MASTER

MAGNETIC THERMOMETRY FROM 1 TO 30 K

Ph. D. Thesis Submitted to Iowa State University, August 1970

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MAGNETIC THERMOMETRY FROM 1 TO 30 K

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MAGNETIC THERMOMETRY FROM 1 TO 30 K¹²

Thomas Charles Cetas

ABSTRACT

Precise measurements of the susceptibilities of chromic methylammonium alum and manganous ammonium sulfate have been used to establish a magnetic temperature scale, T_M , from 0.9 to 18 K which is thermodynamically consistent with NBS-55 at higher temperatures to within 1 mK. The measurements were made with a mutual inductance bridge operated at 33 Hz which is linear and stable to $1:10^6$. T_M is defined and preserved for future use in terms of calibrations of germanium resistance thermometers. Vapor pressure measurements were made on He^3 , He^4 , e-H_2 and natural Ne to assist in the analysis and to provide additional verification of the resistor calibrations.

The results indicate that T_{58} gives temperatures which are 6.7 ± 0.5 mK too low at the He^4 boiling point (4.2 K) and that below 3.6 K, T_{58} (and T_{62}) are related to T_M by $T_M = 1.0018 T_{58}$. Earlier constant volume gas thermometry data are shown to be in excellent agreement with T_M between 3 and 20 K. The NBS-Acoustic scale differs systematically from T_M by 0.03 % from 2 to 19 K with a maximum deviation from a linear relationship of 5 mK. NBS-55 is shown to be smooth to within ± 1 mK between 18 and

30 K, and departs linearly from this smoothness below 18 K. The fact that NBS-55 may differ from thermodynamic temperatures above 18 K introduces the principal uncertainty in how closely T_M approximates the absolute scale below 18 K.

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CHAPTER 1. INTRODUCTION

The recent adoption of the 1968 International Practical Temperature Scale (1), IPTS-68, by the Comité International des Poids et Mesures provides a common basis for comparison of thermal and thermodynamic data from 13.8 to 1300 K. Below about 500 K, IPTS-68 is defined to within one mK and is estimated to be within 0.01 K of the Kelvin thermodynamic temperature, T . Below 900 K, platinum resistors (PTR's) serve as sensitive and reproducible secondary thermometers for interpolating between the fixed points and for intercomparing the scales determined by various laboratories, especially the national laboratories such as the National Bureau of Standards (NBS) in this country, the National Physical Laboratory (NPL) of Great Britain, and the Physico-Technical and Radio-Technical Measurements Institute (PRMI) of the USSR. One of the more important objectives of this new scale is the extension of an international scale to the triple point of equilibrium hydrogen, 13.81 K. Prior to IPTS-68, the lowest defined value (1) on the International Practical Temperature Scale, was the oxygen boiling point at 90.2 K and several national (2) and local scales were established for lower temperatures. However, below 5.2 K vapor pressure measurements of He^4 and below 3.3 K vapor pressure measurements of He^3 provide useful secondary thermometers and temperature scales have been defined in terms of these measurements. The most recently defined vapor pressure scales which have international recognition are T_{58} (3) and T_{62} (4-7) for He^4 and He^3 , respectively.

The current situation with respect to the gap between 5 and 14 K is similar to that which existed below 90 K prior to the adoption of IPTS-68.

The principal reason for the lack of a commonly accepted temperature scale in this region is that before about 1960 no sensitive and reproducible secondary thermometers were available. Thus it was not possible even to define a permanent scale. This void was filled with the development and commercial availability of germanium resistance thermometers (8) (GER's). Hence many thermometry experiments recently have been performed using various techniques and local temperature scales have been defined which can be preserved for internal use and compared with each other.

Thus far, determinations of thermodynamic temperatures between 2 and 20 K have been based on the properties of helium gas, principally He^4 . These have taken the form of isothermal gas thermometry, constant volume gas thermometry (CVGT), and sound velocity measurements (acoustic thermometry). The agreement between the scales established by these various techniques is generally better than 10 mK from 4 to 20 K (9). Below 2 K the vapor pressure-temperature relation for He^4 can be calculated sufficiently well from thermodynamic principles and a minimum number of measured parameters, such as the latent heat of vaporization, to determine a scale which is thermodynamically consistent (10,11,12). Nevertheless, even this vapor pressure relation requires a calibration against some form of primary thermometer at several points above 2 K in order to determine the true thermodynamic temperature. Similar comments apply to the He^3 vapor pressure relation, T_{62} (7). This scale is based on comparisons between He^3 and He^4 vapor pressures above 0.9 K (4) and thermodynamic arguments (5,6) are used to extrapolate the scale to 0.2 K.

An alternative means of determining temperatures below 20 K is to

utilize the susceptibility (11,12) of a nearly ideal paramagnetic salt as measured using a mutual inductance (MI) bridge. The bridge balance, X , is related then to the thermodynamic temperature T , by

$$X = A + B/(T + \Delta + \delta/T). \quad (1)$$

The temperature dependence can be established from paramagnetic theory which is the subject of the next chapter. A is due principally to the MI of the "empty" coils, that is with no salt present, with a small contribution arising from temperature-independent susceptibilities. B is proportional to the magnetic moment of the salt and is dependent on coil geometry. The Δ term depends on the shape of the salt specimen through the demagnetizing parameter and on magnetic interactions in the salt. Finally, δ depends on the salt properties alone. These last two parameters are "non-ideality" corrections in the sense that they represent departures from Curie's Law. Two inherent advantages of magnetic thermometry are that the derived temperatures are independent of He gas and that the sensitivity of modern electronics can be exploited. A distinct disadvantage is the number of parameters of Equation 1 to be determined experimentally.

Durieux (11,12) measured the susceptibility of two single crystal salt samples and one powdered salt sample against the vapor pressures of He^4 and H_2 in order to determine smooth vapor pressure-temperature relationships. He established the constants A , B , and Δ , (the use of δ was not necessary to represent his data) from measurements at 20.2, 4.2, and 2.2 K. The measured susceptibilities then served as a means for

determining intermediate temperatures by interpolation.

The present experiment is similar to Durieux's except that the susceptibility thermometer was calibrated at temperatures above 18 K and then lower temperatures were determined from measured X -values by extrapolation of Equation 1. However, because Δ and δ are most significant at low temperatures, we assumed in addition that T_{58} and T_{62} are proportional, though not necessarily equal, to the thermodynamic scale below about 3 K. Susceptibility measurements on a powdered sample of cerium magnesium nitrate, CMN, were used to verify this assumption. Powdered samples of two salts, chromic methylammonium alum (CMA) and manganous ammonium sulfate (MAS), were measured from 1 to 30 K and yielded identical temperature scales below 18 K. Thus the data were combined and a single magnetic scale, T_M , was defined.

In light of the above method of analysis, as well as the present state of the art of thermometry, the rest of the discussion can be divided quite naturally into three subranges which shall be referred to as the Platinum region (18-30 K), the Intermediate region (4-20 K), and the Helium region (0.9-5.2 K) as follows:

The Platinum region

The magnetic thermometer is not absolute in the sense that temperatures can be calculated from first principles based upon a knowledge of salt properties and cryostat design. Rather it must be calibrated by determining the parameters of Equation 1 by one of the two methods described above, both of which assume that some thermodynamic temperatures are known. When this work began the NBS Platinum Resistance Scale of

1955 (2), NBS-55, was the only scale above 18 K available to the author and thus it was used to establish the magnetic scale. However, published comparisons between NBS-55 and the recently defined IPTS-68 (1) permit calculation of the changes in the magnetic scale which would result if IPTS-68 had been used instead.

The Intermediate region

Three well-documented scales that span the region from 4 to 20 K are described in the current literature. The first is the NBS Provisional Temperature Scale (1965) proposed by Plumb and Cataland (13) which is based on acoustic thermometry and which hereafter is referred to as the NBS-Acoustic scale. Currently, this scale is used as a national standard against which calibrations routinely are distributed. The other two scales are both based on CVGT data. The earlier work of Rogers, et al. (14), which will be referred to as RTAS, supports the NBS-Acoustic scale, especially if one of these two scales is adjusted by a small proportionality constant (0.03 %). On the other hand, the scale of Astrov, Orlova, and Kytin (15) shows rather serious discrepancies with the NBS-Acoustic scale and hence with that of RTAS.

The Helium region

Recently the accuracies of the current He^4 and He^3 vapor pressure scales, T_{58} (3) and T_{62} (7), respectively, have been questioned (9). Acoustic data (16) indicate that the T_{58} value for the He^4 boiling point is 10 mK too low, while a difference of $T - T_{58}$ of 8 ± 3 mK at 4.2 K was observed by RTAS (14) from CVGT data. Furthermore a difference of 6 ± 4 mK

is suggested by an average (9,14) of other recent CVGT work provided all are analyzed using the so-called KKH (17), MR-5 virial coefficients and are referenced to a common temperature near 20.2 K. The conclusion of Astrov, Orlova, and Kytin (15), based upon their data, however, is that the T_{58} value at 4.2 K is correct. If T_{58} is in error, then T_{62} is also since the latter scale is based upon comparisons (4) between the vapor pressures of He^3 and He^4 . Nevertheless, both of these scales are smooth and thermodynamically consistent internally (5,6,10,11,12) at least below 4 K.

The various features of the present work are discussed in the following order. A brief description of the theory of paramagnetic salts is provided in Chapter II as a justification of the technique. This is followed by a discussion of the apparatus and methods of taking data (Chapter III). The results of the vapor pressure measurements and the analysis of the magnetic data leading to the temperature scale T_M are given in Chapter IV. A discussion of T_M is presented in Chapter V in terms of other scales and that chapter concludes with comments on points of vulnerability and directions for further work. Three appendices are included. A discussion of some of the experimental difficulties experienced in the course of this work appears in Appendix A. A tabulation of the present data appears in Appendix B, and previously published (14) calibration data on two GER's used in this work are given in Appendix C.

Preliminary results of the present work appear in a recent review article (9) which surveys thermometry from 1 to 30 K. The conclusions reached in that article were based on incomplete data and hence are

somewhat inaccurate. Nevertheless, the general principles presented are correct. References to much of the primary work on thermometry as well as to other recent reviews are compiled in that paper and hence to list them here would be redundant.

CHAPTER 11. THEORETICAL BACKGROUND

Paramagnetic salts are used routinely below 1 K to establish thermodynamic temperatures (18,19,20), while above 1 K they have been used only to smooth (11,12,21) thermometric data or to interpolate (11,12) between fixed points. The present research is the first attempt to determine temperatures between 0.9 and 18 K by extrapolation of a susceptibility-temperature relationship (Equation 1) which is based upon a temperature scale above 18 K. In this chapter the theory of paramagnetic salts is sketched briefly in order to justify the methods used. No attempt is made to present the complete theory, since several excellent reviews exist in the literature (18,19,22,23).

The chief requirement for a primary thermometer is that the system under study be of such an elementary nature that accurate calculations of the temperature dependence of the particular property can be made from first principles. A system of weakly interacting magnetic dipoles, such as a collection of free magnetic ions, satisfies this requirement. The magnetic energy states ϵ_{m_J} for each ion are the $2J+1$ angular momentum levels,

$$\epsilon_{m_J} = m_J g \mu_B H \quad -J \leq m_J \leq J$$

where $J = L + S$. H is the magnetic field at the ion; J , L , and S , are respectively, the total, orbital and spin angular momentum quantum numbers; g is the Lande' splitting factor, and μ_B is the Bohr magneton. The average magnetization of an ion is given by

$$M/N = Z^{-1} \sum_{m_J} g \mu_B m_J \exp[-m_J g \mu_B H / k_B T], \quad -J \leq m_J \leq J,$$

where k_B is the Boltzmann constant, N is the number of ions in the system, and Z is the microcanonical partition function,

$$Z = \sum_{m_J} \exp[-m_J g \mu_B H / k_B T], \quad -J \leq m_J \leq J.$$

In these expressions T is the thermodynamic temperature. When the summation is performed, the result is

$$M = N g \mu_B B_J(\mu_B H / k_B T)$$

where $B_J(x)$ is the Brillouin function (18). For $k_B T \ll g \mu_B H$, this reduces Curie's Law for the susceptibility

$$\chi = \frac{M}{H} = J(J+1) g^2 \mu_B^2 / 3 k_B T = c / T. \quad (2)$$

This last expression is exact if $J = 1/2$.

For the case of magnetic ions in a crystalline lattice, there are several additional considerations. First, the field, H , which acts on the ion must be determined. The field, H_i , inside a specimen is reduced from the applied external field, H_e , by the product of the shape-dependent demagnetizing factor ϵ , and the magnetization,

$$H_i = H_e - \epsilon M. \quad (3)$$

When Equation 3 is substituted into Equation 2 the measured susceptibility becomes

$$\chi_e = M / H_e = \chi / (1 - \epsilon \chi / T) = c / (T - \epsilon c). \quad (4)$$

Furthermore, the field acting on the ion is not in fact H_i , but rather the local field at the ion; the modification arises from the effects of

surrounding magnetic dipoles in the solid. In the Lorentz approximation (18) this leads to another term similar to ϵc in Equation 4, but of opposite sign. This latter correction cancels with the former for a spherical specimen to yield Curie's Law for the measured susceptibility. The Lorentz approximation is only a first order correction, however, and is not sufficient. Van Vleck (24) treated the question in its full quantum mechanical generality including direct exchange interactions and arrived at an expression for the susceptibility involving an expansion in the inverse temperature.

The strongest effect of the crystal on the energy levels of a magnetic ion is that the "magnetic" electron orbitals are distorted such that they are locked into the symmetry of the lattice, although they do not participate directly in the chemical bond. The effect on the magnetic energy levels is that the energy required to raise the ion to an excited orbital state, or different configuration, is very large (e.g., 10^3 or 10^4 K).¹ Hence the orbital momentum is "quenched" and one uses the "spin-only" form of Equation 2 with $J = S$. In transition metal ions for example, S assumes values between $1/2$ and $7/2$. The Stark effect, due to the electric crystalline field, and the spin-orbit coupling produce further splitting of the ground state degeneracy of from 0.1 to 1 K. These effects are all electrical in character and hence a final degeneracy, (viz. Kramers' doublets, such as $m_j = \pm 1/2, \pm 3/2, \dots$) remains which can be split only

¹ Throughout the text, energies, E , will be given in terms of equivalent temperatures defined by $T = E/k_B$.

by a magnetic field. Finally, the effects of crystalline anisotropy, nuclear hyperfine splitting, and indirect exchange interactions, have been treated (25) using the techniques developed by Van Vleck (24). The effects of all of these sources of splitting can be expressed as an expansion in T^{-1} for temperatures somewhat greater than the ground state splitting.

For a cubic lattice of weakly interacting magnetic ions where exchange between nearest neighbors only is calculated, the high temperature susceptibility has the form (11,12,18) (S.I. units)

$$\chi_e = \frac{M}{H_e} = \frac{c}{[T - (1/3 - \epsilon) c - \theta + \delta/T + \dots]} = \frac{c}{[T + \Delta + \delta/T + \dots]} \quad (5)$$

where H_e is the applied field, c is the Curie constant, $(1/3 - \epsilon) c$ arises from the first order dipole-dipole coupling (Lorentz approximation) and the demagnetizing factor, θ is due to exchange interactions and δ/T results from the electric splitting and from second order dipole-dipole interactions. Rather than write this more generally here, each salt will be discussed individually and the particular variations that result for Equation 5 will be noted.

The effect on the measured susceptibility when powdered samples are used, as in the present experiment, can not be determined easily. If the salt is magnetically isotropic, one expects only a slight reduction in the effective Curie constant due to the lesser magnetic density of the powdered sample when compared to that of a single crystal. If the salt is magnetically anisotropic, the effects (11,12,18,20,21,26) may be more pronounced. Variations in Δ , Equations 1 and 5, for different samples of the same salt

have been attributed (20,21,26) to the size and shape of the crystalline grains, to the density and uniformity of the packing and to the nature of the thermal anchoring to other parts of the apparatus.

Chromic methylammonium alum (CMA) (18), $\text{Cr}(\text{CH}_3\text{NH}_3)(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$, has a nearly cubic structure which is only slightly tetragonal at temperatures below a transition at 160 K. Four different kinds of Cr^{3+} ions go into making up the fcc unit cell. Each Cr ion is at the center of an octahedron of water molecules and is reasonably distant from other Cr ions. Hence the interaction between dipoles is minimized. The ^4F ground state of the Cr^{3+} ion is split into two Kramers' doublets with an energy difference of 0.255 K (11,12,27). The first excited orbital state is 10^4 K (22) above the ground state. For temperatures much higher than 0.255 K, these two doublets behave very much like a $S = 1/2$ state and hence one expects a good approximation to Curie's Law, Equation 2. The theory of CMA has been calculated in detail by O'Brien (28) and others (11,12,29) based upon the work of Van Vleck (24) and Hebb and Purcell (30). A concise account is given by Durieux (11) and colleagues (12) who write

$$\delta = (0.00216 + 0.00063)\text{K}^2 = 0.00279 \text{ K}^2$$

where the origins of the two terms are respectively those mentioned following Equation 5. In particular, the first term is calculated from the results of electron paramagnetic resonance (11,12,27) data. Durieux, et al., suggest $\theta = 12$ mK for CMA and de Klerk (18) quotes $c = 0.079$ (S.I. units) for the Curie constant. Ambler and Hudson (29) have shown that the Hebb and Purcell theory is valid for CMA down to 0.3 K. Durieux, et al. (11,12) have computed the next order correction (proportional to T^{-2} in the

denominator of Equation 5) and show that this term is less than 0.1 mK above 1 K. Thus it is reasonable on the basis of theory to use Equation 5 without additional terms for temperatures above 1 K.

Manganous ammonium sulfate (MAS) (18), $\text{Mn}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$, has a monoclinic structure with two non-equivalent Mn^{2+} ions in the unit cell both of which have a ^6S ground state. Each ion is surrounded by six waters of crystallization with four forming a square and the other two on the line perpendicular to this square and about 15 % farther from the magnetic ion than the first four. The first excited state (31) of MAS is also very high in energy at approximately 3.4×10^4 K. The ground state (18,32) is very complicated when compared to that of CMA, and consists of six singlets and fifteen doublets spread over an energy range of 0.4 K. The nuclear hyperfine splitting is of the same order of magnitude as the electric splitting and consequently no quantitative calculation has been performed for MAS which is equivalent to that worked out in detail by O'Brien for CMA. Nevertheless, it is reasonable to assume that the general form of the susceptibility is given by Equation 5, with all parameters to be determined experimentally. The value of the Curie constant, c , quoted by de Klerk (18) for MAS is 0.26 (S.I. units).

The value of θ is not well established with various workers reporting different θ 's for each specimen that they measured. For example, Durieux, et al. (11,12), quote values ranging from -79 to +32 mK for a single crystal sphere and mention that variations in θ with crystal orientation in the measuring coils are to be expected. Erickson and Roberts (21) quote -9 and +3 mK for two different powdered spheres and suggest that the actual

value of θ for a powdered specimen probably depends more on the nature of the packed pill than on the intrinsic properties of MAS. Since no detailed theory exists for MAS and no experiment to date has required the use of the δ term, no estimate of its magnitude is available.

Cerium magnesium nitrate (CMN) (20,33,34), $\text{Ce}_2\text{Mg}_3(\text{NO}_3)_{12} \cdot 24\text{H}_2\text{O}$, has a hexagonal structure and crystallizes out of a saturated solution in the form of flat hexagonal "dishes." It is magnetically very anisotropic with the susceptibility perpendicular to the crystalline axis, χ_1 , much greater than that parallel to the axis, χ_2 . Since the magnetic ion Ce^{3+} is a rare earth as opposed to a transition metal, the magnetic orbitals lie deep inside the atom and are relatively unaffected by the crystalline field. This implies a somewhat different theory, or at least a different order in which the perturbations are applied. In particular, the spin-orbit coupling is very large for these ions and the 2F ground state is split into doublets with first excited doublet lying 38 K above the lowest doublet. The perpendicular component, χ_1 , obeys Curie's Law nearly ideally from 6 mK to 4 or 5 K, above which the probability of exciting ions to the higher doublet becomes significant. On the other hand, χ_2 , actually increases with temperature in the liquid helium region. Thus additional deviations from Curie's Law arise for powdered samples due to the sampling of χ_2 . For low temperatures (below about 2.5 K)¹, the χ_2 component is negligible and the susceptibility of a powdered sample is still Curie-like.

Presumably, the properties of CMN can be understood completely in

¹ Present results.

terms of a dipole-dipole interaction with a theoretical value (20,35) for $\theta = -0.3$ mK. However, the value of θ is important only for thermometry at temperatures well below 0.9 K and susceptibility data taken at higher temperatures can be represented by Curie's Law. The present situation for CMN recently has been summarized (20) with particular emphasis on its low temperature behavior.

The brief discussion of these three salts suggests that their behavior approximates Curie's Law fairly closely and in particular, that the magnitudes of the correction terms, Δ and δ , are sufficiently small to be tractable. A sound theoretical calculation which evaluates δ exists for the susceptibility of CMA. Nevertheless, the experimental determination of Δ and δ is the most difficult aspect of the analysis of the present results and introduces a significant uncertainty in the conclusions.

CHAPTER III. EXPERIMENTAL APPARATUS AND METHODS

The object of this experiment was to measure the susceptibility of a paramagnetic salt which was in thermal equilibrium with four germanium resistance thermometers, GER's, and a platinum resistance thermometer, PTR. The PTR provided a means for fitting the susceptibility data above 18 K to Equation 1, or equivalently, for calibrating the susceptibility thermometer against NBS-55. The GER's were used as transfer media to relate susceptibility data to the helium vapor pressure scales, T_{58} (3) and T_{62} (7), which were needed to establish the two correction parameters, Δ and δ , Equation 1. In addition, the GER's served as a means for preserving the resulting magnetic scale for future use and for comparing it to other temperature scales.

The lower portion of the cryostat which is submerged in the He^4 bath is sketched, not to scale, in Figure 1; references to this figure will be made throughout the chapter. The susceptibility measurements were made with a low frequency mutual inductance bridge while the resistances were determined with a conventional dc potentiometric method. A description of these two electrical systems will be followed by comments on the construction of the cryostat, the use of the apparatus, and the results of tests of the suitability of the apparatus for the present research. The chapter concludes with a description of vapor pressure measurements on He^3 , He^4 , H_2 and Ne.

Figure 1. A sketch of the thermometry apparatus. This portion of the cryostat is immersed in the liquid helium bath.

The Susceptibility Measurements

The mutual inductance bridge

The ac susceptibilities of the paramagnetic salts were measured at 33 Hz with the mutual inductance (MI) bridge shown in Figure 2. This bridge was developed for precise low temperature thermal expansion (36) measurements in this laboratory and is linear and stable to $1:10^6$. Similar bridges are described by others (37,38). A fixed reference MI, M_0 , provided a constant voltage to the Gertsch Model 1011 AC Ratio Standard autotransformer (RT). The RT setting, X ($X_{\max} = 1.111\ 111\ 0$), is adjusted so that the net voltage in the secondary is zero. Early tests showed that the RT would not operate at the nanovolt levels required by the experiment, so M_0 was increased by a factor of 100 to its present value of 3.7 mH and a 100:1 step-down transformer was placed in parallel with the RT output. A 0.26 μF tuning capacitance in parallel with the RT input (not shown) raised its input impedance at 33 Hz from the original 20 k Ω to 300 k Ω .

Quadrature phase signals in the bridge which typically ranged from 0.3 to 5 μV were nulled out by the resistive network shown. The readings of R_x , a General Radio Model 1434-X decade resistor, were recorded for each data point since they gave additional information about the bridge behavior.

The phase sensitive lock-in detector (39,40), locally built, was coupled to the circuit through a 632:1 Model DI 5551 SIE transformer. Thus, nV level signals in the low impedance circuit were amplified to the μV levels that the high input impedance detector could resolve. A particularly convenient feature of this detector is that both phases (40) of an off-null

Figure 2. A circuit diagram of the mutual inductance bridge.

signal are displayed on twin output meters. One pen (blue) of a two-pen Bristol recorder was driven by the dc output of the detector, and thus the bridge balance could be monitored continuously. The 33 Hz oscillator was tuned to the precise frequency of the detector and was stable to $1:10^4$ in frequency over several weeks. Data were taken with a 15 second time constant in the detector. The random ± 0.15 nV rms bridge noise corresponded to $\pm 2 \times 10^{-7}$ in X at 100 mA rms primary current. The bridge balance, X , was insensitive to changes in the primary current from 100 to 200 mA (2.5 to 5 G magnetic field) when tested with no salt present in the cryostat and with a CMA sample.

The reference MI, M_0 , was constructed in two sections with opposing senses of coil winding to eliminate voltages induced by stray magnetic fields, and a 3 mm gap to minimize capacitive coupling between the concentric primary and secondary coils. The coils were immersed in a liquid nitrogen bath to lower the secondary resistance and to improve the stability of the MI. The bath had a capacity of only one liter and required filling every few hours when taking data. No bridge balance shifts due to M_0 were observed provided care was taken so that the bath was stirred moderately to prevent thermal stratification of the liquid. The lower thermal expansions and hence greater MI stability of the coils which would result make the use of a He^4 bath attractive, although the liquid N_2 bath proved to be adequate for the present work. Anderson (38) describes a method for locating the reference MI near the measuring coils in such a manner that it is unaffected by the salt moment.

The cryostat tail

The design of the cryostat "tail", that is the magnetic portions of the cryostat (see Figure 1), is related closely to the design of the coils. Thus many comments about the coils appear in this section, although their detailed description is the subject of the following section.

Many factors must be considered in order to obtain a system that is sufficiently sensitive to changes in a sample susceptibility and yet is free of spurious effects. The parameter A , Equation 1, must be minimized so that full bridge sensitivity, linearity, and stability are available for determining the susceptibility of the salt and hence the temperature; i.e. so that $dX/X \simeq dX/(X-A) = -dT/T$. All of the temperature-dependence in X must be due to the paramagnetism of the salt, and X must be insensitive to external influences such as stray electromagnetic fields and relative movements of nearby metal, especially ferrous metal. The salt and resistance thermometers must be at the same temperature when data are taken, so the thermal contact must be excellent and no extraneous heat flow between the salt and the thermometers can be permitted. Finally, the coils must be sufficiently sensitive to permit the resolution of ± 0.5 mK or better at all temperatures. All of these requirements were adequately met in the present experiment.

The coils were wound in two sections that were identical except for the polarity of the secondary sections. That is, the net MI of the complete set was very nearly zero if no salt was present. The two sections are sketched in Figure 1 as they appeared on the cryostat, while Figure 2 illustrates their electrical character. For clarity of discussion, the

upper coil in which the salt was placed will be referred to as the main section and the lower coil will be called the astatic section. All of the tail pieces, components, viz. the copper wires, the Vycor support tube, the "coil-foil" (41) shield, and the Pyrex vacuum jacket tail, passed symmetrically through both coil sections. Thus any spurious susceptibility contribution to the main section was cancelled by a similar, but opposite, contribution in the astatic section. The coils were located in the liquid helium bath for MI stability and for low secondary resistance.

The salt was contained in a nylon holder that had an approximately ellipsoidal cavity of major and minor axes of 3.0 and 2.1 cm, respectively. Nylon has a small temperature-independent susceptibility (42) and so the holder introduced no error in χ . In addition, the large thermal contraction of the nylon holder compressed the salt into a tightly bound pill. The salt was anchored thermally to the block with thirty varnished copper wires (B&S #28) and was protected from outside heat sources by a "coil-foil" (41) shield made from vertical copper wires (also B&S #28) that were supported by mylar, nylon netting and GE7031 varnish.

Eddy currents induced in all of these copper wires by the primary field could affect the data in two ways. First, eddy current heating could establish a thermal gradient between the salt and the block. Second the eddy currents have a paramagnetic moment which depends on the resistivity of the copper and the wire diameter (see Appendix A). Since the resistivity of copper changes rapidly with temperature above 4 K, a spurious temperature-dependent susceptibility would be measured. In an early design, eddy currents in the copper wires and in the shield (of a somewhat different

nature) produced an error in X equivalent to 500 mK at 20 K. Thus the choice of wire size represented a compromise between maximizing the thermal conduction up the wires (proportional to the cross-sectional area of the wires, S_w) and minimizing both the eddy current heating ($\sim S_w^2$) and susceptibility ($\sim S_w^3$). Substantial reduction of the effect also resulted from the close similarity of the two coil sections and hence excellent cancellation (to within 0.03%) of the net secondary emf of the "empty" tail; i.e. everything present except the salt.

Eddy currents induced in the block and shields (cf. Figure 1) can introduce errors of a similar nature and magnitude as those above. Specifically the emf induced in the main secondary by the reflected primary flux, that is, the eddy current flux, was greater than that induced in the astatic secondary which was farther from the block. To reduce the effects of these eddy currents, a superconducting lead shield was placed in the He^4 bath around the brass upper portion of the vacuum jacket. A 3.5 cm aperture remained open through which the coil-foil shield passed so the magnetic shielding was not complete. The effect was reduced further by making each section of the secondary coils independently astatic in the horizontal plane, or "radially" astatic as well. This was accomplished by winding an "inner" secondary coil with a given turns-area product ($N \cdot A$) on the outside of each primary section. Concentric with the inner secondary coil, and in the same plane, an "outer" secondary coil was wound with a considerably greater radius and a value of $N \cdot A$ equal to that of the inner coil. The inner and outer coils then were connected in opposition so that each coil section, main and astatic, was independently insensitive to inhomogeneous fields such as those reflected from the block and shields or

those due to power line radiation (60 Hz).

Thermal expansion of the various members supporting the sample from the top of the vacuum can (Vycor tubing, copper block, stainless steel pumping tube and the upper half of the nylon holder) will move the salt with respect to the coils as the block temperature is raised from 4 to 30 K. This could produce another spurious temperature dependence in χ if the measured susceptibility depended on the position of the salt in the coils. This effect occurs only if a salt is present, so there is no way to separate it from the temperature-dependence of the salt susceptibility. Vycor tubing was chosen for use as the member supporting the sample from the block because of its negative thermal expansion (43) which would tend to cancel the positive thermal expansion of the copper block. Furthermore the inner secondary coil, which is most sensitive to the salt susceptibility, was wound in the form of a Helmholtz pair to make the measured susceptibility independent of salt position over a finite distance. After the coils were constructed a "sensitivity profile", Figure 3, was determined by probing the coils at room temperature with a Dy_2O_3 salt specimen of the same shape as the experimental samples. When the cryostat was assembled the coils could be located with respect to the sample so that the salt lay within 2 mm of the center of this profile. Hence the fractional change in χ with position was approximately 1.0/m, and the net movement of the sample is estimated to be approximately $3\mu\text{m}$. Using values of χ found for the two salts, the maximum error that could result from movement of the salt by thermal expansions was estimated to be less than 0.5 mK at 30 K.

Figure 3. Field and sensitivity profiles for the coil system. The lower curve shows the variation in the primary field ($B/B_{\max}$) along the axis as determined by a probe coil. The upper curve shows how the sensitivity of the coils varies with the position of the salt sample. The longitudinal positions and dimensions of the coils are illustrated in relation to these profiles. The + and - symbols refer to the relative phases of each of the secondary sections. See text for a complete discussion.

The coils

Many of the general characteristics of the coils are discussed in the paragraphs above, especially the various constraints that affected their geometry. Now a rather detailed description of the coils can be given. The primary was wound in two identical solenoids which are referred to as the main and astatic sections. Each section, 6 cm long and 1.9 cm radius, had 133 turns of B&S #28 copper wire wound with increased turns density at the ends so as to make the field uniform over about 3 cm (see Figure 3). The centers of the two sections were 11.5 cm apart. The turns were epoxied to a glass-filled phenolic coil-form to provide rigidity and stability. This material was chosen because its thermal expansion (44) is very close to that of copper. The field generated by the primary at 100 mA was 2.5 G, rms. A longitudinal profile of the field as determined with a small probe coil is sketched in Figure 3 along with blocks representing the locations and lengths of the primary coils with respect to this profile.

Each secondary section was wound in two parts and behaved very much like a magnetic quadrupole. With the two identical sections wired in opposition, the total secondary was essentially a magnetic octupole and was both longitudinally and radially astatic. The former minimized the effects of eddy currents in the copper wires to the salt and in the coil-foil shield, while the latter made each section, main and astatic, independently insensitive to outside fields such as the fields reflected from the block and surrounding shields and the fields produced by power line radiation.

The inner secondary coil of each section was wound on the outside of

the primary solenoid in the form of a Helmholtz pair. The mean radius of the pair as well as the separation between the Helmholtz halves was 2.5 cm. Each pair had 1000 turns of B&S #34 copper wire. The outer coil of each secondary section had a radius of 3.8 cm, was centered about the inner Helmholtz pair, and had approximately 400 turns of the same size copper wire so that the turns-area product of the outer coil was equal to that of the inner coil. Glass-filled phenolic coil-forms were used for the secondary as well and all turns were rigidly potted in epoxy. The total dc resistance of the secondary was about 0.35Ω at 4.2 K. A sketch of the longitudinal positions and cross-sectional shapes of the secondary coils is shown in Figure 3. The relative magnetic polarity, or sense, of winding, for each part is indicated by the plus and minus signs. A rather high degree of cancellation of the emf's induced in each part of the secondary was achieved by manually adjusting the wires before potting to yield the best null on an appropriate bridge set-up. The net longitudinal cancellation of the secondary with respect to the primary field was 0.03%; the net radial cancellation, i.e. with respect to outside fields, is estimated from crude data to be better than 0.5%.

The resulting secondary sensitivity for these coils was approximately

$$dE_s/dT = -0.2\text{mV}\cdot\text{K}/\text{T}^2$$

for a CMA salt pill at 100 mA primary current (that is, with a 2.5 G magnetic field). Thus at 1 K, a bridge sensitivity of $0.2\ \mu\text{V}$ was required to resolve one mK, while at 30 K, a sensitivity of 0.2 nV was necessary to attain the same precision in temperature. Note that the latter value is comparable with the random bridge noise. In terms of bridge balance,

X , ($X_{\max} = 1.111\ 111\ 0$) these sensitivities correspond to values of dX/dT of $2 \times 10^{-4}/\text{mK}$ at 1 K and $2 \times 10^{-7}/\text{mK}$ at 30 K. The moment of MAS is three times that of CMA hence the sensitivities are increased by the same factor for MAS.

The salt samples

Reagent grade chromic methylammonium alum (CMA), $\text{Cr}(\text{CH}_3\text{NH}_3)(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$, was purchased from A. D. MacKay, Inc., New York, in crystalline form. The cerous magnesium nitrate salt (CMN), $\text{Ce}_2\text{Mg}_3(\text{NO}_3)_{12} \cdot 24\text{H}_2\text{O}$, was grown from water solutions of $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}^1$ and $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}^2$ mixed according to their stoichiometric ratios. The manganous ammonium sulfate salt (MAS), $\text{Mn}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$, was produced similarly from $\text{Mn}(\text{SO}_4) \cdot \text{H}_2\text{O}^2$ and $(\text{NH}_4)_2\text{SO}_4^2$. The three paramagnetic salts were recrystallized three times in the open air, discarding the liquor with each crystallization so that approximately one-quarter of the original crystals remained. The crystals were stored covered by their saturated solution in sealed jars until they were to be used. No precautions, other than those mentioned, were taken to assure the purity of the salts since any non-ferrous impurities would act only as filler material (if non-magnetic) or would alter slightly the magnetic moment (if paramagnetic). On the other hand, care was taken to avoid macroscopic pieces of metal, such as copper fillings or ferrous chips.

The salt pills were packed from a slurry of finely ground crystallites in Dow Corning silicone oil (50 cs viscosity). The crystals were covered completely with oil during grinding in an ice bath-cooled mortar. When packed into the salt holder, the oil acted as binder and as thermal contact

¹ Purchased from American Potash and Chemical Corporation.

² Obtained from laboratory stores, reagent grade.

agent. In addition, the oil protected the crystals from decomposition in the air through evaporation of the waters of hydration. This last point is important since about one day was required to assemble the cryostat after packing the salt pill.

The Resistance Measurements

The measurements

A diagram of the circuit which was used for the resistance measurements is given in Figure 4. The potentiometer had a sensitivity of $0.1 \mu\text{V}$ but voltage readings were interpolated to $0.03 \mu\text{V}$ with the detector. The detector output was connected to the red pen of the previously mentioned two-pen Bristol recorder. All three current reversing switches were located on the same shaft and were switched simultaneously thus eliminating the effects of apparent thermal emfs (usually $0.3 \mu\text{V}$ or less) without introducing variations in contact voltages in the potential leads. The thermometers were connected in series with Leeds and Northrup NBS-type standard resistors for current measurements. The particular resistor potential to be measured was selected through use of a low thermal switch. Copper leads ran from copper terminal strips at the top of cryostat to this switch. The copper potential leads from the block terminal strips (see below) were connected by spring-loaded copper contacts with the terminal strips at the top of the cryostat. GER currents were supplied by a 45 V dry cell through low noise dropping resistors. Spurious leakage currents were minimized by mounting those circuit elements with a potential near 45 V on a guard plate which was shorted to the negative battery terminal.

Care was taken to keep the measuring currents sufficiently low to

Figure 4. A schematic diagram of the circuit used for the resistance measurements.

prevent significant self-heating and at the same time to maintain sufficient precision. This was somewhat difficult in the GER circuit due to the fact that the four GER's have rather large differences in resistance at a given temperature, especially below 6 K. Generally, the best compromise for the present apparatus was to use currents such that GER voltages were between 1.6 and 4.5 mV. The corresponding thermometer powers were less than $0.01 \mu\text{W}$ near 1 K, less than $0.1 \mu\text{W}$ near 4 K and less than $1 \mu\text{W}$ at 20 K and above. Currents of either 5 or 10 mA were used in the PTR circuit to maintain sufficient sensitivity even though the NBS calibration current was 2 mA. No appreciable self-heating was observed.

The thermometers were mounted in the copper block as is illustrated in Figure 1, and the leads were soldered to terminal strips (14) which served as thermal anchors. The strips were made from copper, 5 cm long and 0.5 cm wide, and were epoxied to the block using nylon netting between the block and the strips to prevent electrical shorts. Equilibrium between the thermometer elements and the block depended on the lead anchoring rather than on the effectiveness of any exchange gas that was present in the thermometer cases. The leads from room temperature passed through the helium bath and entered the vacuum can through nylon-epoxy electrical seals. The leads were looped about in the space between the top of the vacuum can and the intermediate shield and then anchored thermally to the top of this shield. A few more loops were taken in the space between the intermediate shield and the block where the leads again were anchored and then were soldered to the terminal strips. The effective lead length between the block and the bath was approximately 70 cm. This long length was

helpful in reducing the heat flow through the many electrical leads running from the block to the bath. Specifically, there were ten B&S #38 (0.1 mm diameter) copper potential leads, four B&S #30 (0.25 mm diameter) manganin thermometer current leads, and four B&S #30 manganin leads to the temperature controller sensor and heater.

The resistance thermometers

One of the most critical requirements of a secondary thermometer is that its resistance-temperature characteristic be stable. The properties of PTR's are sufficiently well understood from an experimental standpoint that they can be constructed, calibrated, and provided that they are handled carefully, trusted indefinitely (1). This is not necessarily true for GER's, so care must be taken to assure that a particular thermometer is reproducible. A convenient method of verifying the reproducibility is to plot the resistance of one GER against that of another whenever the two are in equilibrium near a given temperature, e.g. 4.2 K. Figures 5 and 6 give such plots for the four GER's used in this experiment, viz. 803, 618, 622, and 248, using 803 as the reference. All four GER's were purchased from Minneapolis-Honeywell between 1962 and 1964 and had been inter-compared prior to the present work.

Two of the four GER's, 803 and 618, have particularly interesting histories. These two were calibrated originally in the CVGT (14) work in Sydney, Australia, in 1965, and the resistance comparison for three points taken at that time is indicated in Figure 5 by the two triangles. They were returned to Ames and used as standards for thermometer calibrations for two years. The crosses in Figure 5 show some of the resulting

Figure 5. The resistance of GER 618 versus that of 803 for several comparisons near 4.2 K. This figure illustrates the reproducibility of these two thermometers over 5 years. The triangles ($\blacktriangle$) represent data taken in 1965 in Sydney, Australia (14); the crosses (+) show data taken from 1966 to 1969 in Ames; the dots ($\bullet$) indicate the present data, 1969 to 1970.

Figure 6. The resistances of GER's 248 and 622 versus that of 803. The encircled crosses ($\oplus$) represent data for 248 taken in an earlier apparatus (14) in 1967; while the crosses (+) indicate the present data for 248. The triangles ($\blacktriangle$) show the present data for 622.

comparison points. In addition, 803 was sent to Washington, D.C. for an NBS-Acoustic (13) calibration. Finally, the two GER's were placed in the present apparatus and the resulting comparisons are represented by the dots. The reproducibility of the two thermometers over a period of 5 years is within ± 0.3 mK.

GER 248 originally was calibrated against an earlier CVGT (45) scale and was used in specific heat experiments (46) in this laboratory. Later it was compared to 803 (and 618) and the data are represented by the encircled crosses in Figure 6. Comparisons resulting from the present work are indicated by the crosses and although each of the two sets of data is self-consistent, a shift equivalent to 1 mK appears between the data sets. This alone is not sufficient to prove that a real shift has occurred because of the lower precision of the earlier data. Nevertheless, since the discrepancy does not appear between 618 and 803, Figure 5, the evidence cannot be dismissed. Other problems with the self-consistency of 248 appear at higher temperatures within the present experiment and further work is necessary to determine if a systematic error occurred in the present resistance measurements or if 248 is unstable.

GER 622 also was calibrated against 803 and 618 was used in many specific heat experiments (47,48,49). Unfortunately, the crystal broke spontaneously during a subsequent recalibration against the standards (803 and 618). It was repaired by CryoCal, Inc., Riviera Beach, Florida, but the calibration changed in the process and so it now must be considered as a new thermometer. The history of 622 is included here as an ominous warning that catastrophies can occur. The stability of 622 for data taken

in the present work is shown by the triangles in Figure 6. More data are required to determine if 622 will remain sufficiently stable to carry the magnetic scale permanently.

The PTR was purchased from Leeds and Northrup (Model 8164, serial number 1654277) and was calibrated at the National Bureau of Standards in 1965 against NBS-55. One year later, a second PTR (serial number 1676930) of the same type was purchased from the same source and also was calibrated at NBS against NBS-55. When later compared here (14) in a common thermometer assembly, differences of as much as 4 mK appeared between the two thermometers from 16 to 22 K. Based upon evidence given in RTAS (14), the first thermometer is believed to be most nearly correct and was selected for the present experiment.

The Cryostat

Various features of the cryostat are discussed in the preceding section of this chapter, but further remarks are necessary to clarify some of the constructional details and the use of the apparatus. Severe tests of the adequacy of the cryostat design were provided by susceptibility measurements on the addenda, i.e. the complete cryostat except for a salt, and by comparison of temperatures indicated by the various GER's when one GER was located physically on the salt holder. Both of these tests are described at the end of this section.

Construction details

The cryostat, Figure 1, was very similar to the ISU comparison apparatus described in RTAS (14): the principal difference was the addition of

a tail for the susceptibility measurements in the present cryostat. The salt sample was suspended 23 cm below the 2 kg copper block in which the GER's, the PTR, and three vapor pressure bulbs were located. The shield was anchored at the top of the block to intercept any stray heat from the outside. The upper or block portion of this shield was made from copper sheet while the lower portion is the previously discussed coil-foil shield. The elements contained within these shields were the only portions of the cryostat that were controlled at the temperatures at which data were taken. An additional intermediate shield surrounded the block shield to provide an intermediate anchor point for the 18 electrical leads and to introduce another thermal lag for the system. The temperature of this shield "floated" between the block and bath temperatures. The rest of the cryostat remained at the temperature of the helium bath.

The brass upper portion of the vacuum jacket was soldered to the jacket top with Wood's metal for easy assembly. A copper-to-Pyrex seal joined the tail portion of the vacuum jacket to a brass flange which was soldered with Wood's metal to the brass portion of the vacuum jacket. The coils were supported from the bottom of the brass can with three brass rods (3 mm diameter) which were bent to absorb the thermal contraction stresses. Finally, a light shield made from black construction paper was wrapped around the tail to block light entering through the slits in the silvering of the glass dewars.

The block was cooled below 4.2 K by pumping on a quantity of He^4 which had been condensed in the 80 cm^3 pot. A 0.5 mm diameter orifice

reduced superfluid flow below the lambda point. Temperatures above 1.6 K were controlled by regulating the pot pressure using a mylar film-type manostat, while manual control was used below 1.6 K. In general, the temperature could be controlled to ± 0.2 mK for 30 min periods or longer. Temperatures above 4.2 K were attained with a 100. Ω manganin wire heater located at the top of the block. An electronic temperature controller using a carbon sensor (old Speer, 560 Ω at room temperature) was used for coarse (± 10 mK) regulation prior to taking data at a given temperature. Approximately 10 mW of power was required to maintain the block temperature at 20 K, and calculations indicate that most of the heat loss was through the ten copper potential leads of the thermometers.

Operation of the cryostat

After the cryostat was assembled for a run, it was inserted into the dewars and all systems were checked. If a salt were present, the vacuum jacket was sealed off with room air inside and was not evacuated until the cryostat had been cooled to 77 K. At this temperature, the vacuum jacket was evacuated and tested for leaks with a mass spectrometer leak detector. If everything was satisfactory, the vacuum jacket was filled with helium exchange gas and the liquid helium transfer begun. Approximately twenty liters of liquid helium were required to cool the cryostat to 4.2 K and about seven liters were consumed daily thereafter. Once at 4.2 K, the vacuum jacket was evacuated and after 24 hours its pressure was reduced to 10^{-6} torr. Any leaks in the vacuum jacket at this state were easily discerned by sealing off the diffusion pump and watching the rate of pressure rise on a cold cathode gauge, or by using the leak detector.

Two or three weeks' time was required to gather all of the data for a particular salt run. This follows from the fact that approximately one hour was needed for each data point. Helium storage in the dewar was sufficient for about twelve hours of continuous operation; hence once the helium was filled, up to ten or twelve data points could be taken before the helium level reached the top of the vacuum can. Enough helium remained in the dewar to keep the cryostat cold for almost one day more if desired. The data were not taken in any particular order from day to day, although on a given day, work would be confined to one temperature region.

Shifts of approximately 10^{-5} in the measured X occurred occasionally between data taken on consecutive days. No one mechanism could be established as the source of the shifts, but solid air settling near the coils in the helium dewar was one possible cause and large shifts in X of 10^{-4} for an MAS run, and 2.65×10^{-4} for a CMA run were undoubtedly due to this cause. Another arose from small fluctuations in the pressure of the helium recovery line into which the helium dewars were vented. The bridge reading did not depend on the helium level in the dewar, so this presumably was due to a change in the temperature of the bath and the glass tail of the cryostat which was within the coils. Measurements of the change in X with this pressure, P , taken at 20 and 32 K yielded $dX/dP = 4.3 \times 10^{-7}$ torr. Few of these "A-shifts" occurred for the MAS data and those that did were generally much less than 10^{-5} . Shifts occurred daily in the CMA runs. It is not clear why the apparatus did not behave the same for both salts.

Nevertheless, the data from two separate days could be normalized at one temperature by adjusting the A constant, Equation 1, or equivalently,

by adding a constant to X for all data taken on one day. The magnetic temperature calculated for all other points taken on those two days then would agree to better than one mK above 4 K and to within ± 0.3 mK below 4 K. This normalization procedure was successful even for the large shifts mentioned in the previous paragraph.

Above 14 K the resolution of the bridge was limited by the random noise (± 0.15 nV rms or $\pm 2 \times 10^{-7}$ in X at 100 mA primary current) rather than by the temperature stability of the salt. This in turn limited the temperature resolution with the CMA sample since the B parameter (Equation 1) for this salt is small. After some data were taken below 16 K, the primary current was doubled to 200 mA (5 G rms magnetic field) in order to obtain a more favorable signal-to-noise ratio. Direct checks at 16 K and at 24 K indicated no detectable change in X or R_X (Figure 2) when the primary current was raised. Later data, which were taken using 200 mA current for temperatures as low as 1.2 K, were completely consistent with the earlier data taken with 100 mA primary current once compensation was made for the daily "A-shifts."

A particular data point was taken in the following manner. Upon changing temperature, the two traces on the recorder were monitored until the salt temperature (blue trace) clearly was stable and in equilibrium with the block (red trace). For a temperature above 4.2 K the thermal stability was fine-tuned by turning off the electronic regulator and using a constant current to provide a constant heat input to the block heater which just cancelled the heat leak to the bath. The mutual inductance bridge was balanced, except for the last significant figure which was

determined from the off-null voltage on the recorder. In this way it was possible to monitor the susceptibility continuously and hence to record a time-averaged value for X . The resistor voltages, including the standard resistors for current measurement, were recorded in a cyclical fashion in order to account for any temperature drifts. The bridge balance X , the quadrature balance, R_X , (Figure 2) and the time of day were recorded two or three times in the course of taking the data for a point. A data point usually required 10 to 20 min to take after a 20 to 50 min equilibration time.

Quite analogous procedures were used for taking vapor pressure data and these are described in a later section of this chapter.

Addenda susceptibility

The susceptibility of the cryostat with no salt present, here referred to as the addenda susceptibility or ΔX_{ADD} , was measured several times during the development of the final apparatus. Many of the apparatus design refinements were concerned with making this contribution small. Only the temperature-dependent susceptibility is important in this experiment, since any constant contribution was absorbed into the A parameter. Figure 7 shows the results of our addenda measurements along with error bars indicating the sensitivities of the two salts. In general, the correction for the addenda is equivalent to one mK or less for CMA and one-third that for MAS. The dots represent the data for the last addenda run and the one in which we have the most confidence. Below 7 K, two earlier addenda runs showed the behavior indicated by the dashed lines. The continued rise in ΔX_{ADD} with decreasing T , as opposed to the constant behavior indicated by the dashed lines, seems most reasonable.

Figure 7. The addenda susceptibility. The dots (●) show the data for the last (and most reliable) measurement. The solid curve shows the behavior which was assumed for correcting the salt data. The dashed lines represent earlier and less reliable determinations. The vertical bars indicate the change in X which was equivalent to 1 mK for the CMA sample or 0.3 mK for the MAS sample.

Nevertheless, negligible differences in the magnetic temperatures result when they are calculated according to the various possible alternatives, and so the simple average given by the solid line was chosen. Above 22 K, the high temperature behavior for an earlier run (dashed line) departs from that of our last and best run (solid line). Using the dashed line would have the effect of changing the B parameter, Equation 1, such that for CMA, the magnetic value for the helium boiling point would be increased by about 0.9 mK. These data should have been taken at 200 mA for better precision, but the low sensitivity (B parameter of Equation 1) of the CMA sample was not expected at the time.

One other interesting feature is the shift at 7.2 K. It is very reproducible, has a magnitude of 5.5×10^{-6} , and has a half-width of about 10 mK. The soft solder junction between the coil-foil shield and block-shield (Figure 1) probably produced the shift as the block was warmed through the superconducting transition temperature of the solder.

As a further check on the validity of the susceptibility results, a test run was made with GER 248 anchored to the outside of the salt holder. High resistance leads prevented direct thermal contact of 248 to the block. When the recorder traces indicated equilibrium between the block and salt the temperatures given by 248 and by the thermometers in the block were the same to within a 0.3 mK.

The Vapor Pressure Measurements

The vapor pressure measurements were quite conventional and, except for the case of superfluid He^4 , the saturated pressure of a small amount of

liquid in a bulb was measured using mercury and oil manometers and a Wild cathetometer. For superfluid helium, the pressure in the helium pot was measured through a vapor pressure line connected to the pumping line near the top of the vacuum jacket. The cathetometer could be read to 0.01 mm and the absolute accuracy of a column height is estimated to be ± 0.02 mm. Care was taken to assure that the telescope was strictly horizontal since the cathetometer was located two meters from the manometers.

The mercury manometer which was used for Ne, e-H₂, and He⁴ above 2.4 K had large bore (25 mm OD) Pyrex tubing. Hence the meniscus was flat and negligible errors were produced. Before assembly, the manometer tubes were thoroughly cleaned with acid glass-cleaners and were rinsed with distilled water and acetone. After drying and evacuation, approximately 6 kg of triply distilled mercury was distilled into the manometer. All mercury heights were corrected to 0°C and standard gravity (980.665 cm/s²) so that the pressures could be expressed in torr.

The oil manometer which was used for He⁴ data below 2.4 was made from 13 mm OD Pyrex tubing. The density of the butyl phthalate (CVC Corp.) manometer fluid had been measured relative to the density of mercury with a pycnometer. The relationship which was established was verified in the present experiment by measuring the vapor pressures of He⁴ near 2.3 K with both the oil and mercury manometers. Before use, the oil was out-gassed in the manometers for several weeks.

A separate oil manometer (also 13 mm OD) which was filled with oil from the same container as the above manometer, was used for the He³ measurements. This manometer was connected to a particular vapor pressure

bulb and after assembly was never exposed to any gas other than He^3 . A valve manifold at the top of the dewar permitted sealing the He^3 in the manometers and bulb when the cryostat was to be removed from the dewars. When more data were to be taken, only a short section of tubing needed to be evacuated before opening the manometer to the bulb. Reproducible data were taken over the course of several months with one filling of the system with He^3 .

All three manometers were referenced to a vacuum produced by a small CVC diffusion pump. This pump also provided a means for evacuating the manometers and bulbs when the measured gas was to be changed. Small fans circulated air about the manometers continuously when data were taken to prevent thermal gradients. Manometer temperatures (about 22.5°C) were read to 0.1°C with conventional mercury-in-glass thermometers. For He^4 vapor pressures above 4.2 K, the mercury manometer was referenced to atmospheric pressure which in turn was determined with an additional manometer.

The three vapor pressure bulbs had 3 mm ID stainless steel sensing lines; and the pot pressure sensing line had a 4.8 mm diameter. Pieces of yarn were placed in all four lines to prevent thermally induced oscillations in the gas and the lines were bent to block radiation. The line to one bulb was vacuum-jacketed for 25 cm above the vacuum can in order to prevent cold spots when measuring vapor pressures above bath temperature.

As indicated above, one of the bulbs was used for He^3 only. The volume of this bulb was 0.5 cm^3 , while each of the other two had a volume

of 2.0 cm^3 . The sensing tube diameters were selected to eliminate the thermomolecular (50) pressure correction for all data. In particular, this correction was negligible for the He^4 measurements above 1.4 K. Below 1.6 K, temperatures were based solely on He^3 vapor pressure measurements.

The aerostatic head in the gas column produced a small pressure difference between the manometers and the liquid surface. A detailed calculation of this effect requires a knowledge of the temperature distribution in the sensing tube, which unfortunately is not known. Hence no correction could be made. Reasonable estimates suggest that for He^4 the aerostatic head can cause errors of up to 0.6 mK at 5 K and 0.3 mK at 3 K; the error becomes negligible at lower temperatures. For neon, the aerostatic head produced an error of the order of 1 mK while for He^3 and H_2 the error is negligible for all of our data.

The vapor pressure grade He^3 was purchased from Monsanto Corporation's Mound Laboratories and the analysis enclosed with the shipment stated the He^4 impurity as 0.01%. When all He^3 vapor pressure measurements were finished, a mass spectrographic analysis¹ on a sample of He^3 drawn from the experimental bulb gave a He^4 concentration of approximately 0.05%. According to Roberts, Sherman, and Sydoriak (6) this results in the uncorrected temperature being too low by about 0.3 mK at 1.6 K and 0.1 mK at 0.9 K. Again, the effect is small and cannot be calculated accurately for our sample so no correction was made.

Normal hydrogen (75 % ortho, 25 % para) was withdrawn from a gas

¹The author is indebted to Mr. Jerry Flesch of the Ames Laboratory Mass Spectrometry Group for all of the analyses mentioned in this section.

cylinder and without further purification was condensed into a vapor pressure bulb. The hydrogen was purchased from Air Products and Chemicals, Des Moines, Iowa, and was stated as 99.92 % pure. However, a mass spectrographic analysis performed after the experiment indicated the following impurity concentrations in atomic percent:

He ³ : ND	Ne: ~0.005	Ar: ~0.01	Xe: < 0.001
He ⁴ : 0.2	O ₂ : < 0.1	Kr: < 0.001	

The bulb contained about 1 g of Nd₂O₃ (51,52) catalyst to induce the ortho-para conversion to the 20 K equilibrium concentration (99.8 % para), hereafter called e-H₂, and twenty hours after condensation, a constant vapor pressure-temperature relationship indicated that the conversion was completed. No implications concerning the effectiveness of Nd₂O₃ as a catalyst can be drawn from these comments since some experimental problems arose while setting up for this run and it is quite probable that the catalyst was contaminated with air or water vapor. Care was taken to avoid mixing the equilibrium hydrogen in the bulb with the normal hydrogen in the manometers by isolating the two with a valve when changing temperatures. The pressure in the manometer was adjusted approximately to the vapor pressure at the new temperature before opening the valve. This prevented the introduction of normal hydrogen to the bulb which would introduce errors in the measured pressure. Unfortunately, it did nothing to remove the unanticipated He⁴ impurity. Further comments on this appear in Chapter IV.

The 99.999 % pure natural neon sample was purchased from Cryogenic Rare Gases, Inc., Newark, New Jersey, and a mass spectroscopic analysis

established upper limits for the following impurities in atomic percent:

H_2 : < 0.03	He^4 : < 0.003	Kr: < 0.001
O_2 : < 0.03	Ar: < 0.002	Xe: < 0.001

The molar isotopic composition was verified as being of natural atmospheric concentration (1), as is shown below (in atomic percent):

	Ne^{20}	Ne^{21}	Ne^{22}
present	91.2 ± 0.3	0.3	8.5 ± 0.3
natural	90.9	0.3	8.8

The two isotopes, Ne^{20} and Ne^{22} , however, do not have the same vapor pressure (53,54,55) at a given temperature and hence the isotopic composition of the vapor is different from that of the liquid. Data were taken in the manner described below to verify that this isotopic separation was not sufficiently great to introduce measurable errors in the results. Furthermore, the method would serve as a check that hydrogen from the bath did not contaminate the Ne sample. The bulb initially was filled with 1.3 cm^3 liquid Ne at 24.8 K. The gas in the manometer system was equivalent to an additional 0.13 cm^3 of liquid or 10 % of the total Ne. Data were taken at 24.8 K, at 26 K, and at the boiling point, 27.1 K, where about 20 % of the total Ne was in the manometer. The equivalent of about 1 cm^3 liquid Ne was withdrawn from the system, the boiling point data were repeated and then data were taken at 26.5 K, 25.5 K, and near the triple point, 24.57 K. No shift appeared at the boiling point, but the latter three points show a systematic reduction in the pressure equivalent to about 1 mK when compared with the first three points taken. A calculation based on Raoult's Law and the known (55) difference in vapor pressures

between the two principal isotopes at a fixed temperature suggests a reduction of approximately 0.5 mK is to be expected. Since the precision of the experiment is ± 1 mK, the error which is introduced is not significant.

Before ending this section, it should be mentioned that several discussions on the techniques of vapor pressure thermometry exist in the literature. Durieux's thesis (11) and the papers which establish T_{62} (4,5,6) were especially useful to the author.

CHAPTER IV. RESULTS

Equation 1, which is repeated below, gives the relationship between the bridge balance, X , and the Kelvin temperature, T , and is the basic equation of this experiment.

$$X = A + B/(T + \Delta + \delta/T) \quad (1)$$

The two parameters, Δ and δ , which represent departures of the susceptibility from Curie's Law, are most significant at low temperatures. One of the more difficult problems in this experiment was to establish their values for each salt. Thus it was necessary to have a provisional scale at the lowest temperatures which is proportional though not necessarily equal to the Kelvin scale. The usefulness of such a provisional scale, T' , can be demonstrated by setting $aT' = T$, in Equation 1. An expression with the same temperature dependence results with new (primed) parameters which are related to the correct parameters by; $A = A'$, $B = aB'$, $\Delta = a\Delta'$, and $\delta = a^2\delta'$. Since thermodynamic arguments played substantial roles in the definitions of T_{58} and T_{62} , these two scales should nearly satisfy this proportionality requirement. The susceptibility of powdered CMN is known to be Curie-like over part of the Helium region (see Chapter II), so measurements on CMN were made in order to verify the thermodynamic consistency of a scale, T_{vp} , defined from T_{58} (3) above 1.4 K and T_{62} (7) below 1.6 K.

The accuracy of a scale based on an extrapolation of Equation 1 depends on the accuracy with which the PTR reproduces NBS-55 in the calibration region, 18 to 30 K. This NBS-55 calibration can be verified by measuring the vapor pressure-temperature relationships of Ne and H_2 and comparing the results with those of others who have used the same basis for ther-

mometry. The H_2 data also serve to test the NBS-Acoustic calibration of GER 803.

The results of the vapor pressure data are presented with a view towards accomplishing the purposes suggested by the above comments. Following this, the analysis and results of the susceptibility data are described and a temperature scale, $T(X)$, is defined in terms of the susceptibility relationships, Equation 1, of the two paramagnetic salts, CMA and MAS. $T(X)$ cannot be used directly in future experiments since the apparatus and analysis techniques are too complicated for useful secondary thermometry. Instead, $T(X)$ is preserved through the calibrations of the GER's. Thus four smoothed resistor scales, $T_M(\text{GER})$, are defined from least squares fits of the GER resistance versus $T(X)$ data. A discussion, including intercomparisons, of these $T_M(\text{GER})$ scales is given in the last section of the chapter. In most of the discussions, the particular GER used to transfer the smoothed scale is unimportant and so the notation T_M is used.

All of the data and results of this research appear in Appendix B. The resistor-fit equations for the various temperature ranges are given first. Then a tabulation of the T_{vp} (misabeled as T_{58} in Appendix B) versus resistance data appears along with values of $T_M(\text{GER})$ calculated for each GER. Vapor pressure data are given for e- H_2 and Ne in terms of pressure versus resistance tabulations and temperatures are computed for these data. The susceptibility data for the paramagnetic salts follow and calculated values of $T(X)$ and $T_M(\text{GER})$ are listed for each point as well. For all data, a point number, $N0$, is given which locates the raw

data for that point (e.g. 6049 refers to laboratory notebook, T0C-6, page 49). Tables 2, 3, and 4 of RTAS (14) are reproduced in Appendix C.

These list the Australian National Standards Laboratory CVGT data on GER's 803 and 618, the GER fit equations based on those data, and the NBS-Acoustic calibration data for 803.

The Vapor Pressure Results

He³ and He⁴

The absolute accuracy of the calibrations against T_{58} (3) and T_{62} (7) is estimated to be within ± 0.5 mK below 4 K within ± 1 mK near 5 K. These estimates are based on the discussion of possible errors in Chapter III and on a comparison, which appears later, between our vapor pressure results and T_M . Between 1.4 and 1.6 K the values of T_{62} determined from He³ data, and of T_{58} determined for He⁴ data, agree to within ± 0.5 mK. Below 1.4 K the consistency of the T_{62} and T_{58} determinations is within 1 to 2 mK and reflects the lower sensitivity of the He⁴ measurements and the fact that the thermomolecular corrections (50) calculated for the present He⁴ data (about 12 mK at 1 K) are based on the Weber-Schmidt equation which has been shown (56) to be inaccurate. The helium vapor pressure scale used in this work, then, is based on T_{58} above 1.4 K and T_{62} below 1.6 K and is hereafter designated T_{vp} . Least squares fits of GER resistance versus T_{vp} data show a root mean square deviation, RMSD, from the fit equation of 0.2 mK, and later comparisons with paramagnetic salt thermometers showed no inconsistencies of a smooth fit of T_{vp} greater than ± 0.3 mK.

The accuracy of the NBS-Acoustic (13) calibration of GER 803 below 5 K can be assessed by a comparison of the differences, $T_{AC} - T_{58}$, reported by Cataland and Plumb (16), and by Kierstead (57) with those we calculate for GER 803. The differences given by Cataland and Plumb and

T	Cataland and Plumb	Kierstead	GER 803
5.0	12 mK	10.5 mK	10 mK
4.2	10	11.9	11
3.2	8		9
2.8	7		6
2.3	6		6

by us were calculated using data obtained near the actual NBS isotherm calibration temperatures. Kierstead does not state whether his differences were computed in that manner or were calculated from a table based on a smooth fit of the NBS calibration data. Since the differences were quoted to 0.1 mK, the latter method probably was used. Kierstead states that two of his GER's were calibrated at the same time and yield temperatures which agree to within 0.2 mK. The good agreement between our values and those of Kierstead for these differences suggests that 803 represents the NBS-Acoustic scale to within ± 1 mK and that the values at 4.2 K and 5.0 K given by Cataland and Plumb (16) are in error.

H₂ and Ne

The principal reason for measuring the vapor pressures of e-H₂ and Ne was to verify that the NBS-55 (2) and the NBS-Acoustic (13) scales are reproduced accurately by the PTR and by GER 803, respectively.

Alternatively, these data permit the tying of the magnetic scale to other thermometric data independent of resistance scales. It is most convenient to evaluate the PTR calibration through the smooth vapor pressure-temperature relations given for IPTS-68 (1) for equilibrium hydrogen ($e\text{-H}_2$) and natural isotopic composition neon. Temperatures computed using these relations and the measured pressures will be referred to as $T_{68}(e\text{-H}_2)$ and $T_{68}(\text{Ne})$, while temperatures calculated from PTR resistances will be designated as T_{68} and T_{55} for IPTS-68 and NBS-55, respectively. The differences $T_{68}(e\text{-H}_2) - T_{55}$ and $T_{68}(\text{Ne}) - T_{55}$ should be the same as the published differences (2), $T_{68} - T_{55}$. Similarly the NBS-Acoustic calibration for GER 803 ($T_{AC}(803)$) can be tested by comparing our $e\text{-H}_2$ vapor pressure data with those of Cataland and Plumb (58) who also used Acoustic temperatures. Figure 8 shows the differences between IPTS-68, NBS-55, and the magnetic scale, T_M . Above 18 K, T_M is identical with NBS-55, by definition. It is used in this plot for convenience only and is not basic to the present discussion.

The agreement between $T_{68}(e\text{-H}_2)$ and T_{68} (Figure 8) is within ± 1 mK except at 17 K where it is within 2 mK. This scatter is slightly less than that of Muijlwijk, et al. (59), for the same comparison. The 17.042 K point is one of the defining fixed points for IPTS-68 and it is unfortunate that our data appear to be bad for this temperature. When our $e\text{-H}_2$ vapor pressure data are expressed in terms of $T_{AC}(803)$ they agree with similar results given by Cataland and Plumb (58) to within ± 2 mK at most points except that again our 17 K point appears low by about 3 mK and in addition, our 13.98 K point lies 3 or 4 mK above theirs. Part of the scatter in this

Figure 8. The differences between IPTS-68, NBS-55, NPL-61, and the magnetic scale, T_M . T_M is identical with NBS-55 above 18 K, by definition. The differences between the first three scales were obtained from the published deviations (2). The crosses (+) represent the e-H₂ vapor pressure results plotted as $T_{68}(\text{e-H}_2) - T_M$. The triangles (Δ) represent the Ne vapor pressure results plotted as $T_{68}(\text{Ne}) - T_{55}$. See the text for a discussion of these data and notations.

comparison arises from the fact that our Acoustic temperatures are based on extrapolations from nearby original NBS isotherm (13) calibration points while their temperatures were obtained from a table based on a computer fit, with its attendant smoothing, of both the original (13) and the more recent isotherms (60).

The agreement of our data with those of others is puzzling to some extent in light of the indicated 0.2 % He^4 impurity in our sample (see Chapter III). Either the determination of the impurity is in error, or the He^4 gas was concentrated in the manometers rather than at the liquid surface. These measurements will be repeated using H_2 which has less than 0.005 % atomic percent impurity before the comparisons are published.

The differences $T_{68}(\text{Ne}) - T_{55}$ are plotted as triangles in Figure 8. The agreement with the published differences, $T_{68} - T_{55}$, is quite good and in fact is improved if 1 to 2 mK are added to the $T_{68}(\text{Ne})$ values to account for the aerostatic head. Furukawa¹, et al. (55), have measured the vapor pressure of Ne at the boiling point and at the triple point using NBS-55 temperatures. Their value of 27.096 ± 0.001 K for the boiling point is the same as ours. The triple point temperature and pressure were not determined in the present work and so our data can be compared only indirectly with their triple point data by calculating $T_{68}(\text{Ne}) - T_{55}$ using their values ($T_{55} = 24.553 \pm 0.001$ K, $P = 325.02 \pm 0.10$ torr). The resulting 4 mK difference is 2 mK less than the same difference for our nearest point (24.57 K, $T_{68}(\text{Ne}) - T_{55} = 6$ mK); the published difference

¹A discussion with Dr. G. Furukawa, of the National Bureau of Standards, Washington, was helpful in interpreting the Ne results.

is $T_{68} - T_{55} = 8$ mK. The triple point pressure used in defining the IPTS-68 (1) triple point temperature ($T_{68} = 24.555$ K) probably is in error since the difference between this value and the triple point temperature of Furukawa, et al. is $T_{68} - T_{55} = 2$ mK, 2 mK less than the difference calculated from the smooth vapor pressure relationship, and it is 6 mK less than the published difference $T_{68} - T_{55}$ at the triple point.

Grilly (61) also reported his vapor pressure results using NBS-55, but he indicates that a possibility exists of systematic errors in the calibration of his PTR. His value for the boiling point is 27.092 K and his triple point data are $T_{55} = 24.544 \pm 0.004$ K and $P = 324.78 \pm 0.36$ torr.

The accuracy of the calibrations of the PTR (NBS-55) and of GER 803 (NBS-Acoustic) additionally can be tested by determining the differences, $T_{AC} - T_{55}$, from our data and from data taken at NBS. Plumb and Cataland give these differences approximately for the Acoustic Scale (13) and more precisely for the new Acoustic isotherms (60). The values of $T_{AC} - T_{55}$ (NBS) used in the following tabulation refer to the Acoustic Scale and were inferred from information supplied by Dr. Plumb¹. They are more accurate than those plotted in the original publication (13).

¹The author is grateful to Dr. H. Plumb of the National Bureau of Standards for providing the necessary data for this calculation.

T	$T_{AC} - T_{55}$ (NBS)	$T_{AC}(803) - T_{55}$
20.05 K	11 mK	14 mK
18.94	6	6
18.01	4	6
16.97	3	4
16.05	1	2
14.99	-2	-3
14.05	-7	-7

Except at 20 and 18 K the agreement is within 1 mK. The minor discrepancy at 18 K probably results from round-off errors. The reason for the discrepancy at 20 K is not understood.

In conclusion, then, we believe that our PTR calibration represents NBS-55 to within ± 2 mK or better. This estimate is based upon comparisons through Ne and H_2 vapor pressure data, and is supported by evidence given in Figure 6 of RTAS in which our PTR is designated as PTR #1. A systematic constant shift of 2 mK between 20 and 30 K would introduce an error of 0.5 mK in the magnetic determination of the boiling point. The NBS-Acoustic calibration of GER 803 has been verified to within ± 2 mK from 15 to 20 K through vapor pressure measurements on $e-H_2$ while comparisons of $T_{AC} - T_{55}$ suggest that both NBS calibrations are valid to within ± 1 mK in that region. Comparisons through T_{58} indicate that an uncertainty in the NBS-Acoustic calibration of GER 803 of ± 1 mK applies near 4 K.

The Susceptibility Results

A brief description of the self-consistency technique used to analyze the data is helpful for the discussions of the individual salt results. The susceptibility data in the Platinum region were fitted to Equation 1 using several reasonable values of Δ and δ to obtain A and B, and from these fits, the linear relationships A (Δ) and B (Δ) were defined. The effects of δ are nearly negligible in the Platinum region. The data in the Helium region then were analyzed in a manner suggested by rewriting Equation 1 as

$$(X - A)(T' + \Delta)/B = a + \delta/T'(T' + \Delta) \quad (6)$$

where the primes have the same meaning as stated in the first paragraphs of this chapter. These have been dropped on Δ and δ since the distinction is insignificant for the present salts. Equation 6 suggests a sensitive method of plotting the low temperature data for X and T_{vp} using the high temperature values of A (Δ) and B (Δ) to determine a and δ . Figure 9 shows how this plot would look if $T_{vp} = T$, and if there were no scatter in the data. In the particular example shown, $a = 1.0000$ and $\delta = 0.003 \text{ K}^2$; the curves are plotted for values of Δ which differ from the correct value by 0, ± 1 , and ± 3 mK. Because the values of A and B, which are determined at high temperatures depend on Δ , some compensation occurs so that if Δ is changed by 1 mK, A and B also are changed and the net shift in calculated temperatures near 4 K is about 0.5 mK.

Figure 9. Plot of Equation 6 for "ideal" case where T is the true thermodynamic temperature ($a = 1.0000$). The dots (●) show how "ideal data" would appear if plotted with an assumed value of Δ which is in error by $\Delta - \Delta' = \pm 1$ mK. The dashed lines are linear "fits" to these "data." The curved solid lines indicate the behavior for values of Δ in error by ± 3 mK. The true values are represented by the straight solid line (no error in Δ) where $\delta = 0.003 \text{ K}^2$ for the hypothetical salt.

CMN

The CMN data were taken with an earlier coil system than that finally used for the CMA and MAS data and a few remarks about these coils appear in Appendix A. Addenda data for these coils indicated only negligible corrections for the CMN data.

The slightly ellipsoidal shape of the salt sample resulted in a demagnetization contribution (62) to Δ of $(1/3-\epsilon) c \approx 0.67$ mK in Equation 5 which is repeated here for convenience:

$$\chi_e = \frac{M}{H_e} = \frac{c}{[T - (1/3 - \epsilon) c - \theta + \delta/T + \dots]} = \frac{c}{[T + \Delta + \delta/T + \dots]} \quad (5)$$

The theory reviewed in Chapter 11 suggests that for CMN $\theta = -0.27$ mK (35). Taken together, the two corrections yield $\Delta = -0.4$ mK for Equations 5 and 1. The present data were fitted to Equation 1 below 2.5 K using T_{vp} with various Δ 's ranging from 0 to -0.9 mK. The parameters A and B which resulted varied somewhat from fit to fit, but the deviations of the data from the fit equation for each Δ were identical. The data are plotted in Figure 10 using the form of Equation 6, where A and B were found from one such fit. The ± 0.3 mK error bars show that no inconsistencies greater than this occurred where the definition of T_{vp} was changed from T_{58} to T_{62} . The rather sharp departure from Curie's Law for this powdered sample (23 mK at 4.2 K) is due to the contributions (34) from X_2 which become appreciable in this region.

Three conclusions can be drawn from this plot. First, T_{vp} is thermodynamically consistent up to at least 2.5 K, as expected. Second, after comparing this plot to Figure 9, it is apparent that a properly aligned

Figure 10. A typical plot of Equation 6 for the CMN data. Here, $T = T_{vp}$ and the parameters A and B were obtained from a least squares fit of the data below 2.5 K to T_{vp} . The error bars correspond to ± 0.3 mK.

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2.5

single crystal of CMN, which obeys Curie's Law to 4 or 5 K, should have been used instead of a powdered specimen in order to verify T_{vp} to a higher temperature, or for that matter, to define a CMN scale. Finally, a powdered CMN thermometer should not be calibrated above 2.5 K when used to determine temperatures below 1 K.

CMA

The B-parameter of Equation 1 was small for the CMA sample and hence dX/dT is very small above 14 K. Thus after some data were taken, the primary current was doubled to 200 mA to increase the sensitivity and the signal-to-noise ratio. At 200 mA rms (5 G magnetic field) the bridge noise was $\pm 10^{-7}$ in X which corresponded to ± 0.4 mK at 30 K. The data taken before the current increase are consistent with those taken afterward as was pointed out in Chapter III. The data were analyzed according to the method outlined in the opening paragraphs of this section. Figure 11 shows the results of a typical fit to Equation 1 of the Platinum region susceptibility data. X_c is the smoothed susceptibility as calculated from the fit constants and X is the measured susceptibility, or bridge reading, with values of Δ and δ assumed to be 0.0017 K and 0.0028 K^2 , respectively. The points were taken on several different days with four or more points taken on a given day. Each day's points have been normalized to those of other days by additive adjustments to X as described in Chapter III. Thus it is meaningless to distinguish between the data of different days. The error bars show the change in X which is equivalent to 1 mK.

Figure 11. A deviation plot resulting from a typical least squares fit of CMA susceptibility data to Equation 1 between 18 and 30 K. T is the NBS-55 scale, X is the measured susceptibility (bridge reading) and X_c is the smoothed susceptibility calculated from the fit equation. The error bars show the change in X equivalent to 1 mK. The data taken on each day have been normalized to a common value of A so no distinction between the points taken on different days was made. See the text for a more complete discussion.

The low temperature data are plotted in Figure 12 in terms of Equation 6 with $T' = T_{vp}$ for values of Δ ranging from 0 to 4 mK. The error bars correspond to ± 0.3 mK. The sharp upward hook in the data above 3.5 K, which is not present in the "ideal" plot, Figure 9, indicates an inconsistency in T_{vp} and introduces a source of real difficulty in the data analysis. The data appear to be represented best by $\Delta = 0.002$ K and $\delta = 0.0028 \text{ K}^2$, which is the theoretical estimate for δ . A more precise analysis made by assuming $\delta = 0.0028 \text{ K}^2$, the proper values of A (Δ) and B (Δ), and a least squares fit to Equation 1, gave $\Delta = 0.0019$ K. The final coefficients for Equation 1 for CMA are given in Table 1. If δ is not fixed, then the plots for $\Delta = 0$ and 4 mK appear to be outside limits

Table 1. The parameters characterizing the paramagnetic salts used in this research. See text.

Salt	A	B	Δ (K)	δ (K ²)	$(1/3-\epsilon)c$ (K)	θ (K)
CMA	0.0271493	0.202039	0.0019	0.0028	0.0076	-0.0095
MAS	0.0319893	0.64898	-0.036	0.0084	0.024	0.012

for representing the data with corresponding uncertainties in the helium boiling point of ± 1 mK. The deviations of the data below 2.5 K from the best fit line in Figure 12 are not the same as for CMN, Figure 10, but they are the same as for MAS (see below). The explanation for the difference is not known so it is concluded that the apparent systematic variation is not real.

Figure 12. A plot of Equation 6 for CMA susceptibility versus T_{vp} data for several values of Δ between 0 and 4 mK. The solid line has a slope $\delta = 0.0028 \text{ K}^2$, which is the theoretical estimate; see the text.

Two further conclusions can be drawn from Figure 12. First, T_{vp} , or T_{58} , is consistent thermodynamically to within ± 0.3 mK below about 3.6 K, but departs from this consistency at higher temperatures. Second, the line of best fit intercepts the ordinate at 0.9982 which implies that below 3.6 K, $T = 1.0018 T_{vp}$, where T represents a CMA temperature scale.

The demagnetization parameter (62), $(1/3-\epsilon)c$ (Equation 5), is approximately +7.6 mK for this sample. Since $\Delta = 1.9$ mK, the calculated value for the Curie-Weiss θ is -9.5 mK in good agreement with $\theta = -12$ mK quoted by Durieux, et al. (11, 12), for a single crystal sphere. The two parameters $(1/3-\epsilon)c$ and θ also are given in Table 1.

MAS

The larger moment of MAS results in a three times greater sensitivity than for CMA, and consequently the data are much more precise. A plot of our data taken in the Platinum region is shown in Figure 13, for $\Delta = -0.035$ K and $\delta = 0.008$ K², where the symbols have the same meaning as in Figure 11. The MAS data were taken before the CMA experiments and a greater number of data points were taken for this salt to gain confidence in the apparatus. As is mentioned in Chapter III, few large shifts occurred for MAS and no corrections were made unless it was obvious that for a given day the data had shifted well outside experimental scatter. Nevertheless, since some adjustments had to be made, distinguishing the points taken on different days still seemed meaningless.

Figure 14 shows the data taken in the Helium region plotted using T_{vp} as for the other two salts. The data are shown for several values of Δ between -40 and -30 mK, and appear to be best represented by Δ in the

Figure 13. The deviation plot resulting from a typical least squares fit of MAS susceptibility data between 18 and 34 K. The comments pertaining to Figure 11 apply here as well.

Figure 14. A plot of Equation 6 for MAS susceptibility versus T_{vp} data for values of Δ between -40 and -30 mK. A value of $\Delta = -36$ mK was assumed to characterize the data.

vicinity of -36 mK. The discussion in Chapter III pointed out that there are no quantitative calculations on MAS to guide our choice of δ , and hence there is more uncertainty in a scale based on MAS alone. However, the scale given by CMA falls within the uncertainty of the MAS scale and so the parameters selected for MAS are those which give the best agreement with the CMA results. The coefficients of Equation 1 for MAS are given in Table 1 along with a calculation of the demagnetization contribution to Δ and the resulting estimate of θ . Because of the wide variation in θ 's quoted by others (see Chapter II) the accuracy of the present value of θ cannot be estimated.

The necessity for using two salts in this work can be illustrated clearly at this point. The MAS data below 3.6 K could be fitted to Equation 1 with $\Delta = -22$ mK and $\delta = 0$ with random scatter of the data from the fit equation. However, if the data in the Platinum region are fitted to Equation 1 using $\Delta = -22$ mK, temperatures calculated near 4.2 K are 15 mK too low. The opposite error arose when concern developed that a term in the denominator of Equations 1 and 5 proportional to T^{-2} may be important to characterize the data accurately. Support for this analysis comes from the magnitude of Δ and δ , and from the apparent systematic variation of the data about a smooth line, such as for $\Delta = -35$ mK in Figure 14. Thus, an analysis which omitted data below 1.4 K and which is based upon $\Delta = -40$ mK and $\delta = 0.013 \text{ K}^2$ appears in a recent review article (9) written before the CMA data were available. The CMA data are not subject to this uncertainty in analysis because Δ and δ are smaller and because an estimate of the T^{-2} term exists (11, 12, 28). The correct

analysis resulted from study of Figure 9 for the "ideal" case and from the observation that the systematic variations below 4.2 K are the same for both the CMA and MAS data in Figures 12 and 14.

The Germanium Thermometer Calibrations

The parameters of Equation 1 which are given in Table 1 for both salts serve to establish temperatures, $T(X)$, for each value of X measured. As stated at the beginning of this chapter, a scale based on the $T(X)$ data can be preserved for use only through calibrations of the four GER's used in this experiment, viz. 803, 618, 622, and 248. Thus a few comments are necessary concerning the calibrations and the fitting procedures which led to a useful magnetic scale $T_M(\text{GER})$.

The data were fitted by a method equivalent to least squares to polynomials of the form

$$\ln(T) = \sum_n A_n [\ln(R)]^{n-1}, \quad n = 1, 2, \dots, n_0 \quad (7)$$

where $n_0 \leq 11$ and $\ln$ is the natural logarithm. While the inverse form of Equation 7 (i.e. $R(T)$) often is used, the above form is most convenient for our purposes. Each thermometer was fitted directly against $T(X)$ using data taken with both salts and in general, values of n_0 between 8 and 10 were required. The data were divided into three temperature ranges, 0.9 - 6.05 K, 3.8 - 20.5 K, and 18 - 34 K, in order to obtain fits with sufficient precision. For the lowest range, the root mean square deviation, RMSD, of the data from the fit equation is 0.15 mK in all cases, while in the middle range, the RMSD is about 0.4 mK for 803, 618, and 622. The resistance versus temperature characteristic of 248 indicates a

difference between the two sets of salt data and consequently the RMSD is larger. Further comments on this appear below. Near 4.4 K, in the lower overlap region, temperatures calculated using the coefficients from the lowest range agree to within 0.1 mK with those determined using the coefficients for the middle range. In the same region, first derivatives agree to within 0.02 %. Near 20 K, in the upper overlap region, calculated temperatures from the two ranges agree to within 0.3 mK and first derivatives to within 0.05 % for GER's 803 and 618.

The resistance of 803 is much higher than that of the other GER's, especially below about 6 K (see for example Figures 5 and 6 or the data tabulations in Appendix B), and so little data were taken on 803 below 4 K. Sufficient cross-calibration data exist with 618 and 248 to extend the range of 803 to about 2 K, but this has not been done. Also, 622 and 248 have not been fitted in the range above 18 K because of uncertainties which have appeared for these GER's at the higher temperatures. There are data available to calibrate them against the PTR and this will be done in the near future after the problems are cleared up. In addition, GER's 618, 622, 248 and an extra thermometer, 638, which was in the block for a time, were calibrated against T_{vp} from 0.9 to 5.2 K.

Since the magnetic scale is carried by fits based upon four GER's, four magnetic scales, $T_M(803)$, $T_M(618)$, $T_M(622)$, and $T_M(248)$, have been defined. Figure 15 shows how temperatures calculated from the various resistor fits in the range from 4 to 20.5 K compare with one another. The top graph gives $T_M(803) - T_M(618)$, where the pluses are for comparisons via the MAS data run and the dots are for the CMA run. For the most part

Figure 15. Comparisons of temperatures calculated from measured resistances and Equation 7 for each GER. The dots (●) represent comparisons resulting from the CMA data and the crosses (+) represent comparisons resulting from the MAS data.

the two resistors reproduce each other to within ± 0.3 mK and, except for three points, always within ± 0.5 mK. These three points are quite likely due to bad resistance readings.

The second graph in Figure 15, compares GER's 618 and 622 where the symbols are the same as above. Some separation between data taken during the two salt runs is indicated, but it is sufficiently small that no errors greater than ± 0.5 mK will be incurred if this thermometer is used to represent T_M . Nevertheless, more intercomparisons of 622 with 618 and 803 are essential to verify the stability of 622 and perhaps to determine which of the two runs is preferable.

The final graph compares 248 with 618 and here a definite problem appears, as mentioned above. At 4 K and below, the data from the two runs superimpose, but they tend to separate as the temperature increases. At 16 K the discrepancy is 1.5 mK. No plausible reason for this separation can be offered at the present time. Some earlier comparisons between 618 and 248 taken by Mr. Marvin Anderson of this laboratory, suggest that the CMA data (dots) are correct, but these earlier data are not sufficiently precise to be definitive. Further experimental work is necessary to determine first if 248 is stable to within 1 mK at 20 K (i.e. $2 \cdot 10^{-5}$ in resistance) and if so, which of the salt data runs gives the correct calibration.

Below 4.2 K the data for 618, 248, and 622 are reproducible and no difference appears between the magnetic temperatures as carried by these resistors.

Our conclusions are that below 5 K the magnetic scale, T_M , can be defined in terms of the fit coefficients of Equation 6 for GER's 618, 622, and 248, and no discrepancies greater than ± 0.3 mK will occur. The histories of GER's 618 and 803, Chapter III, have shown these two resistors to be extremely stable and this is confirmed by Figure 15. In addition, all thermometer calibrations that have been performed in this laboratory in the past have used 803 and 618 as standards. Thus, the magnetic scale from 4 to 20 K is defined as that represented by the fit coefficients of GER's 618 and 803. To be precise, T_M is defined in this region only near data points, i.e. at approximately 0.5 K intervals. It has not been verified that for a given GER, Equation 7 will predict resistances at temperatures between the data points with an accuracy equivalent to 0.5 mK. At higher temperature, T_M is by definition, equal to the NBS-55 calibration of our PTR. Temperatures calculated from the fits of GER's 618 and 803 to susceptibility temperatures above 18 K agree with PTR temperatures with a random scatter of one mK. The coefficients of Equation 7 for each thermometer in each range are given in Appendix B.

CHAPTER V. DISCUSSION

The discussion in Chapters I and IV of this dissertation is presented in terms of three overlapping temperature regions, viz. the Platinum region (above 18 K), the Helium region, (0.9 to 5.2 K), and the Intermediate region (4 to 20 K). This outline is convenient for the present chapter as well where the magnetic scale is evaluated and compared to other thermometry work. The chapter concludes with a brief statement of the nature of this research and the assumptions involved in the establishment of T_M . An additional experiment is suggested and several small tasks are enumerated which should be accomplished before the present work is considered completed.

Comparisons of T_M With Other ScalesThe Platinum region

The discussion in Chapter IV suggests that our PTR represents NBS-55 (2) to within 2 mK. Figures 11 and 13 which show typical fits of susceptibility data in the Platinum region indicate that NBS-55 is smooth to within one mK between 18 and 30 K. Figure 8 shows how NBS-55 departs from this smoothness below 18 K. The actual comparison data between NBS-55 and T_M , not shown, scatter randomly within one mK of the straight line. The line representing IPTS-68 (1) was obtained from the published differences (2) between IPTS-68 and NBS-55, and it is clear from this plot that IPTS-68 is smooth to within one or two mK from 15 to 30 K. Since the two scales are parallel, it also is clear that at least one of the two scales is inconsistent in a thermodynamic sense. That is, the two scales cannot each

be strictly proportional to the Kelvin scale. The differences between NPL-61 (2) and T_M also were obtained from the published differences of NPL-61 from IPTS-68 and are plotted in Figure 8.

The Helium region

A plot of $T_M - T_{vp}$ is given in Figure 16 where T_{vp} is determined directly from vapor pressure measurements and the published tables for T_{62} (7) (below 1.6 K) and T_{58} (3) (above 1.4 K). By using the smooth T_M , we have chosen to show the scatter in our vapor pressure data rather than that in the susceptibility data because the former has the larger variation and because the latter is indicated in Figures 10, 12, and 14. Up to about 3.8 K, T_{vp} deviates linearly from T_M with a proportionality constant $a = 1.0018$ defined by $T_M = aT_{vp}$. The apparent systematic variation below 3.8 K is not real, but the falling away from the straight line at higher temperatures represents an actual characteristic of T_{58} . Both of these comments are made in Chapter IV in relation to Figures 12 and 14. The omission of data between 2.4 and 2.8 K was unintentional. Figure 16 also supports the remarks in Chapter IV that the absolute accuracy of our Helium vapor pressure measurements is approximately ± 0.5 mK. A final conclusion to be drawn from this plot is that the helium boiling point as given by T_{58} is 6.7 ± 0.5 mK too low, based on the assumption that NBS-55 represents the Kelvin scale.

The departure of T_{vp} (or T_{58}) from T has been observed in other recent experiments and these are shown in Figure 17. The triangles represent the results of Cataland and Plumb (16) from He^4 acoustic isotherms, the dots are from He^3 and He^4 acoustic isotherms of Grimsrud and Werntz (63), the

Figure 16. Differences between the magnetic scale, T_M , and T_{vp} . T_M is obtained from smoothed GER calibrations and T_{vp} is obtained directly from vapor pressure data and the appropriate tables (3,7). See text. The deviation between the scales is assumed to be linear up to approximately 3.6 K. The linear portion of the solid line (below 3.6 K) corresponds to the solid line in Figure 12. The departure from linearity above 3.6 K represents a real characteristic of T_{vp} , (compare Figures 12 and 14).

Figure 17. Differences between T_{vp} and T as indicated by recent experiments. The solid line is the same as that in Figure 16. The crosses (+) show the CVGT results of RTAS (14). The triangles (Δ) indicate the He^4 acoustic results of Cataland and Plumb (16). The dots ($\bullet$) represent the He^3 and He^4 acoustic results of Grimsrud and Werntz (63).

crosses show the CVGT results of RTAS (14) and the line indicates the behavior of our data as given in Figure 16. RTAS and Swenson (9) have analyzed the results near 4.2 K of several recent CVGT experiments. They referred all of the thermometers to a common scale near 20 K and used the so-called KKH (17), MR-5 second virial coefficients to correct for non-ideality. They conclude that, taken together, the CVGT experiments suggest that the He^4 boiling point on the T_{58} scale is 6 ± 4 mK too low, in excellent agreement with our results. The difference between NBS-Acoustic temperatures at 4.2 K and the CVGT results appears to be consistent with the discrepancy between acoustically determined virial coefficients (9,64) and the KKH values.

Recent studies (57) on the liquid-vapor critical point of He^4 indicate that use of the NBS-Acoustic (13) scale reveals the expected singularity in (dP/dT) at constant density near the critical point, which T_{58} obscures. The $T_{\text{NBS}}-T_{58}$ relationship which Kierstead (57) uses is very similar in shape to the $T_{\text{M}}-T_{58}$ relation which is shown in Figure 16. This is additional confirmation of the thermodynamic inconsistency of T_{58} above 4 K.

The precision and accuracy of the magnetic thermometer is demonstrated through comparisons of the scatter of the data in Figures 16 and 17. If one assumes that NBS-55 represents T from 18 to 30 K, the boiling point of He^4 is defined to within ± 0.5 mK and a vapor pressure scale is established which is consistent with that boiling point to within the same uncertainty from 0.9 to 5.2 K. Actually to be precise, the present research verifies that in the sense of thermodynamic consistency, the accepted scales, T_{58} and T_{62} , are internally consistent to nearly 4 K, but that they are not consistent with the higher temperature scales, NBS-55 or IPTS-68. This

accuracy of T_M is somewhat illusory however, since T_M depends on the accuracy of the scale in the Platinum region.

The Intermediate region

Figure 18 compares T_M with the NBS-Acoustic (13) scale (triangles) and the CVGT data of RTAS (14) (crosses) through the calibration of GER 803. The lower regions of NBS-55 (2) and IPTS-68 (1) as determined from the PTR calibrations are shown as well. The susceptibility temperatures, $T(X)$, for both salts scatter about the axis within ± 0.3 mK below 4 K, within ± 0.5 mK near 4.2 K, within ± 1 mK up to 16 K, and within ± 1.3 mK up to 30 K. The RTAS data lie within ± 3 mK of T_M except at 12 K and above 15 K. The deviations from T_M of the NBS-Acoustic scale are particularly interesting since this scale has been set up provisionally as a national scale. Internal checks through H_2 vapor pressures (Chapter IV) indicate that the Acoustic calibration on GER 803 is within 2 mK from 14 to 20 K, while comparisons through T_{58} verify this calibration to within 1 mK below 5 K. The discrepancies in the NBS-Acoustic versus T_M differences which appear between Figure 17 and 18 are discussed in Chapter IV as well. The NBS-Acoustic scale lies systematically 4 ± 3 mK above T_M , but if either T_M or the Acoustic scale are adjusted by 0.03% as was done by RTAS for their CVGT data, the two scales would agree at most points to within ± 3 mK. The recent CVGT data of Astrov, Orlova, and Kytin (15) show serious disagreements with the NBS-Acoustic scale and hence with the RTAS scale and with T_M . In particular, their scale deviates from NBS-Acoustic by -12 mK near 7 K to +8 mK near 10 K.

The change in T_M resulting from a calibration versus IPTS-68 can be

Figure 18. Deviations of current scales from T_M between 2 and 20 K. Above 18 K, T_M is identical with NBS-55, by definition. The differences between IPTS-68 and NBS-55 were obtained from the published deviations (2). The crosses(+) represent the CVGT data of RTAS (14). The triangles ($\blacktriangle$) show the NBS-Acoustic isotherm data (13). The line designated T_M (IPTS-68) indicates the scale which would result if the magnetic thermometer had been calibrated on IPTS-68 instead of NBS-55.

computed by assuming that A and B of Equation 1 are evaluated from measurements of X and dX/dT at some fixed temperature, T_0 . Then the change from the NBS-55 calibration to an IPTS-68 calibration is nearly equivalent to adding a constant δT_0 at T_0 and to assuming that dX/dT is unchanged at T_0 (see Figure 8). From Equation 1, one can derive that the change δT_M at any temperature T is given by

$$\delta T_M = \delta T_0 \left[\frac{T + \delta T_0}{T_0 + \delta T_0} \right] \cdot \left[1 + \frac{T_0 - T}{T_0 + \delta T_0} \right] \quad (8)$$

The curved line in Figure 18 indicated as $T_M(\text{IPTS-68})$ is the result of assuming $T_0 = 20$ K and $\delta T_0 = 8.5$ mK. The difference between $T_M(\text{IPTS-68})$ and NBS-Acoustic near 4 K is less than the difference with T_M but discrepancies of 4 or 5 mK are evident between 9 and 15 K.

The NBS-Acoustic scale is absolute in the sense that the experimental data give $R \cdot T$, where R is the gas constant, without the assumption of a calibration temperature. On the other hand, the magnetic method is not absolute, but is precise and can establish consistency between points. Thus a combination of the two scales would suggest that near 20 K, the true thermodynamic temperature lies about half way between IPTS-68 and NBS-55. It is interesting to note that the "best" CCT-64 (2) value for the boiling point of $e\text{-H}_2$ lies 5 mK below the assumed IPTS-68 value.

Concluding Remarks

A magnetic temperature scale, T_M , has been defined from 0.9 to 18 K which is based on susceptibility measurements on two paramagnetic salts

with very different values for the parameters in Equation 1 (see Table 1). The two principal assumptions are that NBS-55 represents the thermodynamic scale, T , above 18 K and that T_{vp} which is defined from T_{58} and T_{62} is proportional to T up to about 3.8 K. A third assumption, that the theoretical value $\delta = 0.0028 \text{ K}^2$ is correct for CMA, was combined with the first two to select the precise set of parameters which define T_M . The degree to which NBS-55 represents T is discussed in Chapter I and in the present chapter, while the accuracy of our PTR calibration against NBS-55 is assessed in Chapter IV. The validity of the assumption concerning T_{vp} was checked partially by results on CMN and in a self-consistent sense by the results on CMA and MAS. The T_M scale probably is accurate to within $\pm 0.5 \text{ mK}$ from 0.9 to 4K and to within 1 or 2 mK at higher temperatures. This accuracy loses much of its significance, however, since uncertainties in the thermodynamic scale above 18 K introduce systematic uncertainties in magnetic temperatures of up to 3 mK near 4 K. Hence, we recommend the continued use of the helium vapor pressure scales, T_{58} and T_{62} , as they now stand until temperatures near 20 K are determined more accurately.

Swenson (9) mentions several projects which have been initiated recently to resolve the dilemma above 20 K. These include additional acoustic thermometry at NBS and NPL as well as gas thermometry at NPL and Leiden. Another helpful experiment would be to use paramagnetic salt thermometry for smoothing as was done in IPTS-68 with PTR's. Equation 1 is a much simpler function of temperature than the 19th order polynomial used in IPTS-68 for the platinum resistivity ratio. The present MI bridge could be improved readily to provide mK precision up to 100 K or so, but an

extrapolation technique, as used in this work, would not be possible due to the uncertainties in the scale near 90 K.

There are a few tasks that remain to be done. First of all more comparison data should be taken to clarify the situation for GER 248 (Figure 15) and to a much lesser extent that for GER 622. An additional calibration of a GER against the NBS-Acoustic scale would serve to verify the NBS-Acoustic calibration of 803, and to permit a better evaluation of the NBS-55 calibration on our PTR. The susceptibility data should be analyzed directly in terms of an IPTS-68 calibration of our PTR in order to define T_M (IPTS-68), Figure 18, independent of any simple adjusting relations, such as Equation 8. A detailed deviation plot will be constructed between T_M and a smoothed scale, T_{618} , which is based on the RTAS results, for internal use. T_{618} has been used for several experiments in this laboratory over the last three years. Specific heat measurements on copper reported earlier and referenced to T_{618} will be reanalyzed using T_M and will be compared with the Copper Reference Equation (65).

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APPENDIX A. EXPERIMENTAL PROBLEMS

Unexpected problems arise in any research and while most of these problems merely are annoying, some are interesting in themselves. Those listed in this appendix are illustrative of the nature of the experiment and were new to the author, although they are not of fundamental significance. Far more time was required to eliminate them than would appear from the brevity of the discussions below.

The complications which could arise due to eddy currents in the metal components near the coils were recognized from the beginning and the basic design of the cryostat was based on minimizing these currents. For example, glass rather than metal was used for the vacuum jacket tail. The magnitude of the effects and the manner in which they would appear was not anticipated however and extensive alterations to the apparatus were necessary to reduce them to acceptable levels. The coils used in the CMN experiment were not designed properly and thus eddy currents, thermal expansions, and inhomogeneous 60 Hz fields all introduced troublesome effects in the experiment. A further effect on the MI measurements resulted from the presence of a brass ring which supported the helium dewar for a short time.

Broadcasting from one bridge component to another introduced residual secondary voltages. This is an example of an ac "ground loop". Another illustration of non-ideal bridge behavior resulted from the 100:1 transformer; see Figure 2. A phase shift between the primary and secondary of this transformer led to quadrature phase signals which were proportional to the RT setting, X. A final example of unexpected problems

concerns a chemical reaction that occurred between the MAS sample and the bare copper thermal contact wires. This raised the possibility that anomalous behavior for X would result. Each of these subjects is discussed in the following paragraphs.

Eddy currents

Eddy currents in the copper wires and shield which thermally united the salt sample and the block produced a large diamagnetic contribution to the addenda susceptibility in the original design. This problem was in addition to the more common one of eddy current heating in the wires which would tend to warm the salt above the block temperature. In order to calculate a general expression (66), consider an infinitely long copper cylinder of radius a in a uniform magnetic field, B_0 . The external field is (S. I. units)

$$H_e = (B_0/\mu_0)\exp(-j\omega t) .$$

The field, H_i , inside the copper cylinder can be represented by a Bessel function of order zero since cylindrical symmetry exists and since there is no dependence on the angle of rotation, so

$$H_i = J_0(k_1 r)b_i \exp(-j\omega t)$$

where b_i is a constant and

$$k_1^2 = \mu\epsilon\omega^2 + j\mu\omega/\rho \approx j\mu\omega/\rho .$$

The symbols have their usual meanings, namely, k_1 is the wave vector inside the copper, r is radial distance from the symmetry axis, μ is the permeability, ϵ is the permittivity, ω is the frequency in radians per second, and ρ is the resistivity. For copper in a 33 Hz ($\omega = 207 \text{ s}^{-1}$)

field, the approximation is very good. The parameter, b_i , can be evaluated at the boundary, $r = a$, where $H_e = H_i$. Thus,

$$J_0(k_1 a) b_i = B_0 / \mu_0.$$

The flux inside the wire is given by $\Phi = \mu \int H_i \cdot dS_w$, where S_w is the cross-sectional area of the wire. By substitution and integration, this becomes:

$$\Phi = 2\pi B_0 \exp(-j\omega t) a J_1(k_1 a) / k_1 J_0(k_1 a).$$

The argument of the Bessel function is small for the present case ($k_1 \sim 1 \text{ cm}^{-1}$, $a \sim 0.1 \text{ cm}$) and so the expression for Φ can be expanded in a power series,

$$\Phi = \pi a^2 B_0 \exp(-j\omega t) \left[1 + j \frac{a^2 \mu \omega}{8\rho} - \frac{a^4 \mu^2 \omega^2}{48 \rho^2} + \dots \right].$$

The emf induced in the secondary coil is given by $\epsilon_s = -N_s d\Phi/dt$ or,

$$\epsilon_s = j\omega N_s B_0 \exp(-j\omega t) \pi a^2 \left[1 + j \frac{a^2 \mu \omega}{8\rho} - \frac{a^4 \mu^2 \omega^2}{48 \rho^2} + \dots \right].$$

The first term is the emf which results if no copper is present. The second produces a quadrature signal in the MI bridge and is related to the eddy current heating losses. The third term has the same phase as a salt moment and contributes to the addenda susceptibility. This term is proportional to a^6 or equivalently, to the cube of the cross-sectional area of the wire, S_w^3 . It is also inversely proportional to ρ^2 ($\rho \sim 10^{-10} \Omega \cdot \text{m}$ at 4 K) which is temperature dependent above 4 K.

In an early design, seventeen B&S #18 copper wires were used to thermally anchor the salt sample. The shield was made from vertical copper strips (0.5 cm wide and 0.1 mm thick), which overlapped each other

slightly. The strips were insulated to prevent electrical shorting, but the overlap permitted significant capacitive coupling. The eddy current susceptibility for this geometry produced errors in X of up to 500 mK at 20 K. Hence, the wire size was reduced to B&S #28 with an area one-tenth that of the former wires while the number of wires was increased from 17 to 30. More importantly, the shield was changed to the coil-foil design.

CMN coils

The coils used in the measurements on CMN were of a different and somewhat less sophisticated design than those used for the later CMA and MAS experiments. The primary solenoid was in one section, 10 cm long, and 1.9 cm radius, with 200 turns (B&S #28 copper wire) wound with increased turns density at the ends so as to make the field uniform over approximately 5 cm. The secondary had a 2.3 cm radius and was in three sections. The main section, which sampled the salt moment, was located at the center of the primary solenoid, was 1 cm long, and had 1000 turns of B&S #38 copper wire. The other two sections were wired in opposition to the main section. Each of these was located 4 cm from the primary center, was 0.5 cm long and had 520 turns. The extra 20 turns on each section was necessary to compensate for the reduced flux near the ends of the primary solenoid. Final adjustments to the secondary sections were made using the appropriate bridge configuration to achieve cancellation of the net emf to within 0.1 %.

There were two flaws with this design. First, the coils were not astatic with respect to external fields, and the three secondary sections each were different distances from the block and shields. Hence, the

reflected fields were not cancelled completely in the three sections. As is mentioned in Chapter III, this produces a temperature-dependent contribution to the addenda susceptibility above 4 K since the magnitude of the reflected field depends on the resistivity of the copper reflecting surfaces. Also 60 Hz power line radiation would induce voltages in the bridge of such a magnitude that the narrow band lock-in detector would not operate at the required sensitivities. The source of the 60 Hz field was the wiring to the lights in the room below and so data could be taken only at night when that room was not occupied.

Second, the "sensitivity profile" (compare Figure 3) for these coils was very sharp. In particular, a probe of the coils with the Dy_2O_3 salt sample indicated that the sensitivity was reduced by 5 % if the salt was 4 mm from the coil center as opposed to less than 1 % for a similar distance in the final set of coils. Thus real concern developed that the thermal expansion of the various members supporting the sample would move the salt with respect to the coils sufficiently far to produce an error in χ . This was not important for the CMN data since the thermal expansions are negligible below 4 K.

Brass ring

An example which illustrates the effects of nearby metal involves a brass ring at liquid nitrogen temperatures that was used to support the helium dewar at the beginning of the experiments. Eddy currents induced in this ring in turn produced an inhomogeneous field in the vicinity of the secondary sections. The stainless steel pumping lines which supported the cryostat, and hence the coils, would expand as the helium in the bath

evaporated. The coils, thus, were moved closer to the ring which increased the magnitude of the magnetic coupling, and a drift in X resulted. The brass ring was removed and the drift disappeared.

Broadcasting

Special care must be taken in low voltage level circuits to avoid spurious current paths such as broadcasting from one component to another. At 33 Hz, the skin depth of normal metals is a few centimeters and so it is important to twist tightly pairs of leads to eliminate magnetic loop antennas. The effects of broadcasting were observed in the present bridge through residual voltages which remained when the secondary coils were shorted. These voltages were dependent on the relative locations of circuit components and on the output level of the oscillator. The receiving antenna was found to be a pair of single conductor coaxial cables connecting the 100:1 transformer secondary to the rest of the circuit, (see Figure 2). In spite of the twisting of the cables, the enclosed area (due to the radius of the cables) was still significant. The problem was eliminated by replacing these two cables with one foil-shielded cable, which contained two tightly twisted inner conductors.

The 100:1 transformer

A phase shift between the primary and secondary voltages of the 100:1 transformer (see Figure 2) introduced large quadrature signals in the bridge which were proportional to the RT setting, X . This phase shift can be understood in terms of the following argument. The equivalent circuit of a transformer primary for the ideal case of no core losses consists

of the self-inductance of the primary, L , in series with the dc resistance R_w of the wire with which the primary is wound. The primary voltage then is given by

$$\epsilon_p = i_p (R_w + j\omega L) = j\omega L i_p (1 - j R_w/\omega L).$$

where ω is the frequency in radians/second. The secondary voltage is proportional to the flux and the voltage which produces that flux:

$$\epsilon_s = j\omega L i_p (N_s/N_p) = \epsilon_p (N_s/N_p) (1 + R_w^2/\omega^2 L^2)^{-1} (1 + j \frac{R_w}{\omega L})$$

where N_s/N_p is the turns ratio of the transformer. Inspection of these two expressions shows that a phase shift $\tan \theta = R_w/\omega L$ exists between ϵ_s and ϵ_p . The ratio of the real and quadrature phase components of the secondary voltage is

$$\epsilon_q/\epsilon_r = R_w/\omega L. \quad (9)$$

The introduction of core losses in to this problem would affect these results only slightly.

The 100:1 transformer was wound on a ferrite core which has negligible losses. The resistance of the primary wire, R_w , was 2.5 k Ω and the inductive reactance, ωL , was 250 k Ω . Thus, the right member of Equation 9 is 0.01. The same value was calculated for the left member using experimental data for X and R_x (see Figure 2).

Copper-MAS reaction

Bare copper wires were used initially for thermally anchoring the salt sample to the block. However, it was observed that the MAS reacted chemically with the copper wires to form an alloy on the wire surface

and a copper sulfate salt. Although no noticeable effect on X could be attributed to this reaction, its existence was unsatisfying and so varnished wires were used thereafter to avoid the problem.

APPENDIX B. DATA AND RESULTS

A computer generated tabulation of the processed data and the results of this research is given in this appendix. The coefficients of Equation 7 for the various resistors in each range are listed first. This is followed by the resistor calibration data against the helium scales (T_{vp}), the vapor pressure data for e- H_2 and natural Ne, the CMN susceptibility data and then the CMA and MAS susceptibility data in each of the three thermometer fit ranges (0.9 - 6.05 K, 4 - 20.5 K, 18 - 34 K). Data that were taken in the overlap regions (4 - 6 K and 18 - 20.5 K) appear in the tabulation for both ranges. Each data point listed consists of a point number, NO, the measured GER and PTR resistances and either the bridge reading, X, or the vapor pressure, P, as the case may be. NO indicates the laboratory notebook and page where the raw data may be located. For example, NO 6117 refers to notebook TOC-6, page 117. All bridge readings, X have been normalized to a consistent value of A, Equation 1, for the particular sample as described in Chapters III and IV. The addenda susceptibility, ΔX_{ADD} , (Figure 7) has been subtracted out as well.

Temperatures computed from these data also are given. $T(X)$ is calculated from X and the coefficients of Equation 1 recorded in Table 1. The CMN data are an exception to this rule in that the coefficients of Equation 1 were determined from a least squares fit of X versus T_{vp} data below 2.5 K. Magnetic temperatures T_M (GER) were calculated for each GER resistance from the smooth resistance scales discussed in Chapter IV. NBS-55 temperatures were calculated from the PTR resistances. The notation

for the scales is altered slightly due to use of the computer. Little ambiguity should result except possibly for the temperature differences given for each point. The difference $T - T_{618}$ under the column headed R803 for instance means $T_M(803) - T_M(618)$.

Ne and e-H₂ vapor pressures are given in terms of mmHg at 0°C and standard gravity (torr). Temperatures were computed from these pressures using the smooth relationships $T_{68}(\text{Ne})$ and $T_{68}(\text{e-H}_2)$ which are given in IPTS-68 (1) and which are discussed in Chapter IV. The data for the GER versus T_{vp} calibrations are given in terms of T_{58} and T_{62} temperatures only. The vapor pressures have not been recorded. T_{vp} temperatures have been mislabeled as T_{58} throughout the tabulations; only the temperatures above 1.6 K are T_{58} values. Those below 1.6 K were determined from He³ vapor pressure data and the T_{62} scale. For historical reasons most of the helium vapor pressure data were taken with GER 638 in the block instead of 622, and thus resistances for that thermometer appear in the tables. The coefficients of Equation 7, which were used to calculate the temperatures, $T_M(638)$, were obtained from a least squares fit of GER 638 versus $T_M(618)$ data, (i.e. via resistance-resistance comparisons).

Too many significant figures have been listed for all parameters (except X) due to use of the computer to generate the tabulations. Resistances were recorded to six digits and are accurate in an absolute sense to a few parts in 10^5 . Pressures were read to 0.01 torr and are probably accurate to ± 0.02 torr. Temperatures were recorded to 0.1 mK at all temperatures although the experimental precision is ± 0.3 mK at the lowest temperatures and ± 1.3 mK at the highest. The accuracy of T_M ,

is cited in the text as ± 0.5 mK below 4 K and ± 1 mK above.

The currents used for the GER resistance measurements were:

Current	Temperature range
1 μ A	0.9 - 1.8 K
2	1.6 - 2.4
5	2.0 - 5.0
10	3.5 - 9.0
20	8.0 - 12
50	12 - 20
100	18 - 34

and the currents used for the PTR measurements were:

Current	Temperature range
10 mA	14 - 23 K
5	18 - 34
2	above 30

The following listing indicates the pages on which the data may be located:

1. Coefficients of Equation 7 for the GER fits	120
2. T_{vp} calibration data	125
3. e-H ₂ vapor pressure data	130
4. Ne vapor pressure data	132
5. CMN susceptibility data	133
6. MAS and CMA susceptibility data $T < 6.05$ K	135
7. MAS and CMA susceptibility data $4.0 < T < 20.5$ K	146
8. MAS and CMA susceptibility data $18 < T < 34$	158

$$\text{Log}_e(T) = \sum A(n) [\text{Log}_e(R)]^{n-1}$$

C ** FIT CONSTANTS FOR GR618 VS T58, FEB 70

A(1)= 4.08282569791208 D 03
 A(2)= -4.80216329788815 D 03
 A(3)= 2.49915472711744 D 03
 A(4)= -7.55048746364330 D 02
 A(5)= 1.45994611995939 D 02
 A(6)= -1.87439326415425 D 01
 A(7)= 1.59846649690235 D 00
 A(8)= -8.73362174561635 D-02
 A(9)= 2.77479791711811 D-03
 A(10)= -3.90651928255291 D-05
 A(11)= 0.0 D0

C ** FIT CONSTANTS FOR GR248 VS T58, FEB 70

A(1)= 7.87936882515696 D 03
 A(2)= -9.34192177568503 D 03
 A(3)= 4.82614051073840 D03
 A(4)= -1.41858692983808 D 03
 A(5)= 2.59540404281853D 02
 A(6)= -3.02738128743858 D 01
 A(7)= 2.19914546381170 D 00
 A(8)= -9.09794672288320 D-02
 A(9)= 1.64146841094631 D-03
 A(10)= 0.0D0
 A(11)= 0.0D0

The notation D-03 means $\times 10^{-3}$

$$\text{Log}_e(T) = \sum A(n) [\text{Log}_e(R)]^{n-1}$$

C *** GR618 VS TM, T<6.05 18 MAR 70
 A(1)= -1.03725059051890 D 03
 A(2)= 1.45190165648008 D 03
 A(3)= -8.82926474066334 D 02
 A(4)= 3.07739829718583 D 02
 A(5)= -6.78800758153538 D 01
 A(6)= 9.84058344950320 D 00
 A(7)= -9.38880916785730 D-01
 A(8)= 5.69198726538138 D-02
 A(9)= -1.99192648162077 D-03
 A(10)= 3.06880363979728 D-05
 A(11)= 0.0 D 00

C *** GR622 VS TM T<6.05
 A(1)= -1.790129337245090 D 03
 A(2)= 2.493712394142970 D 03
 A(3)= -1.516022705331830 D 03
 A(4)= 5.296953009636700 D 02
 A(5)= -1.173907953127580 D 02
 A(6)= 1.713289380171440 D 01
 A(7)= -1.648535400233030 D 00
 A(8)= 1.009460383728240 D-01
 A(9)= -3.572791931699970 D-03
 A(10)= 5.573247864047560 D-05
 A(11)= 0.0

C *** GR248 VS TM, T<6.05, 17 MAR 70
 A(1)= 4.57469049842148 D 03
 A(2)= -5.40680337178804 D 03
 A(3)= 2.78237676441407 D 03
 A(4)= -8.13917961067992 D 02
 A(5)= 1.48078456570930 D 02
 A(6)= -1.71653606015487 D 01
 A(7)= 1.23866132940678 D 00
 A(8)= -5.08902888839017 D-02
 A(9)= 9.11700529303006 D-04
 A(10)= 0.0 D 00
 A(11)= 0.0 D 00

The notation D-03 means $\times 10^{-3}$

$$\text{Log}_e(T) = \sum A(n) [\text{Log}_e(R)]^{n-1}$$

C *** GR803 VS TM 4.<T<20.5, 17 MAR 70

A(1)= 1.84124004320861 D 02
 A(2)= -3.23028217493169 D 02
 A(3)= 2.55363559982819 D 02
 A(4)= -1.16563465235581 D 02
 A(5)= 3.38063153015990 D 01
 A(6)= -6.46603138921035 D 00
 A(7)= 8.16511362005592 D-01
 A(8)= -6.57037816316270 D-02
 A(9)= 3.05918813503719 D-03
 A(10)= -6.28146256257133 D-05
 A(11)= 0.0 D 00

C *** GR618 VS TM, 4.<T<20.5, 18 MAR 70

A(1)= -1.60235089568377 D 01
 A(2)= -4.98392153087712 D 01
 A(3)= 1.14538224412876 D 02
 A(4)= -8.95967495413080 D 01
 A(5)= 3.77219582215270 D 01
 A(6)= -9.66665270781886 D 00
 A(7)= 1.56116006587647 D 00
 A(8)= -1.55925068869218 D-01
 A(9)= 8.82703395242947 D-03
 A(10)= -2.17129245842203 D-04
 A(11)= 0.0 D 00

C *** FIT CONSTANTS FOR GR622 VS TM 4.<T<20.5

A(1)= 2.46225322859626 D 02
 A(2)= -5.33141526887367 D 02
 A(3)= 5.06005465001301 D 02
 A(4)= -2.72722157618749 D 02
 A(5)= 9.23034086547086 D 01
 A(6)= -2.04247995364449 D 01
 A(7)= 2.96427481986291 D 00
 A(8)= -2.72742819062847 D-01
 A(9)= 1.44622123366834 D-02
 A(10)= -3.37148051222236 D-04
 A(11)= 0.0 D 00

The notation D-03 means $\times 10^{-3}$

$$\text{Log}_e(T) = \sum A(n) [\text{Log}_e(R)]^{n-1}$$

C *** FIT CONSTANTS FOR GR248 VS TM 4. <T<20.6

A(1)=	3.82332279843925	D 03
A(2)=	-7.53581235476843	D 03
A(3)=	6.55385089662440	D 03
A(4)=	-3.29888348348436	D 03
A(5)=	1.05972276519030	D 03
A(6)=	-2.25455408408103	D 02
A(7)=	3.17861019989027	D 01
A(8)=	-2.86517068593012	D 00
A(9)=	1.49892032648898	D-01
A(10)=	-3.46859550059492	D-03
A(11)=	0.0	

The notation D-03 means $\times 10^{-3}$

$$\text{Log}_e(T) = \sum A(n) [\text{Log}_e(R)]^{n-1}$$

C *** GR803 VS TM 18.0<T<34.0
 A(1)= -8.03194532259625D 02
 A(2)= 1.59981630783442D 03
 A(3)= -1.35432196900276D 03
 A(4)= 6.35237289792752D 02
 A(5)= -1.78381093987017D 02
 A(6)= 2.99912871810070D 01
 A(7)= -2.79564730401338D 00
 A(8)= 1.11466964250598D-01
 A(9)= 0.0
 A(10)= 0.0
 A(11)= 0.0

C *** GR618 VS TM, 18.0<T<34.0
 A(1)= -6.96121324014937D 03
 A(2)= 1.49957795405850D 04
 A(3)= -1.38163622483529D 04
 A(4)= 7.06249836110494D 03
 A(5)= -2.16328604505802D 03
 A(6)= 3.97071673173939D 02
 A(7)= -4.04402614182693D 01
 A(8)= 1.76305383391999D 00
 A(9)= 0.0
 A(10)= 0.0
 A(11)= 0.0

The notation D-03 means $\times 10^{-3}$

T58(T>1.5) AND T62(T<1.5) VAPOR PRESSURE DATA

15 APR 70

NO	T58	R803 TM(803) T-T58	R618 TM(618) T-T58	R638 TM(638) T-T58	R248 TM(248) T-T58	(OHMS) (KELVINS) (MILLIKELVINS)
3280	4.1793000	0.0000000 0.0000000 0.0000000	450.3009938 4.1856429 6.3429341	341.1831762 4.1858163 6.5162502	324.8235034 4.1855024 6.2024179	
3281	3.7939000	1574.7985034 0.0000000 0.0000000	532.1693564 3.8002536 6.3535827	393.5121296 3.8002526 6.3525852	365.8526828 3.7999803 6.0802947	
3282	4.1814000	1295.3040934 0.0000000 0.0000000	449.8210034 4.1882139 6.8138808	340.8831822 4.1882901 6.8901399	324.5935080 4.1879080 6.5080359	
3285	4.1782000	1297.3440526 0.0000000 0.0000000	450.4309912 4.1849473 6.7473472	341.2931740 4.1849100 6.7099975	324.9135016 4.1845619 6.3619062	
3291	2.0027000	6708.3858296 0.0000000 0.0000000	1698.3060332 2.0062983 3.5983245	1019.2696142 2.0062090 3.5090182	845.8530826 2.0062049 3.5049443	
3292	1.7049000	10382.3923480 0.0000000 0.0000000	2374.1525160 1.7080341 3.1341090	1325.3534924 1.7080026 3.1026322	1077.4484506 1.7079617 3.0617086	
3293	1.5000000	15072.7985380 0.0000000 0.0000000	3156.5368680 1.5029020 2.9020441	1651.9669600 1.5029739 2.9738831	1322.4735500 1.5028719 2.8719113	
4001	1.3006000	0.0000000 0.0000000 0.0000000	4429.3014122 1.3034380 2.8380105	2140.9871794 1.3033709 2.7709332	1685.4062912 1.3034752 2.8751912	
4002	1.3006000	23512.6297380 0.0000000 0.0000000	4430.5113880 1.3032936 2.6936366	2140.7571840 1.3034456 2.8456387	1686.0662780 1.3031854 2.5853760	
4004	1.1059000	0.0000000 0.0000000 0.0000000	6721.0755758 1.1082713 2.3713133	2933.4313302 1.1082004 2.3004473	2268.4246306 1.1080954 2.1953975	

T58(T>1.5) AND T62(T<1.5) VAPOR PRESSURE DATA

15 APR 70

NO	T58	R803. TM(803) T-T58	R618 TM(618) T-T58	R638 TM(638) T-T58	R248 TM(248) T-T58	(OHMS) (KELVINS) (MILLIKELVINS)
4014	2.0979000	11904.9618960 0.0000000 0.0000000	1548.9690200 2.1013696 3.4695610	947.4810500 2.1014093 3.5092506	791.3041736 2.1013009 3.4009487	
4018	2.2026000	5268.1646346 0.0000000 0.0000000	1408.7718240 2.2061729 3.5728736	878.4824300 2.2062577 3.6576826	738.7352250 2.2061025 3.5024829	
4019	2.3969000	4287.3342516 0.0000000 0.0000000	1199.7460046 2.4008281 4.0280970	772.1945558 2.4009119 4.1119381	657.5268492 2.4007727 3.9727057	
4020	2.8020000	2988.1402360 0.0000000 0.0000000	901.7419648 2.8076161 5.6161478	611.8877620 2.8076905 5.6905078	534.6693064 2.8073942 5.3942216	
4021	2.9994000	2572.5385482 0.0000000 0.0000000	799.4240112 3.0052486 5.8486475	553.9289212 3.0053224 5.9223613	490.0701984 3.0050657 5.6657290	
4022	3.2017000	2236.3852714 0.0000000 0.0000000	713.2757342 3.2077809 6.0808517	503.7399250 3.2079083 6.2082740	451.3809722 3.2075608 5.8607735	
4023	3.5004000	1856.3028732 0.0000000 0.0000000	611.3377730 3.5065578 6.1577636	442.5411490 3.5067051 6.3051470	403.9819202 3.5065728 6.1727533	
4061	0.9092000	0.0000000 0.0000000 0.0000000	11682.4663460 0.9103977 1.1977242	0.0000000 0.0000000 0.0000000	3352.2329540 0.9105444 1.3443643	
4082	1.1122000	0.0000000 0.0000000 0.0000000	6621.8675600 1.1144521 2.2520569	2900.1419960 1.1145155 2.3154857	2243.1551360 1.1146575 2.4574813	
4084	0.9167000	0.0000000 0.0000000 0.0000000	11396.7720600 0.9180520 1.3520093	4356.1128760 0.9181400 1.4399634	3294.5341080 0.9181802 1.4802477	

T58(T>1.5) AND T62(T<1.5) VAPOR PRESSURE DATA

15 APR 70

NO	T58	R803 TM(803) T-T58	P618 TM(618) T-T58	R-33 TM(638) T-T58	R243 TM(248) T-T58	(MMMS) (KELVINS) (MILLIKELVINS)
4085	1.0507000	0.0000000 0.0000000 0.0000000	7719.4456080 1.0530781 2.1781417	3254.8349060 1.0530239 2.1239185	2501.6499660 1.3530974 2.1973591	
4099	0.9268000	0.0000000 0.0000000 0.0000000	11035.2792900 0.9281810 1.3810204	4250.7149840 0.9284574 1.6574039	3221.2355740 0.9282203 1.4203337	
4151	0.8920000	0.0000000 0.0000000 0.0000000	0.0000000 0.0000000 0.0000000	0.0000000 0.0000000 0.0000000	3489.5302080 0.8932573 1.2573193	
5112	0.8688000	0.0000000 0.0000000 0.0000000	0.0000000 0.0000000 0.0000000	4909.6018060 0.8701231 1.3231010	3691.6261660 0.8698618 1.0619487	
5112	0.8693000	0.0000000 0.0000000 0.0000000	0.0000000 0.0000000 0.0000000	0.0000000 0.0000000 0.0000000	3688.9262200 0.8701596 0.8595632	
5126	0.8594000	0.0000000 0.0000000 0.0000000	13830.7233800 0.8612661 1.8660691	5025.1994940 0.8612140 1.8139966	3777.1244560 0.8606289 1.2289340	
5142	0.8624000	0.0000000 0.0000000 0.0000000	13687.0262540 0.8641426 1.7426039	4987.7002440 0.8640667 1.6666890	3748.3250320 0.8636974 1.2973516	
7003	4.1939000	1287.6942456 0.0000000 0.0000000	447.5210494 4.2005906 6.6906197	0.0000000 0.0000000 0.0000000	323.3735324 4.2007186 6.8186442	
7004	4.1810000	1295.4740900 0.0000000 0.0000000	449.9110016 4.1877315 6.7315132	0.0000000 0.0000000 0.0000000	324.5935080 4.1879080 6.9080359	
7005	4.1804000	1296.1540764 0.0000000 0.0000000	450.0409990 4.1870350 6.6350170	0.0000000 0.0000000 0.0000000	324.6435070 4.1873848 6.9848200	

T58(T>1.5) AND T62(T<1.5) -VAPOR PRESSURE DATA

15 APR 70

NO	T58	R803 TM(803) T-T58	R618 TM(618) T-T58	R638 TM(638) T-T58	R248 TM(248) T-T58	(OHMS) (KELVINS) (MILLIKELVINS)
7006	4.9908000	910.3117934 0.0000000 0.0000000	329.5634086 4.9968005 6.0005340	0.0000000 0.0000000 0.0000000	260.4847902 4.9972636 6.4636050	
7007	4.3921000	1174.5365088 0.0000000 0.0000000	412.9517408 4.3988850 6.7850040	0.0000000 0.0000000 0.0000000	305.4238914 4.3994889 7.3888892	
7008	4.3875000	1176.9464606 0.0000000 0.0000000	413.6917260 4.3943835 6.8835439	0.0000000 0.0000000 0.0000000	305.8339832 4.3947234 7.2234465	
7009	4.5995000	1171.5565684 0.0000000 0.0000000	380.9123816 4.6059641 6.4640623	0.0000000 0.0000000 0.0000000	288.4842302 4.6064474 6.9474261	
7022	4.1883000	1291.3241730 0.0000000 0.0000000	448.5910280 4.1948209 6.5208509	0.0000000 0.0000000 0.0000000	323.9035218 4.1951429 6.8429428	
7024	0.9422000	0.0000000 0.0000000 0.0000000	10516.7396600 0.9436468 1.4467561	0.0000000 0.0000000 0.0000000	3114.2377140 0.9436052 1.4052404	
7024	1.9093000	0.0000000 0.0000000 0.0000000	1871.3225728 1.9126170 3.3170041	0.0000000 0.0000000 0.0000000	907.2418548 1.9126778 3.3777624	
7026	3.0015000	0.0000000 0.0000000 0.0000000	798.5440288 3.0071321 5.6321035	0.0000000 0.0000000 0.0000000	489.6202074 3.0072409 5.7409345	
7038	0.9008000	0.0000000 0.0000000 0.0000000	12010.7597800 0.9019614 1.1613597	0.0000000 0.0000000 0.0000000	3418.8616214 0.9020048 1.2048224	
7083	3.3776000	0.0000000 0.0000000 0.0000000	650.1269972 3.3838946 6.2945679	0.0000000 0.0000000 0.0000000	422.2015558 3.3840351 6.4351468	

T59(T>1.5) AND T62(T<1.5) VAPOR PRESSURE DATA

15 APR 70

NO	T58	R803 TM(803) T-T58	R618 TM(618) T-T58	R638 TM(638) T-T58	R248 TM(248) T-T58	(OHMS) (KELVINS) (MILLIKELVINS)
7084	4.8145000	978.1904358 0.0000000 0.0000000	351.2729744 4.8215246 7.0246314	0.0000000 0.0000000 0.0000000	272.5145496 4.8212240 6.7240490	
7085	4.8142000	0.0000000 0.0000000 0.0000000	351.3029738 4.8212933 7.0932564	0.0000000 0.0000000 0.0000000	272.5245494 4.8210830 6.8830390	
7086	5.0780000	878.9224212 0.0000000 0.0000000	319.4346112 5.0843414 6.3414430	0.0000000 0.0000000 0.0000000	254.8489029 5.0843748 6.3747720	
7088	5.0661000	883.2123354 0.0000000 0.0000000	320.8095837 5.0722269 6.1268918	0.0000000 0.0000000 0.0000000	255.6248874 5.0721961 6.0960781	
7091	3.9473000	1453.7709240 0.0000000 0.0000000	496.9900600 3.9538707 6.5707211	0.0000000 0.0000000 0.0000000	348.4030318 3.9539314 6.6314187	
7092	4.1891000	1290.6741860 0.0000000 0.0000000	448.3810322 4.1959516 6.8515992	0.0000000 0.0000000 0.0000000	323.8435230 4.1957733 6.6733480	

E-M2 VAPOR PRESSURE DATA (MMHG, 0 DEG C)

15 APR 70

NO	P T68(P) T-T613	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(DHMS) (KELVINS) (MILLIKELVINS)
6180	755.3400300 20.2592550 9.806	0.1103290 20.2494271 -0.022	47.3283267 20.2488215 -0.628	32.5006750 20.2494491 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6181	752.6600300 20.2472330 9.928	0.1100980 20.2373958 0.041	47.3769262 20.2368891 -0.466	32.5239748 20.2373546 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6182	762.2100300 20.2898354 10.278	0.1109000 20.2791667 -0.361	47.2055279 20.2790680 -0.460	32.4428756 20.2795277 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6182	507.7400300 18.9917125 8.752	0.0879790 18.9818125 -1.148	53.0280697 18.9819674 -0.993	35.1427486 18.9829601 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6183	250.3100300 17.0453347 6.928	0.0610150 17.0402542 1.847	64.5475545 17.0381194 -0.288	40.2286977 17.0384071 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6184	100.9100300 15.0120566 6.653	0.0409990 15.0109877 5.574	82.3834762 15.0045606 -0.853	47.6378236 15.0054133 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6185	56.1300300 13.9180160 9.377	0.0331210 13.9157813 7.143	96.0222795 13.9080088 -0.630	53.0496390 13.9086386 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6186	756.3000300 20.2635361 0.000	0.1103870 20.2524479 0.000	47.3167268 20.2516728 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6186	359.5700000 17.9965175 9.210	0.0731320 17.9871014 -0.206	58.4218158 17.9869384 -0.369	37.5616244 17.9873079 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6187	161.2600300 16.0038102 8.166	0.0498030 15.9992784 3.634	72.7249727 15.9959234 0.280	43.6855631 15.9956439 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	

E-H2 VAPOR PRESSURE DATA			(MMHG, 0 DEG C)		15 APR 70		
NO	P T68(F) T-T618	RPT T55 T-T618	R803 TM(303) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6187	101.070000 15.0152316 0.000	0.0410160 15.0130864 0.000	82.3578764 15.0069156 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6189	55.7500000 13.9371655 6.834	0.0332550 13.9367188 6.387	95.7227855 13.9291517 -1.180	52.9296414 13.9303314 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	

NEON VAPOR PRESSURE DATA

(MMHG, 0 DEG C)

15 APR 70

No	P T68(P) T-T55	RPT T55	R803	(KELVINS) (MILLIKELVINS)
6161	358.36 24.8245 6.8	0.226890 24.8177		
6161	538.05 26.0047 6.3	0.266985 25.9984	31.0450 25.9994	
6162	761.28 27.1076 6.3	0.308290 27.1013	29.0037 27.1010	
6164	761.34 27.1079 6.0	0.308316 27.1019	29.0013 27.1024	
6164	632.52 26.5071 5.3	0.285372 26.5018	30.0829 26.5027	
6165	455.46 25.5070 5.5	0.249595 25.5015		
6166	327.14 24.5748 6.2	0.218970 24.5686		
6166	327.13 24.5747 6.3	.218965 24.5684	34.0872 24.5693	

X(CMN) DATA Y(X) IS T58 FIT WITH DELTA=-.0009

15 APR 73

NO	X T(X) T-T58	R248 T58 T-T58	R803 TM(803) T-T58	R618 TM(618) T-T58	R622 TM(622) T-T58	R248 TM(248) T-T58	(OHMS) (KELVINS) (MILLIKELVINS)
4079	0.1241806 4.2014749 23.000	324.8535029 4.1784747 0.000	0.0000000 0.0000000 0.000	450.3209934 4.1855359 7.061	341.1931760 0.0000000 0.000	324.8535028 4.1851889 6.714	
4079	0.1253271 3.5113464 12.761	404.1519168 3.4991858 0.000	0.0000000 0.0000000 0.000	611.4977698 3.5060261 6.840	442.6511468 0.0000000 0.000	404.1519168 3.5053810 6.195	
4080	0.1281459 2.8526799 6.305	523.9895200 2.8463753 0.000	0.0000000 0.0000000 0.000	876.9224612 2.8519656 5.590	597.9080416 0.0000000 0.000	523.9895200 2.8517011 5.326	
4080	0.1293772 2.5023328 0.276	620.5375890 2.5317567 0.000	0.0000000 0.0000000 0.000	1107.5278490 2.5065243 4.768	723.7355250 0.0000000 0.000	620.5375890 2.5062962 4.540	
4080	0.1335284 1.9870153 -0.640	855.2928938 1.9876549 -0.000	0.0000000 0.0000000 -0.000	1724.4855096 1.9910946 3.440	1031.5293690 0.0000000 0.000	855.2928938 1.9909643 3.309	
4081	0.1373969 1.6542741 0.026	1129.5774080 1.6542481 0.000	0.0000000 0.0000000 0.000	2534.9493000 1.6573272 3.079	1394.5121092 0.0000000 0.000	1129.5774080 1.6572317 2.984	
4081	0.1405403 1.4184562 -0.419	1450.7309848 1.4188751 -0.000	0.0000000 0.0000000 -0.000	3591.9781590 1.4217306 2.856	1824.2035152 0.0000000 0.000	1450.7309848 1.4218157 2.941	
4082	0.1439136 1.2534278 0.372	1800.8139830 1.2530557 0.000	0.0000000 0.0000000 0.000	4860.9027800 1.2556527 2.597	2296.5540680 0.0000000 0.000	1800.8139830 1.2557617 2.706	
4082	0.1474748 1.1126207 0.200	2243.2551340 1.1124211 0.000	0.0000000 0.0000000 0.000	6621.3675700 1.1144836 2.062	2900.1419960 0.0000000 0.000	2243.2551340 1.1146313 2.210	
4083	0.1507900 1.0072984 -0.007	2720.6455860 1.0373049 -0.000	0.0000000 0.0000000 -0.000	8690.8261800 1.0090082 1.703	3557.7288440 0.0000000 0.000	2720.6455860 1.0090551 1.750	

X(CMN) DATA T(X) IS T58 FIT WITH DELTA=-.0009

15 APR 70

NO	X T(X) T-T58	R248 T58 T-T58	R803 TM(803) T-T58	R618 TM(618) T-T58	R622 TM(622) T-T58	R248 TM(248) T-T58	(OHMS) (KELVINS) (MILLIKELVINS)
4083	0.1542460 0.9168387 0.118	3294.9341000 0.9167209 0.000	0.0000000 0.0000000 0.000	11397.6720420 0.9180274 1.307	4356.7128640 0.0000000 0.000	3294.9341000 0.9181265 1.406	
4084	0.1526390 0.9567904 -0.046	3017.0396580 0.9568365 -0.000	0.0000000 0.0000000 -0.000	10063.3987280 0.9581684 1.332	3968.9206200 0.0000000 0.000	3017.0396580 0.9583928 1.556	
4085	0.1493330 1.0510218 -0.137	2501.6499660 1.0511592 -0.000	0.0000000 0.0000000 -0.000	7719.4456080 1.0530781 1.919	3254.6349060 0.0000000 0.000	2501.6499660 1.0530974 1.938	
4085	0.1460000 1.1665050 -0.211	2049.9590000 1.1671160 -0.000	0.0000000 0.0000000 -0.000	5831.3833700 1.1694629 2.347	2635.2472940 0.0000000 0.000	2049.9590000 1.1695499 2.434	

MAS DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6022	0.1879760 4.1944812 -0.071	0.0000000 0.0000000 -0.000	1291.2941736 0.0000000 -0.000	448.6410270 4.1945517 -0.000	467.1706564 4.1946309 0.079	323.9835202 4.1943027 -0.249	
6022	0.2043780 3.7984217 -0.011	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	532.6093476 3.7984328 -0.000	548.7090256 3.7984470 0.014	366.0726784 3.7981251 -0.308	
6022	0.2304620 3.3033294 0.076	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	677.8564426 3.3032535 0.000	687.6562466 3.3033138 0.060	435.1412970 3.3029661 -0.287	
6023	0.2943370 2.5063930 -0.008	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	1107.6278470 2.5064015 -0.000	1086.9382608 2.5064601 0.059	620.5375890 2.5062962 -0.105	
6023	0.3602310 2.0082646 0.169	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	1695.0860976 2.0081960 0.000	1610.6977854 2.0082658 0.070	844.6931058 2.0081009 -0.095	
6023	0.4981650 1.4204574 0.011	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	3599.6480056 1.4204464 0.000	3198.2160344 1.4204948 0.048	1453.0609382 1.4204672 0.021	
6024	0.6904700 1.0133492 -0.028	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	8586.3882688 1.0133776 -0.000	6958.8908194 1.0134322 0.055	2698.0060388 1.0133189 -0.059	
6024	0.7798400 0.8944994 -0.102	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	12309.4538060 0.8946013 -0.000	9568.6086240 0.8946431 0.042	3479.1304160 0.8945252 -0.076	
6025	0.7347700 0.9506909 -0.010	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	10292.6941420 0.9507013 -0.000	8170.9465778 0.9507430 0.042	3066.9486598 0.9506988 -0.003	
6025	0.6377420 1.0997757 -0.054	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	6860.3627900 1.0998294 -0.000	5700.5259872 1.0999063 0.077	2301.3139728 1.0997460 -0.083	

MAS DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6026	0.5649570 1.2469720 0.066	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	4947.2210536 1.2469055 0.000	4257.3848506 1.2469166 0.011	1824.0235188 1.2468329 -0.073	
6026	0.4259750 1.6782267 -0.314	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	2465.5206886 1.6785409 -0.000	2269.4846094 1.6785765 0.036	1107.2178552 1.6784295 -0.111	
6026	0.3156930 2.3198719 0.256	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	1280.0043994 2.3196161 0.000	1243.0651382 2.3195648 -0.051	689.1262172 2.3195853 -0.031	
6027	0.3156530 2.3202536 -0.036	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	1279.2944136 2.3202959 -0.000	1242.3051534 2.3203741 0.078	688.9162214 2.3201003 -0.196	
6027	0.2208730 3.4693422 0.177	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	622.7575446 3.4691652 0.000	635.2072956 3.4692775 0.112	409.4118116 3.4689701 -0.195	
6028	0.1879870 4.1941877 -0.095	0.0000000 0.0000000 -0.000	1291.4941696 0.0000000 -0.000	448.6910260 4.1942827 -0.000	467.2206554 4.1943555 0.073	324.0235194 4.1938827 -0.400	
6029	0.1877470 4.2006010 -0.206	0.0000000 0.0000000 -0.000	1287.4742500 0.0000000 -0.000	447.4810502 4.2008067 -0.000	466.0406790 4.2008677 0.061	323.4035318 4.2004026 -0.404	
6098	0.1879620 4.1948549 0.142	0.0000000 0.0000000 0.000	1291.1641762 0.0000000 0.000	448.6110276 4.1947132 0.000	467.1306572 4.1948513 0.138	323.9235214 4.1949329 0.220	
6099	0.1880730 4.1918944 -0.022	0.0000000 0.0000000 -0.000	1292.8541424 0.0000000 -0.000	449.1310172 4.1919169 -0.000	467.6406470 4.1920437 0.127	324.1935160 4.1920989 0.182	
6100	0.2185810 3.5116850 -0.035	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	609.7878040 3.5117196 -0.000	622.8005437 3.5118912 0.172	403.2409350 3.5117785 0.059	

MAS DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6100	0.2185820 3.5116664 0.280	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	609.8878020 3.5113860 0.000	0.0000000 0.0000000 0.000	403.2359351 3.5118136 0.428	
6100	0.2508710 2.9981815 0.122	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	802.7979437 2.9980594 0.000	805.3988917 2.9981578 0.098	491.5061697 2.9981506 0.091	
6101	0.3255290 2.2431379 -0.028	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	1364.4127112 2.2431664 -0.000	1318.6336268 2.2432064 0.040	721.7675644 2.2431680 0.002	
6101	0.3255420 2.2430398 0.139	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	1364.7227050 2.2429007 0.000	1318.8636222 2.2429857 0.085	721.9195613 2.2428282 -0.072	
6102	0.3876810 1.8560428 0.127	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	1991.2501742 1.8559157 0.000	1867.2026552 1.8559726 0.057	948.9110214 1.8559607 0.045	
6102	0.4448120 1.6028313 0.066	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	2729.3754114 1.6027654 0.000	2489.3302124 1.6028093 0.044	1191.1761760 1.6027785 0.013	
6102	0.4448050 1.6028581 0.153	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	2729.6054068 1.6027047 0.000	2489.5502080 1.6027393 0.035	1191.2061754 1.6027533 0.049	
6103	0.4936050 1.4360624 0.141	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	3508.9798190 1.4359212 0.000	3125.5374880 1.4359399 0.019	1426.6714660 1.4359803 0.059	
6103	0.5497980 1.2828049 0.070	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	4608.4078300 1.2827352 0.000	3994.7201040 1.2827720 0.037	1733.8653220 1.2827339 -0.001	
6104	0.5497770 1.2828560 0.100	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	4608.2178338 1.2827565 0.000	3994.6201060 1.2827864 0.030	1733.7353246 1.2827881 0.032	

MAS DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6100	0.2185820 3.5116664 0.280	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	609.8878020 3.5113860 0.000	0.0000000 0.0000000 0.000	403.2359351 3.5118136 0.428	
6100	0.2508710 2.9981815 0.122	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	802.7979437 2.9980594 0.000	805.3988917 2.9981578 0.098	491.5061697 2.9981506 0.091	
6101	0.3255290 2.2431379 -0.028	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	1364.4127112 2.2431664 -0.000	1318.6336268 2.2432064 0.040	721.7675644 2.2431680 0.002	
6101	0.3255420 2.2430398 0.139	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	1364.7227050 2.2429007 0.000	1318.8636222 2.2429857 0.085	721.9195613 2.2428282 -0.072	
6102	0.3876810 1.8560428 0.127	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	1991.2501742 1.8559157 0.000	1867.2026552 1.8559726 0.057	948.9110214 1.8559607 0.045	
6102	0.4448120 1.6028313 0.066	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	2729.3754114 1.6027654 0.000	2489.3302124 1.6028093 0.044	1191.1761760 1.6027785 0.013	
6102	0.4448050 1.6028581 0.153	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	2729.6054068 1.6027047 0.000	2489.5502080 1.6027393 0.035	1191.2061754 1.6027533 0.049	
6103	0.4936050 1.4360524 0.141	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	3508.9798190 1.4359212 0.000	3125.5374880 1.4359399 0.019	1426.6714660 1.4359803 0.059	
6103	0.5497380 1.2828049 0.070	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	4608.4078300 1.2827352 0.000	3994.7201040 1.2827720 0.037	1733.8653220 1.2827339 -0.001	
6104	0.5497770 1.2828560 0.100	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	4608.2178338 1.2827565 0.000	3994.6201060 1.2827864 0.030	1733.7353246 1.2827881 0.032	

MAS DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6104	0.5261180 1.3431575 0.161	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	4116.8176620 1.3429969 0.000	0.0000000 0.0000000 0.000	1599.5680080 1.3430359 0.039	
6105	0.4313970 1.6557964 0.071	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	2540.3191926 1.5557269 0.000	2332.1033570 1.6557535 0.027	1131.2273750 1.6556993 -0.028	
6105	0.3602630 2.0087749 0.207	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	1694.4561102 2.0085681 0.000	1610.1377966 2.0086443 0.076	844.3431128 2.0086740 0.106	
6106	0.2858500 2.5892012 -0.135	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	1043.4491306 2.5893364 -0.000	1028.3094334 2.5893681 0.032	594.2181154 2.5893679 0.032	
6106	0.2305960 3.3011216 -0.031	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	678.6044276 3.3011530 -0.000	688.3492327 3.3012624 0.109	435.4122916 3.3013177 0.165	
6107	0.2040380 3.8058657 0.144	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	530.8513828 3.8057219 0.000	546.9730603 3.8059035 0.182	365.1586967 3.8058460 0.124	
6108	0.1883930 4.1833833 0.040	0.0000000 0.0000000 0.000	1298.0840378 0.0000000 0.000	450.7309852 4.1833433 0.000	469.1896160 4.1835449 0.202	325.0114996 4.1835383 0.195	
6108	0.1883930 4.1832536 0.121	0.0000000 0.0000000 0.000	1298.4040314 0.0000000 0.000	450.7709844 4.1831296 0.000	469.2506148 4.1832111 0.081	325.0384991 4.1832564 0.127	
6109	0.1621855 5.0189135 -0.067	0.0000000 0.0000000 -0.000	902.1119574 0.0000000 -0.000	326.9534608 5.0189867 -0.000	346.9930600 5.0191656 0.179	0.0000000 0.0000000 0.000	
6109	0.1621872 5.0188927 0.077	0.0000000 0.0000000 0.000	902.2319550 0.0000000 0.000	326.9734604 5.0188157 0.000	347.0230594 5.0189091 0.093	0.0000000 0.0000000 0.000	

MAS DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6112	0.1398541 6.0512181 0.115	0.0000000 0.0000000 0.000	614.3277132 0.0000000 0.000	232.0693585 6.0511035 0.000	250.8469830 6.0513180 0.214	203.4779304 6.0513036 0.200	
6112	0.1398555 6.0512516 0.134	0.0000000 0.0000000 0.000	614.3377130 0.0000000 0.000	232.0683585 6.0511175 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6134	0.1807430 4.3968726 -0.064	0.0000000 0.0000000 -0.000	1175.3964916 0.0000000 -0.000	413.2717344 4.3969370 -0.000	432.5253493 4.3969833 0.046	305.6368871 4.3970118 0.075	
6135	0.1807260 4.3973128 0.193	0.0000000 0.0000000 0.000	1175.4104913 0.0000000 0.000	413.2417350 4.3971195 0.000	432.4753503 4.3972930 0.173	0.0000000 0.0000000 0.000	
6135	0.1741730 4.5985510 -0.076	0.0000000 0.0000000 -0.000	1074.9185012 0.0000000 -0.000	381.9843602 4.5986266 -0.000	401.6819662 4.5987754 -0.149	289.0742184 4.5988942 0.268	
6136	0.1741440 4.5994825 0.221	0.0000000 0.0000000 0.000	1074.6085074 0.0000000 0.000	381.8913620 4.5992619 0.000	0.0000000 0.0000000 0.000	289.0192195 4.5995973 0.335	
6136	0.1682020 4.7987105 -0.129	0.0000000 0.0000000 -0.000	987.1232571 0.0000000 -0.000	354.2319152 4.7988395 -0.000	374.1895161 4.7989437 0.104	274.0895181 4.7991198 0.280	
6137	0.1626902 4.9997033 0.111	0.0000000 0.0000000 0.000	909.1518166 0.0000000 0.000	329.2334152 4.9995918 0.000	349.2730144 4.9997608 0.169	260.3347932 4.9995423 -0.049	
6137	0.1506600 5.5032208 0.263	0.0000000 0.0000000 0.000	748.2250352 0.0000000 0.000	276.6484669 5.5029577 0.000	0.0000000 0.0000000 0.000	230.2953940 5.5033297 0.372	
6142	0.1398874 6.0493608 -0.177	0.0000000 0.0000000 -0.000	614.6797062 0.0000000 -0.000	232.1813563 6.0495374 -0.000	250.9679805 6.0496745 0.137	203.5459290 6.0497671 0.230	

MAS DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6142	0.1323376 6.5019828 -3.152	0.0000000 0.0000000 -0.000	527.1094576 0.0000000 -0.000	202.7269454 6.5051349 -0.000	220.4795903 6.5049250 -0.210	184.9083018 6.5062841 1.149	

CMA DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T518	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
7035	0.0639048 5.49442T6 -0.195	0.0000000 0.0000000 -0.000	750.6159874 0.0000000 -0.000	277.4184515 5.4946224 -0.000	297.1790563 5.4945000 -0.122	230.7843842 5.4942947 -0.328	
7035	0.0752168 4.2006686 0.008	0.0000000 0.0000000 0.000	1287.7142452 0.0000000 0.000	447.5080497 4.2006608 0.000	466.1206774 4.2004254 -0.235	323.3835322 4.2006133 -0.048	
7036	0.0943540 3.0034905 -0.130	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	800.1859960 3.0036206 -0.000	803.0959378 3.0033919 -0.229	490.4101916 3.0034248 -0.196	
7037	0.1474970 1.6752243 -0.209	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	2475.4904892 1.6754334 -0.000	2278.3444322 1.6752820 -0.151	1110.3977916 1.6753648 -0.069	
7037	0.1879570 1.2522653 -0.084	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	4893.1721346 1.2523537 -0.000	4216.5656670 1.2522463 -0.107	1809.4138110 1.2524290 0.075	
7038	0.2249920 1.0165633 -0.014	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	8511.1197742 1.0165773 -0.000	6906.6018652 1.0165222 -0.055	2680.7363842 1.0166133 0.036	
7038	0.24990C0 0.9020250 0.064	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	12010.7597800 0.9019614 0.000	9366.1126740 0.9019213 -0.040	3418.8616214 0.9020048 0.043	
7039	0.2385150 0.95102C9 0.140	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	10287.0942540 0.9508807 0.000	8169.1366140 0.9508255 -0.055	3065.1386960 0.9509740 0.093	
7040	0.2098350 1.1015015 -0.098	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	6830.7933814 1.1015991 -0.000	5679.9163994 1.1015729 -0.026	2293.8041230 1.1016338 0.035	
7040	0.1690350 1.4200469 -0.069	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	3601.6279660 1.4201155 -0.000	3200.6259862 1.4199928 -0.123	1453.5309288 1.4201957 0.080	

CMA DATA T<5.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
7041	0.1277920 2.0041918 -0.139	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	1701.6559662 2.0043305 -0.000	1615.7676640 2.0041783 -0.152	847.0230592 2.0042978 -0.033	
7041	0.1147740 2.3026158 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	696.0260792 2.3028363 0.000	
7042	0.0992597 2.7989011 -0.311	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	906.5798680 2.7992117 -0.000	902.2739542 2.7990064 -0.205	536.6982658 2.7991743 -0.037	
7043	0.0882368 3.3046235 -0.149	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	677.3164534 3.3047723 -0.000	687.2322551 3.3045706 -0.202	434.8393030 3.3048053 0.033	
7043	0.0803870 3.7923980 -0.022	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	534.0663185 3.7924201 -0.000	550.1329971 3.7923587 -0.061	366.7496649 3.7924290 0.009	
7045	0.0731401 4.3904931 0.296	0.0000000 0.0000000 0.000	1179.1164172 0.0000000 0.000	414.3817122 4.3901970 0.000	433.6613266 4.3899632 -0.234	306.2238754 4.3902007 0.004	
7045	0.0605255 6.0510227 -0.039	0.0000000 0.0000000 -0.000	614.4307111 0.0000000 -0.000	232.0723585 6.0510615 -0.000	250.8849822 6.0508017 -0.260	203.4999299 6.0508064 -0.255	
7072	0.0729746 4.4063610 -0.155	0.0000000 0.0000000 -0.000	1170.4865898 0.0000000 -0.000	411.7017658 4.4065160 -0.000	431.0313792 4.4062582 -0.258	304.8239034 4.4064826 -0.033	
7073	0.0673663 5.0212637 -0.375	0.0000000 0.0000000 -0.000	901.2819740 0.0000000 -0.000	326.6434670 5.0216387 -0.000	346.7400651 5.0213301 -0.309	258.8948220 5.0215271 -0.112	
7081	0.0756036 4.1671097 -0.160	0.0000000 0.0000000 -0.000	1308.4538304 0.0000000 -0.000	453.7539247 4.1672693 -0.000	472.2255553 4.1670115 -0.258	326.5834682 4.1671932 -0.076	

CMA DATA T<6.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
7082	0.1154050 2.2861218 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	702.9359410 2.2863916 0.000	
7082	0.1961170 1.1914802 -0.070	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	5555.0888960 1.1915506 -0.000	0.0000000 0.0000000 -0.000	1980.9603800 1.1914624 -0.088	
7083	0.1479160 1.6693939 -0.375	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	2493.8401222 1.6697686 -0.000	2293.6941252 1.6696261 -0.142	1116.3376728 1.6696852 -0.083	
7083	0.086E090 3.3837966 -0.098	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	650.1269972 3.3838946 -0.000	661.4067716 3.3836448 -0.250	422.2015558 3.3840351 0.141	
7084	0.069C320 4.8214442 -0.080	0.0000000 0.0000000 -0.000	978.1904358 0.0000000 -0.000	351.2729744 4.8215246 -0.000	0.0000000 0.0000000 -0.000	272.5145496 4.8212240 -0.301	
7085	0.069C333 4.8212945 0.001	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	351.3029738 4.8212933 0.000	0.0000000 0.0000000 0.000	272.5245494 4.8210830 -0.210	
7086	0.0668667 5.0844634 0.122	0.0000000 0.0000000 0.000	878.9224212 0.0000000 0.000	319.4346112 5.0843414 0.000	339.5252094 5.0840262 -0.315	254.8489029 5.0843748 0.033	
7088	0.0668616 5.0723365 0.110	0.0000000 0.0000000 0.000	883.2123354 0.0000000 0.000	320.8095837 5.0722269 0.000	340.8731824 5.0721684 -0.058	255.6248874 5.0721961 -0.031	
7090	0.0605346 6.0493725 0.143	0.0000000 0.0000000 0.000	614.7477048 0.0000000 0.000	232.2033558 6.0492300 0.000	251.0149796 6.0490364 -0.194	203.5769284 6.0490669 -0.163	
7091	0.0782150 3.9534441 -0.027	0.0000000 0.0000000 -0.000	1453.7709240 0.0000000 -0.000	496.9900600 3.9538707 -0.000	514.2897140 3.9536686 -0.202	348.4030318 3.9539314 0.061	

CMA DATA T66.05

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
7092	0.0752720 4.1958464 -0.105	0.0000000 0.0000000 -0.000	1290.6741860 0.0000000 -0.000	448.3810322 4.1959516 -0.000	466.9906600 4.1956229 -0.329	323.8435230 4.1957733 -0.178	
7093	0.0605410 6.0482125 -0.011	0.0000000 0.0000000 -0.000	614.9877000 0.0000000 -0.000	232.2753544 6.0482239 -0.000	251.0789783 6.0481678 -0.056	203.6209275 6.0480734 -0.151	

MAS DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T518	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6022	0.2043780 3.7984217 0.130	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	532.6093476 3.7982914 0.000	548.7090256 3.7983645 0.073	366.0726784 3.7979737 -0.318	
6107	0.2040380 3.8058657 0.267	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	530.8513828 3.8055991 0.000	546.9730603 3.8058356 0.237	365.1586967 3.8057040 0.105	
6108	0.1883930 4.1833833 -0.010	0.0000000 0.0000000 -0.000	1298.0840378 4.1837072 0.314	450.7309852 4.1833936 0.000	469.1895160 4.1835983 0.205	325.0114996 4.1835425 0.149	
6108	0.1883980 4.1832506 0.071	0.0000000 0.0000000 0.000	1298.4040314 4.1831910 0.011	450.7709844 4.1831800 0.000	469.2505148 4.1832646 0.085	325.0384991 4.1832606 0.081	
6028	0.1879E70 4.1941E77 -0.140	0.0000000 0.0000000 -0.000	1291.4941696 4.1943803 0.053	448.6910260 4.1943275 0.000	467.2206554 4.1944041 0.077	324.0235194 4.1938865 -0.441	
6022	0.1879160 4.1944E12 -0.115	0.0000000 0.0000000 -0.000	1291.2941736 4.1947055 0.109	448.6410270 4.1945964 0.000	467.1706564 4.1946794 0.083	323.9835202 4.1943064 -0.290	
6029	0.1877470 4.2006C10 -0.247	0.0000000 0.0000000 -0.000	1287.4742500 4.2009319 0.084	447.4810502 4.2008481 0.000	466.0406790 4.2009133 0.065	323.4035318 4.2004060 -0.442	
6099	0.1880730 4.1918944 -0.068	0.0000000 0.0000000 -0.000	1292.8541424 4.1921708 0.208	449.1310172 4.1919629 0.000	467.6406470 4.1920933 0.130	324.1935160 4.1921027 0.140	
6098	0.1879620 4.1948549 0.097	0.0000000 0.0000000 0.000	1291.1641762 4.1949169 0.159	448.6110276 4.1947578 0.000	467.1306572 4.1948996 0.142	323.9235214 4.1949365 0.179	
6134	0.1807430 4.3968726 -0.001	0.0000000 0.0000000 -0.000	1175.3964916 4.3971056 0.232	413.2717344 4.3968736 0.000	432.5253493 4.3969341 0.060	305.6368871 4.3969914 0.118	

MAS DATA 4.3<T<20.5

15 APR 70

NO	X T(X) T-T613	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6135	0.1807280 4.3973128 0.257	0.0000000 0.0000000 0.000	1175.4104913 4.3970793 0.023	413.2417350 4.3970560 0.000	432.4753503 4.3972435 0.188	0.0000000 0.0000000 0.000	
6135	0.1741730 4.5985510 0.055	0.0000000 0.0000000 0.000	1074.9185012 4.5985666 0.071	381.9843602 4.5984960 0.000	401.6819662 4.5986586 0.163	289.0742184 4.5988440 0.348	
6136	0.1741440 4.5994825 0.351	0.0000000 0.0000000 0.000	1074.6085074 4.5992312 0.100	381.8913620 4.5991313 0.000	0.0000000 0.0000000 0.000	289.0192195 4.5995470 0.416	
6136	0.1682020 4.7987105 -0.006	0.0000000 0.0000000 -0.000	987.1232571 4.7988721 0.156	354.2319152 4.7987160 0.000	374.1895161 4.7988191 0.103	274.0895181 4.7990609 0.345	
6137	0.1626902 4.9997033 0.149	0.0000000 0.0000000 0.000	909.1518166 4.9997614 0.208	329.2334152 4.9995539 0.000	349.2730144 4.9996959 0.142	260.3347932 4.9995193 -0.035	
6109	0.1621865 5.0189195 -0.041	0.0000000 0.0000000 -0.000	902.1119574 5.0191117 0.151	326.9534608 5.0189609 0.000	346.9930600 5.0191100 0.149	0.0000000 0.0000000 0.000	
6109	0.1621872 5.0188927 0.103	0.0000000 0.0000000 0.000	902.2319550 5.0187801 -0.010	326.9734604 5.0187898 -0.000	347.0230594 5.0188534 0.064	0.0000000 0.0000000 0.000	
6137	0.1506600 5.5032108 -0.110	0.0000000 0.0000000 -0.000	748.2250352 5.5034200 0.090	276.6484669 5.5033303 0.000	0.0000000 0.0000000 0.000	230.2953940 5.5036176 0.287	
6090	0.0636803 20.5139598 0.582	0.1154960 20.5138000 0.422	46.2721373 20.5135722 0.194	32.0004800 20.5133783 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6092	0.0680564 18.0292181 0.315	0.0737100 18.0287770 -0.126	58.1736183 18.0291159 0.213	37.4534255 18.0289034 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	

MAS DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6092	0.0680562 18.0293179 1.263	0.0737100 18.0287770 0.722	58.1774182 18.0284677 0.413	37.4556254 -18.0280550 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6093	0.0725250 16.0455614 0.657	0.0000000 0.0000000 0.000	72.2992770 16.0449855 0.081	43.5075649 16.0449049 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6093	0.0725277 16.0444551 0.230	0.0502800 16.0479592 3.694	72.3064769 16.0441514 -0.114	43.5098649 16.0442656 -0.000	47.0699293 16.0441447 -0.121	56.4391356 16.0442758 0.010	
6094	0.0783208 14.0427187 0.179	0.0339910 14.0501515 7.611	94.1481170 14.0422256 -0.315	52.3181536 14.0425401 -0.000	57.0847583 14.0427401 0.200	66.0021799 14.0428360 0.296	
6095	0.0861128 12.0260265 1.193	0.0000000 0.0000000 0.000	130.8813823 12.0251633 0.330	66.2586748 12.0248337 0.000	72.8705425 12.0250754 0.242	80.1053979 12.0250839 0.250	
6095	0.0783218 14.0424164 0.768	0.0000000 0.0000000 0.000	94.1553169 14.0417012 0.053	52.3229535 14.0416483 0.000	57.0895582 14.0419549 0.307	0.0000000 0.0000000 0.000	
6096	0.0979176 9.8788139 0.128	0.0000000 0.0000000 0.000	204.2579148 9.8786210 -0.125	92.5321493 9.8787460 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6096	0.0979174 9.8789038 0.158	0.0000000 0.0000000 0.000	204.2659146 9.8784535 -0.292	92.5321493 9.8787460 -0.000	102.2779544 9.8784655 -0.280	104.0839183 9.8785934 -0.153	
6097	0.0979176 9.8788139 0.188	0.0000000 0.0000000 0.000	204.2619147 9.8785373 -0.149	92.5331493 9.8786862 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6097	0.1128434 8.0615146 0.612	0.0000000 0.0000000 0.000	326.7074657 8.0610036 0.101	134.7443051 8.0609025 0.000	148.4470310 8.0612884 0.386	137.8262434 8.0613614 0.459	

MAS DATA 4.C<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T518	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6112	0.1398541 6.0512181 0.082	0.0000000 0.0000000 0.000	614.3277132 6.0512761 0.139	232.0693585 6.0511366 0.000	250.8469830 6.0513839 0.247	203.4779304 6.0512565 0.120	
6112	0.1398535 6.0512516 0.101	0.0000000 0.0000000 0.000	614.3377130 6.0512293 0.079	232.0683585 6.0511505 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6113	0.1255438 6.9717145 0.519	0.0000000 0.0000000 0.000	452.8199434 6.9715069 0.311	177.6164476 6.9711959 0.000	194.1561168 6.9717086 0.513	168.2916341 6.9714098 0.214	
6114	0.1044637 8.9896159 -0.126	0.0000000 0.0000000 -0.000	254.1089177 8.9896825 -0.120	109.8478030 8.9898020 -0.000	121.3725725 8.9897592 -0.043	118.5016299 8.9899508 0.149	
6114	0.1044625 8.9898242 -0.022	0.0000000 0.0000000 -0.000	254.1039178 8.9897588 -0.087	109.8468030 8.9898463 -0.000	121.3725725 8.9897592 -0.087	0.0000000 0.0000000 -0.000	
6115	0.0917513 10.8946380 0.111	0.0000000 0.0000000 0.000	163.2022359 10.8945720 0.045	78.0017399 10.8945266 0.000	86.0702786 10.8949022 0.376	0.0000000 0.0000000 0.000	
6115	0.0821453 12.9745822 0.178	0.0000000 0.0000000 0.000	111.0508789 12.9742933 -0.111	58.8350233 12.9744039 -0.000	64.4774104 12.9746502 0.246	72.7368452 12.9749035 0.500	
6116	0.0725227 16.0464899 -0.381	0.0503110 16.0511224 4.271	72.2846771 16.0466773 -0.174	43.5005650 16.0468512 -0.000	47.0595294 16.0468859 -0.165	56.4284357 16.0469345 0.083	
6117	0.0724974 16.0564102 -0.123	0.0504030 16.0605102 3.917	72.1975780 16.0567824 0.189	43.4655653 16.0565930 0.000	47.0185298 16.0567156 0.123	56.3878361 16.0570329 0.440	
6117	0.0753646 14.9974114 -0.444	0.0409440 15.0041975 6.342	82.4571754 14.9977880 -0.068	47.6710233 14.9978556 -0.000	51.8024820 14.9980455 0.190	61.0263897 14.9982318 0.376	

MAS DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6118	0.0703358 16.9596047 -0.279	0.0500970 16.9618103 1.927	65.1030490 16.9599744 0.091	40.4680953 16.9598838 0.000	43.6091639 16.9598237 -0.060	52.9979700 16.9600146 0.131	
6119	0.0664112 18.8892502 -0.028	0.0865070 18.8396178 0.339	53.4936651 18.8890752 -0.203	35.3561464 18.8892784 -0.000	37.8007220 18.8892016 -0.077	47.0369296 18.8898698 0.591	
6119	0.0638459 20.4075050 -0.094	0.1134000 20.4076142 0.015	46.6889331 20.4078396 0.240	32.1990780 20.4075992 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6120	0.0638453 20.4072492 0.444	0.1133830 20.4067513 -0.054	46.6929331 20.4068330 0.028	32.2005780 20.4068053 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6121	0.0638513 20.4040523 -1.059	0.1133400 20.4045685 -0.543	46.6999330 20.4050716 -0.040	32.2037780 20.4051118 -0.000	34.2289577 20.4055845 0.473	0.0000000 0.0000000 0.000	
6131	0.0644233 20.0448335 -0.415	0.1064380 20.0437433 -1.502	48.1698183 20.0452075 -0.038	32.8986710 20.0452457 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6131	0.0644234 20.0466198 -0.653	0.1064920 20.0466310 -0.642	48.1619184 20.0470899 -0.183	32.8946711 20.0472730 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6132	0.0669926 18.5760854 -0.264	0.0816500 18.5761589 -0.190	55.1162488 18.5762496 -0.100	36.0893391 18.5763491 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6132	0.0669827 18.5813339 -0.031	0.0817340 18.5817219 0.360	55.0883491 18.5814902 0.128	36.0773392 18.5813618 0.000	38.6188138 18.5814184 0.057	0.0000000 0.0000000 0.000	
6133	0.0714048 16.5005872 0.155	0.0549710 16.5037963 3.364	68.5513145 16.5002101 -0.222	41.9339807 16.5004320 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	

MAS DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T518	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6138	0.1189246 7.4999720 0.341	0.0000000 0.0000000 0.000	384.8523028 7.4996500 0.019	154.5409091 7.4996307 0.000	169.7106057 7.4995933 -0.037	152.2719545 7.4999664 0.336	
6139	0.1006477 9.4874177 0.255	0.0000000 0.0000000 0.000	224.2835142 9.4872752 0.113	99.5250095 9.4871626 0.000	110.0027999 9.4876040 0.441	0.0000000 0.0000000 0.000	
6139	0.1006364 9.4889738 0.251	0.0000000 0.0000000 0.000	224.1965160 9.4888641 0.142	99.4953101 9.4887223 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6140	0.0885791 11.5034143 0.638	0.0000000 0.0000000 0.000	144.4091118 11.5029133 0.137	71.2163756 11.5027760 0.000	78.4564308 11.5029633 0.187	0.0000000 0.0000000 0.000	
6140	0.0885744 11.5039615 0.127	0.0000000 0.0000000 0.000	144.3901121 11.5035913 -0.243	71.2055759 11.5038345 -0.000	78.4489310 11.5036167 -0.218	84.8537029 11.5039214 0.087	
6141	0.0714373 16.4870217 0.559	0.0548220 16.4898113 3.348	68.6573134 16.4867295 0.267	41.9803802 16.4864628 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6142	0.1398874 6.0493608 -0.214	0.0000000 0.0000000 -0.000	614.6797062 6.0496309 0.056	232.1813563 6.0495752 0.000	250.9679805 6.0497444 0.169	203.5459290 6.0497250 0.150	
6142	0.1323376 6.5019828 -0.026	0.0000000 0.0000000 -0.000	527.1094576 6.5021316 0.123	202.7269454 6.5020089 0.000	220.4795903 6.5022034 0.195	184.9083018 6.5022854 0.276	
6143	0.1086680 8.4986398 -0.143	0.0000000 0.0000000 -0.000	289.3392131 8.4987567 -0.026	121.9615607 8.4987828 -0.000	134.6023079 8.4988740 0.091	128.0844383 8.4992283 0.445	
6143	0.1086696 8.4984632 -0.171	0.0000000 0.0000000 -0.000	289.3512129 8.4986039 -0.030	121.9655606 8.4986342 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	

MAS DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T518	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6144	0.0970985 10.0027225 -0.301	0.0000000 0.0000000 -0.000	198.4380312 10.0031084 0.085	90.4941901 10.0030232 0.000	100.0049999 10.0033277 0.305	102.3159536 10.0033673 0.344	
6144	0.0970967 10.0029981 -0.336	0.0000000 0.0000000 -0.000	198.4240314 10.0034144 0.080	90.4891902 10.0033343 0.000	100.0019999 10.0034958 0.161	0.0000000 0.0000000 0.000	
6145	0.0939868 10.5030417 -0.331	0.0000000 0.0000000 -0.000	177.3844522 10.5034132 0.040	83.0603388 10.5033731 0.000	91.7321653 10.5033671 -0.006	95.7670846 10.5035101 0.137	
6145	0.0840262 12.5066630 -0.140	0.0000000 0.0000000 -0.000	120.1377986 12.5070969 0.094	62.2619774 12.5070032 0.000	68.3559164 12.5072663 0.263	76.1776382 12.5072394 0.236	
6146	0.0801834 13.5013415 -0.486	0.0000000 0.0000000 -0.000	102.1059789 13.5017764 -0.051	55.4134459 13.5018273 -0.000	60.5973940 13.5022187 0.391	69.2343077 13.5022404 0.413	
6146	0.0801830 13.5014533 -0.423	0.0000000 0.0000000 -0.000	102.1040789 13.5018967 0.020	55.4131459 13.5018766 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6147	0.0768603 14.4986597 -0.269	0.0000000 0.0000000 -0.000	88.2229178 14.4988828 -0.046	49.9806002 14.4989288 -0.000	54.4281557 14.4991948 0.266	63.5178648 14.4993252 0.396	
6147	0.0739493 15.5020930 -0.268	0.0450290 15.4873864 -14.975	77.2671273 15.5024184 0.057	45.5605444 15.5023614 0.000	49.4026060 15.5023691 0.008	58.7154128 15.5027644 0.403	
6148	0.0694016 17.3822182 0.005	0.0651850 17.3834677 1.254	62.1969780 17.3825071 0.294	39.2159078 17.3822135 0.000	42.1845782 17.3823317 0.118	51.5579844 17.3827179 0.504	
6149	0.0653226 19.5049888 0.000	0.0967180 19.5044828 0.000	50.5374946 19.5044868 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	

MAS DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T61E	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
6149	0.0653236 19.5044047 0.254	0.0967080 19.5039080 -0.242	50.5399946 19.5039395 -0.211	34.0032600 19.5041505 -0.000	36.2666373 19.5041312 -0.019	45.4205458 19.5047130 0.563	

CMA DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T518	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
7035	0.0633048 5.4944276 -0.561	0.0000000 0.0000000 -0.000	750.6159874 5.4948641 -0.125	277.4184515 5.4949888 -0.000	297.1790563 5.4947816 -0.207	230.7843842 5.4945762 -0.413	
7035	0.0752168 4.2006686 -0.034	0.0000000 0.0000000 -0.000	1287.7142452 4.2005399 -0.162	447.5080497 4.2007024 -0.000	466.1206774 4.2004712 -0.231	323.3835322 4.2006167 -0.086	
7043	0.0803870 3.7921980 0.135	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	534.0663185 3.7922627 0.000	550.1329971 3.7922635 0.001	366.7496649 3.7922705 0.008	
7044	0.0803390 3.7958235 -0.322	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	533.1273372 3.7961452 -0.000	549.2690144 3.7959623 -0.183	366.2346752 3.7966072 0.462	
7045	0.0731401 4.3904931 0.356	0.0000000 0.0000000 0.000	1179.1164172 4.3901446 0.008	414.3817122 4.3901368 0.000	433.6613266 4.3899170 -0.220	306.2238754 4.3901814 0.045	
7045	0.0605255 6.0510227 -0.072	0.0000000 0.0000000 -0.000	614.4307111 6.0507946 -0.300	232.0723585 6.0510948 -0.000	250.8849822 6.0508689 -0.226	203.4999299 6.0507609 -0.334	
7046	0.0522054 8.0612183 0.221	0.0000000 0.0000000 0.000	326.6694665 8.0614136 0.416	134.7413051 8.0609973 0.000	148.4670306 8.0607028 -0.295	137.8472430 8.0604745 -0.523	
7046	0.0439512 12.0226581 0.034	0.0000000 0.0000000 0.000	130.9253814 12.0233238 0.720	66.2783744 12.0226039 0.000	72.8993420 12.0221864 -0.418	80.1309973 12.0221033 -0.501	
7047	0.0397603 16.0187800 0.110	0.0000000 0.0000000 0.000	72.5266747 16.0187140 0.044	43.6021640 16.0186696 0.000	47.1770282 16.0180432 -0.626	56.5460345 16.0177738 -0.896	
7047	0.0397606 16.0183989 0.000	0.0000000 0.0000000 0.000	72.5291747 16.0184260 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	

CMA DATA 4.0<T<20.5

15 APR 70

NO	K T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
7047	0.0397609 16.0180178 0.000	0.0000000 0.0000000 0.000	72.5309747 16.0182186 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
7056	0.0415287 14.0484869 0.038	0.0340250 14.0553030 6.854	94.0670593 14.0481348 -0.314	52.2863771 14.0484486 -0.000	57.0521295 14.0480807 -0.368	65.9733403 14.0479197 -0.529	
7057	0.0385570 18.0247477 0.817	0.0736460 18.0241727 0.242	58.2012180 18.0244099 0.479	37.4663253 18.0239306 0.000	40.1962980 18.0239649 0.034	49.5290047 18.0231705 -0.760	
7058	0.0365958 20.5168281 0.662	0.1155580 20.5169000 0.734	46.2605374 20.5165388 0.373	31.9952800 20.5161656 0.000	33.9939631 20.5163413 0.176	42.9906701 20.5164940 0.328	
7064	0.0439583 12.0175588 -0.499	0.0000000 0.0000000 -0.000	131.0523789 12.0180200 -0.038	66.3185736 12.0180580 -0.000	72.9431411 12.0177970 -0.261	80.1699986 12.0175662 -0.492	
7065	0.0397267 16.0615795 -0.421	0.0504590 16.0662245 4.224	72.1535785 16.0618955 -0.105	43.4461655 16.0620001 -0.000	46.9997300 16.0613207 -0.679	56.3720363 16.0609671 -1.033	
7066	0.0370342 20.4993384 0.365	0.1152060 20.4992893 0.316	46.3278367 20.4993458 0.372	32.0273797 20.4989736 0.000	34.0308597 20.4988521 -0.122	43.0288697 20.4997177 0.744	
7070	0.0369390 20.5101518 -0.162	0.1154320 20.5106000 0.276	46.2862371 20.5099681 -0.356	32.0061799 20.5103240 -0.000	34.0074599 20.5099385 -0.385	43.0052699 20.5100787 -0.245	
7072	0.0729746 4.4063610 -0.087	0.0000000 0.0000000 -0.000	1170.4865898 4.4063442 -0.104	411.7017658 4.4064481 -0.000	431.0313792 4.4062048 -0.243	304.8239034 4.4064607 0.013	
7073	0.0673463 5.0212437 -0.351	0.0000000 0.0000000 -0.000	901.2819740 5.0214072 -0.207	326.6434670 5.0216145 -0.000	346.7400651 5.0212756 -0.339	258.8948220 5.0215114 -0.103	

CMA DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(DHMS) (KELVINS) (MILLIKELVINS)
7074	0.0561044 6.9753640 -0.229	0.0000000 0.0000000 -0.000	452.2709544 6.9753459 -0.247	177.4034519 6.9755927 -0.000	193.9691205 6.9753704 -0.222	168.1596367 6.9754307 -0.162	
7075	0.0496230 8.9858032 -0.631	0.0000000 0.0000000 -0.000	254.3349132 8.9862333 -0.206	109.9238015 8.9864394 -0.000	121.4685706 8.9858865 -0.553	118.5746285 8.9859500 -0.489	
7076	0.0475924 9.8808089 -0.568	0.0000000 0.0000000 -0.000	204.1359172 9.8811765 -0.200	92.4881502 9.8813768 -0.000	102.2299554 9.8810524 -0.324	104.0499190 9.8809554 -0.421	
7077	0.0457009 10.8884938 0.257	0.0000000 0.0000000 0.000	163.4097317 10.8884734 0.237	78.0784384 10.8882367 0.000	86.1652767 10.8879466 -0.290	91.2611747 10.8878142 -0.422	
7077	0.0427299 12.9652230 0.130	0.0000000 0.0000000 0.000	111.2178878 12.9651314 0.033	58.8994110 12.9650981 0.000	64.5533545 12.9649611 -0.137	72.8082719 12.9647162 -0.382	
7078	0.0406209 14.9953152 -0.380	0.0409140 15.0004938 4.799	82.4851751 14.9952177 -0.477	47.6805232 14.9956951 -0.000	51.8164818 14.9952463 -0.449	61.0423896 14.9948849 -0.810	
7079	0.0390579 16.9637412 0.109	0.0601500 16.9663793 2.747	65.0747492 16.9639268 0.294	40.4565954 16.9636326 0.000	43.5975640 16.9631482 -0.484	52.9884701 16.9627220 -0.911	
7080	0.0370002 20.5076631 0.178	0.1153750 20.5077500 0.265	46.2965370 20.5073365 -0.149	32.0114799 20.5074850 -0.000	34.0129599 20.5073314 -0.154	43.0114699 20.5073557 -0.129	
7081	0.0756036 4.1671097 -0.218	0.0000000 0.0000000 -0.000	1308.4538304 4.1670785 -0.249	453.7539247 4.1673274 -0.000	472.2255553 4.1670722 -0.255	326.5834682 4.1671979 -0.130	
7084	0.0690320 4.8214452 0.037	0.0000000 0.0000000 0.000	978.1904358 4.8207096 -0.697	351.2729744 4.8214070 -0.000	0.0000000 0.0000000 -0.000	272.5145496 4.8211666 -0.240	

CMA DATA 4.0<T<20.5

15 APR 70

NO	X T(X) T-T618	RPT T55 T-T618	R803 TM(803) T-T618	R618 TM(618) T-T618	R622 TM(622) T-T618	R248 TM(248) T-T618	(OHMS) (KELVINS) (MILLIKELVINS)
7085	0.0690333 4.8212945 0.119	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	351.3029738 4.8211755 0.000	0.0000000 0.0000000 0.000	272.5245494 4.8210256 -0.150	
7086	0.0668667 5.0844634 0.103	0.0000000 0.0000000 0.000	878.9224212 5.0843989 0.038	319.4346112 5.0843605 0.000	339.5252094 5.0840055 -0.355	254.8489029 5.0843841 0.024	
7088	0.0669516 5.0723365 0.099	0.0000000 0.0000000 0.000	883.2123354 5.0721384 -0.099	320.8095837 5.0722372 -0.000	340.8731824 5.0721409 -0.096	255.6248874 5.0722001 -0.037	
7090	0.0605346 6.0493725 0.104	0.0000000 0.0000000 0.000	614.7477048 6.0493132 0.045	232.2033558 6.0492686 0.000	251.0149796 6.0491079 -0.161	203.5769284 6.0490271 -0.241	
7091	0.0782150 3.9538441 -0.107	0.0000000 0.0000000 -0.000	1453.7709240 3.9534710 -0.480	496.9900600 3.9539509 -0.000	514.2897140 3.9537557 -0.195	348.4030318 3.9539017 -0.049	
7092	0.0752720 4.1958464 -0.149	0.0000000 0.0000000 -0.000	1290.6741860 4.1957141 -0.281	448.3810322 4.1959955 -0.000	466.9906600 4.1956708 -0.325	323.8435230 4.1957770 -0.219	
7093	0.0605410 6.0482125 -0.053	0.0000000 0.0000000 -0.000	614.9877000 6.0481924 -0.073	232.2753544 6.0482655 -0.000	251.0789783 6.0482414 -0.024	203.6209275 6.0480369 -0.229	
7094	0.0522038 8.0617332 -0.466	0.0000000 0.0000000 -0.000	326.6244674 8.0618993 -0.300	134.7033059 8.0621990 -0.000	148.4270314 8.0618742 -0.325	137.8172436 8.0617416 -0.457	
7095	0.0415439 14.0336500 -0.847	0.0000000 0.0000000 -0.000	94.2590574 14.0341522 -0.345	52.3614764 14.0344973 -0.000	57.1366286 14.0342629 -0.234	0.0000000 0.0000000 -0.000	
7096	0.0378284 18.9170557 -1.725	0.0869610 18.9181875 -0.594	53.3478665 18.9180094 -0.772	35.2886471 18.9187811 -0.000	37.7256227 18.9181333 -0.648	46.9611304 18.9177333 -1.048	

MAS DATA 18.0<T<34.0

15 APR 79

NO	X T(X) T-T55	RPT T55 T-T55	R803 TM(803) T-T55	R618 TM(618) T-T55	R622 TM(622) T-T55	R248 TM(248) T-T55	(OHMS) (KELVINS) (MILLIKELVINS)
6088	0.0572782 25.5972361 1.318	0.2528300 25.5959184 0.000	31.8551814 25.5958529 -0.066	24.6561534 25.5960112 0.093	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6088	0.0596395 24.0273399 0.125	0.2024110 24.0272148 0.000	35.3770462 24.0269713 -0.243	26.5541345 24.0268904 -0.324	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6089	0.0604585 22.8314957 0.738	0.1688820 22.8307576 0.000	38.5400146 22.8302780 -0.480	28.1946181 22.8298875 -0.870	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6090	0.0622236 21.5006341 0.414	0.1364150 21.5002203 0.000	42.6775732 21.4994529 -0.767	30.2628974 21.4994264 -0.794	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6090	0.0636903 20.5139598 0.160	0.1154960 20.5138000 0.000	46.2721373 20.5134689 -0.331	32.0004800 20.5134787 -0.321	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6091	0.0633508 20.7225239 -0.501	0.1197220 20.7230244 -0.000	45.4635454 20.7233612 0.337	31.6143839 20.7231426 0.118	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6091	0.0633595 20.7233312 0.357	0.1197220 20.7230244 0.000	45.4617454 20.7238358 0.811	31.6132839 20.7237474 0.723	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6092	0.0680564 18.0292181 0.441	0.0737100 18.0287770 0.000	58.1736183 18.0294497 0.673	37.4534255 18.0295637 0.787	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6092	0.0680562 18.0293179 0.541	0.0737100 18.0287770 0.000	58.1774182 18.0288030 0.026	37.4556254 18.0287189 -0.058	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6119	0.0664112 18.8892502 -0.368	0.0865070 18.8896178 -0.000	53.4936651 18.8888999 -0.718	35.3561464 18.8887214 -0.896	37.8007220 0.0000000 -0.000	47.0369296 0.0000000 -0.000	

MAS DATA 18.0<T<34.0

15 APR 70

NO	X T(X) T-T55	RPT T55 T-T55	R803 TM(803) T-T55	R618 TM(618) T-T55	R622 TM(622) T-T55	R248 TM(248) T-T55	(JHMS) (KELVINS) (MILLIKELVINS)
6119	0.0638+59 20.4075050 -0.109	0.1134000 20.4076142 -0.000	46.6889331 20.4077671 0.153	32.1950780 20.4076164 0.002	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6120	0.0638+63 20.4072+92 0.498	0.1133830 20.4067513 0.000	46.6929331 20.4067607 0.009	32.2005780 20.4068219 0.071	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6121	0.0638+13 20.4040523 -0.516	0.1133400 20.4045685 -0.000	46.6999330 20.4049999 0.431	32.2037780 20.4051272 0.559	34.2289577 0.0000000 0.000	0.0000000 0.0000000 0.000	
6122	0.0604917 22.8049+23 -1.421	0.1682380 22.8063636 -0.000	38.6100139 22.8057145 -0.649	28.2302177 22.8053830 -0.981	29.7491025 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6122	0.0604940 22.8031051 -0.531	0.1681660 22.8036364 -0.000	38.6155138 22.8037878 0.151	28.2333177 22.8032520 -0.384	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6122	0.0604949 22.8023+62 0.265	0.1681260 22.8021212 0.000	38.6172138 22.8031923 1.071	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6123	0.0574838 25.4913570 -0.725	0.2492700 25.4920821 -0.000	32.0697793 25.4918706 -0.212	24.7747522 25.4915484 -0.534	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6123	0.0574841 25.4910575 -0.966	0.2492680 25.4920235 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6124	0.0559598 27.1098021 -1.518	0.3086860 27.1113198 -0.000	28.9881101 27.1099583 -1.361	23.0451695 27.1100167 -1.303	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6124	0.0559628 27.1064140 0.196	0.3084850 27.1062183 0.000	28.9947100 27.1061802 -0.038	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	

WAS DATA 18.OCT<34.O

15 APR 70

NO	X T(X) T-T55	RPT T55 T-T55	R803 TM(803) T-T55	R618 TM(618) T-T55	R622 TM(622) T-T55	R248 TM(248) T-T55	(OHMS) (KELVINS) (MILLIKELVINS)
6125	0.0541011 29.3856540 -2.632	0.4059900 29.3882863 -0.000	25.4354456 29.3856119 -2.674	20.9507905 29.3848602 -3.426	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6125	0.0541022 29.3841940 -0.882	0.4058420 29.3850759 -0.000	25.4379456 29.3838182 -1.258	20.9521905 29.3832051 -1.871	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6126	0.0510979 33.9984713 0.651	0.6517890 33.9978203 0.000	20.1720983 33.9982438 0.423	17.5990240 33.9981469 0.327	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6126	0.0510983 33.9977604 0.406	0.6517610 33.9973544 0.000	20.1723983 33.9979235 0.569	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6127	0.0510988 33.9968717 0.033	0.6517300 33.9968386 0.000	20.1732983 33.9969627 0.124	17.5996240 33.9971933 0.355	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6127	0.0510997 33.9952723 0.231	0.5516220 33.9950416 0.000	20.1748982 33.9952547 0.213	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6128	0.0530930 30.8022595 0.094	0.4745000 30.8021654 0.000	23.5867641 30.8021216 -0.044	19.8102019 30.8023231 0.158	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6129	0.0590197 24.0449143 -0.186	0.2029440 24.0451007 -0.000	35.3306467 24.0458922 0.792	26.5297347 24.0457464 0.646	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6130	0.0622126 21.5084466 -0.937	0.1366230 21.5093833 -0.000	42.6473735 21.5083493 -1.034	30.2482975 21.5081907 -1.193	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6130	0.0622146 21.5070258 0.109	0.1365670 21.5069163 0.000	42.6516735 21.5070819 0.166	30.2504975 21.5068695 -0.047	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	

MAS DATA 18.0<T<34.0

15 APR 70

NO	X T(X) T-T55	RPT T55 T-T55	R803 TM(803) T-T55	R618 TM(618) T-T55	R622 TM(622) T-T55	R248 TM(248) T-T55	(OHMS) (KELVINS) (MILLIKELVINS)
6131	0.0644204 20.0466198 -0.011	0.1064920 20.0466310 -0.000	48.1619184 20.0470881 0.457	32.8946711 20.0470880 0.457	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6131	0.0644233 20.0448305 1.087	0.1064380 20.0437433 0.000	48.1698183 20.0452059 1.463	32.8986710 20.0450598 1.316	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
6132	0.0669927 18.5813309 -0.391	0.0817340 18.5817219 -0.000	55.0883491 18.5812866 -0.435	36.0773392 18.5808800 -0.842	38.6188138 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6132	0.0669926 18.5760354 -0.074	0.0816500 18.5761589 -0.000	55.1162488 18.5760466 -0.112	36.0893391 18.5758705 -0.288	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6149	0.0653226 19.5049388 0.506	0.0967180 19.5044828 0.000	50.5374946 19.5044676 -0.015	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
6149	0.0653236 19.5044047 0.497	0.0967080 19.5039080 0.000	50.5399946 19.5039202 0.012	34.0032600 19.5037592 -0.149	36.2666373 0.0000000 -0.000	45.4205458 0.0000000 -0.000	

CMA DATA 18.0<T<34.0

15 APR 70

NO	X T(X) T-T55	RPT T55 T-T55	R803 TM(803) T-T55	R618 TM(618) T-T55	R622 TM(622) T-T55	R248 TM(248) T-T55	(OHMS) (KELVINS) (MILLIKELVINS)
7048	0.0355803 23.9618071 0.996	0.2004400 23.9608108 0.000	35.5386446 23.9614054 0.595	26.6397336 23.9609949 0.184	27.9666203 0.0000000 0.000	36.3029370 0.0000000 0.000	
7048	0.0355799 23.9629441 2.133	0.2004400 23.9608108 0.000	35.5376446 23.9618095 0.999	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	
7057	0.0383570 18.0247477 0.575	0.0736460 18.0241727 0.000	58.2012180 18.0247545 0.582	37.4663253 18.0246116 0.439	40.1962980 0.0000000 0.000	49.5290047 0.0000000 0.000	
7058	0.0369958 20.5163281 -0.072	0.1155580 20.5169000 -0.000	46.2605374 20.5164345 -0.465	31.9952800 20.5162684 -0.632	33.9939601 0.0000000 -0.000	42.9906701 0.0000000 -0.000	
7059	0.0360081 22.8045650 -0.473	0.1682030 22.8050379 -0.000	38.6104139 22.8055744 0.536	28.2297177 22.8057268 0.689	29.7497025 0.0000000 0.000	38.3206168 0.0000000 0.000	
7060	0.0353737 24.5637902 -0.318	0.2188330 24.5641083 -0.000	34.0976590 24.5647955 0.687	25.8698413 24.5682281 4.120	27.1104289 0.0000000 0.000	35.3222468 0.0000000 0.000	
7061	0.0346162 27.0559456 0.048	0.3065200 27.0558974 0.000	29.0826092 27.0560029 0.105	23.0991690 27.0562246 0.327	24.0249597 0.0000000 0.000	31.7137829 0.0000000 0.000	
7062	0.0340216 29.3970415 -0.572	0.4064200 29.3976139 -0.000	25.4188458 29.3975294 -0.084	20.9399906 29.3976352 0.021	21.6452835 0.0000000 0.000	28.8486115 0.0000000 0.000	
7066	0.0370042 20.4993384 0.049	0.1152060 20.4992893 0.000	46.3278367 20.4992468 -0.043	32.0273797 20.4990619 -0.227	34.0308597 0.0000000 -0.000	43.0288697 0.0000000 -0.000	
7067	0.0353730 24.565813 1.423	0.2188440 24.5644586 0.000	34.0956590 24.5656632 1.205	25.8730413 24.5656350 1.176	27.1095289 0.0000000 0.000	35.3207468 0.0000000 0.000	

CMA DATA 18.0<T<34.0

15 APR 70

NO	X T(X) T-T55	RPT T55 T-T55	R803 TM(803) T-T55	R618 TM(618) T-T55	R622 TM(622) T-T55	R249 TM(249) T-T55	(OHMS) (KELVINS) (MILLIKELVINS)
7068	0.0340269 29.3743860 -0.408	0.4053680 29.3747939 -0.000	25.4508455 29.3745679 -0.226	20.9587904 29.3754049 0.611	21.6660833 0.0000000 0.000	28.8741113 0.0000000 0.000	
7069	0.0383745 17.9966438 -0.458	0.0732700 17.9971014 -0.000	58.3654163 17.9969060 -0.195	37.5379246 17.9971973 0.096	40.2762972 0.0000000 0.000	49.6132039 0.0000000 0.000	
7070	0.0369990 20.5101618 -0.438	0.1154320 20.5106000 -0.000	46.2862371 20.5098658 -0.734	32.0061799 20.5104218 -0.178	34.0074599 0.0000000 -0.000	43.0052699 0.0000000 -0.000	
7071	0.0360123 22.7937574 -0.012	0.1679080 22.7937692 -0.000	38.6472135 22.7926921 -1.077	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	0.0000000 0.0000000 -0.000	
7071	0.0360127 22.7927286 -0.271	0.1678880 22.7930000 -0.000	38.6488135 22.7921325 -0.868	28.2477175 22.7933591 0.359	29.7699023 0.0000000 0.000	38.3450165 0.0000000 0.000	
7080	0.0370002 20.5076631 -0.087	0.1153750 20.5077500 -0.000	46.2965370 20.5072350 -0.515	32.0114799 20.5075804 -0.170	34.0129599 0.0000000 -0.000	43.0114699 0.0000000 -0.000	
7096	0.0378284 18.9170557 -1.132	0.0869610 18.9181875 -0.000	53.3478665 18.9178409 -0.347	35.2886471 18.9182262 0.039	37.7256227 0.0000000 0.000	46.9611304 0.0000000 0.000	
7097	0.0367694 20.9997234 -0.464	0.1254940 21.0001878 -0.000	44.4344557 21.0001271 -0.061	31.1188888 20.9999055 -0.282	33.0043700 0.0000000 -0.000	41.9166808 0.0000000 -0.000	
7098	0.0353769 24.5542357 0.287	0.2185140 24.5539490 0.000	34.1200588 24.5550826 1.134	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	0.0000000 0.0000000 0.000	

APPENDIX C. ADDITIONAL CALIBRATION DATA

The following three tables, which are reproduced from RTAS (14), give additional calibration data on GER's 803 and 618. Table 2 summarizes the CVGT data taken at the National Standards Laboratory, Sydney, Australia, in 1965. Table 3 lists the coefficients of Equation 7 which were determined from a least squares fit of the data in Table 2. Table 4 gives the NBS-Acoustic (13) calibration data for GER 803.

Table 2. A summary of the experimental CVGT calibration data for Ge thermometers GR618 and GR803.

Run	Measuring current (μ A)	<u>R (Ω)</u>		T (K)					
		GR618	GR803	T ₅₈	PTR	CVGT		calculated ^a	
						initial ^b	adjusted ^c	GR618	GR803
RJT-1	3	2331.2	10132.8	1.700	-	-	-	-	-
RJT-1	3	1632.4	6375.5	2.042	-	2.047	-	-	2.047
JSR-1	10	1364.5	5049.9	2.237	-	2.245	-	-	2.245
JSR-2	3	1251.1	4522.2	2.344	-	2.356	2.352	2.351	2.349
JSR-1	10	1170.7	4148.2	2.427	-	2.432	-	2.433	2.435
JSR-1	10	1037.2	3557.9	2.593	-	2.598	-	2.597	2.600
JSR-1	10	898.61	2971.7	2.808	-	2.815	-	2.814	2.814
JSR-1	10	795.93	2556.6	3.007	-	3.014	-	3.015	3.014
JSR-2	3	791.80	2542.3	3.017	-	3.029	3.024	3.024	3.022
JSR-1	10	668.77	2067.9	3.328	-	3.332	-	3.332	3.331

^aCalculated from Table 3.

^bCalculated using Kilpatrick et al. (17) virial coefficients designated MR-5.

^cInitial temperatures calculated for JSR-2 reduced by 0.15%.

Table 2. (continued)

Run	Measuring current - (μ A)	GR618	GR803	T ₅₈	PTR	CVGT		calculated ^a	
						initial ^b	adjusted ^c	GR618	GR803
JSR-2	3	545.22	1621.0	3.741	-	3.757	3.751	3.750	3.750
JSR-2	10	442.75	1271.7	4.221	-	4.233	4.227	4.228	4.230
RJT-1	10	442.08	1269.7	4.222	-	4.233	-	4.232	4.233
RJT-1	10	442.07	1269.6	4.224	-	4.232	-	4.232	4.233
RJT-2	10	413.91	1177.8	-	-	4.392	-	4.394	4.395
JSR-2	10	378.23	1062.95	-	-	4.633	4.626	4.625	4.626
JSR-2	10	327.96	905.26	-	-	5.018	5.010	5.010	5.010
JSR-2	10	284.79	773.01	-	-	5.425	5.417	5.416	5.414
JSR-2	10	248.53	663.55	-	-	5.840	5.831	5.832	5.830
JSR-2	10	219.87	578.02	-	-	6.237	6.228	6.228	6.226
JSR-2	10	186.70	479.66	-	-	6.803	6.793	6.792	6.790
JSR-2	10	156.11	389.40	-	-	7.469	7.458	7.461	7.462
RJT-1	10	149.41	369.71	-	-	7.637	-	7.635	7.637
JSR-2	10	140.21	342.77	-	-	7.909	7.897	7.895	7.896
JSR-2	10	123.77	294.61	-	-	8.447	8.434	8.434	8.436

Table 2. (continued)

Run	Measuring current (μ A)	GR613	GR803	T ₅₈	PTR	CVGT		calculated ^a	
						initial ^b	adjusted ^c	GR618	GR803
JSR-2	10	107.86	-	-	-	9.092	9.078	9.079	-
JSR-2	10	107.50	247.29	-	-	9.110	9.096	9.096	9.098
JSR-2	10	97.230	217.67	-	-	9.623	9.609	9.609	9.611
RJT-2	10	89.148	194.615	-	10.144	10.087	-	10.086	10.086
JSR-2	10	81.816	173.88	-	-	10.609	10.593	10.593	10.592
JSR-2	10	71.569	145.39	-	11.484	11.482	11.465	11.465	11.463
JSR-2 ^d	10	63.369	123.10	-	12.378	12.378	12.359	12.364	12.362
RJT-2	10	57.154	106.63	-	13.235	13.228	-	13.223	13.221
RJT-1	10	47.840	82.877	-	14.966	14.959	-	14.962	14.960
JSR-1 ^d	10	43.507	72.144 ^e	-	16.050	16.050	-	16.049	-
RJT-2 ^d	10	37.032	57.224	-	18.195	18.199	-	18.198	18.199
RJT-2 ^d	10	32.012	46.297	-	20.511	20.513	-	20.510	20.511

^dCalibration temperatures.

^eThis resistance appears to have been recorded incorrectly, and this point has been ignored in the least squares fits for GR803.

Table 2. (continued)

Run	Measuring current (μ A)	GR618	GR803	T_{58}	PTR	CVGT		calculated ^a	
						initial ^b	adjusted ^c	GR618	GR803
RJT-2 ^d	10	28.154	38.455	-	22.864	22.863	-	22.860	22.861
RJT-2 ^d	10	25.123	32.705	-	25.194	25.192	-	25.193	25.191
RJT-1 ^d	100	22.864	28.672	-	27.295	27.295	-	27.296	27.296
RJT-2	100	17.552	20.102	-	34.074	34.082	-	-	-
RJT	100	10.032	10.159	-	54.360	-	-	-	-
RJT	100	8.897	8.865	-	60.425	-	-	-	-
RJT	100	6.258	6.056	-	85.637	-	-	-	-
RJT	100	5.947	5.744	-	90.883	-	-	-	-

Table 3. The fit constants for Equation 7 which were used to obtain the calculated NSL temperatures shown in Table 2. The notation D-03 means $\times 10^{-3}$. $\text{Log}_e(T) = \sum A(n)[\text{Log}_e(R)]^{n-1}$.

	GR618	GR803
A(1)	1.0791517940 D 03	2.6563737373 D 01
A(2)	-2.3137690777 D 03	-3.4965424664 D 01
A(3)	2.2107975212 D 03	2.3770163867 D 01
A(4)	-1.2349857746 D 03	-9.1240863489 D 00
A(5)	4.4687088288 D 02	2.1151730605 D 00
A(6)	-1.0954691786 D 02	-3.0254197055 D-01
A(7)	1.8442433742 D 01	2.6099854354 D-02
A(8)	-2.1071550176 D 00	-1.2447445817 D-03
A(9)	1.5647852069 D-01	2.5205585083 D-05
A(10)	-6.8237230388 D-03	0
A(11)	1.3275654893 D-04	0

Table 4. Calibration data for GR803 as supplied by the National Bureau of Standards, based on the Acoustic scale (13). Two independent calibrations, the same to within 1 mK, were made, and only the second is given below. The first column contains temperatures as supplied with the "Original" calibrations. The second column contains temperatures for the calibration points which have been "Adjusted" to compensate for recently found errors which occurred in the transfer of the calibration from the Acoustic interferometer to the NBS calibration apparatus (H. Plumb, NBS, Washington, D. C. Private communication, 1967.)

<u>Temperature</u>		<u>Resistance</u> (Ω)	<u>Current</u> (μ A)
Original	(K) Adjusted		
2.318	2.320	4671.5	.52
2.807	2.808	2986.9	.73
3.208	3.212	2233.9	1.03
4.206	4.209	1285.29	1.71
5.019	5.023	902.16	2.54
6.060	6.053	614.59	2.86
6.977	6.978	452.83	3.29
8.066	8.065	326.83	8.09
8.989	8.987	254.45	8.40
9.887	9.883	204.10	8.63
10.901	10.898	163.126	8.82
12.018	12.018	131.134	15.6
12.962	12.962	111.314	15.7
14.048	14.048	94.088	17.5

Table 4. (continued)

Original	Temperature		Resistance (Ω)	Current (μA)
	(K)	Adjusted		
14.991		14.993	82.552	21.5
16.050		16.052	72.287	21.6
16.969		16.968	65.087	27.6
18.005		18.008	58.332	27.7
18.940		18.944	53.249	28.8
20.049		20.052	48.200	30.5