tance to oxidation and thus are restricted to applications involving low operating temperatures. They are used chiefly for resistors that carry relatively high currents, and for this reason rapid dissipation of heat from the surface of the resistor is desirable. In this application, resistor temperature may vary over a wide range, but temperature changes are relatively unimportant.

Copper-manganese-nickel resistance alloys, generally referred to as manganins, have been adopted almost universally for precision resistors, slide wires and other resistive components with values of 1 kΩ or less, and are also used for components with values up to 100 kΩ.

Originally, manganin was the name of a specific alloy, but the term is now generic and covers several different compositions (see Table 1). All manganins are moderate in resistivity (from 380 to 480 nΩ · m, or 230 to 290 Ω · circ mil/ft) and low in TCR (less than ±15 ppm/°C).

Manganins are stable solid-solution alloys. The electrical stability of these alloys, verified by several decades of experience, is such that their resistance values change no more than about 1 ppm per year when the material is properly heat treated and protected. Manganin-type alloys are characterized by rather steep, parabolic relations between resistance and temperature (see Fig. 3). This severely restricts the range of temperature over which resistance is stable, thus limiting the use of manganins to devices for which operating temperatures are both stable and predictable. For some applications, the maximum of the parabola (peak, or peak temperature) is kept near room temperature by controlling composition, minimizing the effects of small changes in ambient temperature. The temperature coefficient of commercial manganin is usually less than ±10 ppm/°C for an interval of 10 °C (18 °F) on either side of the peak.

When instruments are designed for operation above ambient temperature, the chemical composition of the manganin is chosen so that the peak will occur in the operating temperature range. So-called "shunt manganin," which carries high currents and consequently gets hot in use, usually has a peak temperature from 45 to 65 °C (115 to 150 °F).

Manganins are susceptible to selective oxidation or preferential corrosive attack. This may occur during heat treatment, wire manufacture, or coil fabrication. Selective oxidation results in formation of a copper-rich (manganese-depleted) zone on the wire. This copper-rich sheath has the effect of greatly increasing the temperature coefficient of resistance and raising the peak temperature well beyond the range where any precision resistor would ordinarily be used.

The resistivity of manganin—roughly 500 nΩ · m (300 Ω · circ mil/ft) at 25 °C (77 °F)—is adequate for most instrumentation purposes. The thermoelectric potential versus copper is very low, usually less than −2 μV/°C from 0 to 100 °C (32 to 212 °F).

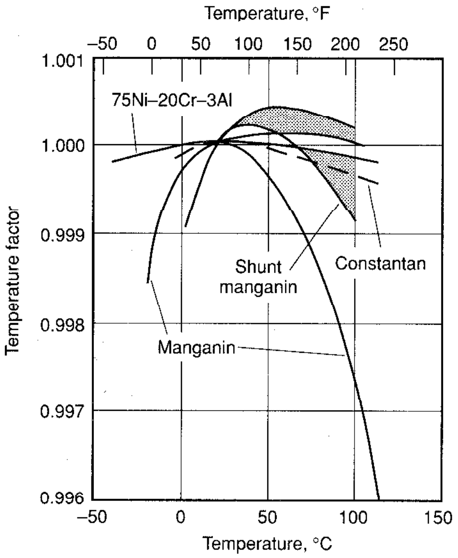

Fig. 3 Variation of resistance with temperature for four precision resistor alloys. To calculate resistance at temperature, multiply resistance at room temperature by the temperature factor.

Constantan, like manganin, has become a generic term for a series of alloys that have moderate resistivities and low temperature coefficients of resistance. Nominally, constantans are 55Cu-45Ni alloys, but specific compositions vary from about 50Cu-50Ni to about 65Cu-35Ni. The temperature coefficient of conventional constantan can be held within ±20 ppm/°C of ambient temperature. However, the difference in TCR between the low (−55 to 25 °C, or −67 to 77 °F) and high-temperature ranges (25 to 105 °C, or 77 to 220 °F) is about 20 ppm. Thus, the specification is ±20 ppm/°C over one temperature range or ±40 ppm/°C over both ranges. A variation of constantan with 3% Mn improves the flatness of the resistance temperature curve and provides a TCR of ±20 ppm/°C from −55 to 105 °C (−67 to 220 °F). All constantans contain iron and cobalt in addition to manganese.

The temperature coefficient of resistance of constantan is very low and parabolic like that of manganin, but remains flat over a much wider range (Fig. 3). Other properties are given in Table 1; specific property values vary somewhat with composition. Constantans are considerably more resistant to corrosion than manganins.

Use of constantans as electrical resistance alloys is restricted largely to ac circuits, because thermoelectric potential versus copper is quite high for these materials (about 40 μV/°C at room temperature). However, if the circuit voltage is high enough to overshadow thermoelectric effects, constantans may be used in dc circuits as well.

Nickel-Chromium-Aluminum Resistance Alloys. Nickel-chromium alloys containing small amounts of other metals—usually aluminum plus either copper, manganese, or iron—have resistivities about 2½ to 3½ times that of manganin. Ni-Cr-Al resistance alloys have been adopted almost universally for the construction of wire-wound precision resistors having resistance values of about 100 kΩ, and are also used for resistors with values as low as about 100 Ω. The temperature coefficients of resistance of these alloys are vastly superior to those of manganin and constantan, being less than ±20 ppm/°C between −55 and 105 °C (−67 and 220 °F). The difference in TCR between the hot region (25 to 105 °C) and the cold region (−55 to 25 °C) is about 20 ppm/°C for constantan (and about 10 ppm/°C for newer constantan), but only about 5 ppm/°C for the original quaternary Ni-Cr-Al alloys, and only 1 ppm/°C for the new quaternary alloys. The high resistivity and low TCR of Ni-Cr-Al alloys are obtained by an order-disorder type of heat treatment at approximately 540 °C (1000 °F). Therefore, if desired, the temperature coefficient can be decreased without resorting to melt selection, which is required for alloys that do not respond to heat treatment. The availability of smaller temperature coefficient ranges is dependent on wire size and alloy composition. Table 2 gives the available commercial ranges. Electrical stability of quaternary Ni-Cr-Al alloys is excellent—1 to 10 ppm/year or less. Their thermoelectric potential versus copper is also excellent—about 1 μV/°C at temperatures from 0 to 100 °C (32 to 212 °F).

As indicated in Table 1, the mechanical properties of Ni-Cr-Al alloys are higher than those of manganin and constantan. Wires made of Ni-Cr-Al alloys are available in diameters as small as 0.01 mm (0.0004 in.), whereas wires of copper-base alloys such as constantan are seldom produced in diameters smaller than 0.025 mm (0.001 in.). Because the resistance of a wire varies inversely with the square of its diameter, it is possible with small-diameter Ni-Cr-Al wires to produce miniature resistors that are exceedingly high in resistance.

The Ni-Cr-Al alloys resist oxidation better than other commercial electrical resistance alloys. This is an advantage in resistors that are not covered with enamel, teflon, or other coatings. It is a disadvantage for making acceptable soldered or brazed joints, because it necessitates greater care in joint preparation. However, suitable soldered or silver-brazed connections can be made readily using appropriate fluxes.

Other Precision Resistance Materials. In high-resistance precision resistors, where TCR limits are less stringent, 80Ni-20Cr alloys may be used. 80Ni-20Cr alloys have temperature coefficients from four to six-