resistivity, and (7) lack of a phase transition in the pressure range of interest. Some of these desirable features tend to be mutually exclusive. For example, those materials with high sensitivity to pressure and high resistance tend to be nonlinear and often have phase transformations at relatively low pressures. Mercury and bismuth are good illustrations. Item three above suggests the use of a metallic element which can be obtained in very high purity, but a perusal of likely candidates indicates relatively large variations of resistance with temperature as discussed below. If all of the above properties are desired, the possibilities become greatly restricted. Ease of construction along with items three and four suggest the use of chemically inert metals sufficiently malleable to draw wire to form coils. The use of a high resistivity metal, although not necessary, simply reduces size and improves accuracy since it tends to lessen the effects of contact resistances and contact emfs.

In addition to convenience and simplicity, one of the significant features of the resistance gage as compared to other commonly used gages, both primary and secondary, is the relatively constant absolute sensitivity of the gage over all currently-available hydrostatic pressures. This feature means that the percentage detectable variation in pressure decreases at the higher pressures and makes the gage very appealing in this range.

The dominant reason for the selection of manganin as a suitable gage is the low sensitivity of resistance to temperature. Manganin is a Cu-Mn-Ni alloy specially prepared for use in precision resistors to have a high resistance with a low temperature coefficient of resistance at room temperature. A gold-chromium alloy (2.1 percent Cr) has been used for precision resistors and also considered as a pressure gage (Darling and Newhall, 1953).

A graph of resistance as a function of temperature at atmospheric pressure for manganin, Au-2.1 percent Cr, and Advance (a trade name for a particular constantan alloy) is shown in figure 4 for comparison. In contrast to these three and to similar alloys, pure metals such as copper, aluminum, platinum, and silver have temperature coefficients between 0.003 and 0.004 $°C^{-1}$, which means that on the scale of figure 4 they would be off the graph when less than one degree from room temperature. The seriousness of this problem can be seen by considering the use of aluminum wire for which the relative resistance changes for one degree elevation in temperature would offset a one kbar pressure increase. Both Advance and Au-2.1 percent Cr wire, as seen in figure 4 have a significantly lower temperature coefficient than manganin over the temperatures of interest, but when the other items listed above are considered they appear less favorable. The seriousness of the temperature variation drastically restricts the possible gage materials. Schultz (1943) suggested the use of a 15.0 percent Mn-84.1 percent Ag alloy because of a high pressure coefficient and relatively low temperature coefficient,

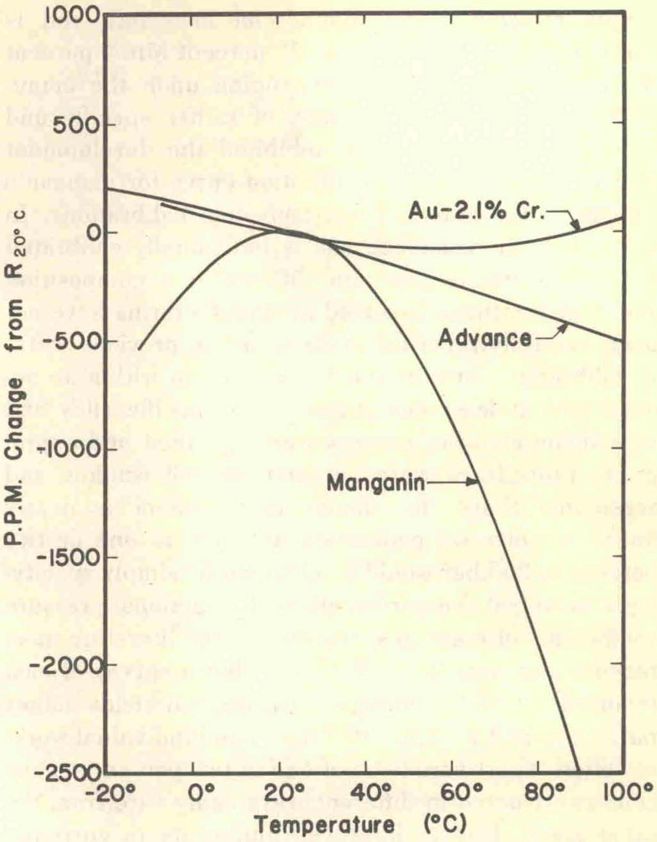

FIGURE 4. Variation of resistance with temperature for typical sample of manganin, Advance, and Au-2.1 percent Cr.

Ebert and Gielessen (1947) measured the pressure and temperature coefficients of a large number of alloys, and indicated how the pressure coefficient varies with concentration for several alloys. They also indicated the possible use of Ag-Mn alloys and report data on at least two alloys which show promise: 78 At percent Ag-22 At percent Mn with a pressure coefficient of 3×10^{-6}/bar and a temperature coefficient of 1×10^{-5}/°C, and 82 At percent Ag-10 At percent Mn-8 At percent Sn with a pressure coefficient of 0.9×10^{-6}/bar and a temperature coefficient of 2.5×10^{-6}/°C. Darling and Newhall (1953) proposed the use of Au-2.1 percent Cr, and several studies have been directed to its use as discussed below.

Reference to tables of low temperature coefficient alloys (1961, Metals Handbook) reveals at least three new alloys (76% Ni, 17% Cr, 4% Si, and 3% Mn; 75% Ni, 20% Cr, 3% Al, and 2% Cu; and 72% Fe, 23% Cr, 5% Al, and 0.5% Co) which show promise and are different from those above. Of course, pressure data must be obtained to determine the pressure coefficients of resistivity, stability, and related properties.

b. The Manganin Gage

The term "manganin" is a generic term which refers to one of several closely related compositions of copper-manganese-nickel alloys which, in their widest variations range between 67–87 percent Cu, 10–27 percent Mn, and 0–20 percent Ni. The wire generally used for wire-wound resistors and used in high-pressure gages is simply referred to as commercial manganin and is approximately 84 percent Cu, 12 percent Mn, 4 percent Ni, and varies somewhat depending upon the manufacturer. The use of an alloy of rather specific and critical concentrations has inhibited the development of a universal pressure calibration curve for manganin similar to the standard thermocouple calibrations. In practice each resistance coil is individually calibrated to form a pressure gage, and differences in composition and heat treatment involved in manufacturing have not been carefully reported or discussed in previous work. A calibration curve would be feasible to within an accuracy of at least one percent if a specific alloy and wire manufacturing process were specified and appropriate procedures were outlined for coil winding and seasoning. Since the change in resistance is nearly linear, a universal calibration accurate to one or two percent to 20 kbar would be obtained by simply specifying a universal pressure coefficient. Fractional pressure coefficients of resistance reported in the literature most recently are near 2.3×10^{-6} bar^{-1}, but a survey of past reported values beginning with Bridgman yields values ranging from $2.1-2.5 \times 10^{-6}$ bar^{-1}, and individual workers often report variations of one to two percent in gage coils constructed in different ways using wire from the same spool. Due to improved uniformity in currently available commercial wire, similarly constructed and seasoned coils using wire from the same spool can now be expected to have pressure coefficients equal to within a small fraction of one percent.

Since relative resistance can be measured without excessive difficulty to a few parts in 10^6 using either a precision Mueller bridge, a Carey-Foster bridge, or potentiometric techniques, pressure sensitivity of one to two bars is not difficult to obtain if adequate care is taken. To assure long-term accuracy in this range is more difficult, of course. With this type of sensitivity available, the question of stability, reversibility, and changes of the zero-pressure resistances as well as the pressure coefficient with temperature become significant when applied to an individually calibrated gage.

c. Stability and Reversibility

Bridgman (1911a) in his early work reported a drift of both the zero-pressure resistance and the pressure coefficient with time unless an appropriate "seasoning" or "artificial aging" procedure was followed. This type of procedure is common practice when manufacturing precision wire-wound resistors from manganin or other resistance alloys and is effectively a low-temperature annealing of the strains induced in the wire by the winding process. For manganin a temperature of 140 °C is generally recommended for 48 hours or more. Longer anneals at 125 °C are also effective. The initial resistance generally decreases by one to two percent during this temperature anneal and is then stabilized to at least a few parts in 10^6. To stabilize the pressure coefficient the gage must be exposed to pressure as high as one expects to use the gage at least once and preferably two or three times. For the temperature anneal Bridgman (1940a, b) used a cycle of heating to 140 °C for several hours followed by quenching to dry-ice or liquid-nitrogen temperature repeated several times and claimed that this procedure improved stabilization. The temperature cycling apparently relieves localized strain regions and thus improved uniformity.

Boren, Babb, and Scott (1965) report short-term stability (before and after pressure excursions) of the order of one part per million on appropriately wound and seasoned manganin gages to 25 kbar when using the Bridgman temperature season and only one pressure season. If the gage is not pressure seasoned, a significant nonreversible resistance change generally referred to as pressure hysteresis is observed, but following appropriate seasoning this hysteresis is of the order of one bar or less. The manner in which the coil is wound is important if minimal creep and hysteresis are to be obtained. Tightly wrapped close-pack winding causes straining of the wire during a pressure excursion and results in non-reproducible effects due to the difference in compressibility of the coil form and the resistance wire, and relaxation of these strains with time. Bowman and Johnson (1957) have described a practical, strain-free mounting in which the wire forms a helical coil of small radius, which in turn is placed in helical grooves around an insulating form. Boren, Babb, and Scott (1965) report that coils so constructed have good short-term stability and reproducibility on increasing and decreasing pressure of approximately one ppm. Coils wound loosely around a bobbin which are not close-packed yield instabilities and hysteresis of only a few ppm and are very adequate for all but the most exacting work. This is the type of coil generally used by early workers who often reported no hysteresis or creep due to lack of sensitivity in the resistance measurement. Stability and reversibility appear to be uninfluenced by extremely high pressure according to Barnett and Bosco (1967), who reported stability to within the accuracy of their measurements after excursions to over 50 kbar. In practice, most workers wind coils non-inductively. This precaution decreases noise level if any electronic amplifiers are used in the null detection system and also allows use of low-frequency resistance-bridge measurements if desired. Whether dc or ac techniques are used, it is imperative that a four-lead measurement of resistance be made.

One of the two most serious problems with state of the art manganin gages is the long-term stability. Good quality commercial resistance standards made of manganin are stable to approximately one ppm per year. To attain this high stability, relatively large wire and surface coating are used to reduce oxidation and similar surface deterioration which changes the conduction cross section of the wire. Surface deterioration of a fraction of a micro-inch will drastically affect resistance. Low-strain configurations and careful annealing also reduce drift. If such care is taken the only major resid-