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A Critical Review of the Effect of Pressure on Thermocouple EMF's

by

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ABSTRACT

The effects of high pressure on the emf's of thermocouples are critically reviewed and best currently available thermocouple corrections are presented. The important factors affecting these thermocouple corrections are discussed including pressure-temperature gradients, contamination and deformation. A novel method for simultaneous and continuous in situ measurement of pressure and temperature within a high pressure cell through use of dual thermocouples is briefly described.

Paper to be presented at Symposium on the Accurate Characterization of the High-Pressure Environment, October 14-18, 1968, U. S. Dept. of Commerce, National Bureau of Standards, Gaithersburg, Maryland.

$$Q = \frac{\pi^2}{3} \frac{k^2 T}{e} \left[\frac{\partial \ln B}{\partial \varepsilon} + \frac{\partial \ln \lambda}{\partial \varepsilon} \right]$$

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I. Introduction

As high pressure research has progressed in the past few years to include more quantitative experiments, the need for more accurate measurement of temperature and pressure has become more critical. Temperature is a particularly sensitive variable because of its importance in numerous thermally activated processes prevalent in materials. Since thermocouples provide the primary means for in situ temperature measurement in most high pressure experiments carried out at elevated temperatures, the effect of pressure on the electromotive force (emf) of thermocouples is often very important.

The central purpose of this paper is to review critically our current knowledge of the effects of pressure on the emf on thermoelectric materials and to discuss the consequences of these effects on the accurate in situ measurement of temperature at high pressure. In addition, the concept of using thermocouples to monitor continuously any local, in situ pressure changes will be described.

II. Determination of Pressure Effects on Thermoelectricity

The current theoretical understanding of thermoelectricity and the electronic properties of metals and alloys is inadequate to permit any reliable quantitative calculations of the effect of pressure on thermal emf's. Thus, we must rely upon experimental determinations of the effect of pressure on thermoelectric behavior.

A. Moderate Temperature-Hydrostatic Pressure Range

The pressure effects on thermal emf's of metals and alloys have been measured in hydrostatic systems by either single wire or composite thermocouple methods. Bridgman[1] carried out the first measurements of the effect of pressure on thermal emf's of various materials using the single wire method illustrated in Fig. 1a. Bridgman's results were accurate to within a few per cent for the conditions studied (0 to 12 kbar and T_2-T_1 = 100°C). His work included some 20 metals and alloys but his measurements did not include most of the thermocouple materials commonly used.

Bell, England and Boyd[2] have recently extended the single wire hydrostatic method to measure accurate corrections on Pt-Pt 10% Rh and chromel-alumel thermocouples up to ~10 kbars and ~500°C. The magnitude of the corrections obtained are in reasonably good agreement with experimental data from non-hydrostatic experiments to be discussed later in this section. Since a detailed paper by Bell et al[2] on these results is included in this symposium, no further discussion of their results needs to be included here.

The related composite thermocouple method for measuring the pressure effects on thermocouples in a hydrostatic system is shown schematically in Fig. 1(b). This method was first attempted by Birch in 1939 over the limited pressure interval 0 to 4 kbars and for temperatures up to ~470°C.[3] Unfortunately, Birch failed to recognize the important principle that only that part of the temperature gradient lying within the pressurized zone can contribute to the pressure correction of thermocouples. Thus, his deduced corrections were substantially smaller than the true ones. It is perhaps fair to remark that at least several other researchers have been caught by the same trap in attempts to measure pressure effects on thermocouples.

Bloch and Chaisse[4] have correctly used the composite thermocouple method to determine the effect of pressure on copper-constantan thermocouples over the range 0 to 5 kbars and -196°C to 89°C. This is the most reliable data available for low temperature work and it is of particular

interest for quantitative hydrostatic studies of magnetic and crystallographic transitions at low temperatures. Their copper-constantan results are in excellent agreement with Bridgman over the limited mutual range of measurement. Figure 2 summarizes some of the best current data available for thermocouple corrections obtained from hydrostatic systems.

In both of the above methods of measurement the pressure gradient in the seal regions from P_J to P_o is essentially isothermal. In addition, the internal temperatures T_J and T_o are at the same temperature as the known external baths. As the internal pressure is increased from the atmospheric pressure P_o to a higher value, P_J, the thermal emf output of a composite thermocouple (or single wire) will continuously deviate from its corresponding value at P_o for fixed values of T_J and T_o. Thus, accurate, absolute corrections for pressure effects on thermocouples can be obtained. The available physical properties of seal and pressure vessel materials have restricted measurements under the above hydrostatic circumstances to pressures less than about 15 kbars and temperatures of no more than several hundred degrees.

B. Higher Pressure-Temperature Range

1. General Problems

Thermocouple corrections at much higher pressures and/or temperatures than discussed above are often needed. Such corrections have been achieved with much experimental difficulty using non-hydrostatic systems but they are only approximate because of: (1) uncertainties in the absolute pressure associated with non-hydrostatic systems used, (2) lack of a precise knowledge of the temperature within the high pressure region, (3) non-isothermal pressure seals and (4) other effects including plastic deformation. In general, the higher the superimposed range of temperature and pressure the more difficult it is to obtain reliable, approximate corrections.

These and other problems in achieving accurate high pressure-high temperature measurement using thermocouples have been discussed by Hanneman and Strong.[5,6] They show that chemical contamination of thermocouples can

frequently occur within high pressure cells at elevated temperatures and that this can strongly alter the output of a thermocouple. Chromel-alumel thermocouples are particularly susceptible to sizable high temperature drift with time in pyrophyllite cells while Pt/Pt 10 Rh thermocouples appear to be relatively inert.

The magnitude of the effect of plastic deformation (such as experienced within seal regions of non-hydrostatic cells) upon the thermal emf of Pt/Pt 10 Rh and chromel/alumel was found generally to be within a few per cent of the total pressure correction at high pressures. As long as a high resistance insulating tubing such as BN or alumina surrounds thermocouple wires at high temperatures, the electrical shunting effect on thermocouple output should be negligible.

One of the most important modifications of thermocouple corrections that can vary from one type of cell to another is the presence of temperature gradients within a pressure gradient region. The total pressure-induced contribution to the emf of a thermocouple is given by the following general expression:[6]

$$\partial E_p = \int_{T_o}^{T_J} \left[\frac{\partial Q}{\partial P}\right] P(\tau)\, dT \qquad (1)$$

where $\partial Q/\partial P$ is the pressure dependence of the thermopower of the couple and $P(\tau)$ is the pressure-temperature function along the thermocouple path into the cell. One can independently express P in terms of T in Eq. (1) without explicitly including the distance variable since both follow continuous paths simultaneously. The quantities T_J and T_o are the internal couple junction temperature and the temperature where the pressure drops to atmospheric pressure, P_o, respectively. The quantity $\partial Q/\partial P$ is, to a first approximation, a constant for the most common thermocouple materials and ∂E_p is nearly proportional to a temperature shift. Thus, the resultant decrease in temperature correction produced by a superimposed pressure-temperature gradient is approximately proportional to the normalized area under a plot of the temperature-pressure path of that thermocouple. Figure 3 shows schematically

a diagram of a typical temperature-pressure path of a thermocouple (i.e., T_o CD) in a typical cell. The area AD T_o T_J corresponds to the maximum theoretical correction if seals were isothermal. The ratio CD T_J T_o/AD T_J T_o is the fraction of the maximum correction applicable to the particular cell and P_J, T_J and T_o of interest. Correction modifications due to the superimposed pressure-temperature gradient effects sometimes exceed 10% of the total temperature correction. The above types of gradient modifications apply to both relative and absolute pressure-induced thermocouple corrections in any kind of apparatus.

Actual measurement of the approximate pressure-temperature gradient function along a thermocouple path within any given cell assembly is a difficult problem. To determine approximate temperature gradients within a cell and its seal region, thermocouples are placed with their junctions in a series of positions from the center of the cell sequentially toward the seal. The raw mv values of all thermocouples (and hence the approximate temperatures) along the path, are determined from experiments where both the cell pressure and internal temperature are varied over the desired range. Care must be taken so that the extra thermocouples do not substantially alter the temperature gradients within the cell. The pressure gradients within a cell can be similarly approximated by a series of localized pressure calibrations as described earlier by Hanneman and Strong.[6] In carrying out such experiments it should be borne in mind that the local pressure within a non-hydrostatic cell at fixed applied load can be dependent upon the temperature.

2. Methods of Determination and Results

Three major classes of measurement methods have been utilized to evaluate absolute emf corrections in non-hydrostatic systems including: (1) a modified Bridgman method,[7] (2) direct thermal noise technique,[8] and (3) indirect, self-consistent, calibration methods.[5]

Modified Bridgman Method

A modified Bridgman method was used in a key study by Bundy to obtain thermocouple corrections over a much wider pressure range than

previously studied (e.g., 0 to 72 kbars).[7] Figure 4 illustrates schematically the Bundy apparatus. The maximum temperature gradient that could be achieved by this apparatus was approximately 100°C because of the sizable thermal conductivity of the system between the hot and cold pistons. It was shown that errors due to a small temperature gradient in the seal regions of the cell did not exceed 5% of the thermocouple corrections obtained. Bundy's results for three common types of thermocouples are shown in Fig. 5. Recent similar measurements by I. Fujishiro, H. Mii and S. Sakaida[9] have recently extended the single wire alumel data of Bundy out to 130 kbars for a 100°C gradient with an opposed anvil apparatus.

Getting[10] has attempted the very challenging task of obtaining absolute thermocouple corrections for Pt/Pt 10 Rh couples up to 40 kbars and 1000°C by the single wire modified Bridgman technique in a piston cylinder apparatus. Although these experiments have met with the great difficulties inherent in obtaining accurate corrections in this high temperature range, some approximate corrections have been deduced. While in common agreement with nearly all workers over the range 0 to 100°C up to 40 kbars these results do come into substantial disagreement with other higher temperature measurements to be described later as well as extrapolations of the lower pressure high temperature measurements of Bell et al.[2]

Since all of the methods described so far have relied essentially upon external heat sources for the known temperature gradients set up within the high pressure cell, the corresponding range of experimental results have been mostly restricted to rather limited temperature differentials within the cells, especially at higher pressures. In order to extend thermocouple corrections to the important region of higher temperatures at high pressures, new methods of measurement using internally heated cells have been devised. These will be described in the next two sections of this paper.

Thermal Noise Method

Studies using the thermal noise method to obtain thermocouple corrections at high pressure and temperature have recently been initiated.[8]

Briefly, this method is based on the fundamental principle that a small pressure independent thermal noise is present in a resistor (or conductor). This may be given by: $(\Delta E)^2/(R\Delta f) = 4kT$ where $(\Delta E)^2$ is the mean squared voltage fluctuations in a conductor of resistance R measured over the frequency interval Δf and kT is the usual thermal energy term. Experiments using this technique are very difficult as they require extremely low noise measurement circuitry and a low noise ambient. Furthermore, d.c. heating is necessary in internally heated high pressure cells to hold noise to a tolerable level. Thus, salt type cells cannot be used because of electrolysis effects. Since the magnitude of the mean voltage fluctuations is of the order of a microvolt per 1000°K, measurements must be carefully made.

The most notable results to date at high pressure and temperature using the thermal noise method are those of Wentorf.[8] He has determined approximate corrections for Pt/Pt 10 Rh thermocouple up to 1000°C and 40 kbars. The very limited data available are in reasonable agreement with the absolute corrections of Hanneman and Strong[6] obtained by a totally different approach that is described in the next section. For example, at 40 kbars and 1000°C the absolute correction to a Pt/Pt 10 Rh thermocouple determined by Wentorf is +40°C compared to a value of +36°C deduced previously by Hanneman and Strong.

Indirect Self-Consistent Methods

The most extensive approximate determinations of absolute type pressure corrections for thermocouples have been obtained from indirect, self-consistent measurements. Until recent advances in low-noise electronics made the thermal noise technique possible, only indirect type measurements could be used to obtain corrections in the important range of high temperature at high pressure.

The first major effort to determine corrections in this region was that of Hanneman and Strong[5] who used the following indirect methods to deduce approximate absolute couple corrections: (1) comparison of experimental and thermodynamically calculated results of the effect of

pressure on numerous single-component phase transformations and diamond growth from metal-carbon systems, and (2) correlation of results of high pressure-high temperature diffusion data. The scheme upon which the first class of indirect methods was carried out can be described most simply by referring to Fig. 6. This figure shows schematically three independent types of phase transformation common to various systems at high pressure. The solid curve A with a very steep temperature-pressure transformation boundary is typical of phase changes with a large ratio of volume change to entropy change such as graphite to diamond. Solid curve B shows a transformation with a relatively low slope (dT/dP) which is typical of melting curves of metals with low volumes of fusion. Solid curve C depicts a transformation with a volume decrease on going to the higher temperature phase. Typical examples of this transformation include the melting of many semiconductors and the $\alpha \rightarrow \gamma$ transformation in iron. The dashed lines are representative of uncorrected, experimental curves that are found for each of the types of transformations. By designing a high pressure cell to measure simultaneously two or more phase transformations (of different types) within the central isobaric pressure region, approximate thermocouple corrections to obtain a best fit of both sets of data can be deduced. Such data provides not only the approximate temperature corrections at pressure but also the temperature coefficient of the internal cell pressure at fixed load. A series of such experiments over various pressure-temperature ranges with a variety of different materials permits a reasonable self-consistent approximation of absolute thermocouple corrections of a given type of thermocouple. The most sensitive types of combinations of transformations are A vs C or B vs C since the C transitions have opposite slopes to the other two types. Numerous experiments of the above types have been carried out by Hanneman and Strong with self-consistent results.

The second independent method they used to test the approximate magnitude of the thermocouple corrections was based on high pressure diffusion experiments and theory. This approach has two indicators of the

size of the correction. The first is to find, by a best fit of data, the appropriate temperature correction at a given pressure and composition which gives a constant value of activation volume for diffusion, V^*, over the temperature range of experimental data while maintaining a linear log D_p vs 1/T plot, where D_p is the diffusion coefficient at a pressure P and temperature T. The second approach is based upon a comparison of the value V^* calculated from the experimental atmospheric and high pressure diffusion coefficients at fixed temperature with that obtained from experiments in the hydrostatic range and from theory. The approximate absolute thermocouple corrections deduced from diffusion data in the iron-vanadium and iron-nickel systems at 20 and 40 kbars are in reasonably good agreement with those obtained up to 1300°C by the other methods described above (i.e., within ~20%). Further details on the diffusion analysis are treated in reference 5. A complete plot of the approximate absolute corrections for Pt/Pt 10 Rh couples deduced from the best fit of all the indirect data of Hanneman and Strong and the thermal noise results of Wentorf adjusted for a pressure gradient factor of unity are presented in Fig. 7. Corresponding approximate absolute corrections for chromel/alumel couples are shown in Fig. 8. The corrections shown should be added to the uncorrected temperature.

III. Effects of Pressure on the Relative Differences Between Various Thermocouples

The relative correction differences due to pressure induced effects on thermocouples can be deduced by simply subtracting the known absolute corrections of two different types of thermocouples at a given temperature and pressure. In the limited pressure-temperature region where hydrostatic measurements have been made and for small thermal gradient regions (i.e., $\Delta T \leq 100°C$) this yields satisfactory relative corrections because the absolute corrections are fairly reliable.

In the more uncertain high pressure-high temperature region, more accurate relative correction measurements can be obtained by direct

experiments than can be deduced from absolute data. Such experiments have been reported for a direct comparison of chromel-alumel versus Pt/Pt 10 Rh couples by Hanneman and Strong[6] and by Peters and Ryan.[11]

In order to obtain direct relative data at high temperature, two different types of thermocouples are brought into an internally heated high pressure cell via equivalent pressure-temperature paths. Their junctions are both placed at the same position (i.e., pressure and temperature) and the wires are insulated throughout the cell. When the emf outputs of the two different thermocouples are referred to standard thermocouple tables there is an apparent temperature discrepancy which increases with pressure at a given temperature. This data, together with a knowledge of the approximate cell pressure and internal gradients, permits a good approximation of relative corrections.

The best approximate relative corrections (for a pressure-temperature gradient correction factor of unity) for Pt/Pt 10 Rh versus chromel/alumel couples are shown in Fig. 9. The estimated accuracy of these relative measurements is approximately $\pm$10%. Since these data are more reliable than any absolute corrections at high temperatures, any absolute data obtained on both types of couples must be in approximate agreement with the data in Fig. 9 if it is correct. Limited additional relative correction data has been published for Pt/Pt 13 Rh and iron/constantan.[5]

More extensive measurements of relative thermocouple corrections, especially at higher temperatures and pressures and for other types of couples, are needed. These data will be particularly helpful for the direct quantitative comparison of the published results of various workers on the same physical phenomena who have used different thermocouples. In this regard, it is urged that workers evaluate the pressure-temperature gradient effects in their cells and beware of the other sources of errors from thermocouple measurements described earlier in this paper.

IV. Discussion and Conclusions of Absolute Corrections

The present theoretical knowledge of thermoelectricity and electronic properties of metals is insufficient to predict quantitatively the pressure dependences of thermocouples. We have shown that quantitative measurements of corrections for the pressure-induced deviations of thermocouples are very difficult in the high pressure-high temperature regime.

The most accurate corrections to date have been obtained in the range -200 to several hundred degrees centigrade and 0 to 15 kbars where hydrostatic cells can be used and deformation, contamination and other problems can be minimized. A summary of some of the key results is shown in Fig. 2. Many of the results in this region are accurate to within a few per cent.

Outside of the hydrostatic pressure range the next most reliable data to date has been obtained from the modified Bridgman technique within a limited temperature range (0 to 100°C). These results are generally believed to have an accuracy of better than 10 per cent. Some of these by data are shown in Fig. 5.

The uncertainties in absolute corrections rise substantially in the range up to 50 kbars and 1300°C where approximate corrections have been proposed. Nearly all of the indirect and thermal noise data[5,6,8] are compatible with the corrections given in Figs. 7 and 8. In addition, the magnitude of the corrections are compatible with extrapolations from lower pressure data achieved from direct determinations.[2,7]

The only sizable discrepancy (i.e., >20%) from the absolute corrections shown in Fig. 7 are those of Getting[10] mentioned earlier. His Pt/Pt 10 Rh corrections are of the same sign as Hanneman, Strong and Wentorf[6,8] but they are only about one half as large. On the other hand, chromel/alumel absolute corrections deduced by Getting are in fairly close agreement with those of Hanneman and Strong. At ~1000°C and 40 kbars, for example, the Getting corrections are nearly 0°C which is in good

agreement with the best corresponding value of only ~+1°C from our laboratory under the same conditions. The major problem with the Getting data is that the difference in absolute corrections between Pt/Pt 10 Rh and chromel/alumel thermocouples does not agree with established relative corrections. On the other hand the data of Hanneman and Strong do meet this necessary self-consistency requirement. Gradient effects, deformation or contamination could possibly contribute to the discrepancy in the Getting corrections.

Until more quantitative measurements can be carried out, it appears that the absolute corrections given in Figs. 7 and 8 are the most adequate ones presently available. It should be stressed, however, that these corrections are quite approximate with uncertainties of at least ±20%. More accurate and complete measurements are clearly needed but such tests are very difficult.

V. Simultaneous and Continuous In Situ Measurement of Pressure and Temperature

One of the major problems in research and applied technology in the area of high pressure has been the lack of an accurate, reliable method for continuous and simultaneous in situ measurement of high pressures and temperatures. Since accurate thermodynamic or kinetic studies under high pressure require a means of independently evaluating the true pressure and temperature at the sample, preliminary work in our laboratory was undertaken to develop a reliable, convenient method to accomplish this requirement.

Pressure measurement in most previous high pressure investigations has relied completely on precalibration methods, which use first order phase transformations of standard materials at room temperature to determine the relation between external press load and internal cell pressure for a given apparatus and cell geomtry. In some cases approximate continuous measurements of pressure has been possible by use of resistance measurement of manganin or similar wire but this is limited to <250°C and is sensitive to several variables. For various reasons the apparent pressure based upon

press load in a subsequent experiment often does not indicate the true internal cell pressure. For example, the pressure within a high pressure cell varies as a function of temperature and time due to thermal expansion, phase changes in the sample holder or specimen, gasket leakage and relaxation of stresses in the apparatus. Concurrently, the measurement of the true temperature in an internally-heated, high pressure cell requires a knowledge of the effect of pressure on the electromotive force of thermocouples as described above.

By utilizing two different thermocouples which have differing, known pressure dependences, one can uniquely monitor continuously both pressure and temperature within any high pressure cell. In this method the junctions of two different thermocouples are placed together at the desired location in a high pressure cell and both couples are surrounded by insulating material leading out of the cell to cold junctions. These leads are then connected to sensitive potentiometers or other devices for accurately reading the emf output of both thermocouples. Such measurements require choice of thermocouple materials which will not be susceptible to chemical contamination drift. Figures 10 and 11 show the approximate pressure effects for Pt 40 Rh/Pt 10 Rh and Au/Pt A0 Rh thermocouples which have been used for simultaneous in situ measurements of pressure and temperature. The concurrent placement of both thermocouple emf's on Fig. 10 fixes the pressure. Then by reference to a more detailed graph similar to Fig. 11 the corresponding temperature can be directly determined. Such determinations have absolute accuracies only as good as the absolute corrections available for thermocouples. However, relative changes of pressure within a cell during a given experiment can be seen to less than a kilobar under optimum circumstances.[12]

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Fig. 3 Schematic of the pressure-temperature profile along a thermocouple path in typical and ideal high pressure cells.

Fig. 4 Schematic diagram of modified Bridgman method for measuring effect of pressure on thermal emf's.

Fig. 5 Summary of pressure corrections for thermocouples for temperature gradient of 100°C in non-hydrostatic range by the modified Bridgman method.

Fig. 6 Schematic diagram of various types of phase transformations used in indirect determinations of thermocouple corrections.

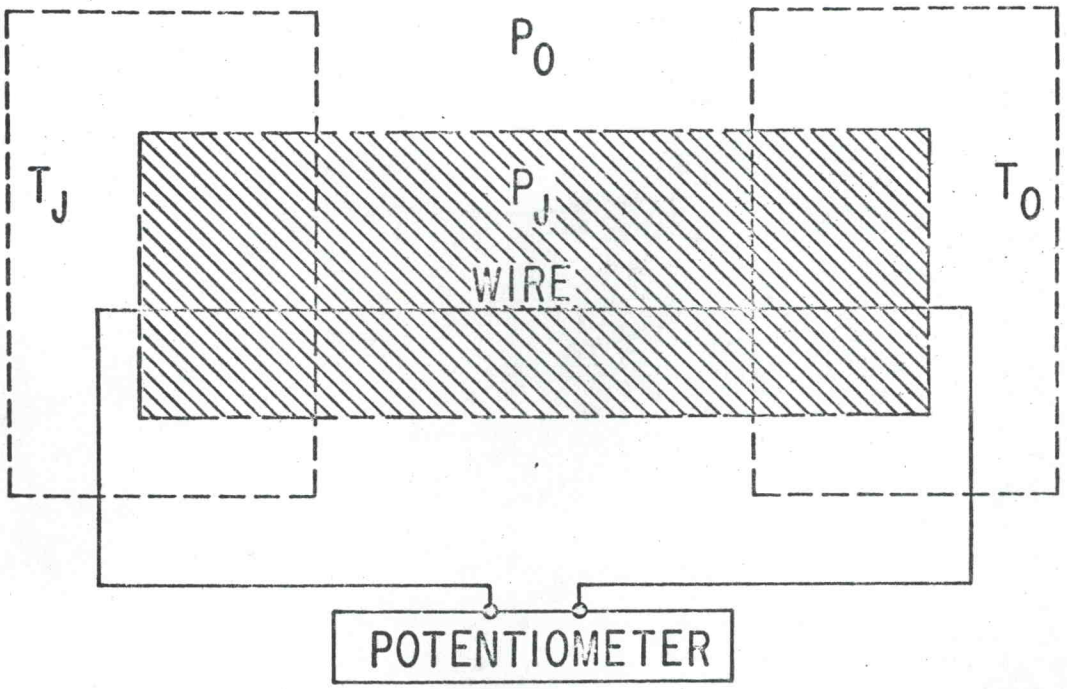
Fig. 7 Preferred approximate absolute pressure corrections for Pt/Pt 10 Rh thermocouples up to 1300°C and 50 Kb for gradient factor equal to unity.

Fig. 8 Approximate absolute pressure corrections for chromel/alumel thermocouples up to 40 Kb and 1000°C.

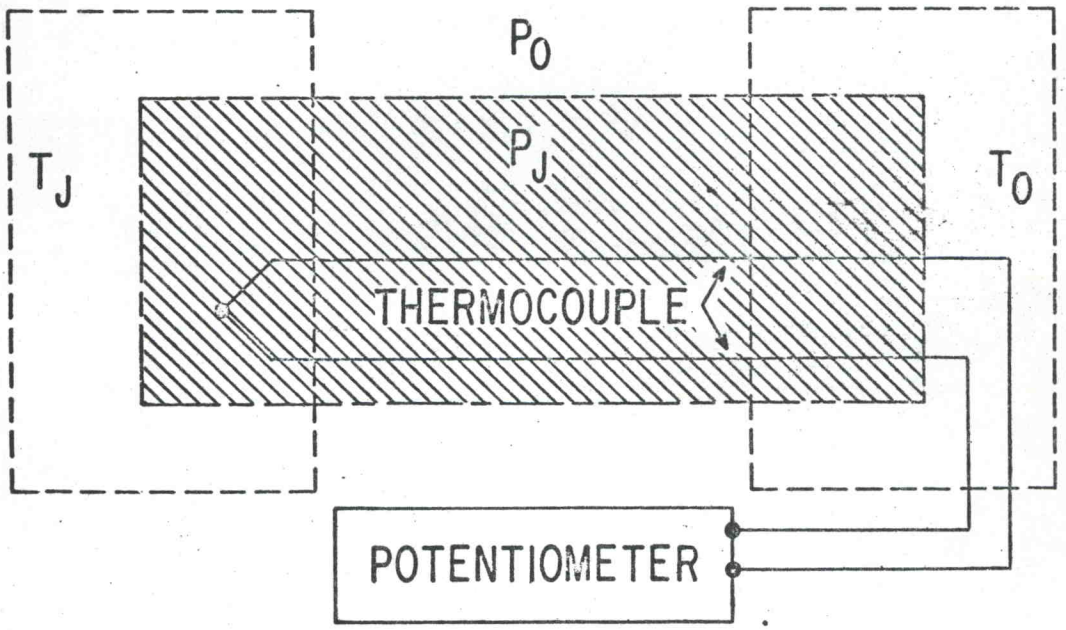
Fig. 9 Approximate relative corrections between Pt/Pt 10 Rh and chromel/alumel thermocouples up to 1000°C at 20 and 40 Kb intervals. Gradient factor equal to unity.

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Fig. 11 Pressure effect on calibration of Au/Pt 40 Rh thermocouples for temperature determination.



I (a)



I (b)

Figure 1

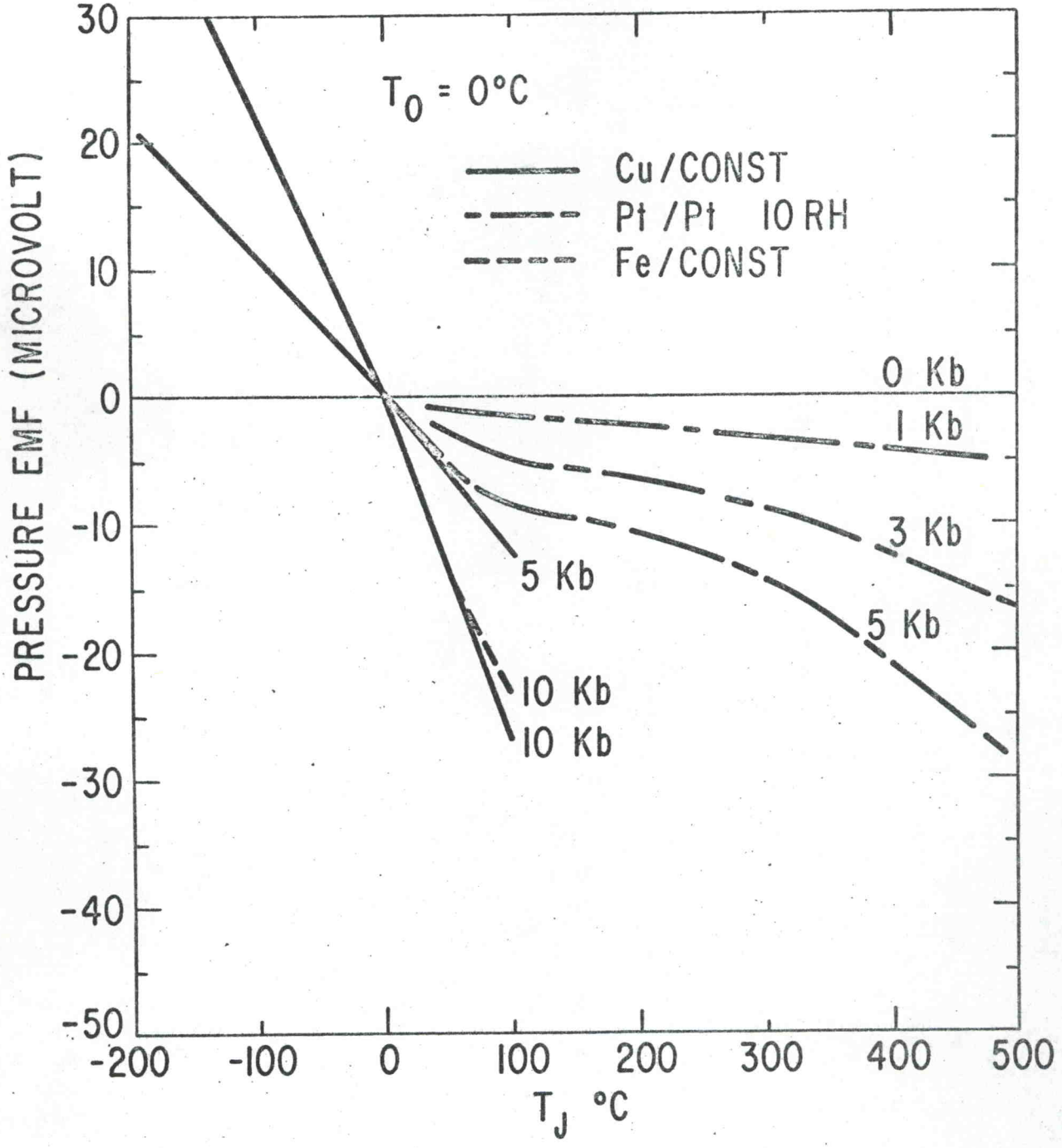

30
20
10
0
-10
-20
-30
-40
-50
PRESSURE EMF (MICROVOLT)
T_0 = 0°C
Cu/CONST
Pt /Pt 10 RH
Fe/CONST
0 Kb
1 Kb
3 Kb
5 Kb
5 Kb
10 Kb
10 Kb
-200
-100
0
100
200
300
400
500
T_J °C

Figure 2

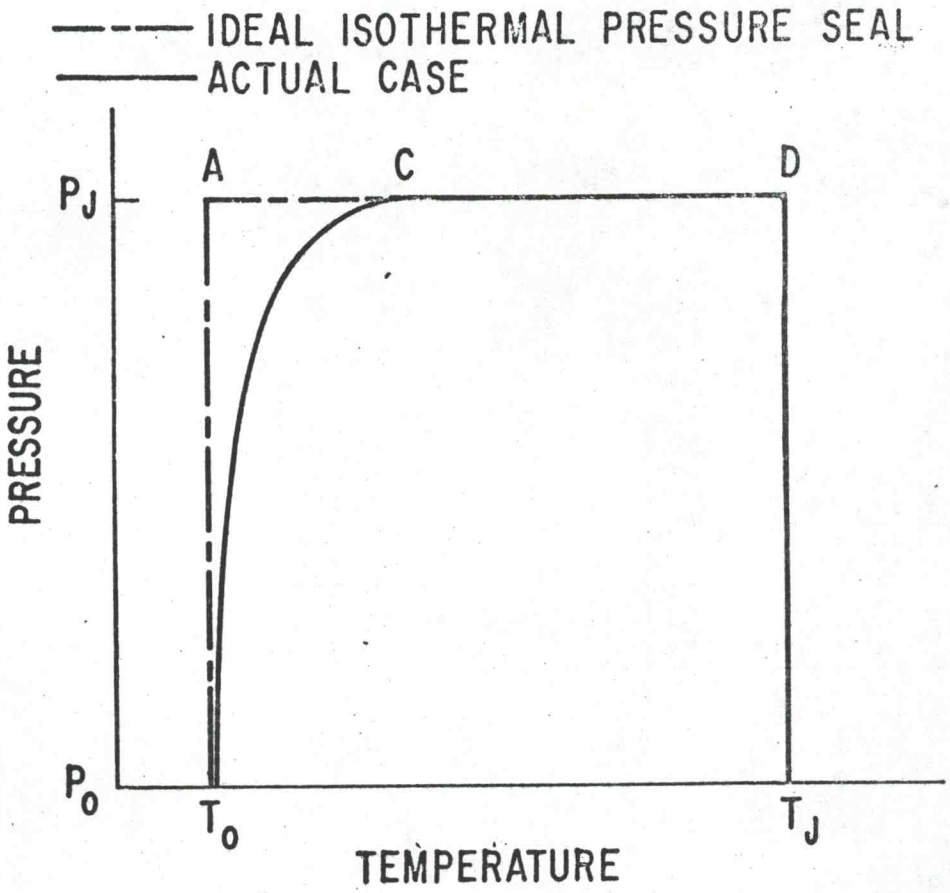

IDEAL ISOTHERMAL PRESSURE SEAL
ACTUAL CASE
A
C
D
P_J
P_0
PRESSURE
T_0
T_J
TEMPERATURE

Figure 3

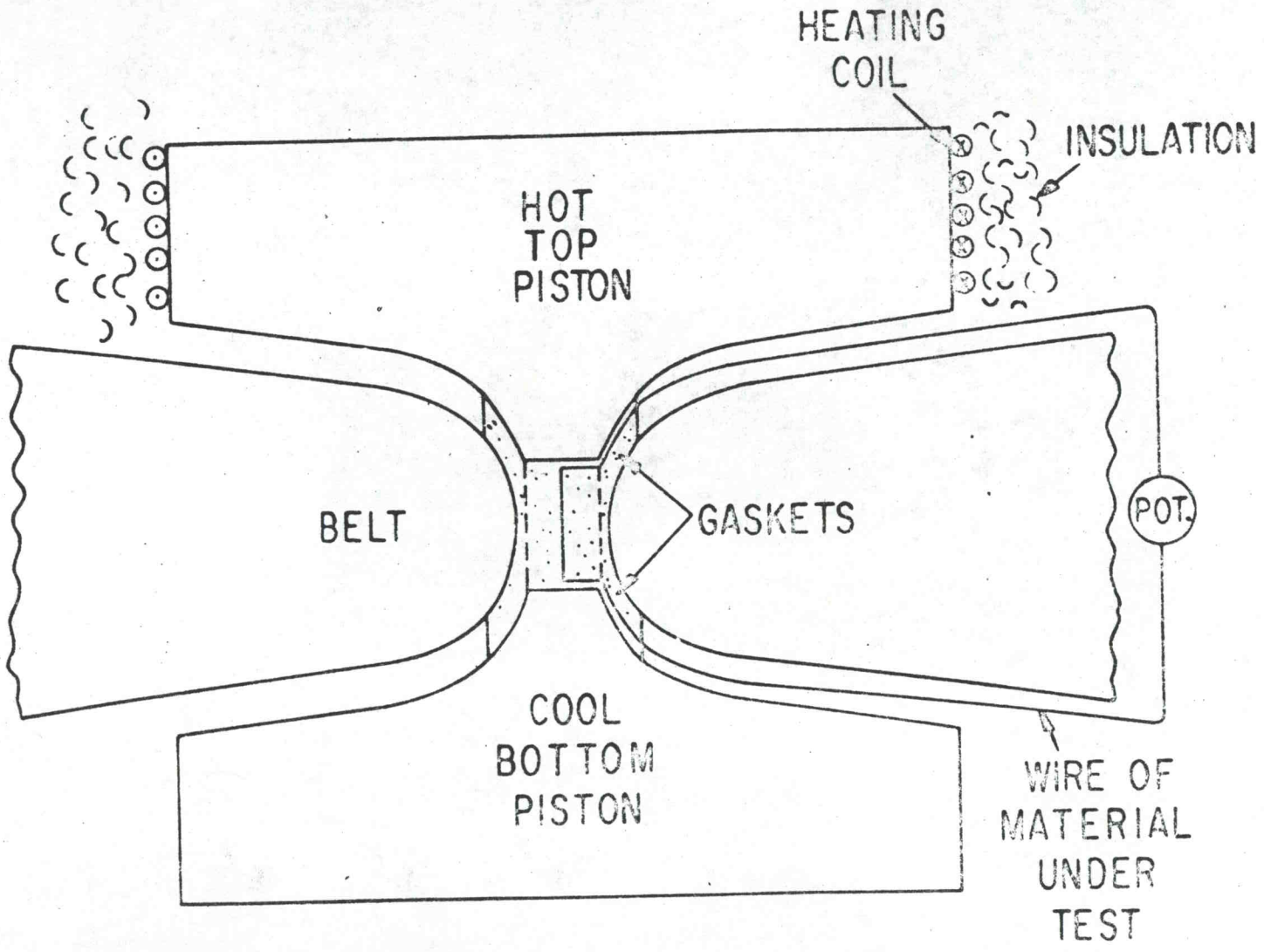

HEATING
COIL
INSULATION
HOT
TOP
PISTON
BELT
GASKETS
POT.
COOL
BOTTOM
PISTON
WIRE OF
MATERIAL
UNDER
TEST

Figure 4

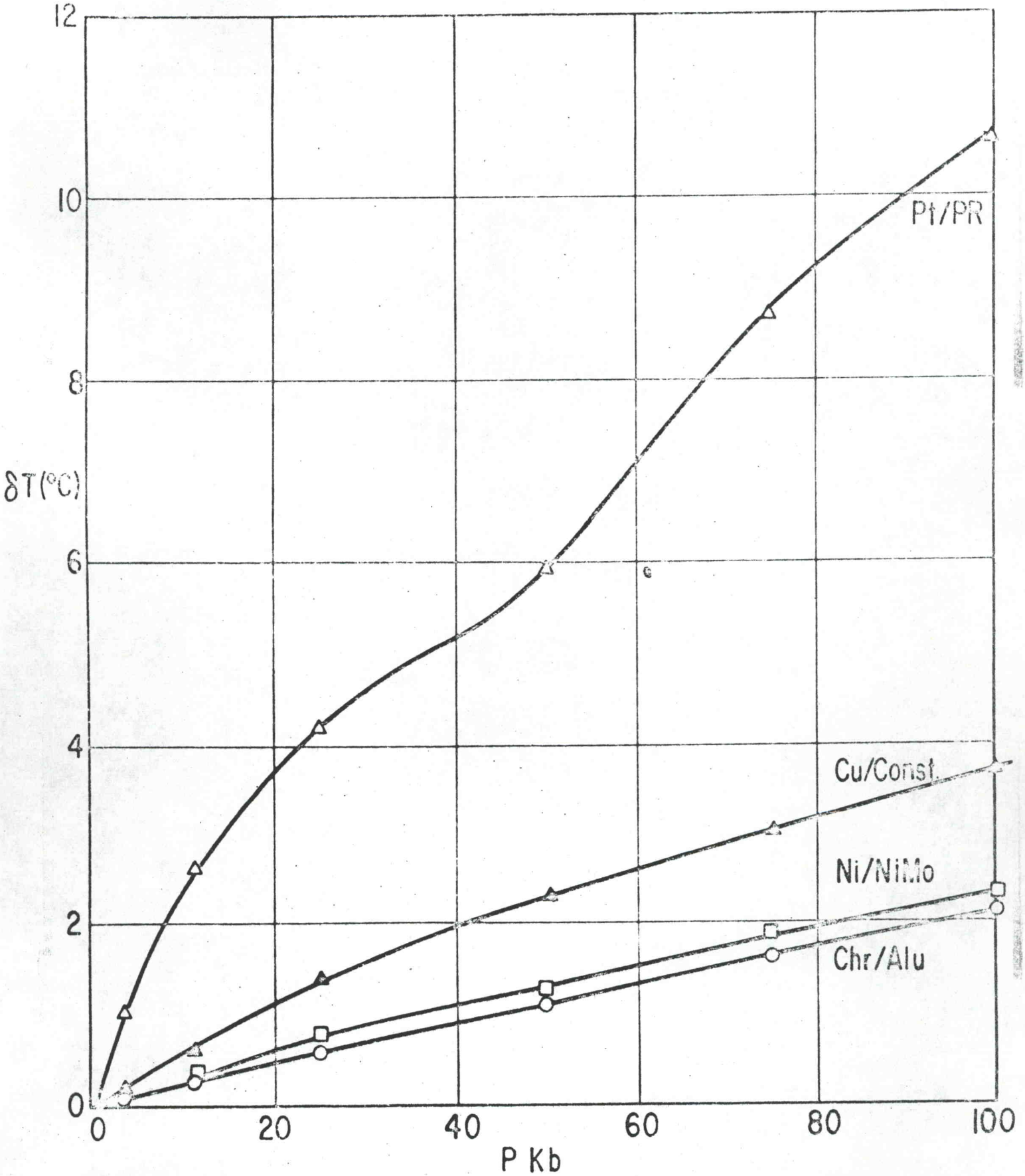

12
10
8
6
4
2
0
δT(°C)
0
20
40
60
80
100
P Kb
Pt/PR
Cu/Const.
Ni/NiMo
Chr/Alu

Figure 5

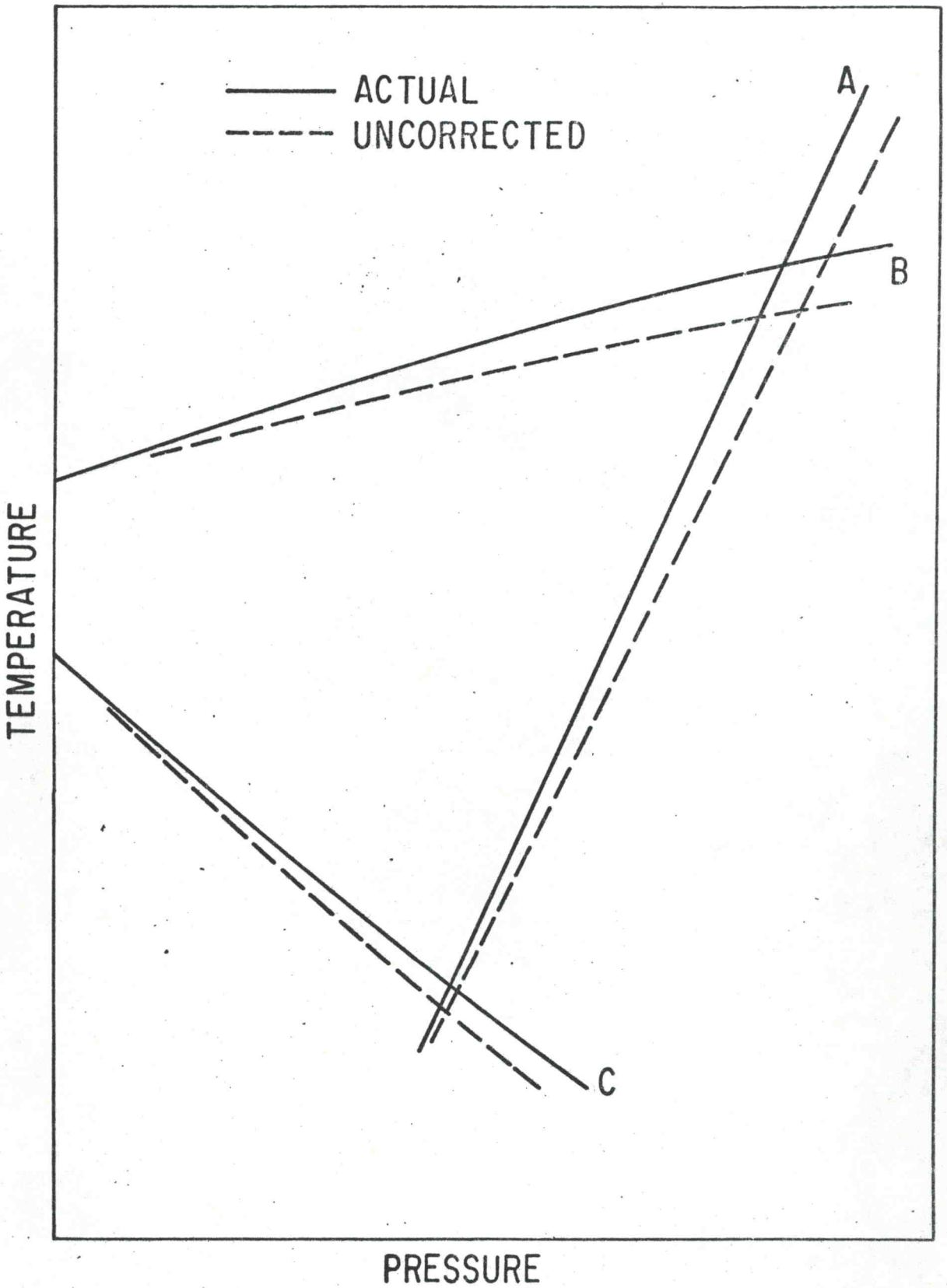


Figure 6

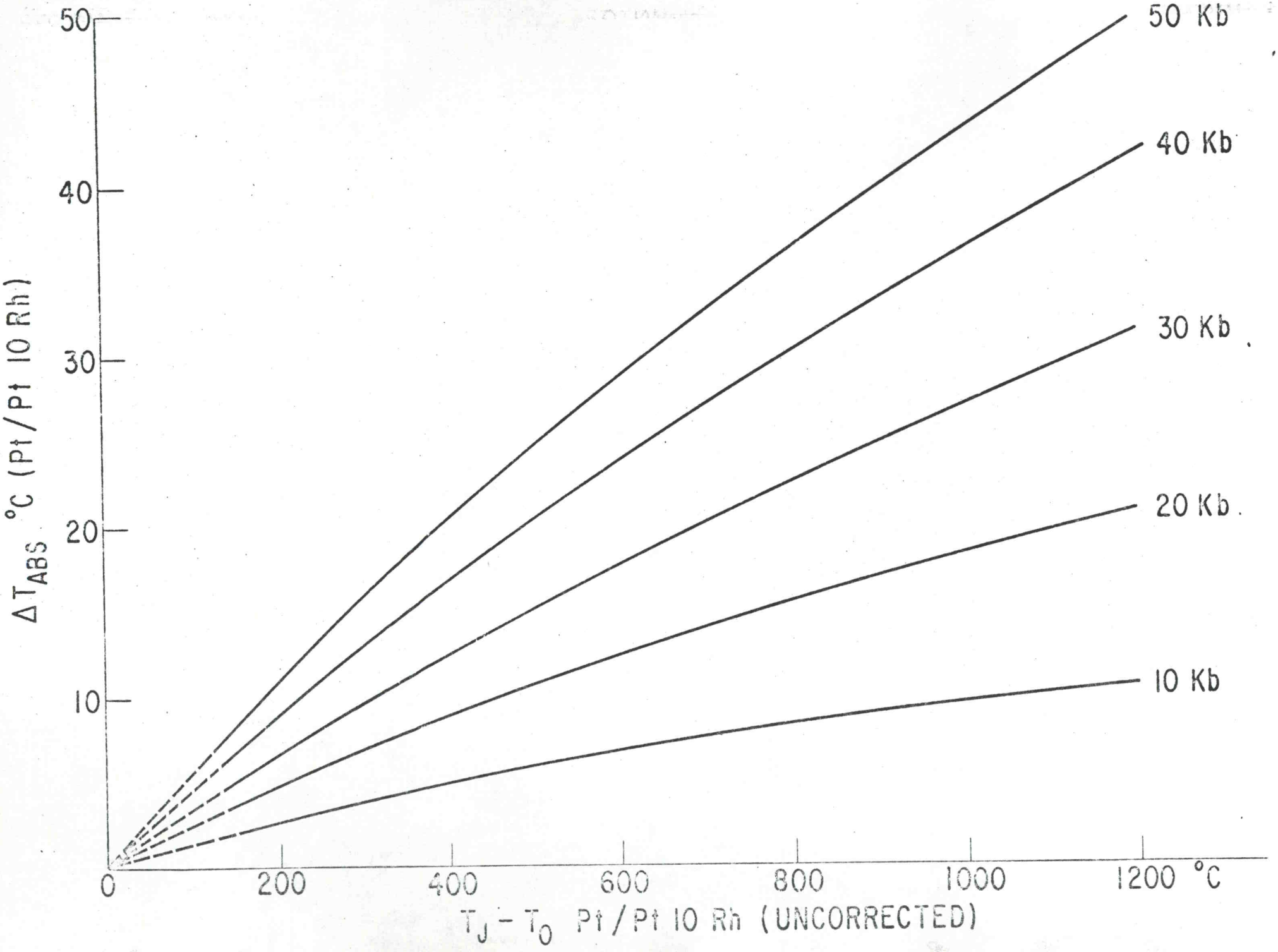

50
40
30
20
10
ΔT_{ABS} °C (Pt/Pt 10 Rh)
50 Kb
40 Kb
30 Kb
20 Kb
10 Kb
0
200
400
600
800
1000
1200 °C
$T_J - T_0$ Pt/Pt 10 Rh (UNCORRECTED)

Figure 7

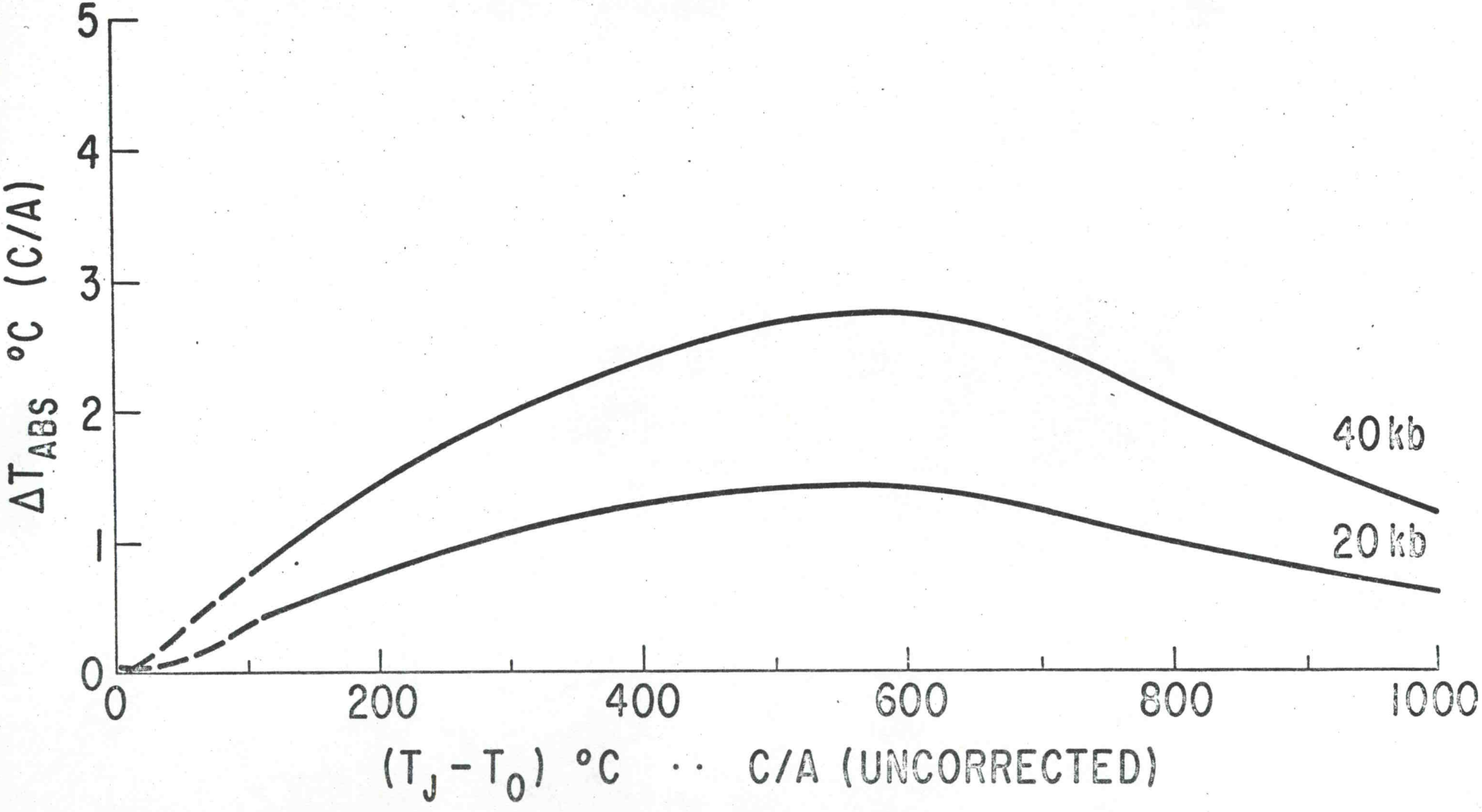

5
4
3
2
1
0
ΔT_{ABS} °C (C/A)
40 kb
20 kb
0
200
400
600
800
1000
$(T_J - T_0)$ °C ·· C/A (UNCORRECTED)

Figure 8

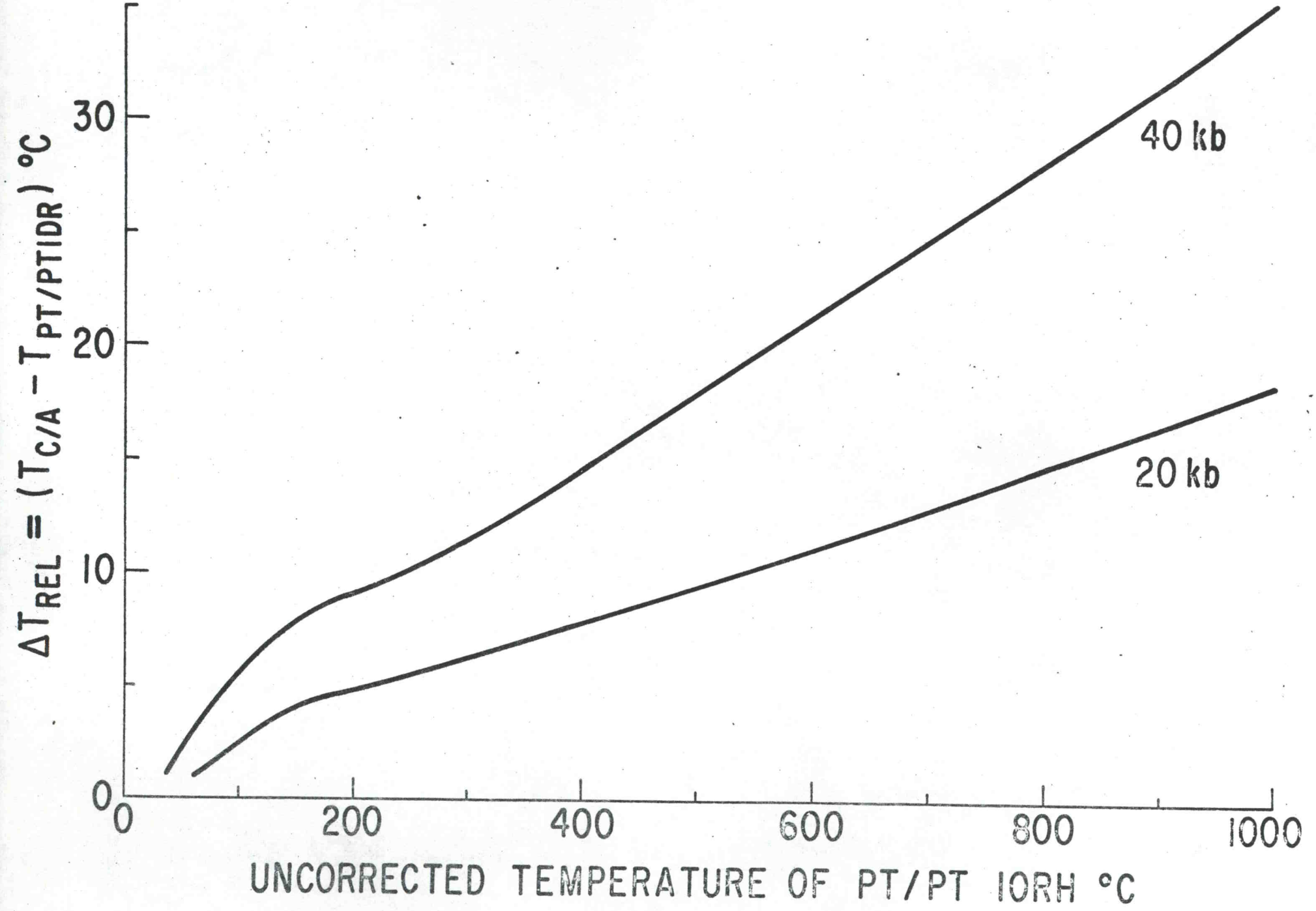

$\Delta T_{REL} = (T_{C/A} - T_{PT/PTIDR})$ °C
30
20
10
0
0
200
400
600
800
1000
40 kb
20 kb
UNCORRECTED TEMPERATURE OF PT/PT 10RH °C

Figure 9

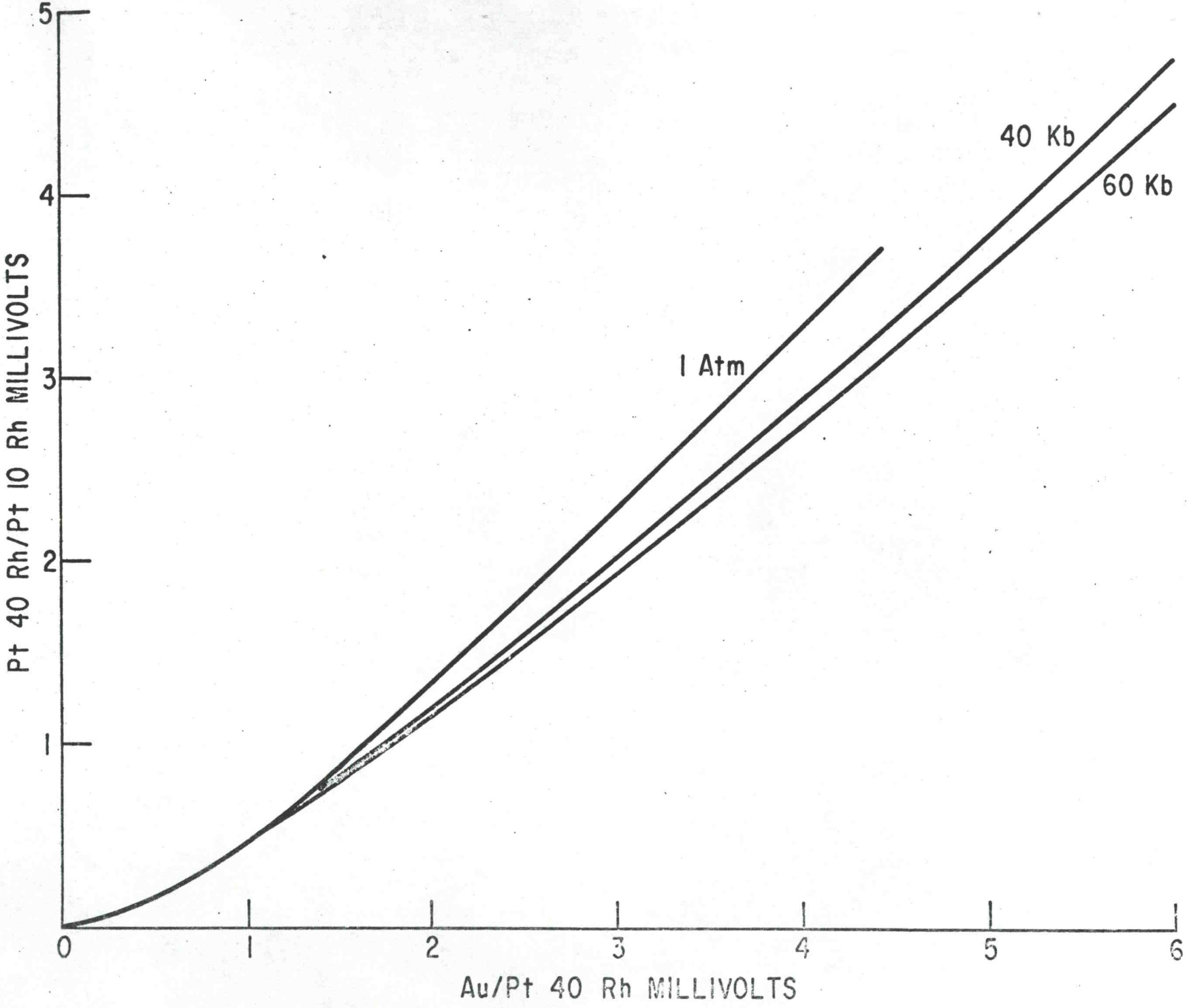

Pt 40 Rh/Pt 10 Rh MILLIVOLTS
5
4
3
2
1
0
1
2
3
4
5
6
Au/Pt 40 Rh MILLIVOLTS
40 Kb
60 Kb
1 Atm

Figure 10

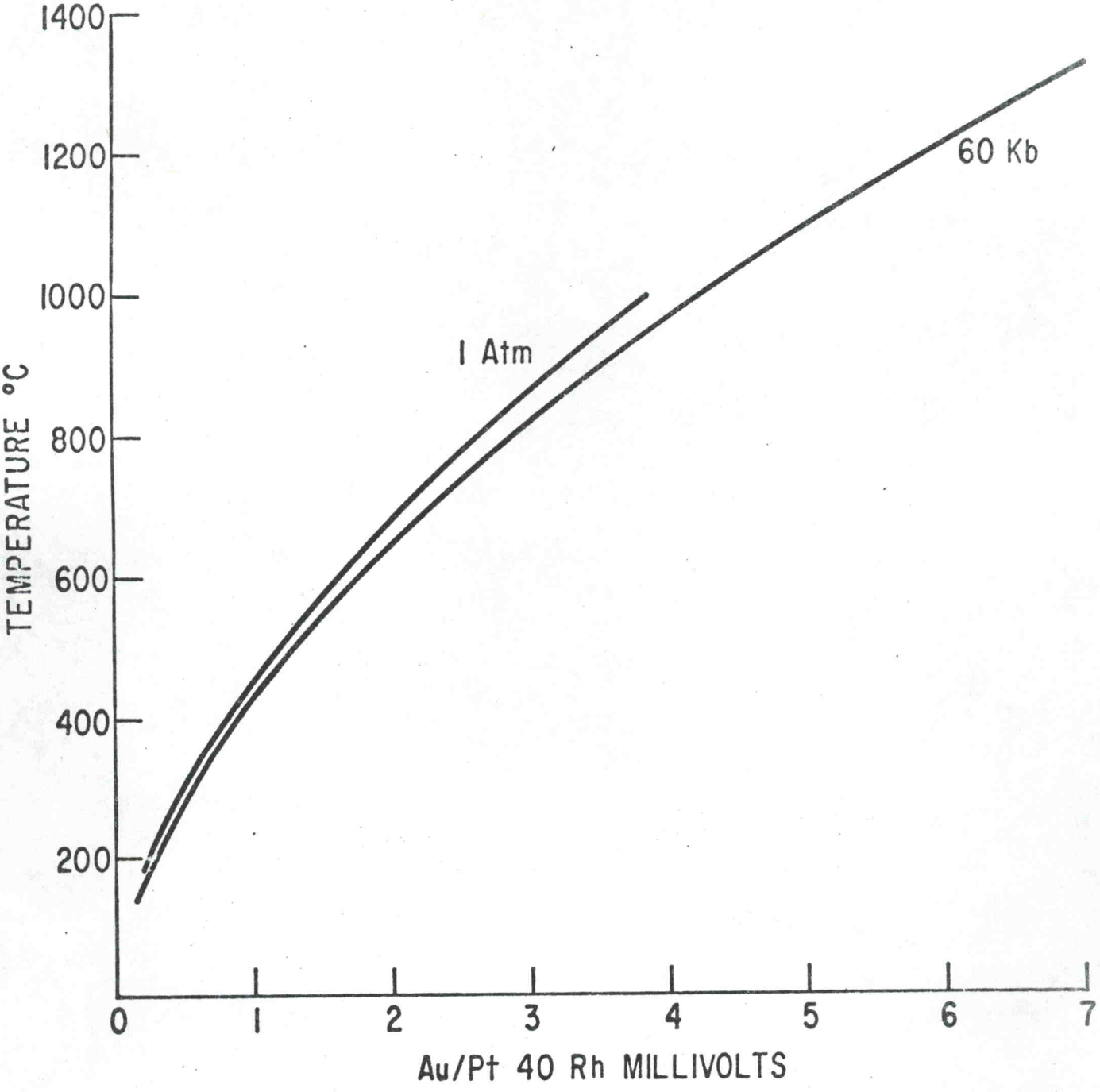

1400
1200
1000
800
600
400
200
TEMPERATURE °C
60 Kb
1 Atm
0
1
2
3
4
5
6
7
Au/Pt 40 Rh MILLIVOLTS

Figure 11