temperatures. Boyd et al. (1990) reported on precision calibration measurements of this type of sensor over the temperature range of 78 to 300 K. A total of 37 sensors were measured. Their sensitivities increased by a factor of 1.7 to 1.8 as the temperature was decreased from 278 K to 78 K. The zero offset changed by about 1% F.S. over this temperature range. The curves for both the sensitivity and the zero offset indicate that they will continue to change as the temperature is reduced below 78 K, but at a slower rate. A thermal hysteresis of about ±0.1% F.S. was reported after many thermal cycles. An excitation of 1 mA was used with these sensors which had a bridge resistance of about 5 kΩ. The power dissipation was about 5 mW. Hershberg and Lyngdal (1993) have shown that for pressure measurements at about 10 K or below, the power dissipation in the sensor should be less than about 5 mW. The normal power dissipation at 300 K in these transducers using the commercial electronics is about 50 mW.

Measurements made in our laboratory with a 5 MPa sensor containing a silicon diaphragm with a diffused silicon strain gage showed a sensitivity increase of 1.9 between 300 K and 76 K with almost no change between 76 K and 4 K. Such behavior is consistent with results reported by Clark (1992) in which the sensitivity increased by about a factor of 1.8 between 300 K and 77 K with little change below that temperature. The large change in sensitivity between 300 K and 77 K means that the temperature of the pressure transducer must be measured accurately for use in this temperature range. For lower temperatures, the transducer temperature need not be measured accurately. Walstrom and Maddocks (1987) tested a series of rather inexpensive semiconductor pressure sensors in the temperature range of 1.6 to 4.2 K. These sensors had an initial failure rate of about 20% upon cooldown, but those that survived could be cooled repeatedly. They found that the sensitivity at 4.2 K was about a factor of 2.4 to 2.6 higher than the room temperature value. They also found that the sensitivity at 1.6 K was about 5% higher than the value at 4.2 K, and that the sensitivity at high pressure ($P \approx 100$ kPa) was about 5% less than the sensitivity at low pressure ($P < 10$ kPa).

For dynamic pressure measurements in a gas, the temperature of the gas and the silicon strain gage can vary with time. Some corrections may be necessary when using these transducers for dynamic pressure measurements between 77 K and 270 K when the dynamic temperature is large. The piezoresistive pressure sensors are commonly used for pressure measurements in cryocoolers because of their small size and fast response.

4.4 Piezoelectric Pressure Sensors

Piezoelectric pressure sensors convert the stress applied to the sensing element (typically quartz crystal) to an electrical charge of the order of picoCoulombs. A high-impedance charge amplifier converts the charge to a voltage output that will decay with time when the stress remains constant due to charge leakage through resistance in the output leads. These sensors therefore can only measure pressure changes or dynamic pressures. Some commercial piezoelectric sensors have the charge amplifier built into the sensor package to eliminate the need for special low noise coaxial cables between the sensor and the charge amplifier at room temperature. The charge amplifier converts the high impedance charge output from the sensor to a low impedance voltage output. Any low-noise cable between the sensor and the charge amplifier must have insulation resistances as high as 10^{13} Ω. Sensors with a built-in charge amplifier are powered with a low-cost 24 to 27 VDC, 2 to

20 mA constant-current supply. The voltage output is usually ±5 V at full scale. A long coaxial or two-conductor ribbon cable can be used to connect the sensor to the room-temperature electronics without signal degradation.

Materials and mounting techniques in many of these sensors are compatible with cryogenic use. Some special models designed specifically for cryogenic operation and calibrated at 77 K are commercially available. A low frequency limit in the range of 0.5 Hz for a 5 % error is typical for these piezoelectric pressure sensors due to charge dissipation in the circuit resistance and capacitance. Resonant frequencies are generally greater than 250 kHz. Resolutions of 2×10^{-5} of full scale are possible. Models with full scale dynamic pressure from 0.3 MPa to 35 MPa are available. They can be used with static pressures much higher than the full scale dynamic pressure, which makes them very useful for measurements of small dynamic pressure amplitudes superimposed upon a large static pressure. Typical applications are in the measurement of dynamic pressures in regenerative cryocoolers, such as pulse tube cryocoolers. A typical sensor package is about 38 mm long with a 3/8-24 UNF-2A thread or M6 thread for mounting. A brass or copper gasket is available for a leak-tight seal at cryogenic temperatures, but other models have rubber O-ring seals that cannot be used at low temperatures. Miniature models are also available with a 10-32 (4.8 mm) mounting thread and a total length of about 15 mm.

Piezoelectric pressure sensors are usually calibrated by the manufacturer at room temperature. Such a calibration is more complex than that with other pressure sensors because of the need to use a rapid pressure change or dynamic pressure. Calibrations at 77 K are available for some models. The temperature coefficient of sensitivity is about 0.07 %/°C. In-house calibrations are often performed by comparison with piezoresistive pressure sensors, which can be calibrated with static pressure from a room temperature sensor, but are also capable of measuring high frequency dynamic pressure.

5. FLOW

Many types of flowmeters have been used successfully at cryogenic temperatures for measurements of gas or liquid flows. Some are mass flowmeters while others are volumetric flowmeters. The determination of mass flow rate from a volumetric flow measurement requires a measurement of the fluid density. Some volumetric flowmeters contain a densitometer to yield an inferential mass flowmeter. The measurement of mass flow of cryogenic fluids is particularly important for custody transfer of cryogens from tank trucks to the customer. Pipe sizes commonly used for this application vary from 3 to 9 cm with volumetric flow rates up to about 20 L/s. For liquefied natural gas (LNG), pipe sizes up to 20 cm are commonly used with flow rates up to about 100 L/s (Brennan et al., 1976). Due to space limitations, we cannot discuss all the types of flowmeters used for cryogenic service. The flowmeters considered here and their type (M = mass, V = volumetric, N = neither) are: positive displacement (V), angular momentum (M), turbine (V), differential-pressure (N), thermal or calorimetric (M), and hot-wire anemometer (M). The differential-pressure element can be in the form of an orifice, venturi, packed screens, or laminar-flow channels. Other flowmeters not discussed here but used for cryogenic service are: ultrasonic (V), vortex shedding (V), dual turbine (M), and Coriolis or gyroscopic (M). Detailed descriptions of many types of flowmeters used in cryogenic service are given by Alspach et al. (1966), Brennan, et al. (1971), Brennan,et al. (1974), and Brennan and Takano (1982). A discussion of the NIST cryogenic flowmeter calibration facility for use with liquid nitrogen and argon is given by Brennan et al. (1976). Most cryogenic flowmeters can be calibrated to an uncertainty of ±0.5% for volume flow and ±0.2% for mass flow in this facility (Brennan, et al., 1972). The repeatability of individual flowmeters may be larger than these uncertainty values.

5.1 Positive Displacement Flowmeter (Volume Flow)

The positive displacement flowmeter works on the principle that the flowing liquid must displace some mechanical element. The movement of the mechanical element is then sensed electronically. The various mechanical elements used are screw impeller, rotating vane, and oscillating piston. A detailed description of these various types of positive displacement flowmeters and an evaluation of them for cryogenic service is given by Brennan, et al. (1971). They are generally used with moderate flow rates (1 to 10 L/s) and are capable of being operated over a 5 to 1 flow range, which means the minimum flow is 1/5 of the maximum flow. A pressure drop of about 30 kPa is typical with these meters at maximum flow. With care it is possible to achieve an uncertainty of ±1% with these meters. It is important to subcool the liquid below the saturation curve to prevent the formation of vapor in the flowmeter. A disadvantage of these meters is that they are subject to wear and need to be recalibrated periodically.

5.2 Angular Momentum Flowmeter (Mass Flow)

The angular momentum flowmeter has a rotating member with vanes oriented parallel to the axis. The rotating member is driven by an electric motor through a constant torque clutch (hysteresis drive) as shown in Fig. 17. The liquid enters the meter through a flow straightener and passes by the rotating vanes. The liquid tends to retard the rotational speed of the rotor in a manner that is inversely proportional to the mass flow rate. Rotor speed is sensed by a magnetic pickup, and the resulting signal treated electronically to indicate mass flow rate. A flow range of 8 to 1 is typical with these meters. Maximum flow rates for these meters may vary from about 2 kg/s to 15 kg/s. Pressure drops of 20 to 50 kPa are typical with these flowmeters at maximum flow. They have been tested with liquid hydrogen (Alspach et al., 1966) and liquid oxygen, nitrogen, and argon (Brennan et al., 1974). Flowmeters of this type are often used as custody transfer flowmeters on delivery vehicles. Uncertainties of ±2% or less are typical for these flowmeters.

5.3 Turbine Flowmeter (Volume Flow)

The turbine flowmeter consists of a freely rotating bladed rotor, supported by bearings, inside a housing, and an electrical transducer that senses rotor speed. Rotor speed is a direct function of flow velocity. They are used mostly for liquid flows and have a useful range of at least 10 to 1. Calibrations with liquid cryogens may differ from water calibrations by up to ±2% (Alspach and Flynn, 1965). They are susceptible to errors caused by upstream swirl, so some means of flow straightening is usually required for accurate measurements. An evaluation of several cryogenic turbine flowmeters was reported by Brennan et al. (1972). They ranged in size from 3.2 to 5.1 cm with maximum flow rates between 5 and 14 L/s. Maximum pressure drops ranged from 20 to 100 kPa. Uncertainties were generally less than ±1%.

A commercial turbine flowmeter with ball bearings has even been used for measuring flow in normal and superfluid helium with flow rates between 0.01 L/s and 0.3 L/s (Daney, 1988). It had a bore diameter of 9.35 mm. The meter output was about 0.5% higher for superfluid helium compared with normal helium. However, care must be taken with superfluid helium to prevent cavitation. A custom-made turbine flowmeter with magnetic bearings has also been used for liquid helium flow (Rivetti et al., 1987). The success of these meters depends very much on maintaining a low drag from the bearings. To insure this, the liquid must be free of solid particles such as frozen air or water. An upstrem filter is often used with these flowmeters. Short term repeatability of ±0.15% was reported for the magnetic-bearing flowmeter. Like other flowmeters with moving parts, they do have a limited lifetime.

Turbine flowmeters have been reported to have response times in the range of 1 to 10 ms, depending upon blade angle, flowmeter size, and flow rate (Alspach and Flynn, 1965). These authors also report on the successful use of these meters in reverse flow. As a result, they can be used to a limited extend in transient flow or oscillating flow for frequencies less than about 1 to 10 Hz.

5.4 Differential Pressure Flowmeter

The differential-pressure flowmeter can be used with either gas or liquid flows. They operate on the principle that the pressure drop across some flow element is proportional to the flow rate. These meters can be used at cryogenic temperatures if the pressure transducer is located at ambient temperature or if a compatible pressure transducer is used at the cryogenic temperature. These flowmeters have no moving parts; thus, they are desirable for applications that require high reliability. The most common type of flow element is the sharp-edge orifice plate. Usually the orifice plate is designed for flow in one direction with the sharp edge of the orifice on the entrance side. A symmetric design for the orifice plate as shown in Fig. 18 has been used in our laboratory for use with oscillating flow (Radebaugh and Rawlins, 1993). When used for oscillating flows, it is important that the connecting lines are of the same length and that the differential pressure transducer is symmetrical. We have experienced some problems with shifts in the zero reading of differential pressure transducers when the differential pressure changes sign.

The relation between the mass flow rate and the pressure drop ΔP across the orifice is given by

$$\dot{m} = C_o A_o [2\rho\Delta P/(1-\beta^4)]^{1/2}, \qquad (14)$$

where C_o is the orifice or discharge coefficient ($\approx$0.6), A_o is the cross-sectional area of the orifice, ρ is the fluid density, and β is the ratio of the orifice diameter to the tube inside diameter. Because of the square root dependence of $\dot{m}$ on ΔP, a range of 10 for ΔP yields a range of 3 in $\dot{m}$. This low flow range is a disadvantage of the orifice meter. The orifice coefficient determined from a water calibration can be used for most liquid cryogens with ±2% uncertainty (Brennan et al., 1974). The uncertainty for use with gas can be somewhat higher. To obtain high accuracy with these meters it is necessary to have a straight length of tube upstream of the orifice that is at least 20 times the tube diameter, and a length at least 5 times the tube diameter should be placed downstream of the orifice. Alternatively, flow straighteners in the form of tube bundles can be used if length is restricted. Equation (14) shows that this flowmeter is neither an intrinsic mass flowmeter nor an intrinsic volumetric flowmeter because of the square root dependence on the density. The simple design of these meters means that they can be scaled over a very wide range of flow rates. Pressure drops can be made quite small, although for ΔP less than about 1% of the mean pressure, the signal-to-noise ratio may begin to decrease.

A disadvantage of the orifice meter is the large amount of turbulence created by the flow through the orifice. This problem is reduced by using a venturi as the flow element, as shown in Figure 19. The throat diameter is usually about one-half the tube diameter. The flow rate through the venturi meter is governed by the same relationship as for the orifice meter, Eq. (4); however, the discharge coefficient is near unity. Venturi meters have been used in many applications for measuring flow rates of normal, supercritical, and superfluid helium (Daney, 1988, and Rivetti, et al., 1993). Short term repeatability of ±0.5% was reported. Discharge coefficients varied by about 3% over a flow range of 10 to 1 and for temperatures between 1.7 and 4.2 K. The design requirements of the venturi prevent it from being used for reverse flow, such as in fully-reversing oscillating flow.

The third type of flow element that can be used in differential- pressure flowmeters is the laminar flow element. The laminar flow element gives rise to a linear relationship between mass flow rate and pressure drop. As a result, it can be used over a wider range of flow rates than can the orifice meter and the venturi meter. The governing equation is given by

$$\dot{V} = \dot{m} / \rho = \Delta P / Z_f , \tag{15}$$

where $\dot{V}$ is the volumetric flow rate and Z_f is the flow impedance of the laminar element. For laminar flow in a gap, the flow impedance is given by

$$Z_f = 12 \mu L / w t^3 , \tag{16}$$

where μ is the viscosity, L is the length of the gap, w is the width of the gap, and t is the thickness of the gap. Equation (15) shows that the laminar flow element is intrinsically a volumetric flowmeter. In order to achieve laminar flow conditions the gap thickness must be sufficiently small. As an example, for helium gas with $\dot{m}$ = 1 g/s, P = 2 MPa, L = 1 cm, and ΔP = 20 kPa, the gap thickness must be less than 34 μm at 80 K and less than 9.8 μm at 10 K. The gap width must be 116 mm at 80 K and 240 mm at 10 K. Even though the overall gap width can be achieved with many parallel gaps, the outside dimensions of the laminar flow element will be relatively large. The small gap thickness at cryogenic temperatures makes the laminar flow element difficult to fabricate. No commercial laminar flow elements are available for cryogenic use. A custom-made device has been used with some success to measure oscillating mass flow rate at temperatures of about 10 K in high pressure helium gas (Radebaugh and Rawlins, 1993). One caution to note on the use of a gap flow element for measuring oscillating flow is that the high velocity gas flow in the gap can lead to a significant inertance term, which will cause the phase of the pressure drop to lead that of the flow (Yuan, et al., 2010). The inertance I (fluid equivalent of electrical inductance) of a gap is given by

$$I = \frac{\rho L}{w t} , \tag{17}$$

and the complex impedance is given by

$$Z_I = j \omega I , \tag{18}$$

where $j^2 = -1$ and ω is the angular frequency of sinusoidal oscillation. The presence of j in Eq. (18) indicates that the component of the dynamic pressure drop due to the inertance leads the flow by 90 °. The phase shifting becomes more important at higher frequencies. For oscillating flow the compliance (fluid analog of electrical capacitance) must also be considered to calculate the phase between the pressure drop and the flow.

The fourth type of flow element that can be used in differential flowmeters is that of packed screen or packed spheres. Correlations for the friction factor in such a packing must be used to find the relation between the pressure drop and the flow. With such geometries the relation between the pressure drop and flow is non-linear. The effect of inertance is generally less in packed screen or packed spheres compared to that in gaps because of slower fluid velocities.

5.5 Thermal or Calorimetric (Mass Flow)

In the thermal flowmeter, the flowing fluid is heated with a constant power $\dot{Q}$, which causes its temperature to rise by an amount ΔT. A thermocouple or thermopile measures this temperature difference between the outgoing and incoming fluid flow. The mass flow rate is given by

$$\dot{m} = \frac{\dot{Q}}{C_p \Delta T}, \tag{19}$$

where C_p is the specific heat of the fluid. This flowmeter is a true mass flowmeter. A commercial thermal flowmeter was used by Bugeat et al. (1987) to measure mass flow rates around 10 mg/s of hydrogen and helium gas at temperatures between 100 and 300 K. They reported a non-linearity of less than 2% and a response time of about 0.22 s at 158 K in hydrogen gas for a flow of 9 mg/s. This type of flowmeter should work with flow in either direction.

5.6 Hot Wire Anemometer (Mass Flow)

The hot-wire or constant temperature anemometer (CTA) infers mass flow rates from the changing heat transfer rates associated with a heated element (Perry, 1982). The resistively heated element, often a fine wire, has a large temperature coefficient of resistance and a large length-to-diameter ratio. With feedback electronics, the electrical power to the element is varied automatically to maintain the element at a constant resistance (temperature) as the flow rate varies. The power, or voltage squared, is correlated to the mass flow rate from a calibration of the device against a standard flowmeter at ambient temperature. For an ideal gas, the CTA is a true mass flowmeter (Rawlins et al., 1993).

We have used commercial hot-wire anemometer probes successfully for the measurement of helium gas flows at temperatures down to 77 K (Rawlins et al., 1993, and Radebaugh and Rawlins, 1993). The calibration changes in a linear manner with the gas temperature, but it is not a strong function of this temperature. The probes were fabricated with a 3.8 µm diameter tungsten wire about 2 mm long attached to the wire supports. The wire was heated to about 297 K to give high sensitivity and reproducible results. Since the power input with this high wire temperature was about 1 W, the CTA was turn on only briefly in order to make the needed measurements. The response time of the CTA was measured to be less than 15 µs in zero flow. The response time is even faster at finite flow rates. The fast response time of the CTA makes it ideal for measuring turbulence, transient flow, or oscillating flow. Because of the fine wire, it can only be used in very clean gas flows.

The CTA has been used with modified commercial vacuum fittings as shown in Fig. 20 to measure oscillating mass flow rates in compressed helium gas at temperature down to 77 K within a pulse tube refrigerator (Rawlins et al., 1993). Oscillating frequencies up to 30 Hz could be measured. To provide the necessary temperature correction, an identical tungsten wire probe to serve as an RTD was inserted in the assembly from the opposite side (see Fig. 20). The diameter of the tubes extending from the device shown in Fig 20 was 3.2 mm. Consequently, this type of flowmeter can be made with very small gas volumes, which is necessary for measurements of the oscillating gas flow within small Stirling or pulse tube refrigerators. Several layers of stainless steel screen on each side of the probes ensured that the flow was uniform in both directions. The integrated mass flows measured for each direction of flow agreed to within 1.6% for measurements near 80 K.

6. LIQUID LEVEL

A common measurement problem in cryogenics is that of determining the level of cryogens in storage dewars or within an experimental apparatus. For the heavier cryogens (hydrogen and helium excluded), a measurement of the hydrostatic head with a differential pressure gage can be correlated to the liquid level. This technique is commonly used on storage dewars of liquid nitrogen for approximate (±10%) indications of liquid level. More precise measurements can be made with capacitance liquid-level gages that are available for use with liquid nitrogen from a few different manufacturers. The detection of liquid level at discrete locations (for level control) is often performed in many commercial devices with a self-heated resistance or diode thermometer. The higher heat transfer rate in the liquid phase causes the temperature of the thermometer to decrease when it is immersed in the liquid. When several of these thermometers are located at varying heights, a semi-continuous reading of liquid level is available. For continuous readings, a vertical wire or foil can be resistively heated (Wexler and Corak, 1951, and Maimoni, 1956). The resistance of the wire will be a function of the liquid level. The heat input to the liquid cryogen with this device can be minimized by using a current pulsed periodically to update the previous reading. Modern electronics makes this a simple task.

Greater sensitivity and less heating occurs when the wire is made with a superconducting material that has a critical temperature slightly above the normal boiling temperature of the liquid cryogen of interest. A current very near the critical current is passed through the wire so only the portion in the liquid remains in the supercoducting state. Again, intermittent use reduces the total heat dissipation. For liquid nitrogen, the wire can be a high temperature superconductor. For liquid helium, the wire must be a low temperature superconductor such as tantalum (T_c = 4.4 K). The current through the wire must be varied if the temperature of the helium bath is lowered. These superconducting level sensors are commercially available from several manufacturers.

7. MAGNETIC FIELD

Instruments which measure magnetic field are usually called gaussmeters, teslameters, or magnetometers. For measurements of weak magnetic fields, the Superconducting Quantum Interference Device (SQUID) magnetometer is unsurpassed. It can detect changes in magnetic field as small as 10^{-15} T (Fagaly, 1987). They can be used for fields up to about 1 mT.

For measurement of high magnetic fields at cryogenic temperatures, magnetoresistive sensors or Hall-effect sensors can be used. The principle of magnetoresistive sensors is that the resistance of a metal or semimetal changes with the applied magnetic field. This change can vary from 2 to 3% change in a nickel-iron alloy to as much as 10^6 in bismuth. For small values of magnetic field, the change in resistance is proportional to the square of the magnetic field, whereas for larger fields it may have several higher order terms. Magnetoresistance is also a function of temperature. This complex behavior makes it difficult to use magnetoresistive sensors for measuring magnetic fields over a wide range of temperatures and fields.

The Hall-effect sensor works as follows: A current is passed through the sensor in the x direction. With a magnetic field applied in the z-direction, a voltage in the y-direction is generated that is related to the magnetic flux density B. With proper cancellation of offset voltages, the output of the Hall-effect element is given by

$$V = \left(2\mu_H \frac{w}{L} R \right) IB, \tag{20}$$

where μ_H is the electron Hall mobility, w/L is the effective width-to-length ratio for the Hall element, I is the excitation current, R is the resistance of the Hall element, and B is the magnetic flux density. Any temperature dependence comes about as a result of μ_H and R. The expression within the parentheses makes up the Hall sensitivity γ. It is a weak function of B. Glowacki and Ignatowicz (1987) showed that $Cd_xHg_{1-x}Te$ (x = 0.175) films produced good Hall-effect sensors for use between 4.2 and 20 K. There was no temperature dependence in this range and the Hall sensitivity varied by about 20% between a magnetic flux density of 0.1 and 2 T. The output was very reproducible after many thermal cycles.

Commercial cryogenic Hall-effect sensors are available along with the control electronics from a variety of manufacturers. The usual materials are InAs, InSb, and GaAs. Sample and Rubin (1977) have measured the temperature dependence and the linearity of several of these Hall sensors. They recommend the Hall sensor over other magnetic field sensors for use at cryogenic temperatures. These sensors are available in axial or transverse field models. Typical diameters are about 6 mm and a length of 5 mm for the axial sensor. The transverse sensor is flat with a width of 5 mm and a length of 16 mm. They can be used in magnetic fields up to ±15 T with deviations from linearity less than 1.5%. Outputs at 4.2 K and 77 K are within ±1.5% of the calibration at 300 K. Repeatability after many thermal cycles is within 1%. However, they are susceptible to damage from thermal shock after repeated cycling.

8. CONCLUSIONS

We have discussed and compared the various sensors and instrumentation that are commonly used for measurements at cryogenic temperatures. In most cases, commercial products are available for this need. We have reviewed available instrumentation for measurements of temperature, strain, pressure, flow, liquid level, and magnetic field at cryogenic temperatures. The comparisons of various sensors should allow the reader to quickly determine which sensor is best suited for the task at hand. The references cited should be useful if more details are needed.

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TABLES

Table 1. Thermocouples useful for cryogenic temperatures.

Type	**Positive Wire**	**Negative Wire**	**US Color Code**	**T Range (K)**	**Std. Error**
E	Chromel	Constantan	+ purple; - red	3-1173	1.5 K
J	Iron	Constantan	+ white; - red	63-1073	1.5 K
K	Chromel	Alumel	+ yellow; - red	3-1573	1.5 K
T	Copper	Constantan	+ blue; - red	3-673	1 % of T
Au-Fe	Chromel	Au-0.07 at% Fe	-	1-573	0.2 % of V

Table 2. Characteristics of various commercial thermometers.

Sensor	Excitation	Useful range	Interchangeibility	Reproducibility	Long-term drift	B field $\Delta T/T$ in 10 T
Pt (PRT) Pt100	1 mA	70-800 K <70 K cal.	0.5-0.1 K (A) 1-0.25 K (B)	5 mK	10 mK	1% at 77 K 0.1% at 0 °C
Rh-Fe	1 mA	0.65-500 K	poor	0.2 mK	0.2 mK	poor
Cernox^{TM}	10 mV	0.1-420 K	poor	0.02% of T	25 mK	< 0.5%
Ge	1-3 mV	0.05-100 K	poor	0.5 mK	1-10 mK	poor
Carbon-glass	1-3 mV	1-325 K	poor	1 mK@4K	4 mK	<5%
Carbon	1-3 mV	0.1-300 K	5% of T	0.1% of T	8 mK	<5%
Ru-O	10 mV	0.01-40 K	5-10% of T	15 mK	40 mK	<1%
Thermistor			poor			good

Si diode	10 µA	1.4-500 K	0.25 K (A) 0.5 K (B)	5-20 mK	10-40 mK	poor
Thermocouple	-	1.2-1500 K	1 K	20 mK	50 mK	<5%
Capacitance	5 V at 5 kHz	1.4-290 K	poor	0.3 K	1 K	<0.05%

Table 3. Typical wire tempering lengths for thermometer leads of various sizes and materials. Data from Ekin, 2006.

Material	T_h (K)	T_c (K)	Tempering length for various wire gauges (cm)			
			0.080 mm (#40 AWG)	0.125 mm (#36 AWG)	0.200 mm (#32 AWG)	0.500 mm (#24 AWG)
Copper	300	80	1.9	3.3	5.7	16
	300	4	8.0	13.8	23.3	68.8
Phosphor bronze	300	80	0.4	0.6	1.1	3.2
	300	4	0.4	0.7	1.3	3.8
Manganin	300	80	0.2	0.4	0.4	2.1
	300	4	0.2	0.4	0.7	2.0
Stainless steel 304	300	80	0.2	0.3	0.6	1.7
	300	4	0.2	0.3	0.5	1.4

FIGURES

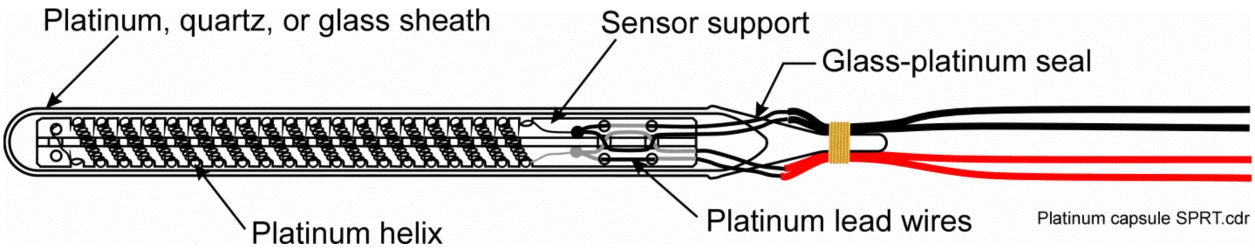

Figure 1. Cross section of a standard platinum resistance thermometer (SPRT).

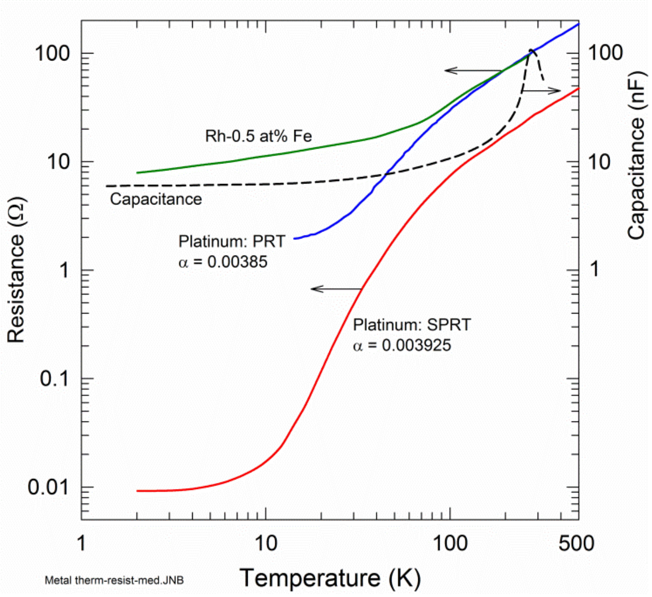

Figure 2. Characteristics of metallic resistance thermometers and capacitance thermometers.

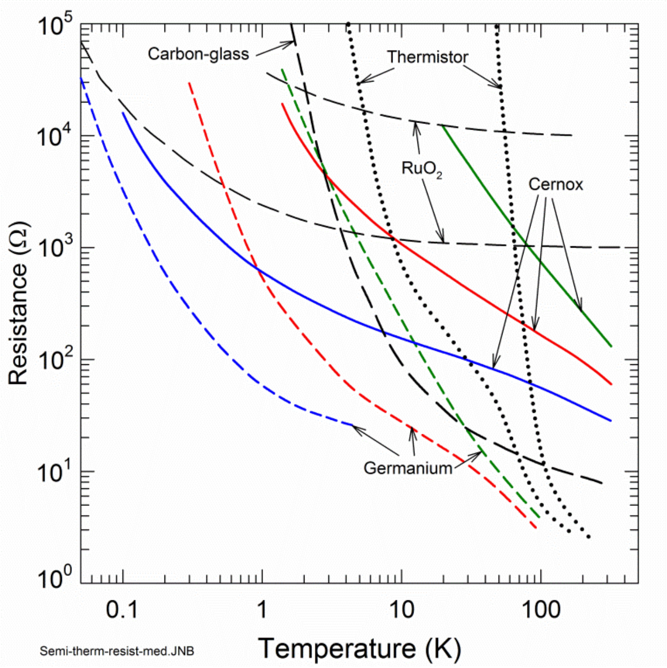

Figure 3. Characteristics of semiconductor and semiconductor-like thermometers.

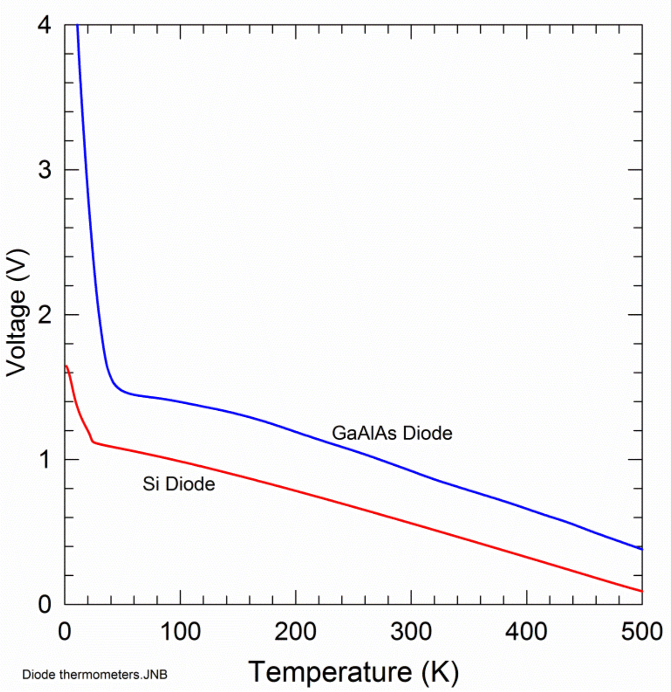

Figure 4. Characteristics of two types of diode thermometers with 10 µA current.

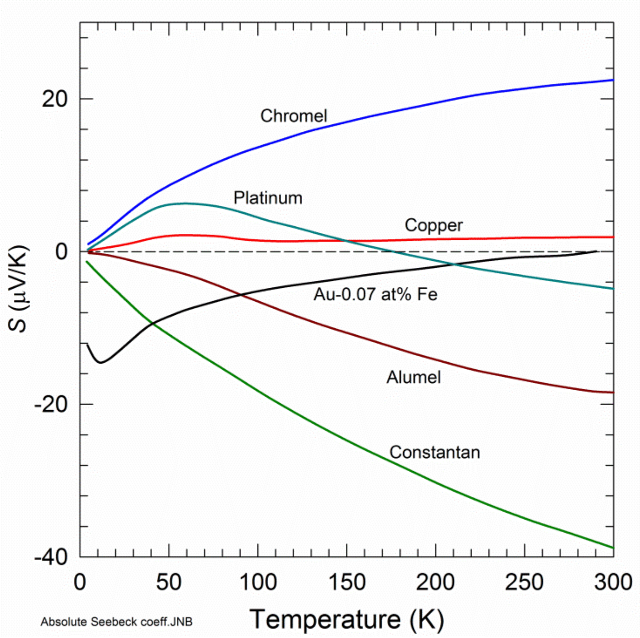

Figure 5. Absolute Seebeck coefficient of several metals used in thermocouples.

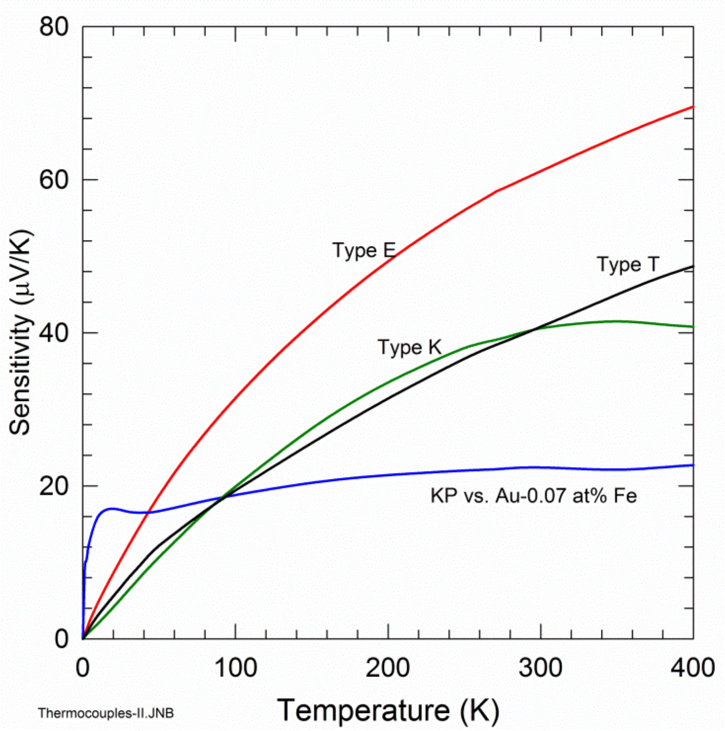

Figure 6. Relative Seebeck coefficient or sensitivity of common thermocouple types useful for cryogenic temperatures.

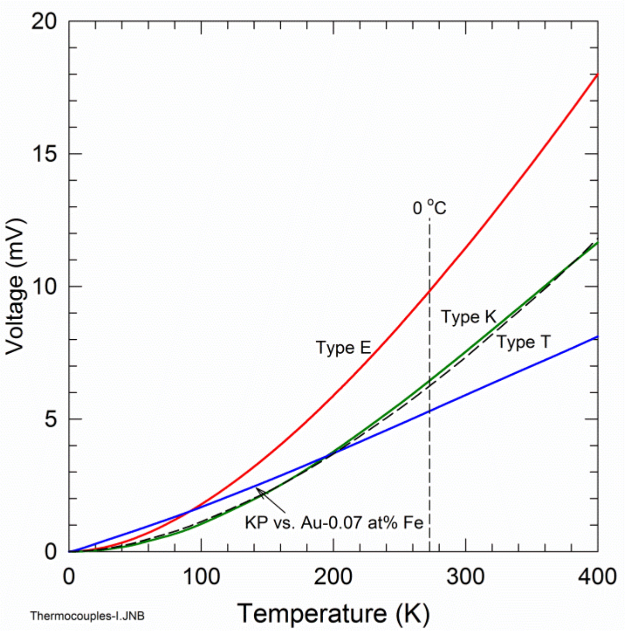

Figure 7. Voltage output of common cryogenic thermocouples with a 0 K reference temperature. The voltage at 0 °C should be subtracted from these readings to convert to a 0 °C reference temperature.

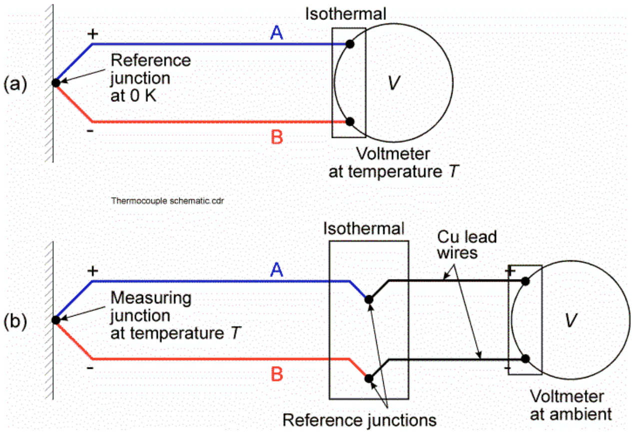

Figure 8. Schematic of a thermocouple measurement system with (a) 0 K reference temperature and (b) some other reference temperature.

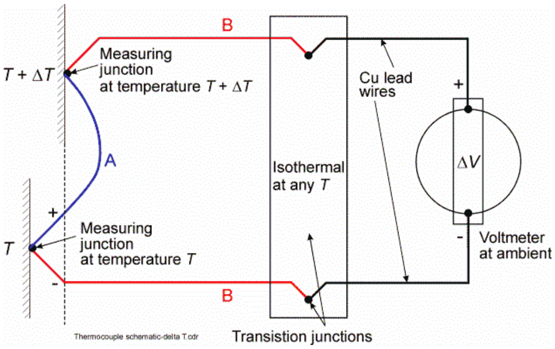

Figure 9. Schematic of a thermocouple measurement system for measuring small temperature differences.

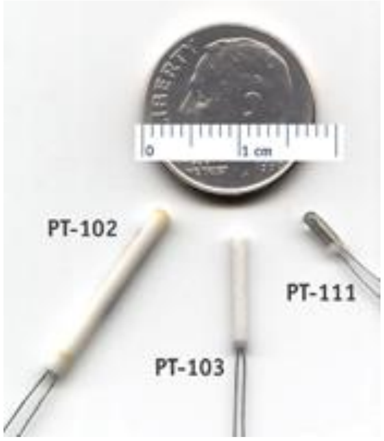

Figure 10a. Photo of several typical industrial wire-wound platinum resistance thermometers. Photo courtesy Lake Shore Cryotronics.

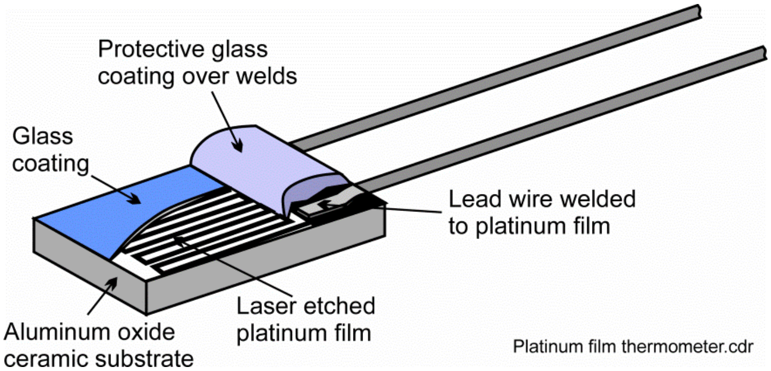

Figure 10b. Drawing of a platinum film resistance thermometer. Typical dimensions are 2 mm × 2 mm.

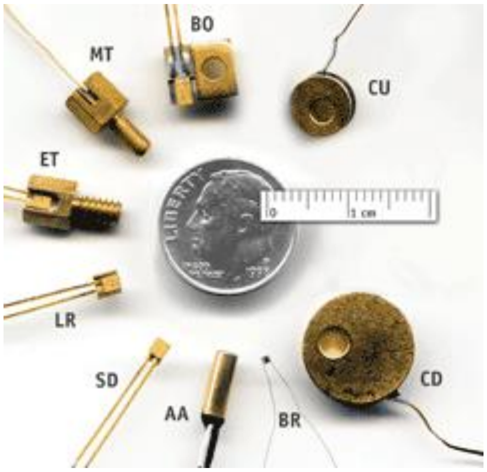

Figure 10c. Photo of various types of packages available for many resistance and diode thermometers. Photo courtesy Lake Shore Cryotronics.

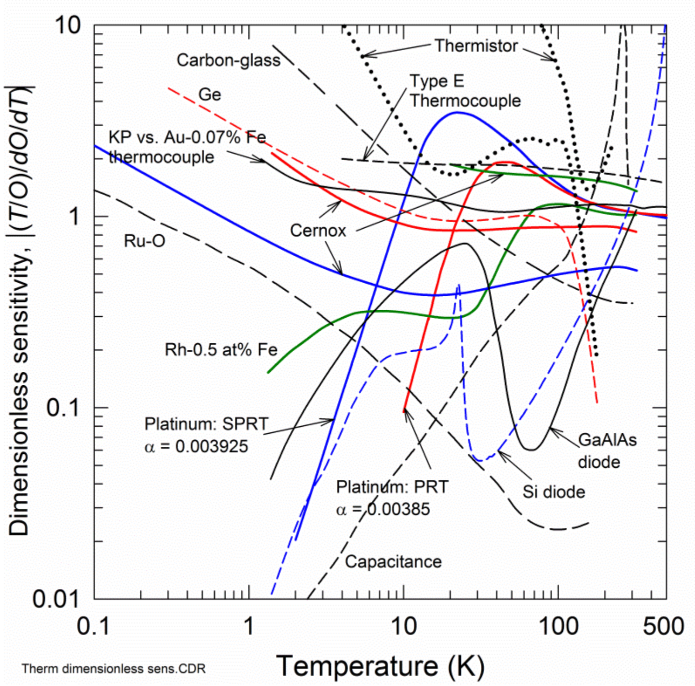

Figure 11. Dimensionless sensitivity of many types of thermometers. Sensitivity for thermocouples are shown with voltage for 0 K reference temperature. The parameter *O* can be *R*, *V*, or *C*.

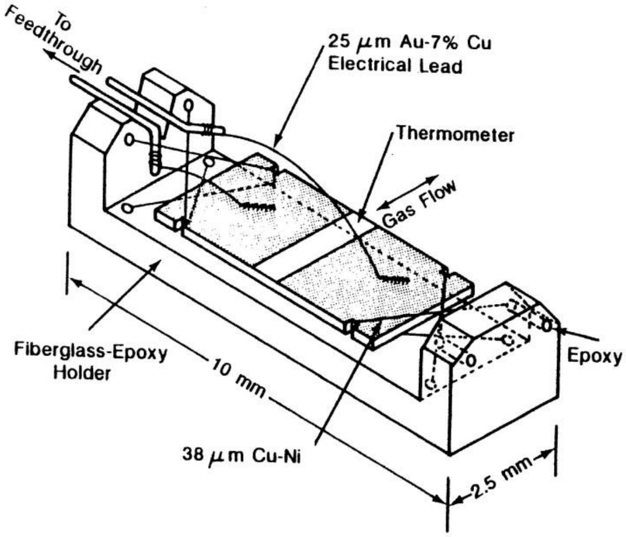

Figure 12. Drawing of a silicon-on-sapphire (SOS) thermometer for dynamic temperature measurements of flowing fluids at low temperature.

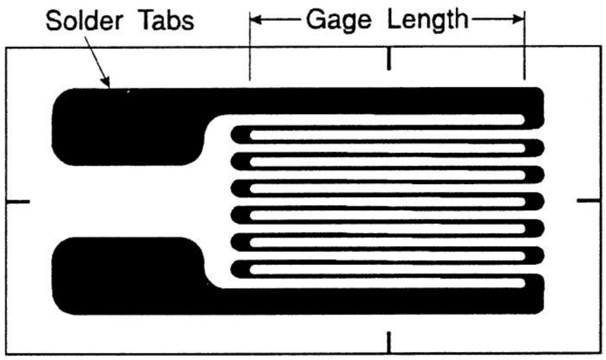

Figure 13. Geometry of a metal foil strain gage.

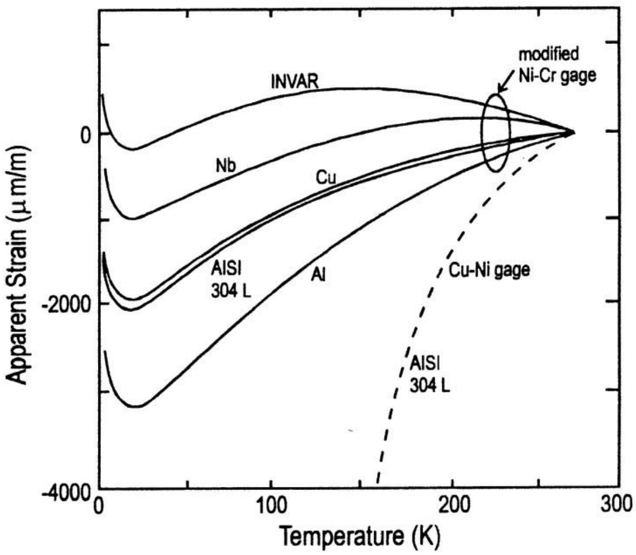

Figure 14. Apparent strain caused by temperature change from 280 K for Ni-Cr gages and Cu-Ni gages on various test materials.

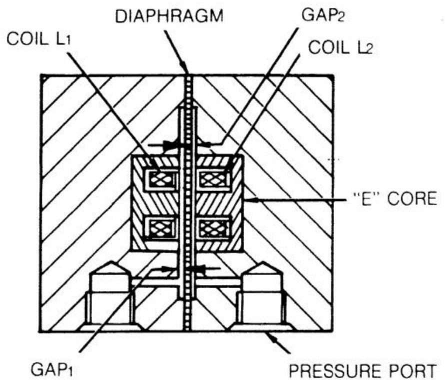

Figure 15. Cross section of a variable reluctance pressure transducer.

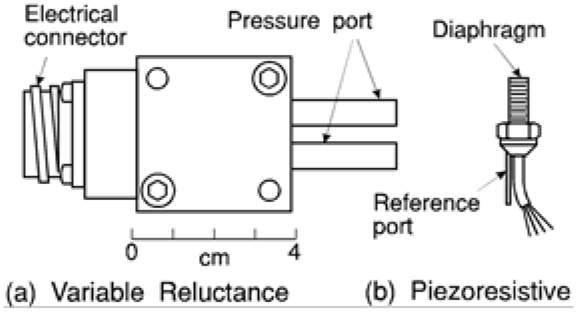

Figure 16. Two types of pressure transducers adaptable to cryogenic temperatures.

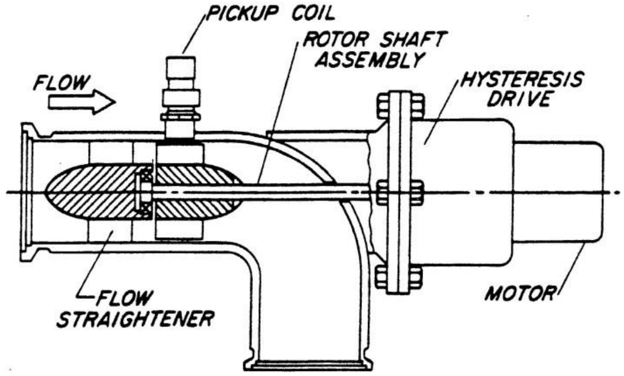

Figure 17. Angular momentum flow meter. From Brennan, et al., 1974.

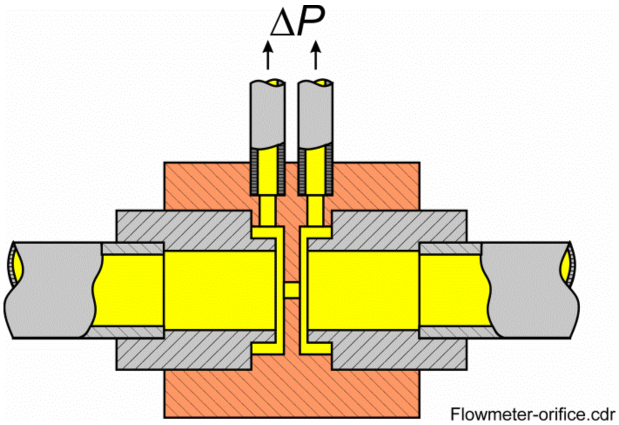

Figure 18. Orifice flowmeter for oscillating flow.

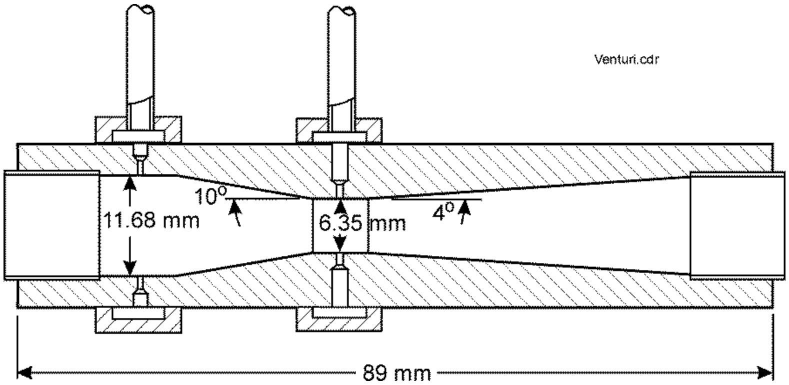

Figure 19. Cross-section of a venturi flowmeter.

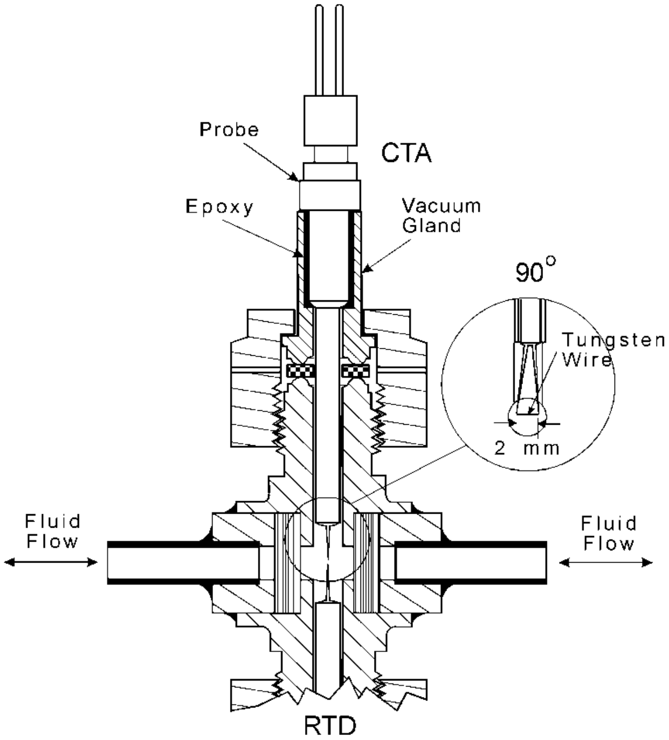

Figure 20. Modified vacuum assembly with CTA and RTD probes in place.