Cryo-Thermometry Using Thick Film Resistors

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Abstract

Here I present my findings on the suitability of thick-film barium ruthenate resistors for use as cryo-thermometers on the yet-to-be-built superconducting wigglers at CESR. These resistors are highly desirable as thermometer candidates due to their cheapness and portability, and all current results indicate that they will work well. In addition to tests done to obtain T-R (temperature vs resistance) graphs and equations for each kind of resistor, tests were done on the resistors' response to I^2R heating. The resistors show high sensitivity (dR/dT) to temperature change, especially below 20 Kelvin, and should work well as cryo-thermometers. The resistors still need to be tested for their response to high magnetic fields, and more accurate resistance measurements need to be made before a final curve can be fit and they can be put into service.

Introduction

The decision at LNS to begin conducting lower-energy experiments in the near future has led to the development of superconducting "wigglers" that will be used to lower beam energy without sacrificing beam luminosity. It is imperative that these wigglers be kept well below their superconducting temperatures during operation, and the best way to verify this is through the use of reliable thermometers. It was proposed that thick-film resistors, long used in solid-state and low temperature physics as thermometers, might be developed as cryo-thermometers at CESR. Two temperature regions are of particular interest: the first, around $77K$, is the desired operating temperature of the high T_c leads which will carry $200 - 350$ amperes to the magnets; the second region is around $4.2K$, the desired operating temperature of the superconducting wire used in the magnets. I investigated the properties of $20k\Omega$, $56k\Omega$, and $100k\Omega$ resistors manufactured by Dale Electronics for their response to temperature change and I^2R heating. I measured resistances across a temperature range from about $200K$ to liquid helium ($4.2K$) temperature and, for the $100k\Omega$ resistors, response to power dissipation up to about a tenth of a watt. From this we now have a good idea of the suitability of these thick-film resistors as cryo-thermometers, with only a few minor tests left until they are ready for use.

Temperature-Resistance Tests and Results

Method

One resistor of each kind ($20k\Omega$, $56k\Omega$, $100k\Omega$) was epoxied onto a polished copper plate and mounted upon a small cryostat. This cryostat was wired with two calibrated resistors (germanium for $T < 30K$ and platinum for higher temperatures) and a heater. The leads

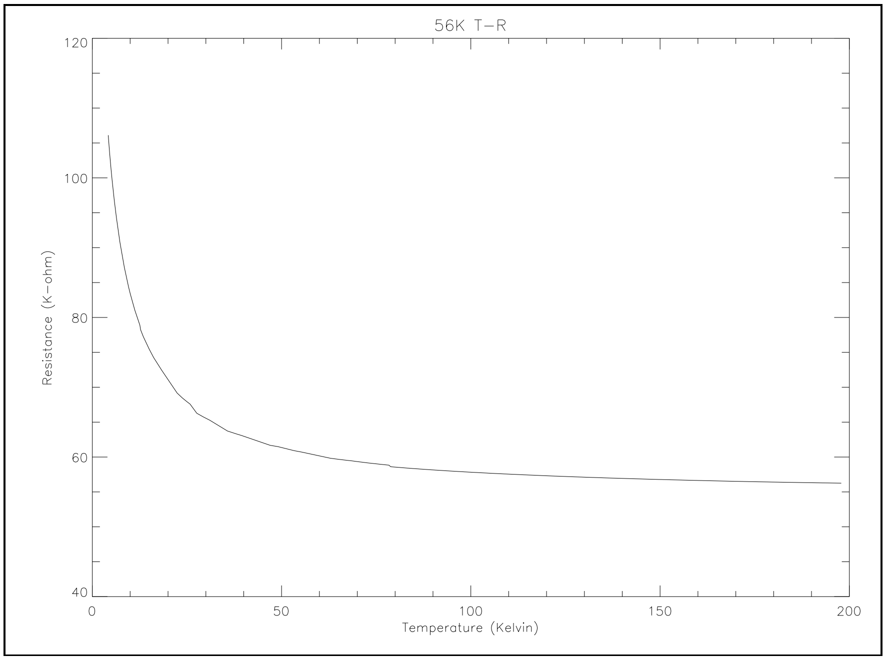

FIGURE 1. Graph of temperature (Kelvin) versus resistance ($k\Omega$) for $56k\Omega$ resistors.

from the resistors being tested were wired to Hewlett-Packard 3478A multimeters, whose input impedances (on the order of $10^{10}\Omega$) was sufficiently high to take the resistance readings at face value. The calibrated thermometer was wired to an AC resistance bridge, which was then outputted to a heater (via a pre-amp). The testing of the resistors was done in stages. First, for the upper temperatures ($77K - 200K$), the cryostat was immersed, partially and then totally, in liquid nitrogen and allowed to cool down. Readings were taken "on the fly" for each resistor individually (with the $100k\Omega$ resistor data actually taken during a number of different runs), thus requiring the cooldown procedure to be performed multiple times. For the lower temperature range ($4K - 77K$), the cryostat was immersed in liquid helium and heated to about $30K$ using the heater. Readings were taken for all three resistors at the same time. From $30K$ to $77K$, the cryostat was lifted out of the liquid helium part way and allowed to heat up. A small amount of helium exchange gas was put into one of the cryostat's valves to facilitate better heat exchange.

Results and Discussion

The results obtained for the $56k\Omega$ resistors are displayed in Fig. 1 and Fig. 2. The results for the $100k\Omega$ and $20k\Omega$ resistors are displayed in figures 6-9 at the end of this report. All three resistors showed good sensitivity to temperature change, especially at temperatures below about $25K$. The $20k\Omega$ resistors rose to about 175% of their intial (around $200K$) temperature at $4K$. The $56k\Omega$ resistors did even better, rising to 188% of their initial resistance, while the $100k\Omega$ resistors rose to about 187% of their resistance at $200K$. The resistors showed good values of dR/dT at the important temperatures (around $77K$ and $4K$), as summarized in Table 1.

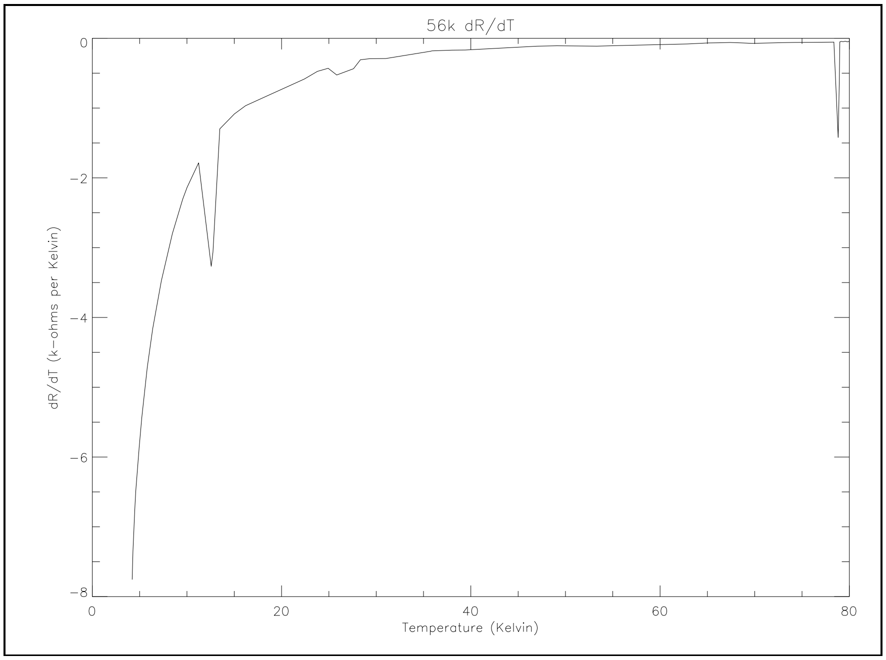

FIGURE 2. Temperature (Kelvin) versus dR/dT ($k\Omega$ per Kelvin).

TABLE 1. Approximate dR/dT values at $77K$ and $4K$

Temperature	$20k\Omega$	$56k\Omega$	$100k\Omega$
$77K$	15Ω/Kelvin	58Ω/Kelvin	80Ω/Kelvin
$4K$	3000Ω/Kelvin	8000Ω/Kelvin	12000Ω/Kelvin

Discrepancies were found between resistance readings taken at the same temperature (that is, at the the same calibrated resistor reading), but during different runs. It is these discrepancies that give the dR/dT graphs their sharp peaks and the the T-R graphs their slight discontinuities (Fig. 3). Although the possibility of natural unreliability on the part of the resistors cannot be ruled out, a far more likely explanation involves thermal gradients caused by the partial immersion of the cryostat in the cryogens coupled with the natural heat capacity of the resistors. The calibrated thermometers were located near the top of the cryostat, whereas the resistors were mounted on the bottom. The distance between the two was approximately $10cm$, and it is quite likely that a small temperature gradient existed when the cryostat was only partially immersed in the liquid nitrogen or helium. A quick look at figure 3 supports this theory: the resistance reading taken at $77K$ while the cryostat was *fully* immersed in liquid nitrogen and, presumably, relatively free of thermal gradients is lower than the reading taken when the cryostat was *partially* immersed in liquid helium. Further analysis is needed to determine the exact nature of the discrepancies and how they might affect the resistors' usefulness.

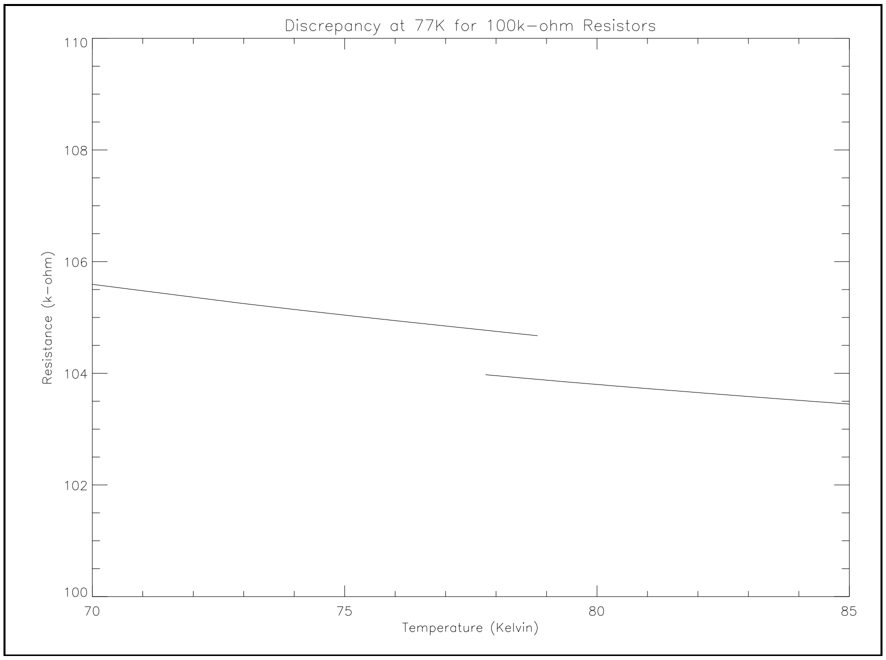

FIGURE 3. Discrepancies found in the $100k\Omega$ resistor around $77K$.

Curve-Fitting

For the purpose of curve-fitting, the discrepancies described above were eliminated by offsetting the different sections of the T-R curve to fit together. Although a linear offset of the type applied by no means results in an accurate T-R curve, it is useful for the purpose of determining the form of the best fit curve. The $56k\Omega$ data was used for the fitting, with the assumption that the $100k\Omega$ and $20k\Omega$ will be fit by the same function with different parameters. A number of different types of functions were fit to the data using various curve-fitting routines in IDL, and a table of the results appears below.

TABLE 2. χ^2 values and parameters for four types of curves

Function Type	Form	χ^2
Geometric	$\ln T = a_0 + a_1(R - a_2)^{a_3}$	0.0011146918
Logarithmic	$\ln T = a_0 + a_1 \ln R + a_2(\ln R)^2 + a_3(\ln R)^3$	0.0066678261
Polynomial	$\ln T = a_0 + a_1 R + a_2 R^2 + \ldots$	0.091595794
Hyperbolic	$T = a_0 + \frac{a_1}{a_2(R-a_3)^{a_4}+a_5}$	0.47308976

It is likely that some of the difficulty that has been encountered trying to fit a curve to my data is a result of the slight inaccuracy of the data and the offsets that had to be applied. This is apparent when we look at the relative ease and accuracy with which a third-order logarithmic polynomial was fit to the upper part of the $56k\Omega$ data (from $77K$ up to $200K$), which was taken all in one run and contains no offsets of any kind. The following function was fit to this data with a χ^2 of about 1.5×10^{-5}:

$$\ln T = 1548.5557 - 388.49005 \ln R - 85.054257(\ln R)^2 + 21.446420(\ln R)^3$$

This seems to suggest that, once accurate data is taken across the entire temperature range from $4K$, a logarithmic polynomial fit to the natural log of the temperature may very well be easy to obtain. At any rate, the curve-fitting that has been done so far will greatly reduce the effort required to fit the more accurate data to be taken.

Power Test

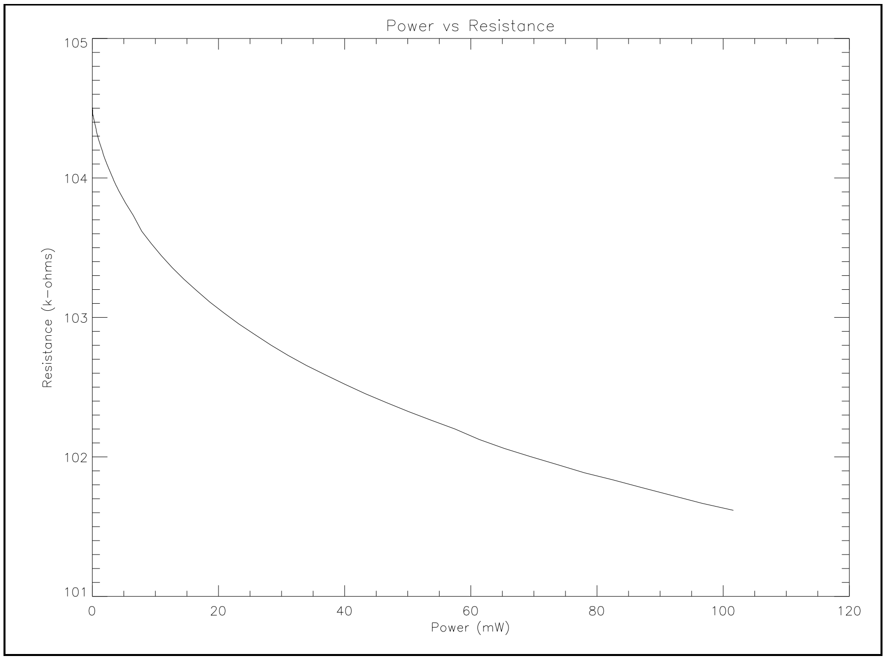

FIGURE 4. Power vs Resistance for one of the $100k\Omega$ resistors

Ten $100k\Omega$ resistors were tested for their response to I^2R heating by running currents ranging from $.002mA$ to $1mA$ through them at a temperature of $77K$ and measuring the voltage drop. A slight problem was encountered when it was found that the multimeters being used changed ranges (that is, switched input impedances) in the middle of the spread of values we were looking at. At a voltage of $3V$, the input impedance of the multimeter switched from $10^{10}\Omega$ to $10^7\Omega$, a value only 2 orders of magnitude higher than the resistance being tested. The resulting dip in measured resistance gave a false picture of the reality of the situation, implying a “cutoff” power value above which the resistor would rapidly heat up. The steadiness of dR/dP after the false “breaking point”, however, clued me in to the underlying reality, and a simple offset of the following form, derived directly from the equation for resistors in parallel, was applied to all data taken in the upper range:

$$R_{real} = \frac{R_{meas} R_{impedance}}{R_{impedance} - R_{meas}}$$

The resulting values of R_{real} were then taken to be the actual resistance values. A graph showing the full response of one of the resistors is shown in Fig. 4, while Fig. 5 gives a closer look at the low power part of the graph up to about $.4mW$. Since we know the value of dR/dT at $77K$ for the $100k\Omega$ resistors (about $80\Omega/K$, we can make an estimate of how much current it took to heat up the resistors by one degree. That value is approximately $.054mA$, or, in terms of power, $.03mW$. By the time the resistors had $1mA$ going through them, their temperature had risen to approximately $130K$.

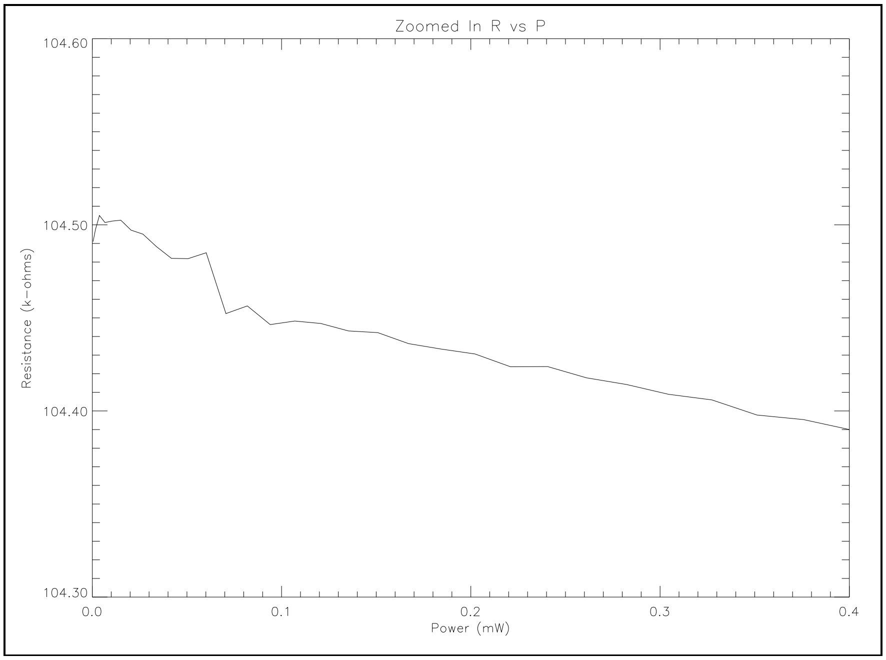

FIGURE 5. Power vs Resistance for low powers (up to $.4mW$)

Variability

A small test was done with 7 of the $100k\Omega$ resistors to see how reliable and consistent the resistance readings were at $77K$. The cryostat was immersed in liquid helium and allowed to cool down four separate times, and resistance readings were taken each time. The results appear below in Table 3.

TABLE 3. Repeatability of $100k\Omega$ resistors at $77K$.

Number	1	2	3	4	5	6	7
Average	107.866	104.878	104.561	105.499	104.178	109.891	103.752
Std. Dev.	.012093	.011092	.0081788	.0079599	.0089063	.020567	.0082231

The values for the standard deviation of the $100k\Omega$ resistors seem to be pretty standard across the batch, ranging from 8 to 20 Ω. Further tests need to be done to determine the standard deviation more precisely, as the values shown above were calculated from only four runs. In addition, the next variability test should be run with some sort of thermometer to make sure the readings are being taken at the same temperature each time.

Conclusions

We now have strong evidence that thick-film resistors will make excellent and affordable thermometers for the new superconducting wigglers at CESR, and perhaps even for other applications around the accelerator. All three types of resistors show excellent sensitivity at low temperatures (dR/dT) and reasonable sensitivity elsewhere. What remains to be done is to alter the cryostat so that the resistors are located closer to the calibrated thermometers and are thus thermally coupled with them. After that, more accurate resistance readings can be taken and a curve (most likely a logarithmic polynomial) can be fit to the data. In addition, it needs to be determined how the resistors vary across a batch and what parameters need to be adjusted in the fitted curve to account for this. Finally, a test of the resistors in high magnetic fields should be conducted.

Acknowledgments

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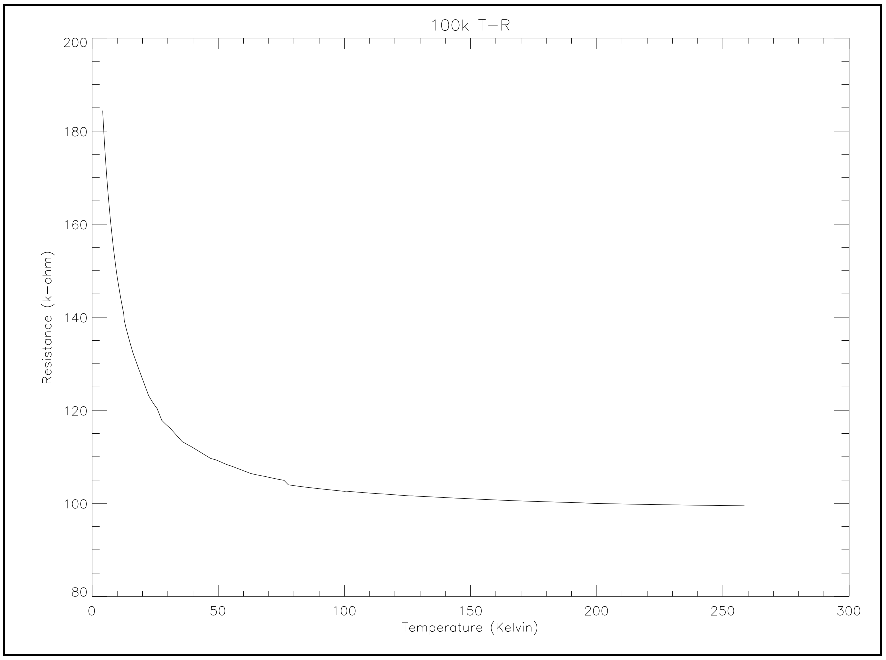

FIGURE 6. Graph of temperature (Kelvin) versus resistance ($k\Omega$) for $100k\Omega$ resistors.

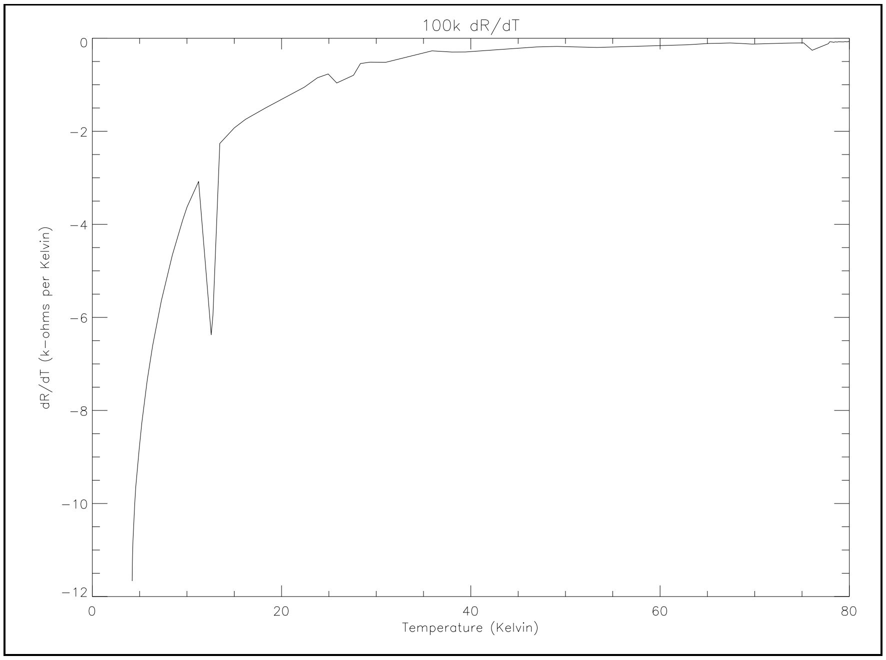

FIGURE 7. Temperature (Kelvin) versus dR/dT ($k\Omega$ per Kelvin).

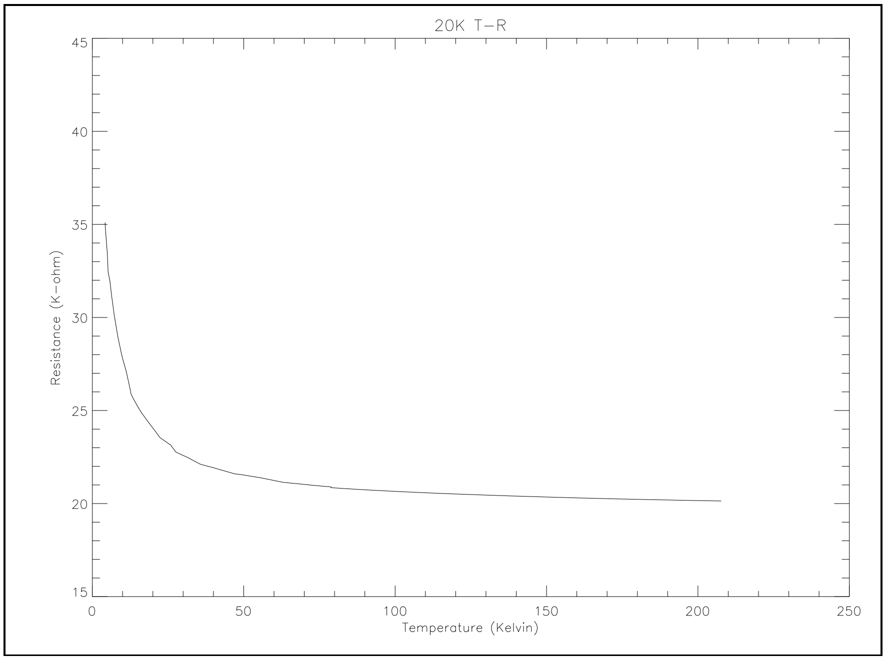

FIGURE 8. Graph of temperature (Kelvin) versus resistance ($k\Omega$) for $20k\Omega$ resistors.

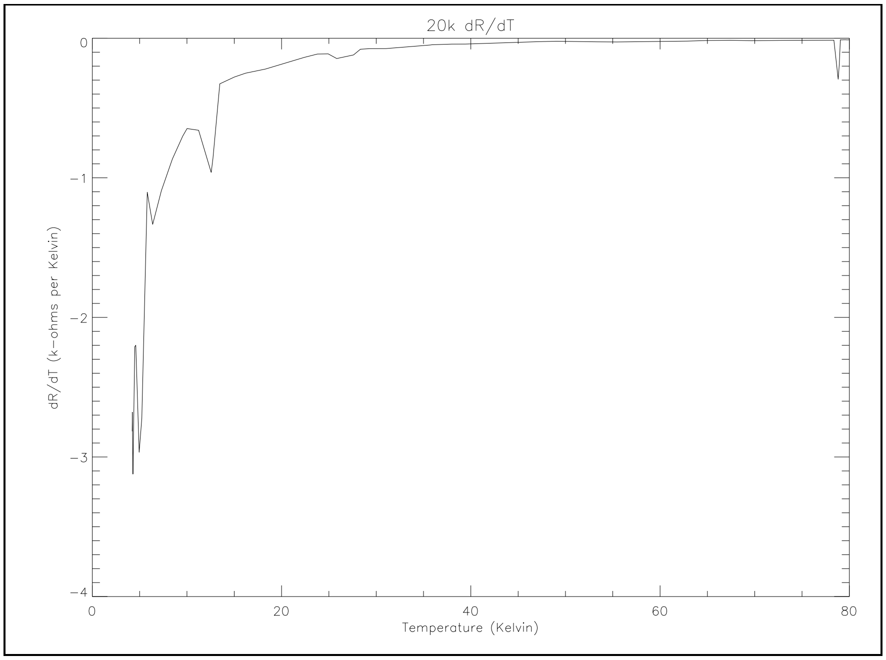

FIGURE 9. Temperature (Kelvin) versus dR/dT ($k\Omega$ per Kelvin).