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CRYOGENIC TEMPERATURE MEASUREMENT

by Donald H. Sinclair, Howard G. Terbeek,
and Jerry H. Malone
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at Cryogenic Engineering
Conference sponsored by the Cryogenic Society of America
Boulder, Colorado, June 17-19, 1970

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TABLE OF CONTENTS

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Abstract

This paper discusses the state-of-the-art of cryogenic temperature measurement. The characteristics of metallic and semiconductor resistance thermometers, thermocouples, and other types of thermometers are discussed. Comments on calibration, installation, and associated measuring circuitry are given for the more common types of thermometers. Also, recent changes in temperature scales are presented. References are included where more detailed information can be obtained.

0-1. Introduction

During the past two decades considerable effort has gone into the technology of cryogenic temperature measurement. As a result, there now exist numerous sensors and methods of measurement; the problem is one of selecting a measuring system to match the requirements of a given application. To make such a choice one must have a clearly defined knowledge of these requirements and an understanding of the characteristics, advantages, and disadvantages of the various thermometers and measuring systems. The intent of this paper is to provide information which will help in the selection and use of instrumentation for cryogenic thermometry.

In 1962 R. J. Corruccini wrote an excellent survey paper on cryogenic temperature measurement technology.[1] Our paper will include known advances since 1962 in three particular areas of this technology: (a) temperature scales and transfer standards, (b) characteristics of common thermometers, and (c) some problems related to the application of sensors and techniques.

By necessity the discussions will be brief. However, references are given where more detailed and comprehensive information can be obtained. Some specialized subjects have been omitted intentionally such as temperature measurements below 1 K, gas thermometry, and vapor pressure thermometry.

0-2. Temperature Scales

Since 1962 there have been two significant changes in the definition of cryogenic temperature scales which bring thermometry into closer agreement with the theoretical thermodynamic temperature scale. Also, the name kelvin and the symbol K are assigned to designate the unit of thermodynamic temperature.

2.1 International Practical Temperature Scale of 1968. The most recent revisions of the recognized temperature scales were adopted in October 1968 by the International Conference on Weights and Measures. The new scale is known as the International Practical Temperature Scale of 1968 (IPTS-68). It replaces both the IPTS-48 and the NBS-1955 Scale. The primary reference point, the triple point of water, remains unchanged at 273.16 kelvins on the absolute scale. The lower limit of the new scale is set at the triple point of hydrogen 13.81 K, so that the IPTS-68 now includes most of the range of the NBS-1955 Scale. Other minor revisions result in differences between the IPTS-68 values and values from the preceding scales as shown in figure 1. The curve was plotted from data published by the NBS.[2,3] The differences range from minus 9 to plus 15 millikelvin (mK) for temperatures below 90 K, and from minus 13 to plus 34 mK for temperatures in the range from 90 to 300 K.

2.2 NBS Provisional Scale of 1965. In 1965 Plumb et al. at the NBS developed a provisional scale to cover the range from 2 to 20 K including the previously undefined 5 to 10 K range.[4] The temperature scale was established by means of an acoustical thermometer which relates temperature to the speed of sound in helium gas. The Bureau has calibrated a set of germanium resistance thermometers against the acoustical thermometer and now maintains these thermometers as reference standards for calibrating other thermometers of acceptable quality in the 2 to 20 K range.

Currently, the most accurate definition of temperature is expressed in the following scales:

1. International Practical Temperature Scale of 1968 (IPTS-68), from 13.8 K up.
2. NBS Provisional Scale of 1965 (NBS-65), 2 to 20 K.
3. Helium Vapor Pressure Scale of 1958 (T-58), 1 to 5.2 K.

(Temperatures from 0 to 1 K are best measured by magnetic thermometry techniques.) A comparison of the scale ranges is given in figure 2. This definition of temperature is usually passed on to the application engineer by means of standard thermometers which have been calibrated by the NBS.[5]

The experimenter should bear in mind that the temperature scales are being revised from time to time. He therefore should identify the scale to which his thermometer is calibrated and should apply whatever adjustments are needed to properly correlate with tabulated thermodynamic and thermal physical properties.

2.3 Transfer Standards. The best available sensors to be used as calibration transfer standards are the platinum resistance thermometer (PRT) and the germanium resistance thermometer (GeRT) as indicated in figure 2. The PRT is suitable for a wide range of temperatures going as low as 13.8 K, or even 10 K. To qualify as a transfer standard, the PRT must have a quality factor at least 1.3925. This factor is defined as the ratio of resistance at the steam point, 373.15 K, to resistance at the ice point, 273.15 K. The GeRT is best suited for temperatures from 2 to 20 K but is useful up to 100 K. For best accuracy the doping of the germanium crystal must be gauged to suppress the resistance at low temperature and to yield a resistance-temperature curve with a minimum of irregularity.

2.4 Interpolation. Temperatures and corresponding values of a dependent variable for the common cryogenic thermometers cannot be related by simple mathematical expressions. And the revisions introduced in the IPTS-68 have made the mathematical relations even more complex, at least for platinum resistance. Accurate interpolation between calibration points by high order polynomial equations is difficult and time consuming unless a computer is available.

There is, however, a relatively simple mathematical procedure for interpolating between the calibration points for a particular thermometer when there exists a table of variables vs temperatures for a comparable thermometer. The procedure is entirely adequate for thermometer data reduction in most engineering applications. It will be discussed later under the heading "Calibration."

0-3. Characteristics of Cryogenic Thermometers

Many thermometer characteristics are considered when determining if a thermometer can satisfy a specific application. Some of these characteristics are: range, sensitivity, repeatability, interchangeability, calibration difficulty, ruggedness, heat capacity, size, compatibility with surrounding environment, compatibility with associated instruments, installation errors, total costs, dynamic performance, etc.

It is beyond the scope of this paper to analyze all of the above performance characteristics for all known cryogenic thermometers. For example the dynamic performance of thermometers will not be included here; reference 6 contains an excellent discussion of this subject. Discussions of characteristics will be divided into three thermometer groupings: (1) resistance thermometers, (2) thermocouples, and (3) other less common thermometers.

3.1 Resistance Thermometers.

3.1.1 General comparison. Probably the most common resistance thermometers in use today for cryogenic temperatures are the following three types:

A. Platinum Resistance Thermometer (PRT)

B. Germanium Resistance Thermometer (GeRT)

C. Carbon Resistance Thermometer (CRT)

Figure 3 is a photograph of a typical CRT, GeRT, and three PRT.

Figure 4 is a plot of resistance-temperature relationships for typical CRT, GeRT, and PRT. Also shown for comparison are two less common resistance thermometers, a typical Platinum Film Resistance Thermometer (PFRT) and a Gallium Arsenide Diode Thermometer (GaAsDT). The GaAsDT, which is really a junction device, is treated as a resistance thermometer to simplify comparison with the other four true resistance thermometers. This type of plot is useful for visualizing the general temperature dependence of a thermometer. The results given are typical and do not necessarily represent the best obtainable thermometers. Some general points of information which these plots show are:

A. The three semiconductor types of resistance thermometers (GeRT, CRT, and GaAsDT) have a decreasing resistance with an increasing temperature while the opposite is true for the metal types, PRT and PFRT.

B. PRT is very sensitive to temperature, the resistance changing more than a thousand to one in going from 300 K to 10 K.

C. The temperature sensitive ranges of the GeRT and the CRT are similar and extend from about 100 K down through 2 K. Their resistances become large, about 6000 ohms at 2 K for the typical sensors shown here (fig. 4). This order of resistance poses measurement problems associated with electrical noise and impedance loading.[7]

D. The GaAsDT has an even higher effective resistance and is sensitive to both the magnitude and the direction of the current.

E. Both the GaAsDT and the PFRT have high residual resistance at low temperatures.

Thermometers are usually compared on the basis of sensitivity. Thermometer sensitivity can be presented in different ways; each way has advantages which accent certain characteristics of the various thermometers in preference to others. Figures 5 and 6 are examples of thermometer sensitivity plots.

Figure 5 shows a comparison of performance factor vs temperature for the five thermometers shown in figure 4. This performance factor is a normalized ratio of the fractional change in the resistance of the thermometer for a fractional change in temperature. A high performance factor is desirable. The factor is useful for selecting a type of thermometer which will have adequate sensitivity to measure absolute temperature to an allowable uncertainty. For example, from a sensitivity standpoint only, temperatures within the 14 to 300 K range would best be measured using a PRT, while a GeRT would be the selection for temperatures from 4 to 14 K.

Figure 6 gives sensitivity in percentage change in resistance per kelvin as a function of temperature. These results are useful when determining the accuracy to which the thermometer's resistance must be measured in order to determine temperature within an allowable error limit (ΔT). For example at 50 K, to measure within a 0.1 K limit of error, resistance must be measured to within 0.5% for PRT, 0.3% for GeRT, 0.07% for CRT, 0.04% for PFRT, and 0.007% for GaAsDT for the typical thermometers shown.

3.1.2 PRT. Most cryogenic temperature measurements above 14 K can be made satisfactorily using a commercial PRT. Performance tests on a number of such sensors[8] indicated that their quality varied from poor to excellent. In general, the reliability of commercial PRT was found to be poor, with 12 of the initial 38 tested failing mechanically beyond repair. However, the better types (not necessarily higher priced) had excellent reliability. The PRT shown in figure 7 is one of the best of those tested. It has these features:

A. Excellent repeatability. Unless the PRT is abused, its calibration will repeat within 0.01 K for its lifetime.

B. Moderate cost, less than $150.

C. Good interchangeability. These PRT have matched resistance difference ratios

$$\left(Z = \frac{R_T - R_1}{R_2 - R_1} \right)$$

called Cragoe's functions.[8,9,10] This means that absolute resistance matching is not necessary since the "Z" factor normalizes resistance. Also, since the "Z" factor compares resistance differences, constant residual resistance is cancelled out. This "Z" factor will be discussed in more detail later in the calibration section.

D. Calibration to within 0.04 K by measurements at only two or three temperatures.

E. Ruggedness and reliability. This PRT will withstand acceptance testing, calibration, and repeated field installations without failure. Lewis Research Center's specifications for ruggedness are: (a) 50 g's or 0.5 inch double amplitude (whichever is smaller) from 20 to 2000 Hz for 15 minutes, (b) impact shock of 100 g's for 10 milliseconds triangular wave, (c) velocity loading greater than 100 ft/sec. of liquid hydrogen, and (d) 2000 psi pressure differential with less than 10^{-7} cubic centimeter helium per second leak rate.

The main disadvantage of PRT is their relatively large size.

3.1.3 PFRT. Platinum film resistance thermometers are made by depositing a thin film of platinum on an insulated substrate. Their resistance-temperature relation is similar to that of pure platinum wire except they have a very high residual resistance that predominates at low temperatures (fig. 4). Their sensitivity (figs. 5 and 6), interchangeability, and stability cannot compare with those of a wire type PRT. Their main advantage is their low heat capacity which enables them to respond to transient temperatures.[11,12]

Other metals and semiconductor materials have been used for thin film resistance thermometers.[13,14,15] Also, thermocouples in the form of thin-film deposits are being used.[16]

The very small mass and volume, and the capability of being deposited on unusual surface configurations enable thin-film thermometers to be used where conventional thermometers would create considerable errors or disrupt normal heat flow. These relatively new thermometers show promise in measuring previously unmeasurable temperatures. However, further development is required before their advantages can be fully realized.

3.1.4 GeRT. Doped germanium resistance thermometers are usually used to measure temperatures less than 20 K when uncertainties less than 0.1 K are required. Since pure germanium resistance is excessively high at low temperatures, impurities are added to reduce the sensor resistance. These impurities determine the sensor resistance vs temperature relationship. The typical GeRT shown in figure 3 with characteristics as shown in figures 4, 5, and 6 is intended for temperature measurements from 1.5 to 100 K. Its main advantage is reproducibility within 0.01 K which makes selected types of these thermometers suitable for transfer standards.[17,18] The GeRT's main disadvantage is its poor interchangeability and complex resistance-temperature relationship. Different modes of conduction influence the resistance of the sensor causing the irregularity shown in figures 5 and 6. Hence, each GeRT requires calibration at frequent intervals of temperature depending on the intended usage range.[18,19,20]

Figure 8 shows a drawing of a typical GeRT. The doped germanium sensor is mounted in a strain-free manner within a metal shell. The shell is filled with helium gas at pressures greater than one atmosphere at 300 K and sealed.

3.1.5 CRT. The ordinary carbon composition resistor has been found useful for measuring temperatures in the 2 to 80 K range. It has a negative coefficient of resistance that varies as the reciprocal of absolute temperature thus making it more and more sensitive as temperature decreases. The resistance-temperature relation depends to a large extent on the specific composition of the resistance element and varies widely from one brand to another. The relation was formulated originally by Clement and Quinnell and verified by others[21,22] in a basic equation,

$$\log R + K/\log R = A + B/T, \qquad \text{Eq. 0-1}$$

where the constants A, B, and K are determined from calibration measurements. There are those who claim that a three-parameter, more complex equation will give temperatures accurate to within 10 mK from 0.6 to 4.2 K.[23] Generally, however, the carbon resistor is regarded as subject to an uncertainty of 1 percent as a temperature sensor. This is related to a lack of long-term stability.

The carbon resistor does have certain advantages--small size (as small as 0.003 in^3), low initial cost, good sensitivity in the cryogenic range (fig. 6) and the adequacy of a 3-point, or even 2-point calibration--that make it worth considering for temperature measurements where accuracy within 0.1 K or 1% of temperature is acceptable.

3.1.6 <u>GaAsDT</u>. Since 1962 the gallium-arsenide diode thermometer (GaAsDT) has become commercially available for cryogenic temperature measurements. This thermometer operates on the principle that the forward voltage drop across a diode is a function of temperature. It differs from true resistance thermometers in that its resistance is current sensitive and polarity must be observed.

The main advantage of the GaAsDT is its wide temperature range from 1 to 300 K. The characteristics presented in figures 4, 5, and 6 are typical of GaAsDT tested at Lewis Research Center in 1965 and by a supplier.[24] They exhibited a marked decreasing sensitivity with decreasing temperatures. However, newer improved GaAsDT are reported to have usable sensitivity below 20 K.[25] Quoted sensitivities at the 100-microampere current level are 15 ohms per K at 20 K and 64 ohms per K at 4.2 K, or expressed in voltage signal sensitivity, 1.5 mV per K at 20 K and 6.4 mV per K at 4.2 K. These sensitivities may appear high but it must be kept in mind that they exist at a bias voltage greater than

1 volt. This is the reason for the low performance factor shown in figure 5 and the low percentage change in signal per K as shown in figure 6. This GaAsDT requires a voltmeter with a resolution of 0.005% to detect a change of 0.1 K at 20 K. Also, a high impedance voltmeter is required to avoid loading effects, since at 20 K the GaAsDT resistance is 14,000 ohms. Furthermore, since the GaAsDT is current sensitive, current regulation at microampere levels must be within 0.5% if measurements within 0.1 K are required.

3.2 Thermocouples. Thermocouples have well known advantages which make them the best choice for some cryogenic temperature measurements. Some of these advantages are: small size, low heat capacity, low initial cost, relative ease of installation, and standardized calibrations. The main disadvantage of thermocouples is low sensitivity. For this reason thermocouples cannot ordinarily compete with GeRT, CRT, and PRT for accurate measurement of cryogenic absolute temperatures.

Since 1962 Powell et al. at the NBS have standardized calibration tables for thermocouples in the cryogenic temperature range.[26,27,28,29] Figure 9 shows a comparison of the thermoelectric voltage vs temperature referenced to zero K for three of the more common low temperature combinations:

ISA Type	Material
E	*Chromel vs constantan
T	Copper vs constantan
K	*Chromel vs *Alumel

Also shown is the calibration of a more recent combination of Chromel vs gold-0.07 atomic % iron.

*Chromel and Alumel are registered tradenames.

Figure 10 shows the sensitivities (μV/K) for the above four thermocouple combinations and also for Chromel vs gold-2.1 atomic % cobalt and copper vs gold-2.1 atomic % cobalt. The gold-2.1 atomic % cobalt thermocouple combinations have a high sensitivity; however, they also have poor reproducibility which limits their usefulness.[16]

The type E, Chromel vs constantan thermocouple is recommended[27] for cryogenic thermocouple applications above 20 K because it has:

A. Larger sensitivity than types "T" and "K" (figure 10)

B. Good homogeneity

C. Low thermal conductivity, less than 0.005 of that of copper at 10 K which reduces heat conduction through the wires to the measuring junction.

D. Ready availability.

The Chromel vs gold-0.07 atomic % iron thermocouple looks promising for applications below 20 K because of its higher sensitivity. Also, its sensitivity curve is fairly linear from 1 to 280 K.[27] However, to our knowledge the stability of this thermocouple has not been reported.

3.3 <u>Other Thermometers</u>.

3.3.1 <u>Thermistor</u>. For cryogenic applications thermistors are not as popular as other resistance thermometers. Thermistors have resistance vs temperature characteristics similar to those of GeRT and CRT, but with higher negative temperature coefficients. Unlike GeRT and CRT their temperature range is not restricted to low temperatures. However, the usual commercial thermistors made for applications at 200 K and above are difficult to use at cryogenic temperatures because their resistances become excessively large. Some thermistors are made especially for cryogenic use.[30] Their main advantages are: (1) low initial cost, (2) small size, and (3) high sensitivity.

3.3.2 Acoustical thermometers. These thermometers operate on the principle that the velocity of sound in any medium--gas, liquid, or solid--is a function of temperature.[31,32] For an ideal gas, the speed of sound is proportional to the square root of absolute temperature. As discussed earlier in the section on Temperature Scales, NBS has developed a gas acoustical thermometer[4,33] and has used it to define absolute temperature from 2 to 20 K. This thermometer measures the velocity of sound at a fixed frequency in helium gas at low pressure in a resonance tube of variable length.

Acoustical thermometers which measure the velocity of sound in solids have mainly been used for the measurement of temperatures greater than 300 K. However, their principle of operation is applicable for cryogenic temperature measurements. One factor which has limited the use of acoustical thermometry is that the associated instrumentation is specialized and complicated compared with instrumentation for resistance thermometers and thermocouples.

3.3.3 Quartz-crystal thermometer. This thermometer works on the principle that the resonant frequency of a quartz crystal varies in relation to temperature.[34] Its main advantage is that the temperature measurement can be obtained readily in a digital form with a resolution of 0.01 K or better. The quartz thermometer has sensitivity that is high in terms of Hz per kelvin but very low in terms of percentage change in frequency per kelvin, since the resonant frequency is high. Stability is claimed to be about 0.01 K at the ice point for a 30 day period. However, for transfer standard usage the thermometer would have to be recalibrated to correct for this aging effect. Also, to our knowledge the stability of quartz-crystal thermometers at cryogenic temperatures has not been reported. Problems of heat capacity, impedance matching, and thermal conduction through the necessary coaxial cable tend to restrict the quartz-crystal thermometer to certain laboratory applications.

3.3.4 Thermal-noise thermometer. Another type of cryogenic thermometer is based on the temperature dependence of thermal noise as generated in a resistor. The essential components of a noise thermometer are a resistor to generate the thermal noise and a preamplifier. The amplifier must have a high gain and introduce less noise than the thermal noise being measured. Reference 35 describes the use of a Josephson Junction as a preamplifier for thermal-noise thermometry applications, where a Josephson Junction is a weak electrical contact between two pieces of superconducting metals. The range of temperature measurement is from 0.001 to 10 K, and practical applications are very limited.

3.3.5 Nuclear magnetic resonance thermometer. Thermometers based on the temperature dependence of the Nuclear Magnetic Resonance frequency in antiferromagnetic and ferromagnetic materials have been demonstrated.[36] This is a specialized type of thermometry and its use is very limited.

0-4. Application

Selection of the type of thermometer most appropriate for a given application is only one factor entering into the successful performance of a cryogenic temperature measuring system. Equally important are these additional factors:

A. Calibration of the thermometer must be accomplished within the required accuracy and in a form that is convenient for data reduction.

B. Installation of the thermometer in the experiment must be accomplished in a reliable manner and with installation-related errors commensurate with the allowable uncertainty in measurement.

C. Measuring circuitry and other associated instrumentation must be compatible with the measurement requirements and with the selected thermometer.

These three subjects will be discussed briefly in relation to the use of the more common thermometers, PRT, GeRT, CRT, and thermocouples.

4.1 Calibration. Accuracy requirements in measuring cryogenic temperatures are usually greater than in measuring higher temperatures. Errors of a fraction of a kelvin in some situations can result in unacceptably large errors in experimental results. Procedures and techniques for calibrating cryogenic temperature sensors therefore should be planned and performed carefully to obtain accuracies which are realistic and in keeping with the requirements of the applications.

As mentioned previously, the relations of a variable vs temperature for most cryogenic thermometers cannot be expressed by simple equations. Accurate calibration requires very careful measurements at many temperatures plus interpolations by means of complex polynomial equations. However, once the calibration of the thermometer has been defined in terms of values of a variable vs unit increments in temperature, other comparable thermometers can be calibrated with relatively few measurements. Interpolation between measured values is performed with the use of Z ratios, or Cragoe functions,[8,9] where:

$$Z = \left[\frac{U_T - U_{T1}}{U_{T2} - U_{T1}}\right]_S \simeq \left[\frac{U_T - U_{T1}}{U_{T2} - U_{T1}}\right]_X , \quad T1 < T < T2 \qquad \text{Eq. 0-2}$$

U represents a value of the variable at temperature T; subscript S designates a standard or calibrated thermometer, X a comparable thermometer. Values of U vs T for thermometer S are compiled into a standard table. U values for thermometer X are measured at calibration temperatures T1 and T2 and are calculated for intermediate temperatures using a rearrangement of eq. 0-2,

$$U_{T,X} = U_{T1,X} + \left[\frac{U_T - U_{T1}}{U_{T2} - U_{T1}}\right]_S \left[U_{T2} - U_{T1}\right]_X \qquad \text{Eq. 0-3}$$

To validate the use of this interpolation procedure a statistical sample of the X thermometers must be calibrated at no less than one temperature in addition to T1 and T2. The Z ratios (eq. 0-2) obtained from these measurements are compared with Z ratios obtained from U values in the standard table at the same temperatures or with Z ratios obtained from corresponding measurements at the same temperatures on a thermometer that is known to comply with the standard table. If the ratios agree within acceptable limits of error, then the use of this procedure is justified. The Z ratios faithfully reflect any nonlinearities in the standard sensor calibration as defined in the table. The increments in the table should be small enough that linear interpolation between listed values will not introduce significant errors.

Point calibrations are obtained from comparison measurements with sensors immersed in liquid cryogens--hydrogen, nitrogen, helium, oxygen, or neon. Because of uncertainties associated with bath conditions such as stratification and superheating, a calibrated sensor should be used rather than vapor pressure to determine the actual temperature in the liquid.[8]

4.1.1 PRT. A reference table for platinum resistance vs temperatures from 10 to 300 K has been established at the NASA Lewis Research Center. The table was derived from average values from NBS calibrations[5] for six primary standard type PRT. The six calibrations were compared in the nonlinear range from 20 to 80 K using Z ratios. Deviations from the average ratios did not exceed the equivalent of 5 mK. Ratios in the 80 to 300 K range were found to agree within 10 mK.

An evaluation of various commercial PRT revealed that certain small, rugged, high resistance types are obtainable having a quality that compares favorably with the high quality of the primary standard type PRT.[8] Comparisons with transfer standard PRT in terms of Z ratios (eq. 0-2) showed differences within the equivalent of 0.04 K in the nonlinear range. Hence, a two-point calibration, at approximately 20 K and 77 K, plus interpolation by standard table and Z ratios will suffice to calibrate such PRT from 20 to 80 K with uncertainties within 0.04 K. An additional measurement at the ice point will serve as a basis for extending the calibration up to 300 K with the same order of uncertainty. Tables of resistance vs temperature for individual sensors can be produced readily by a computer using a program which applies (eq. 0-3) to data taken from a standard PRT table and two calibration points.

Another recognized method of calibrating a PRT is by measuring its resistance at the ice point and applying W_T ratios from a standard ratio table, where W_T is the ratio of resistance at temperature T to resistance at the ice point. This method, however, does not cancel out the residual resistance as does the Z ratio method. The residual resistance is normally about 0.1 percent of the ice point value, and it may vary widely even among sensors of the same type. At the low temperatures, these variations are large enough to cause W_T differences equivalent to 0.1 K or more at 20 K.

4.1.2 CRT. The carbon resistor as a temperature sensor has a useful range generally from 2 to 80 K. At higher temperatures, instability and diminishing sensitivity result in excessive uncertainties. Generally a resistor, or samples from a particular lot of resistors, must be calibrated at three temperatures or more, preferably in the range of interest. Comparison calibrations in helium, hydrogen (or neon), and nitrogen coolant baths will suffice to determine the constants for the equation of Clement and Quinnell,

$$\log R + \frac{K}{\log R} = A + \frac{B}{T} \qquad \text{Eq. 0-1}$$

The equation then can be used to compute values or R vs T for a calibration table. Once a table has been established, it can be used as a basis for Z ratio interpolations for other CRT from the same lot. This data reduction procedure makes use of equations 2 and 3 as discussed earlier.

4.1.3 GeRT. The resistance-temperature curves for GeRT are more irregular than those for the platinum and carbon resistors. They reflect very small differences in the amount of doping in the crystal and tend to differ for individual sensors even from the same lot. Hence, even nominal accuracy requires a multipoint calibration of each sensor. This is best accomplished by comparison in a cryostat with a comparable sensor having a calibration traceable to the NBS. Interpolation between calibration points requires an equation

$$\log R = \sum_{n=0}^{m} A_n \, (\log_{10} T)^n \qquad \text{Eq. 0-4}$$

with n no less than seven.[18] The Z-ratio technique for interpolation may yield values as acceptable as other more involved methods, and certainly better than linear interpolation.

4.1.4 Thermocouples. Tables of thermovoltage and thermopower for the common types of thermocouple[27] and for miscellaneous combinations of thermocouple materials[29] have been developed and refined by Sparks, Powell, and Hall at the NBS. As a means for comparing thermocouple materials, the Bureau also has tables of thermovoltage and thermopower for the common materials referenced to platinum and to "normal" silver.[28]

"Normal" silver (ag-0.37 atomic % Au) is preferred over platinum at temperatures below 50 K because it is much less sensitive to imperfections and impurities.

It is very unlikely that a particular thermocouple will produce voltages that coincide exactly with those in the table or with those produced by another thermocouple of the same type. Usually a single calibration will suffice to provide a ratio factor whereby the standard table can be modified to suit a given thermocouple. This calibration can be performed by comparing a given thermocouple with a calibrated thermocouple of the same type. The ratio of the voltage from the uncalibrated thermocouple to the voltage from the calibrated thermocouple becomes the calibration factor for the test thermocouple. This factor must be adjusted to compensate for any deviation of the reference thermocouple calibration from the standard table.

Thermocouple calibration information and services available from the NBS include the standard tables in printed form or in the form of decks of computer cards; a computer program called FACTOR, written in FORTRAN II or IV; modified tables and data card decks processed by the NBS computer for thermocouples for which calibration data are submitted. The tables and card decks can be produced for either the kelvin (absolute) scale or the Celsius scale and for any specified reference temperature within the 0 to 280 K range. These services, especially the computer services, are described in more detail in reference 26.

4.2 Installation. Proper installation of a thermometer is just as important as selecting a thermometer with adequate performance characteristics and accurate calibration. Care must be taken to install the thermometer so that the measured temperature is the true temperature.[7]

Some of the installation factors to be considered are:

A. Thermal impedance of the sensor to the medium whose temperature is to be measured.

B. Conductive heat to the sensor through its leads and mounting hardware, such as a probe housing.

C. Radiant heat transfer to the sensor.

D. Self-heating of energized thermometers.

E. Parasitic thermovoltages should be minimized since low level d.c. signals are being measured. This is accomplished by thermoelectrically balancing the signal leads, that is, like metals are used for the leads whenever possible and thermal gradients are matched in each signal lead.

F. Electrical hum should be minimized by twisting leads and by proper shielding and grounding.

G. Reliability of installation; that is, lead continuity must be assured, electrical insulation maintained, vibration effects considered, system thoroughly checked out after installation, etc.

H. Time-lag effect of the thermometer and its mounting hardware on the measurement.[6]

Figure 11 shows the method of installation that was developed[37] to obtain accurate wall temperature measurement using a GeRT of the type shown in figures 3 and 8. This installation was complicated by the fact that the sensor was at liquid helium temperatures in a vacuum and exposed to high radiant heat flux. To appreciate the installation problem the construction of the GeRT shown in figure 8 must be considered. As temperature decreases, the heat transfer from the GeRT shell to the Ge sensor decreases, since the sealed helium gas within the GeRT shell condenses. The heat transfer to the Ge sensor through its four electrical leads then becomes dominant. The installation shown in figure 11 provides for:

A. Good thermal contact between the GeRT shell and the tank wall.

B. Heat sinking of the four electrical sensor leads to the wall temperature.

C. Decreasing the thermal conduction path through the four leads by using low thermal conductivity (manganin) lead wires.

D. Shielding the electrical leads from radiant heat.

Figure 12 illustrates a PRT sensor of excellent quality that lends itself to good installation practices for immersion probe applications. Being hollow, it has a relatively large surface area and hence a desirable large surface-to-volume ratio. It can be mounted readily in a probe tube or installed directly in a hole without damage and without changing its calibration. In probe form it can be left exposed for fast response or else protected partially or completely as required. When the sensor is totally enclosed in a sealed probe, thermal equilibrium between the sensor and the enclosure can be enhanced by including helium gas in the probe. Thermal impedance can be reduced further through a split pin which is mounted in the end of the probe and makes light contact with the inner surface of the sensor.

The leads are made of manganin to minimize heat conductivity to the sensor. Copper should be avoided because of its high thermal conductivity at cryogenic temperatures. For example, with end temperatures of 20 K and 90 K, copper leads conduct 65 times more heat than manganin leads of the same size. Furthermore, four 30-gage copper leads conduct 10 times more heat than a 3/16-inch o.d., 0.020-inch wall stainless steel tube of the same length with end temperatures of 20 K to 90 K. Other low conductivity metals can be used for leads in cryogenic installations, but manganin is preferred because its thermopower is low also.

Wire junctions should be made by welding, especially when subject to cryogenic temperatures. Where welding is impractical, wires should be joined mechanically by twisting or hooking, and then the junction should be soldered to insure good conductivity. To suppress parasitic thermovoltages, a low-thermal solder (70% cadmium, 30% tin) is recommended for junctions not subject to cryogenic temperatures. Whereas this type of solder tends to break down at cryogenic temperatures, ordinary lead-tin solder should be used for junctions which may be cycled to low temperatures.

Thermocouple installations appear simple; however, certain precautions must be taken to insure satisfactory measurements. The following is a list of good installation practices:

A. Keep the reference junctions at a temperature close to the expected range of temperatures to be measured.

B. Maintain the thermocouple wires at temperatures between the reference and measured temperatures; it is not good practice to extend thermocouple wires from a junction at a cryogenic temperature through an ambient temperature zone and then to a reference junction at another cryogenic temperature. Also, only small (e.g., 36 gage) copper wires should be brought out as signal leads from the reference junction, and connections should be made at a uniform temperature.

C. Heat sink the thermocouple leads in the vicinity of the measuring junction and the lead wires in the vicinity of the reference junction.[38]

D. For multiple installations use thermocouple wires from the same spool.

E. Use thermocouple wire that has been tested to insure that inhomogeneity is not excessive.

F. Keep thermocouple wire bends, kinks, strains, and general working to a minimum.

G. Reduce junctions to a minimum. This means connectors, switch contacts, splices, etc., should be minimized.

H. Protect thermocouple wires from contamination.

I. Field check the complete installation.

Thermocouples are particularly suited for measuring small temperature differences. References 39 and 40 contain examples of how thermocouples are used in combination with a PRT. The PRT is used to measure the temperature of the reference junction, and the thermocouple measures small temperature differences from the reference junction.

Another example of a special thermocouple for cryogenic temperature application is a "slingshot" thermocouple, so called because of the Y frame that supports it.[16] This thermocouple design is the result of an effort at the Marshall Space Flight Center to develop a thermocouple with fast response for measuring ullage gas temperatures in liquid hydrogen tanks. Various design parameters including dimensions, angle formed by the thermocouple junction, orientation of the couple, wire welds, cleanliness of the junction, and others were found to have significant effects on response time.

An unusual wide-range cryogenic temperature sensor was developed at the Aerojet General Corporation.[16] The sensor combines a pair of Chromel and constantan thermocouple wires joined in series with a carbon resistor. In operation the resistor is powered by a constant current supply so that the potential across the resistor increases at low temperatures where the sensitivity of the thermocouple decreases. The result is a combination sensor with higher sensitivity throughout the range from liquid helium to ambient temperatures.

4.3 Measuring Circuits. All of the cryogenic thermometers discussed here are electrical in nature and require some form of circuit to measure the temperature dependent variable. Proper selection of this measuring circuit is most important to insure that it is compatible with the sensor and with the application requirements. Thermocouple circuitry is well documented and will not be discussed further here except to note that advancements in low-noise, high-gain amplifiers with high common mode rejection have improved thermocouple measurements as well as other low-level voltage measurements.

The two most commonly used measuring circuits for resistance thermometers are the potential ratio circuit and the bridge circuit. Each can give satisfactory performance; however, for a particular application, one may take preference over the other.

4.3.1 Potential ratio. A potential ratio circuit as shown in figure 13 is particularly useful for applications where two or more of the same type of resistance thermometers are used to measure temperatures at about the same magnitude. For example, a potential circuit is good for measuring temperature stratifications in a cryogenic storage tank, or for calibrating many resistance thermometers of a given type in one circuit.

In a potential ratio circuit a constant current is passed through a known resistance connected in series with the resistance thermometer, and the voltage drops across both resistors are measured. The resistance of the thermometer is then calculated from Ohm's Law.

Some advantages of a potential ratio resistance measuring circuit are:

A. A true four-lead resistance measurement is made. This will eliminate the effects of lead wire resistance provided that the resistance thermometer has four leads and a voltmeter with high input impedance is used.

B. Parasitic thermoelectric voltages in the circuit are easily cancelled by either (1) averaging signal voltage measurements with current flowing in opposite directions, or, (2) measuring the thermoelectric voltage with the current off and algebraically deducting this value from the current-on voltage measurement.

C. Measurements need not be accurate in terms of absolute voltage because voltage ratios are used in calculating the resistance.

D. Versatile ranges of resistance and current are easily obtained.

One disadvantage of a potential ratio circuit is that unless the resistance thermometers have matched absolute resistance, standardized data reduction cannot be obtained. A resistance vs temperature calibration must be used for each thermometer. Another disadvantage is that the thermometer's total resistance is measured, and for many applications only a small change in a relatively large resistance is of interest.

4.3.2 Bridge circuit. A bridge circuit is less versatile than a potential ratio circuit. However, it can overcome the two disadvantages listed above. First, the inconvenient data reduction feature of a potential ratio circuit is solved by providing a separate bridge for each resistance thermometer. And by matching the bridge circuit to the thermometer's calibration for a desired range of temperature, the signal output as a function of temperature can be standardized for all thermometers which have matched resistance-difference (Z) ratios. With reference to equation 2, the Z function expresses the fraction of the resistance span R_{T1} to R_{T2} which is realized in going from T1 to T2. It, therefore, relates to temperature the percent of full scale output of a bridge which measures resistance linearly from R_{T1} to R_{T2}. Unlike the potential ratio circuit the bridge circuit can balance out any undesired resistance, R_{T1}, so that only the resistance change, R_{T1} to R_{T2}, is measured.

Figure 14 shows a double bridge type circuit which is described in detail in reference 8. Notice that relays are used for remote control of zero, calibrate, and monitor functions. Care should be taken in choosing relays for such an application. Some reed relays have been found to generate thermoelectric voltages in excess of 100 microvolts. By comparison, good quality electromechanical relays designed for low power switching will generate thermoelectric voltages less than 8 microvolts.

4.4 Radiation Effects. With the increasing use of nuclear energy and superconducting magnets, more cryogenic temperature measurements are being made in the presence of nuclear and strong magnetic radiations. In such cases, the effects of these radiation environments on the measuring system must be considered. References 41 and 42 deal with this subject. Reference 41 is an excellent source of information on nuclear radiation effects on commercial thermometers. Detailed discussion of this subject is beyond the scope of this paper.

0-5. Concluding Remarks

Two decades of research have produced significant developments in the art of cryogenic temperature measurements. Temperatures above 1 K are now defined more precisely in terms of the Helium Vapor Pressure Scale of 1958 (1 to 5.2 K), the NBS Provisional Scale of 1965 (2 to 20 K), and the International Practical Temperature Scale of 1968 (13.8 K and up). This definition of temperature is transferable by means of NBS-calibrated thermometers of acceptable quality, primarily the germanium resistance thermometer (GeRT) from 1 to 20 K and the platinum resistance thermometer (PRT) above 14 K.

In general applications temperatures above 14 K can be measured with proven types of rugged, high resistance commercial PRT that are available at moderate cost. Those of better quality calibrate from 20 to 300 K to within 0.1 percent of absolute temperature with measurements at only three known temperatures, 20, 77, and 273 K (approximate). GeRT are useful for temperatures from 2 to 20 K to within 0.02 K but require calibration at frequent intervals of temperature. The carbon resistance thermometer (CRT) calibrates from 2 to 80 K with measurements at three temperatures, e.g., 4.2, 20, and 77 K; however, accuracy is rated no better than 0.1 K or 1 percent of temperature because of lack of long-term stability.

The NBS has developed standardized tables of thermoelectric voltage vs temperature for cryogenic thermocouples. Chromel/constantan is recommended for measurements above 20 K, Chromel/gold-0.07 atomic % iron for 20 K and below.

Two areas of investigation which need further effort are the development of GeRT with better interchangeability and the advancement of thin-film thermometry to a point where installation is routine and performance can be adequately predicted.

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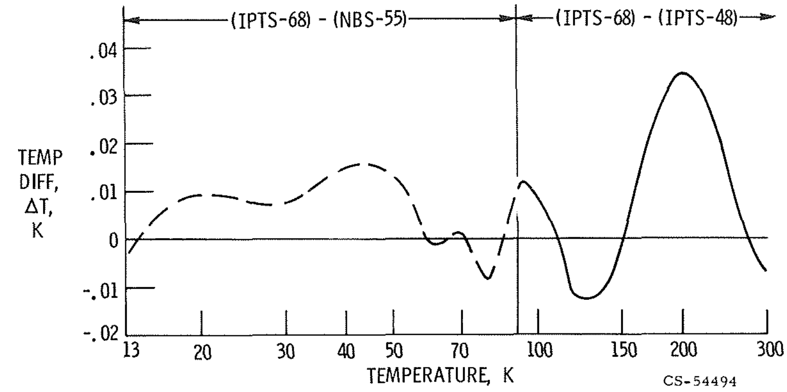

Figure 1. - Differences between IPTS-68 and previous temperature scales (IPTS-48 and NBS-55).

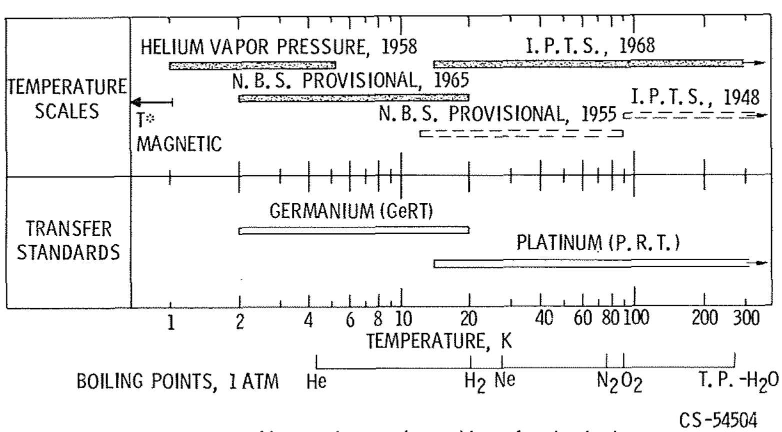

Figure 2. - Ranges of temperature scales and transfer standards.

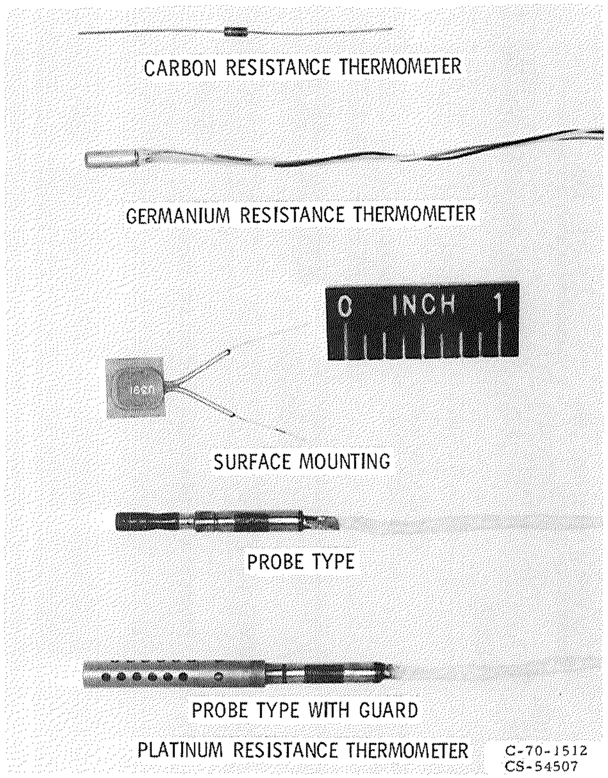

Figure 3. - Typical resistance thermometers.

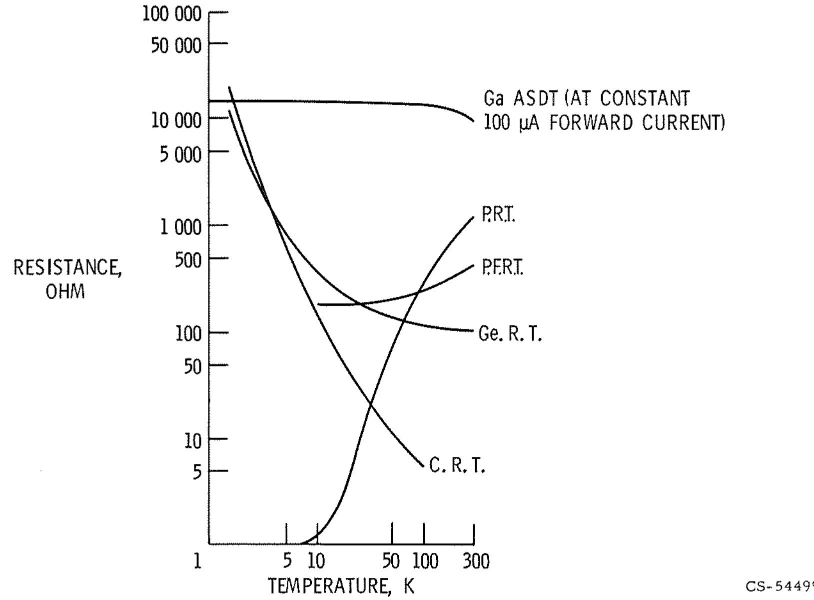

Figure 4. - Resistance versus temperature. Typical cryogenic resistance thermometers.

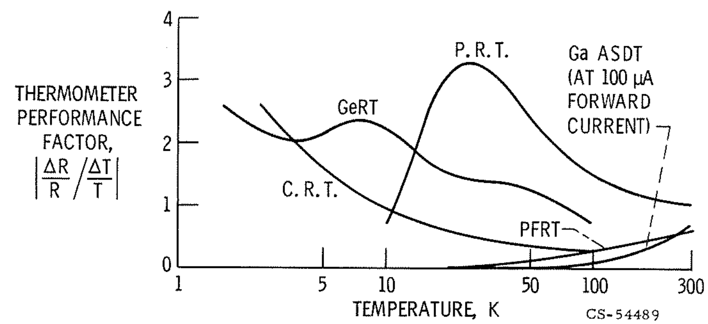

Figure 5. - Typical thermometer performance factor. Expressed as fractional resistance change for a fractional change in temperature versus temperature.

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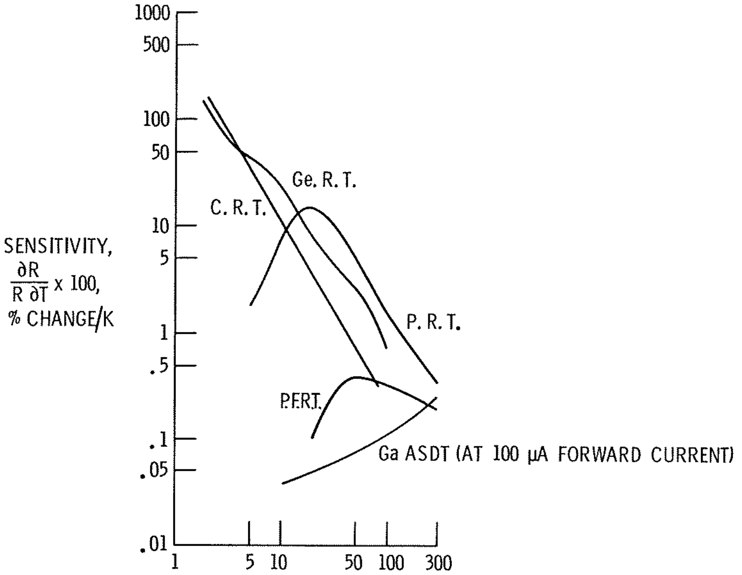

Figure 6. - Sensitivity of typical resistance thermometers expressed as percentage change in resistance per Kelvin.

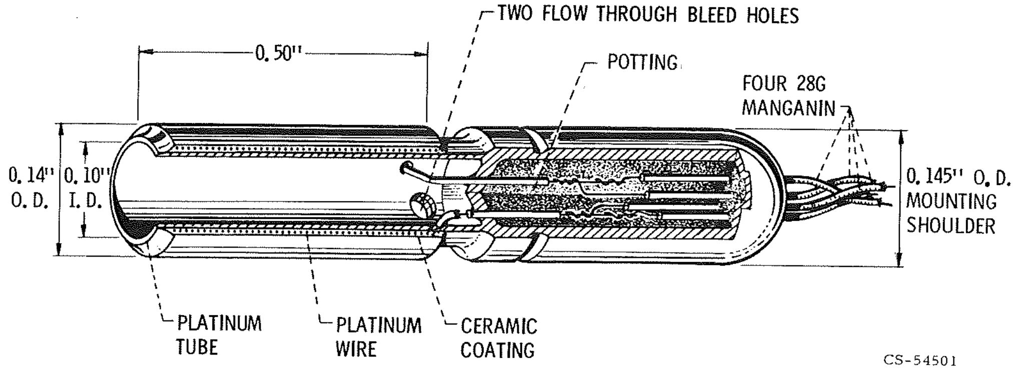

Figure 7. - Typical platinum resistance thermometer.

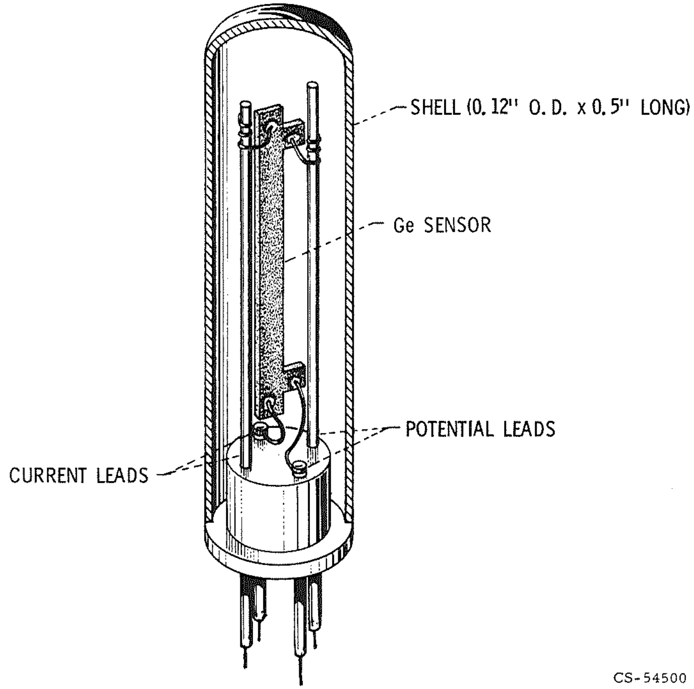

Figure 8. - Typical germanium resistance thermometer.

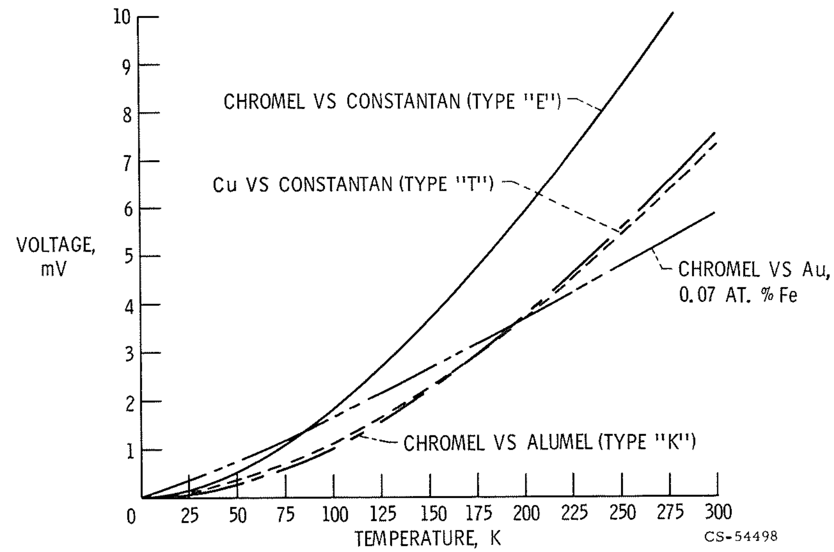

Figure 9. - Thermoelectric voltage for cryogenic thermocouples (referenced at 0 K).

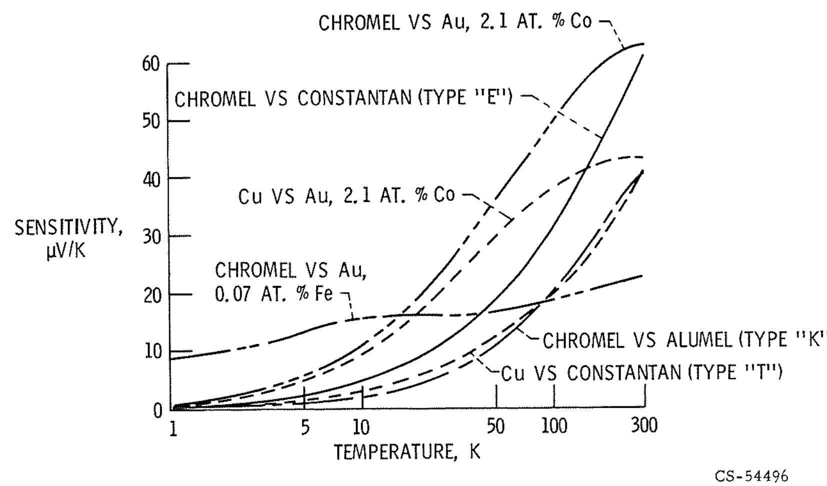

Figure 10. - Sensitivity in microvolts per Kelvin for cryogenic thermocouples.

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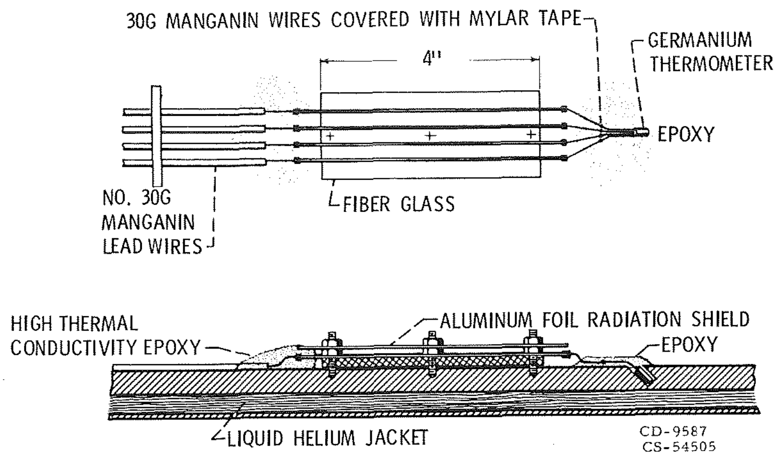

Figure 11. - Installation of germanium resistance thermometer (taken from ref. 37).

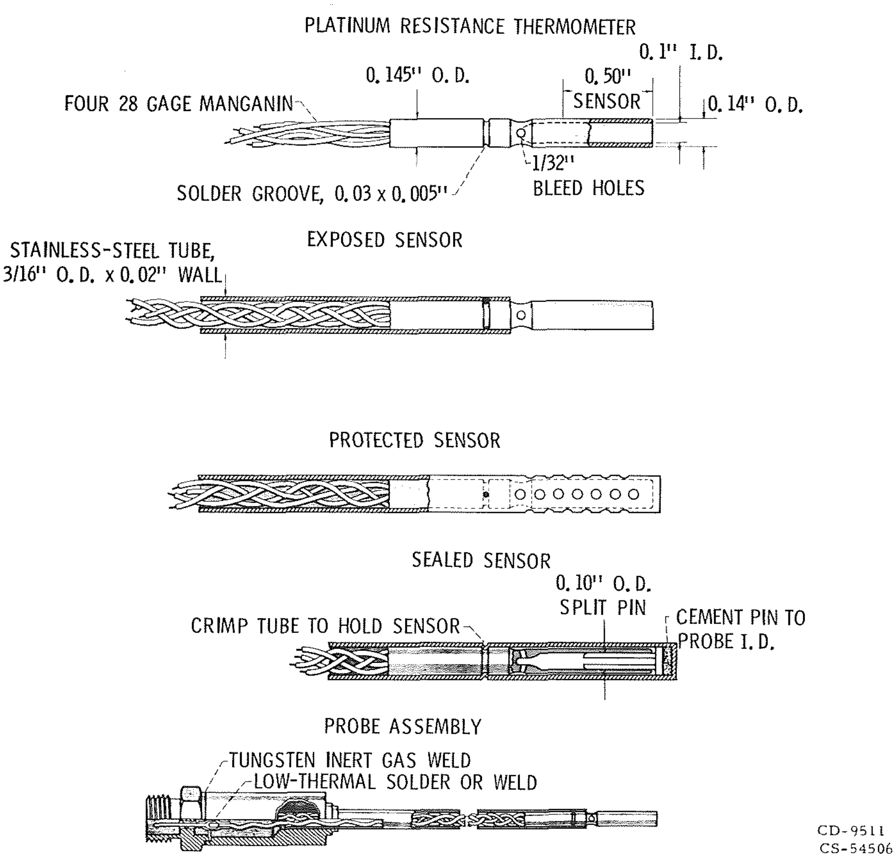

Figure 12. - Platinum resistance thermometer probes taken from reference 8.

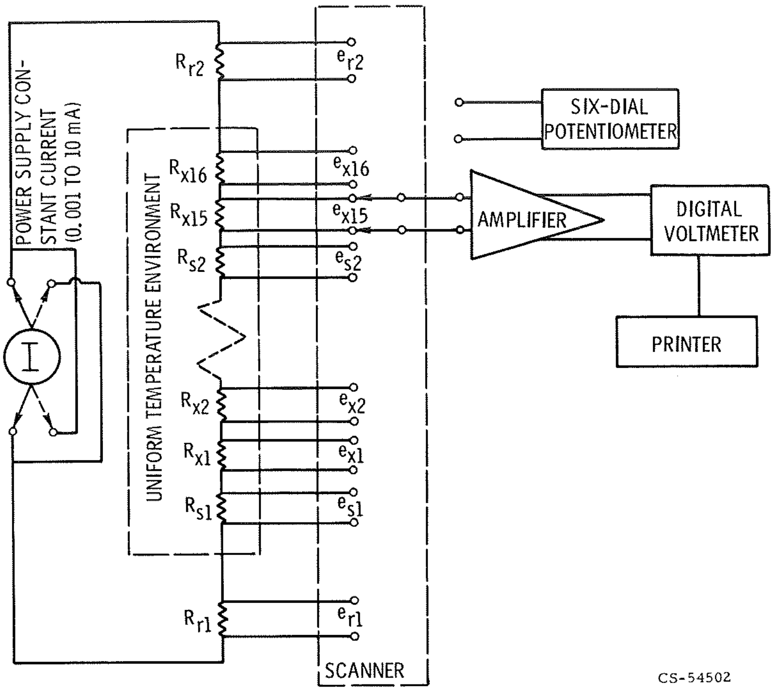

Figure 13. - Potential ratio resistance measuring circuit taken from reference 8.

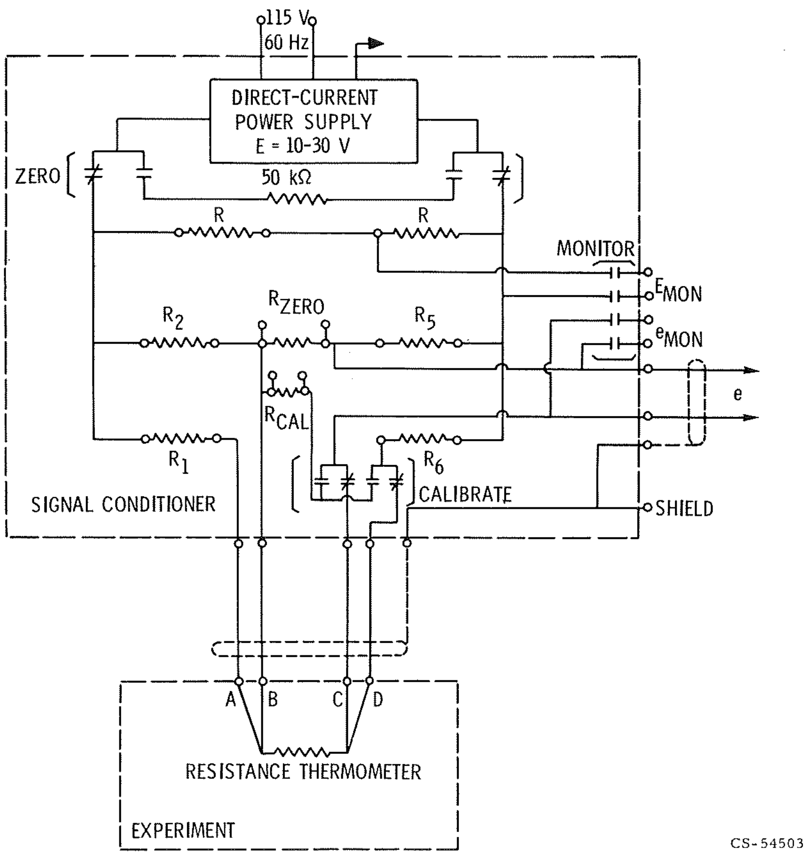

Figure 14. - Resistance thermometer and bridge signal conditioner measuring system, taken from reference 8.

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