NBSIR 74-355

CARBON THIN FILM THERMOMETRY

DRA

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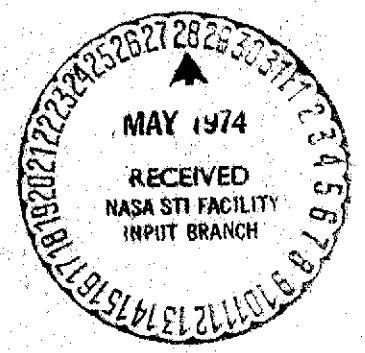

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Final Report

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ABSTRACT

This is a summary of work done on NASA (Marshall Space Flight Center) purchase order H-92167A concerning Carbon Thin Film Thermometry. Optimum film deposition parameters were sought on an empirical basis for maximum stability of the films. One hundred films were fabricated for use at the Marshall Space Flight Center; 10 of these films were given a precise quasi-continuous calibration of temperature vs. resistance with 22 intervals between 5 and 80 K using primary platinum and germanium thermometers. Sensitivity curves were established and the remaining 90 films were given a three point calibration and fitted to the established sensitivity curves. Hydrogen gas-liquid discrimination set points are given for each film.

Key words: Calibration; carbon films; low temperature; thermometry; vacuum deposition.

INTRODUCTION

Thin film thermometry has attracted attention for a number of years, primarily from the desire to know true surface temperatures under transient conditions. Also, thin film sensors have the advantage that they can be fabricated quickly in large quantities. Previous work [1, 2] has shown that carbon films can be used to give a high level signal in gas-liquid discrimination at cryogenic temperatures; also, the resistance calibrations at the boiling points of helium, hydrogen, and nitrogen and at room temperature suggest that the resistance vs. temperature characteristic is nearly linear on a log-log scale. This suggests that the carbon films could have useful thermometer properties for the entire cryogenic range.

The purpose of the present work is to investigate and develop the thermometry properties of carbon films particularly in the difficult range from 14 to 20 kelvins and to provide MSFC with approximately 100 useful sensors for further use and evaluation. The areas of effort include the optimization and refinement of the thin film deposition process, precision calibration of ten of the carbon film sensors and three point calibration of the other 90 films.

THIN FILM FABRICATION

The carbon films are fabricated in a vacuum system with pressures between 10^{-6} and 10^{-8} torr. The carbon is vaporized by a high intensity electron beam and the carbon vapor is condensed on an insulating substrate; most commonly, this substrate may be quartz or pyrex glass.

The physical and electrical properties of the film are highly dependent on the deposition parameters; namely, deposition rate, substrate temperature, film thickness, background pressure, and the nature and cleanliness of the substrate. The optical appearance of the films may range from a dull opaque black to a shiny translucent blue. The surface adhesion of the films also vary; some films may rub off easily and others are difficult to scratch with a steel

point. The electrical properties, resistance vs temperature, also vary; some films are more sensitive to temperature than others. For some films, the resistance is stable on thermal cycling to cryogenic temperatures; other films are not stable. Most films seem to have an upward drift in resistance due to aging at room temperature although there have been some films where the drift is less than 0.001 percent of the total resistance for periods of 15 months or more.[1]

It is known that the crystal structure of the films can take various forms. Gjonnes[3] has found by electron diffraction studies that the film structure contains a mixture of 6-ring and staggered 8-ring structures similar to those found in tetraphenylene. On the other hand, Jenkins, et al.[4] have found mixtures of graphite and diamond crystalites on the order of 25-50 Å diameter. Also, Fischback[5] reports a definite role of the substrate surface condition in determining the crystal structure.

Presumably, it is the variety of possible crystal structures which causes the great variety in the physical and electrical properties of the films; and the great latitude in the film fabrication and vacuum deposition parameters which makes such a variety possible. It remains to find those fabrication and deposition parameters which will produce films with a useful temperature sensitivity, which are stable on thermal cycling, and have no long term drift due to room temperature annealing.

To relate these desirable properties to a particular film crystal structure is beyond the scope of this present work; rather it was our task to see if there is a semi-empirical relationship between the film deposition parameters and the electrical properties of the films and to produce some useful films (approximately 100) for further testing in NASA facilities.

At the request of NASA, a joint effort was arranged with an independent contractor under NASA contract NAS 8-25097 to fabricate the carbon films; testing, calibration and evaluation were done at NBS.

Films were deposited under various deposition rates, thickness and substrate temperature. It was found that the substrate temperature is the primary factor in determining the temperature sensitivity; lower substrate temperatures produce more sensitive films. The film deposition rate seems to be the primary factor determining stability on thermal cycling; high deposition rates tend to produce films which are unstable and often are seen to crack and peel from the substrate. The condition of the substrate also seems to be important in stability and drift, however, at present, there is no clear qualitative guideline. The thickness also plays a role in stability and sensitivity; the thicker films seem to be less sensitive.

The thickness of the films ranged from a few hundred to a few thousand Angstroms; the deposition rate ranged from 1 to 20 Angstroms per minute; and the substrate temperatures ranged from 100 to 300 centigrade.

The first parameter which was optimized was the substrate temperature at or near 200 centigrade. This was chosen so that the sensitivity of resistance vs temperature is useful in the cryogenic range between 4 and 80 kelvin; if the resistance ratio between room temperature and boiling nitrogen is on the order of two, then the resistance vs temperature is nearly linear on a log-log plot.

Secondly, the deposition rate was optimized. Initial efforts were concentrated at low deposition rates on the order of 1 Angstrom per minute since it was known[1] that at low deposition rates the films were more stable; however at these low rates it was difficult to obtain reproducible results from run to run. This is possibly due to the effect of background gases in the deposition system; the rate of impingement of gas molecules being about 300 times the carbon at these rates. At slightly higher rates, from 3 to 10 Angstroms per minute, fairly reproducible results could be obtained in the film resistance and sensitivity from run to run, and also among the samples in the same run; however, it appears that there is some sacrifice in stability and drift in some of the films. It was felt that reproducibility was the first achievement which should be made

in order to study the semi-empirical relationship between deposition parameters and electrical properties of the films.

Accordingly, eight deposition runs were made as production runs; the deposition parameters for each run are listed in Table 1. The substrate temperature was held at 200°C except for runs 001 and 002 which were held at 155°C. The deposition rates were at 8 and 17 Angstroms per minute and thicknesses ranged from 2300 to 8700 Angstroms as indicated in Figure 1. The background pressures during deposition were about 3×10^{-6} torr.

Figures 2, 3, and 4 show resistance vs temperature plotted on a log-log scale with the resistance normalized to the room temperature value. The curves are smooth lines connecting data points at room temperature and the boiling points of nitrogen, hydrogen, and helium respectively. The brackets indicate the spread among sensors deposited in the same batch. Figure 2 shows the effect of substrate temperature on sensitivity and also the effect of deposition rate at 155°C. Figure 3 shows the rate effect at 200°C; and Figure 4 shows the effect of thickness.

Thirty three sensors were deposited in each run. The substrates were modified transistor headers consisting of ground pyrex glass with Kovar pin feedthroughs for electrical contact. Twenty five of the most stable sensors were chosen from each of the four runs labeled 003, 005, 006 and 008 for a total of 100 sensors. From each batch of 25, two sensors were chosen for detailed calibration; they were designated 3-1, 3-2, 5-1, 5-2, 6-3, 6-5, 8-1 and 8-2. In addition there were two cylindrical samples 7-B and 7-C which were calibrated; these two samples were deposited previous to the present work and were included for general interest.

TABLE I

Carbon Film Deposition Parameters

Batch (1)	Temp. °C	Pressure Torr	Rate			Time Hours	Thickness (2)		
			Monitor Hz/Min	Substrate (2) Flat °A/Min	Cone °A/Min		Monitor Hz	Flat °A	Cone °A
001	155	$3X10^{-6}$	11	17	5.5	8:00	4700	7300	2300
002	155	$2x10^{-6}$	5.5	8.5	2.7	8:28	2725	4200	1400
003	200	$3X10^{-6}$	11	17	5.5	7:35	5600	8700	2800
004	200	$3X10^{-6}$	5.5	8.5	2.7	7:45	2600	4000	1300
005	200	$3X10^{-6}$	11	17	5.5	7:47	5450	8400	2700
006	200	$3X10^{-6}$	11	17	5.5	4:00	2725	4200	1400
008	200	$3X10^{-6}$	11	17	5.5	2:30	1500	2300	(3)
009	200	$3X10^{-6}$	11	17	5.5	4:13	2750	4300	1400

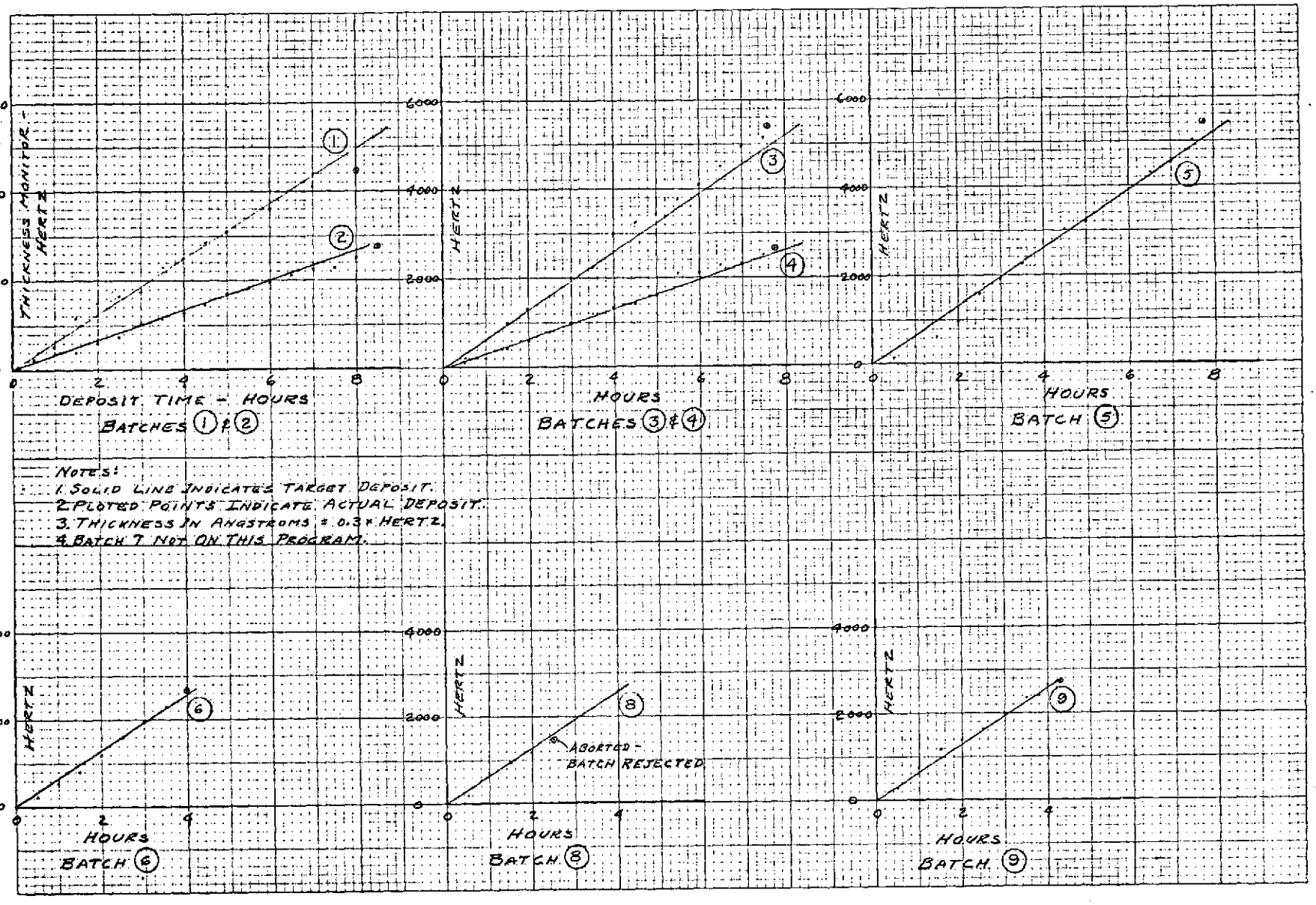


Figure 1. Carbon film deposit rate and thickness.

Chart I

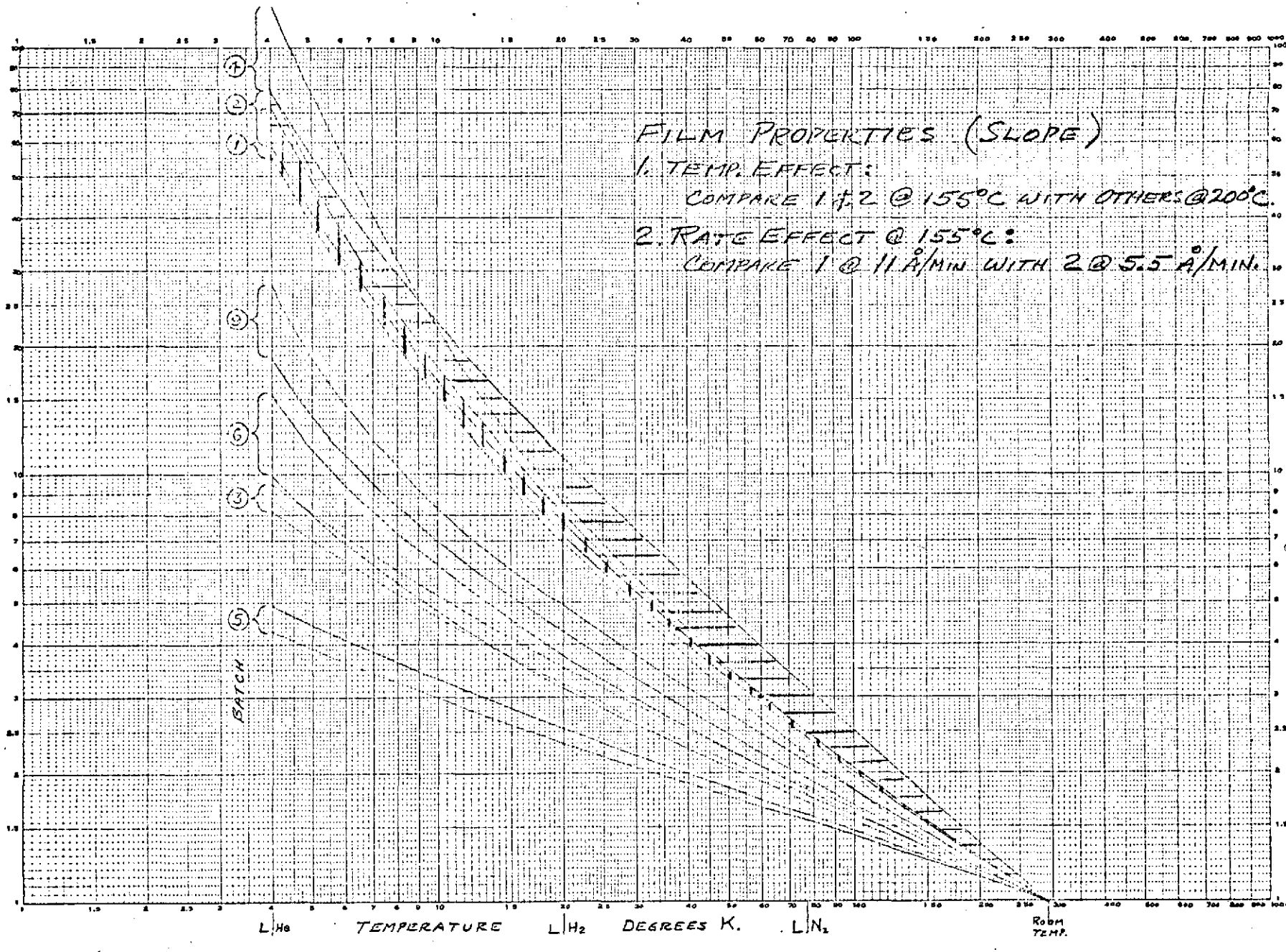


Figure 2. Film properties - Effect of substrate temperature and deposition rate. Chart II

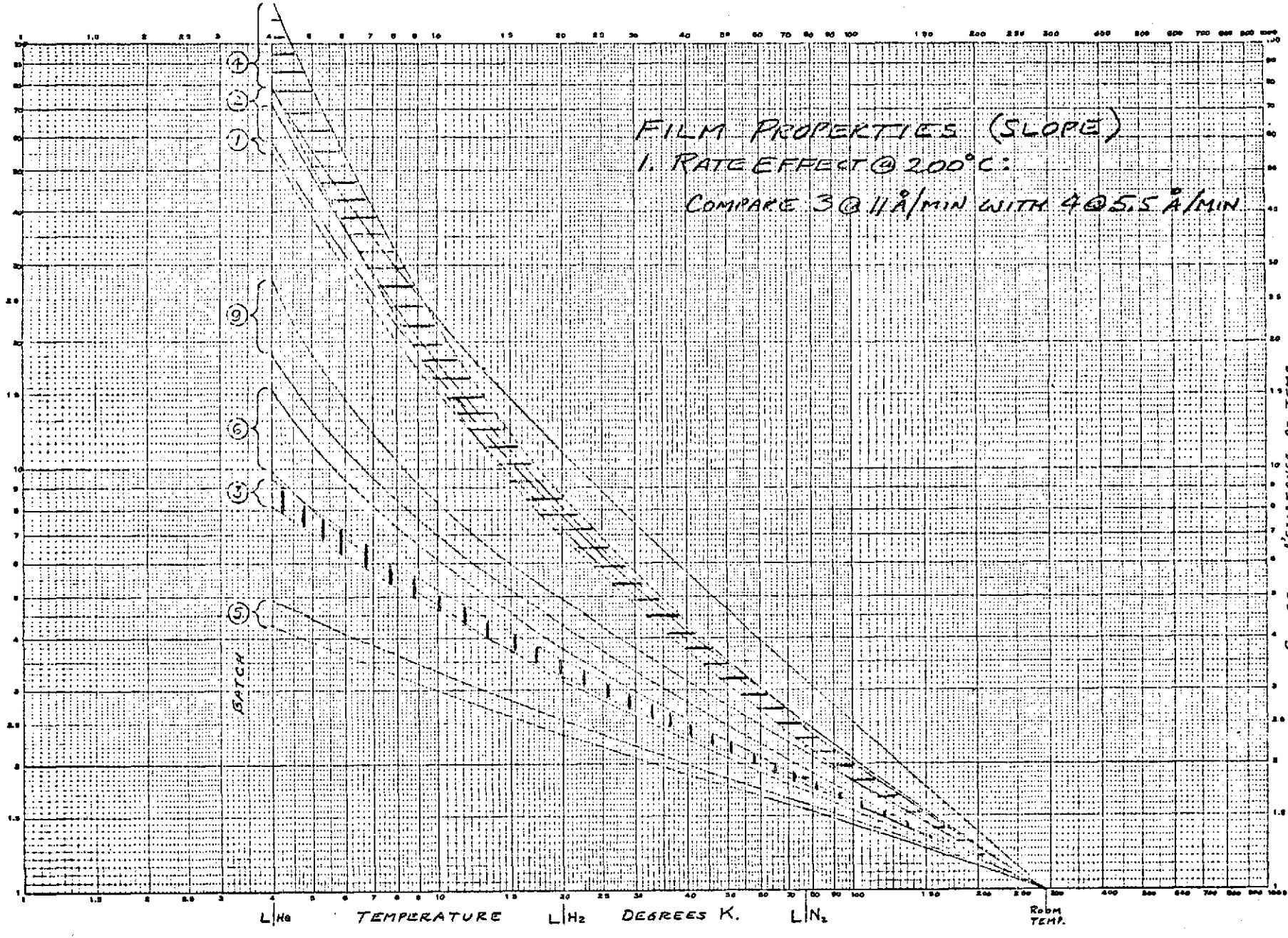


Figure 3. Film properties - Rate effect at 200°C. Chart III

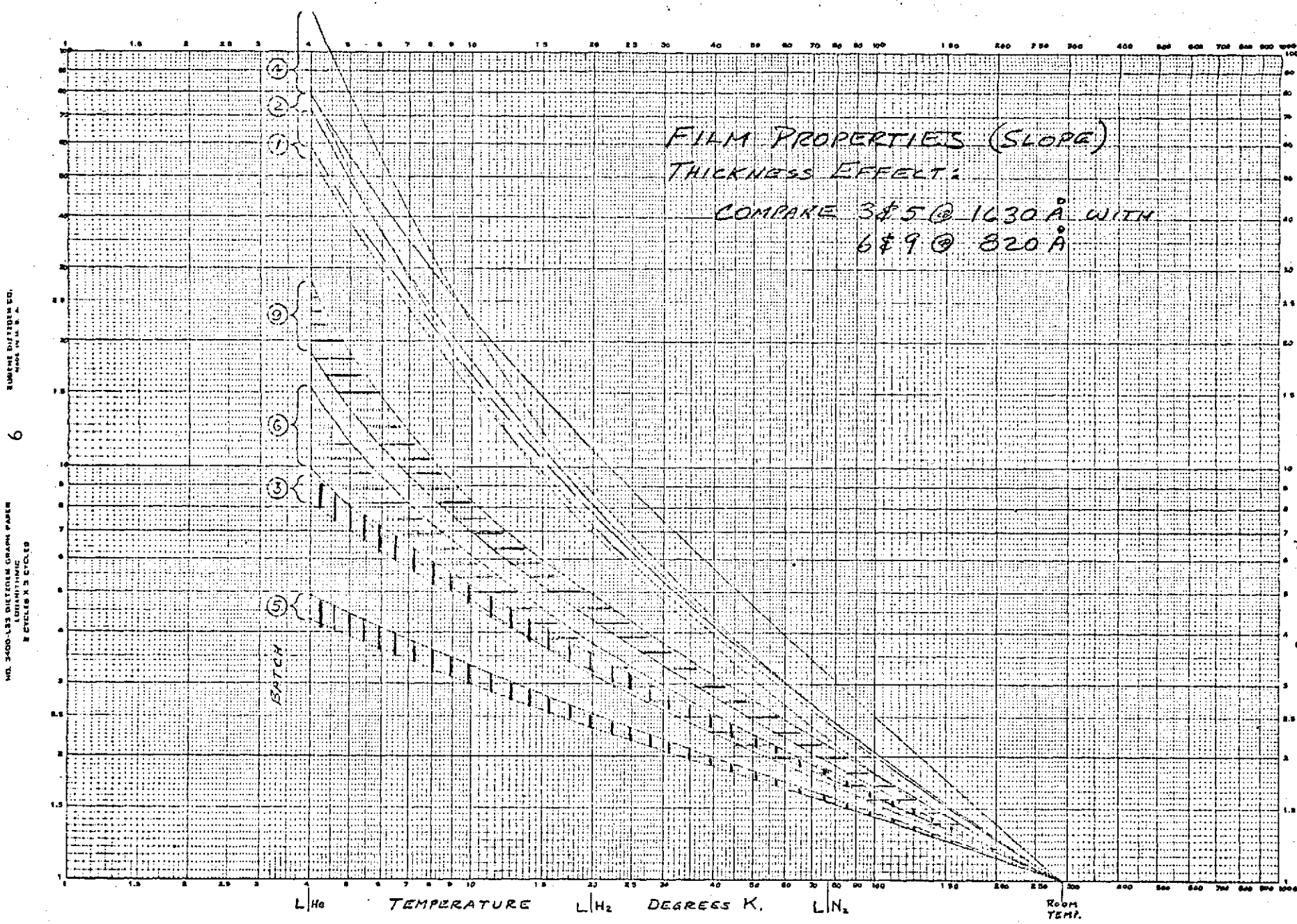


Figure 4. Film properties - Thickness effects.

Chart IV

THERMOMETER CALIBRATIONS

It is seen in figures 2-4 that the three point calibrations suggest that the resistance vs temperature is almost linear on a log-log scale if a smooth curve is drawn through the three points.

Until this present work, there has been very little data (and no precision data) at temperatures between the cryogen boiling points. Precision thermometry requires that intermediate points be known and that there be good interpolation formula between calibrated values. Also, from a qualitative point of view, the thermometer engenders more confidence in its use if there are no bumps or wiggles in the calibration curve.

With these points in mind, a precision calibration was obtained for 10 of the carbon films for temperatures between 6 and 80 K. Special attention is given to the range 13-20 K which is approximately the interval between the freezing and boiling points of hydrogen. It was expected that the carbon films would be particularly useful in this range.

The calibration was done in the cryostat used for the NBS thermocouple calibration program. This cryostat is described in detail in NBS Monograph 124 by Sparks, Powell, and Hall and is shown schematically in figure 5. A very basic sketch of the system wiring is shown in figure 6. The carbon resistors were thermally connected to the variable temperature block by imbedding the resistors in a copper ring which was in turn clamped to the variable temperature block.

The primary thermometers used to determine the temperature of the variable temperature block were a capsule type platinum resistance thermometer for temperatures above 20 K and a germanium resistance thermometer for temperatures below 20 K. Temperatures above T = 20 K are based on IPTS-68 while those below T = 20 K are based on NBS P2-20 (1965).

All measurements of resistance (primary and carbon thin film thermometers) were made using the standard four terminal method. The voltage measuring device was a Fluke model 8300A digital voltmeter. The mininum input

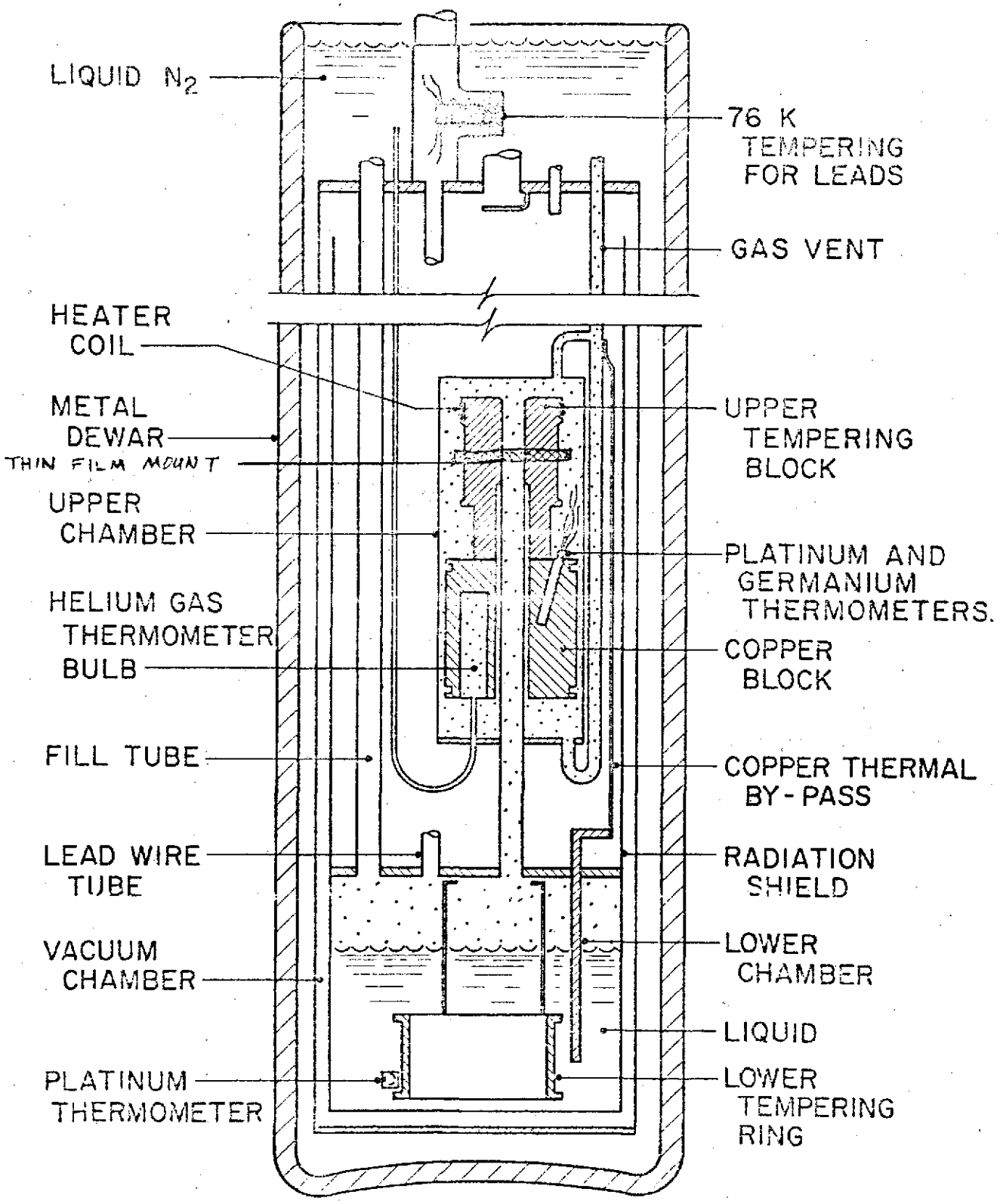


Figure 5. Calibrated cryostat.

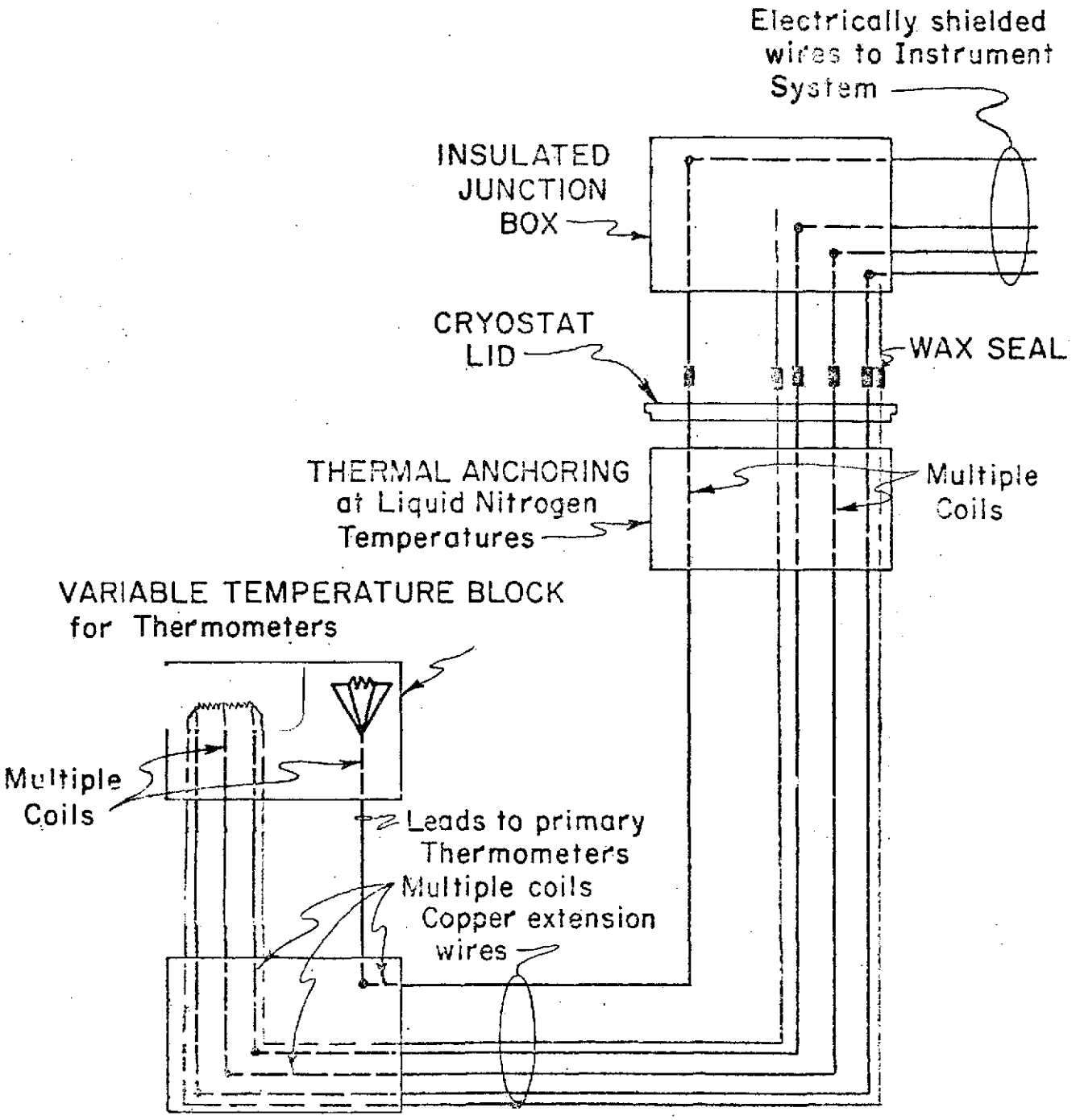


Figure 6. Electrical circuits.

resistance of this device on the ranges used is 100 mega ohms; this high input impedance allows this instrument to be used as a potentiometer in that essentially no current flows in the measurement arms. The general approach used in making all measurements was to pass current through a standard resistor and the specimen and measure the voltage across each. A similar set of voltages were taken with the current reversed through both the standard resistor and the specimen. The average of the forward and reverse voltages and knowledge of the resistance of the standard resistor allow the carbon thin film resistance to be computed. Several runs were made at a given constant temperature with different carbon resistor currents being used. No appreciable current dependence was detected.

The results of the calibrations and also other data for the films are contained in appendices to this report:

Appendix A contains the graphical representations of the data for the 10 calibrated films. The circles represent the data points and the line represents the fitted curve which is an expression of log T as a polynomial in log R. Appendix B contains the coefficients of the polynomial and a comparison of the calculated values with the experimental values. It is seen that the residuals are on the order of a few hundredths of a degree which is about the same order of accuracy as the calibrations.

Appendix C contains the three point calibrations for the other 90 films as well as some data on the long term drift for each of the runs. This data was taken over a period of 10 months. Appendix D contains information on the hydrogen gas-liquid discrimination set points.

CONCLUSIONS AND RECOMMENDATIONS

The calibrations show that the carbon film resistance vs temperature curve is smooth with no noticeable bumps or wiggles in the entire cryogenic range between 6 and 80 kelvin. The films are sensitive in the subcooled hydrogen range making these films useful for hydrogen slush applications. The film deposition process has been refined to the point where reasonable reproducibility and stability of the films may be achieved.

The empirical approach to carbon film fabrication has produced a film which should be useful for many temperature and phase sensing applications. It is felt that further refinement of the processes for precision thermometry should be pursued in order to obtain films which are consistently stable and free of drift; improvements could possibly be obtained by a study of the film crystaline properties as obtained by electron diffraction and microscopy and relating these structural properties with the electrical properties; a study of this nature has been beyond the scope of this project. Fundamental research along these lines seems to be justified since there have been several films produced "accidently"[1] which are completely stable and have no measurable long term drift. It is also possible that further semi-empirical variations of the deposition parameters may produce these desired refinements; however, it is our present view that a fundamental study at this point would be more productive.

REFERENCES

[1] J. C. Jellison and R. S. Collier, Advances in Cryogenic Engineering, Vol. 14, p 322-330 (1969).

[2] R. S. Collier and J. C. Jellison, Advances in Cryogenic Engineering, Vol. 15, p 251-261 (1970).

[3] J. Gjonnes, Acta Cryst., Vol. 13(1):54 (1960).

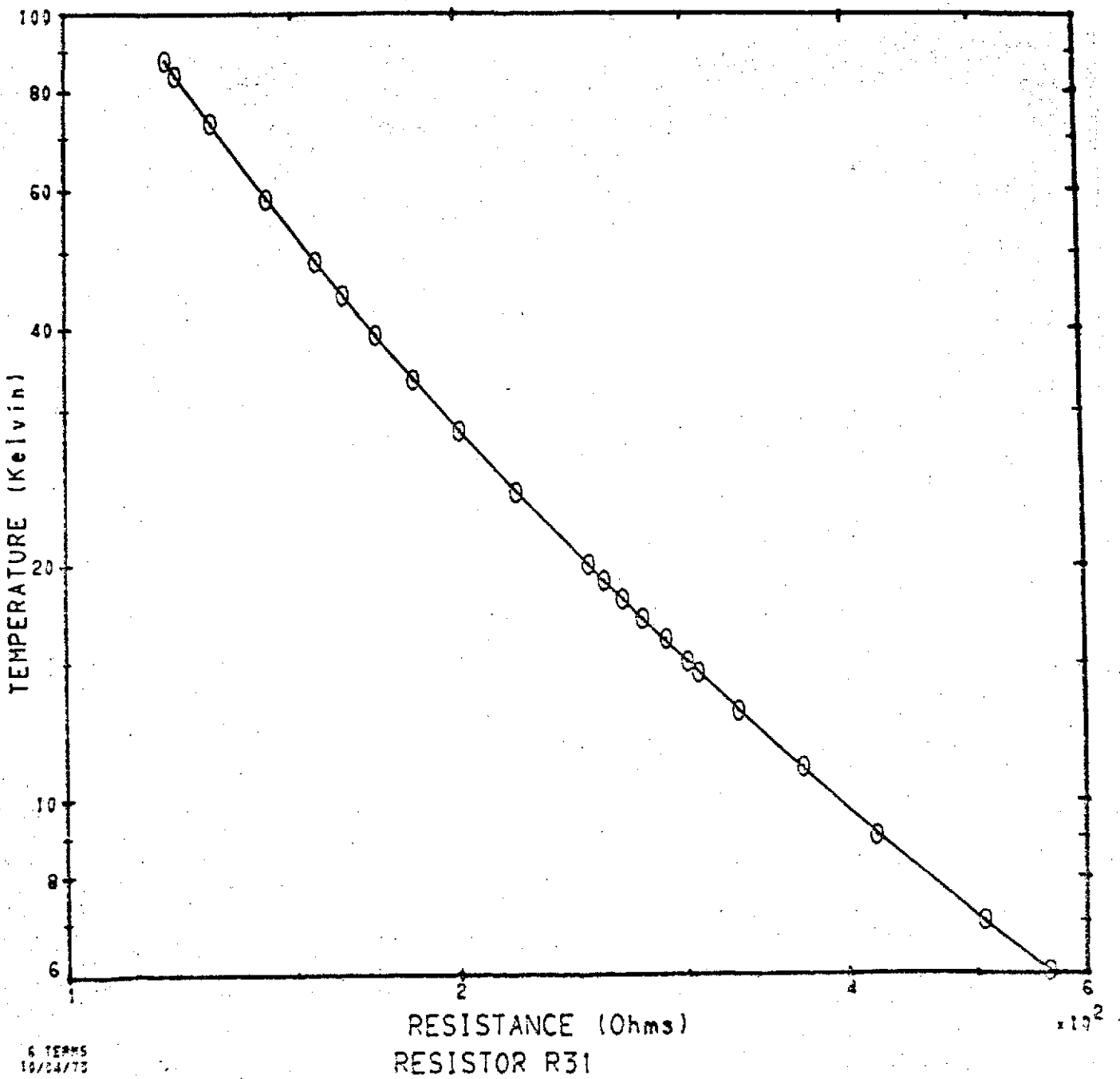
[4] G. M. Jenkins, J. A. Turnbull and G. K. Williamson, J. Nuclear Materials (Netherlands), Vol. 7(2):215 (1962).

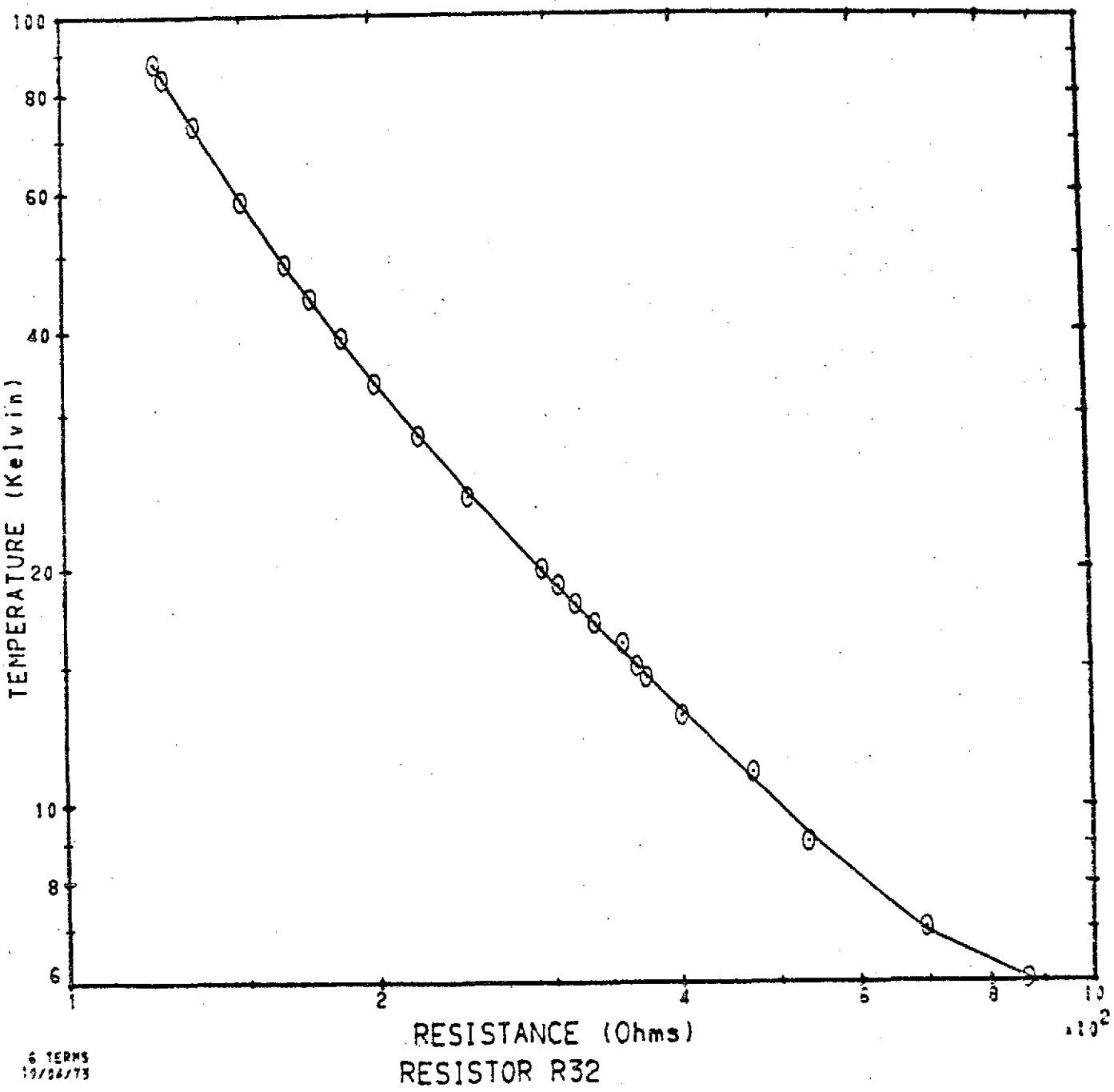
[5] D. B. Fischback, NASA Report CR-97494.

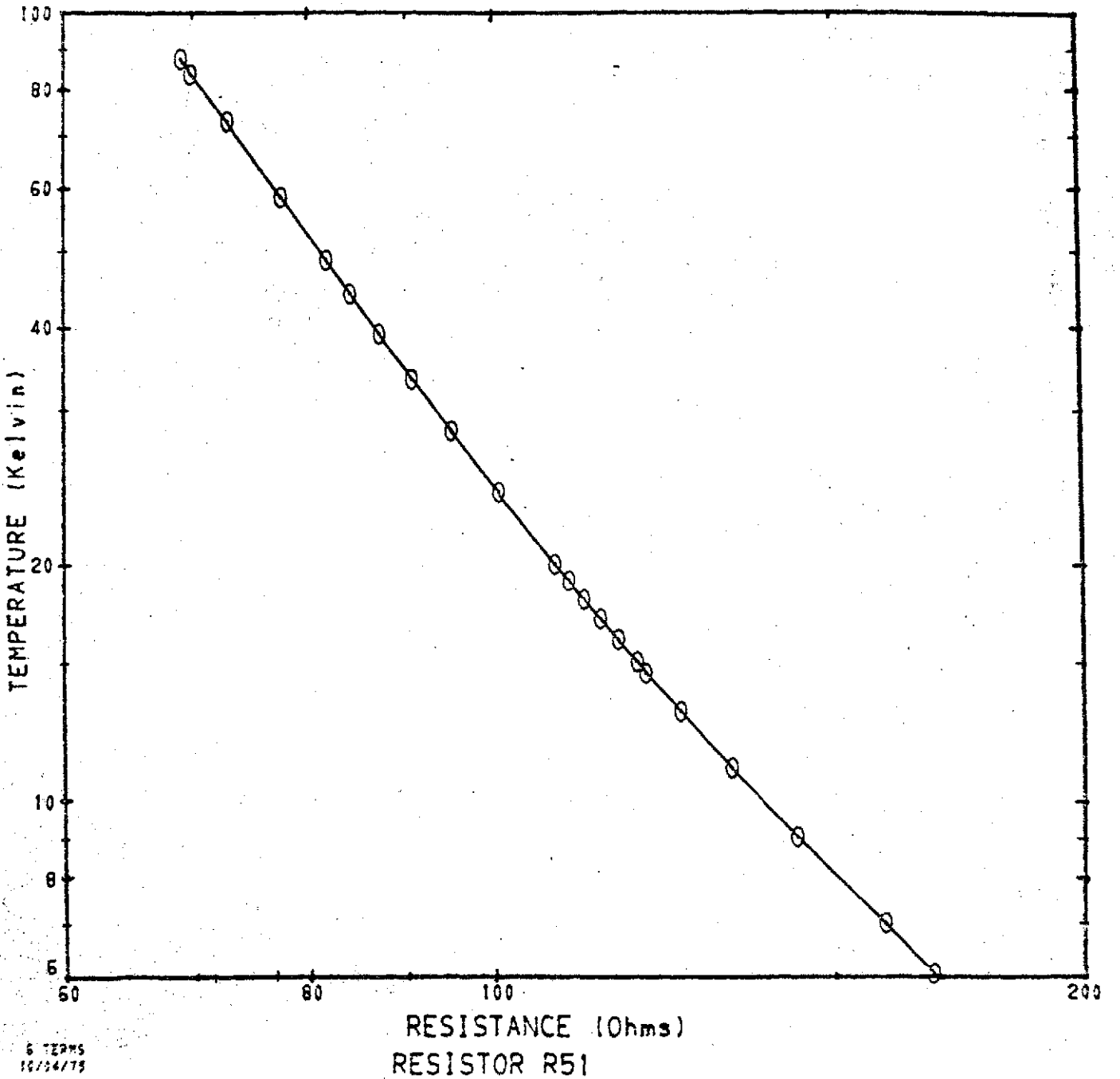
APPENDIX A

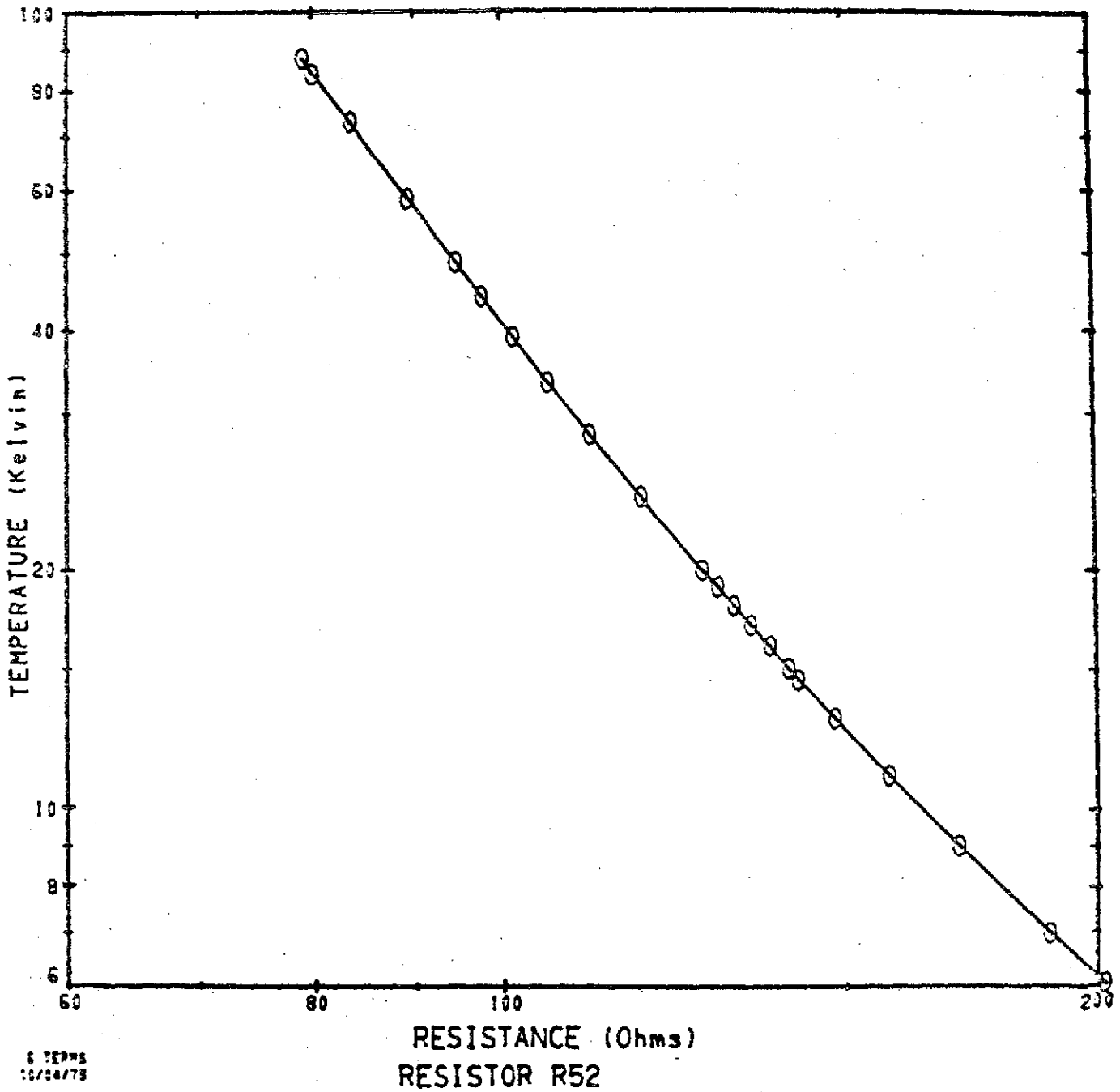
GRAPHICAL REPRESENTATIONS OF THE CALIBRATED FILMS.

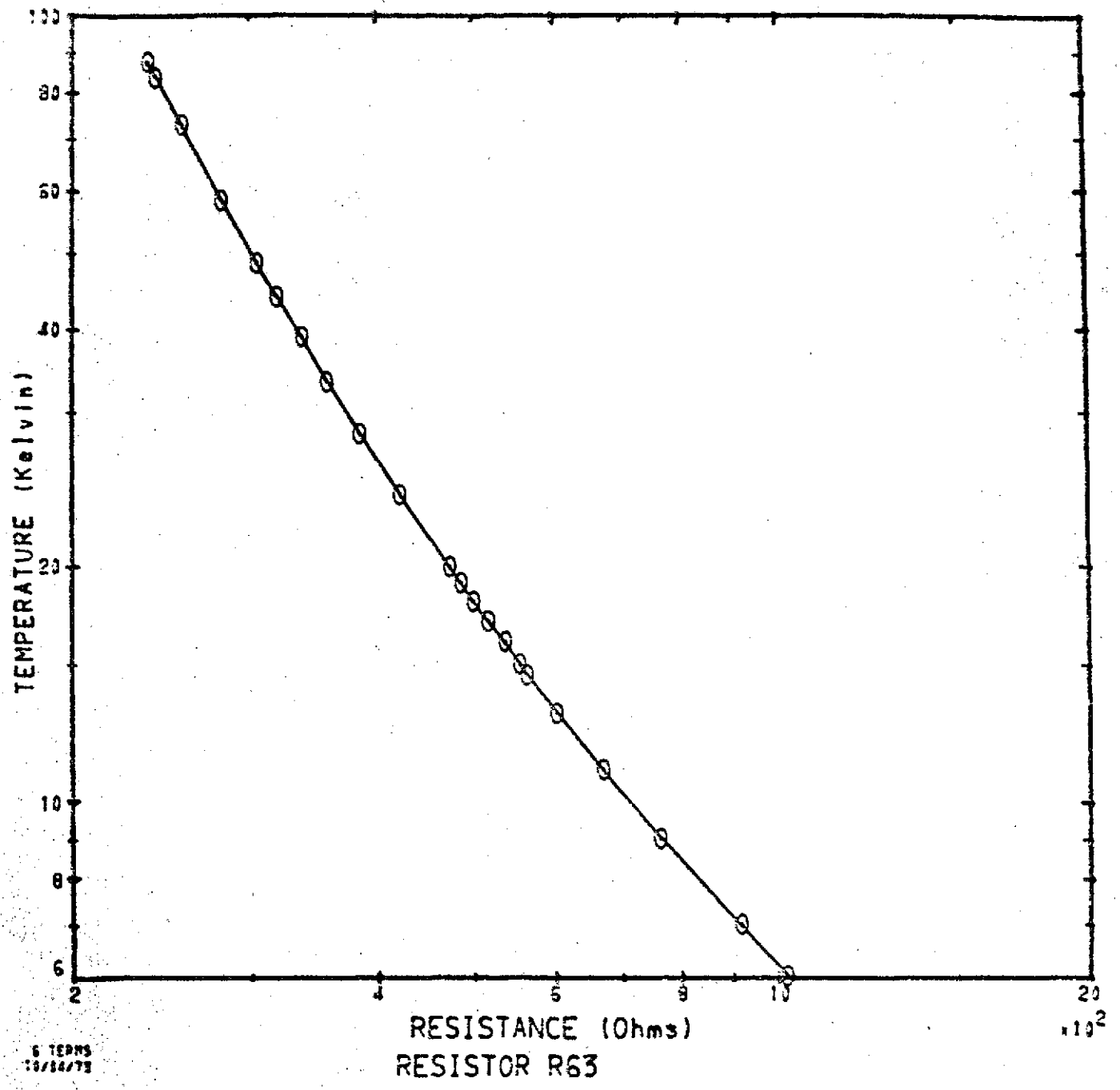
The following graphs show the resistance vs temperature for each of the ten calibrated films. The dotted circles represent the data points and the solid lines is the mathematical fit described in Appendix B.

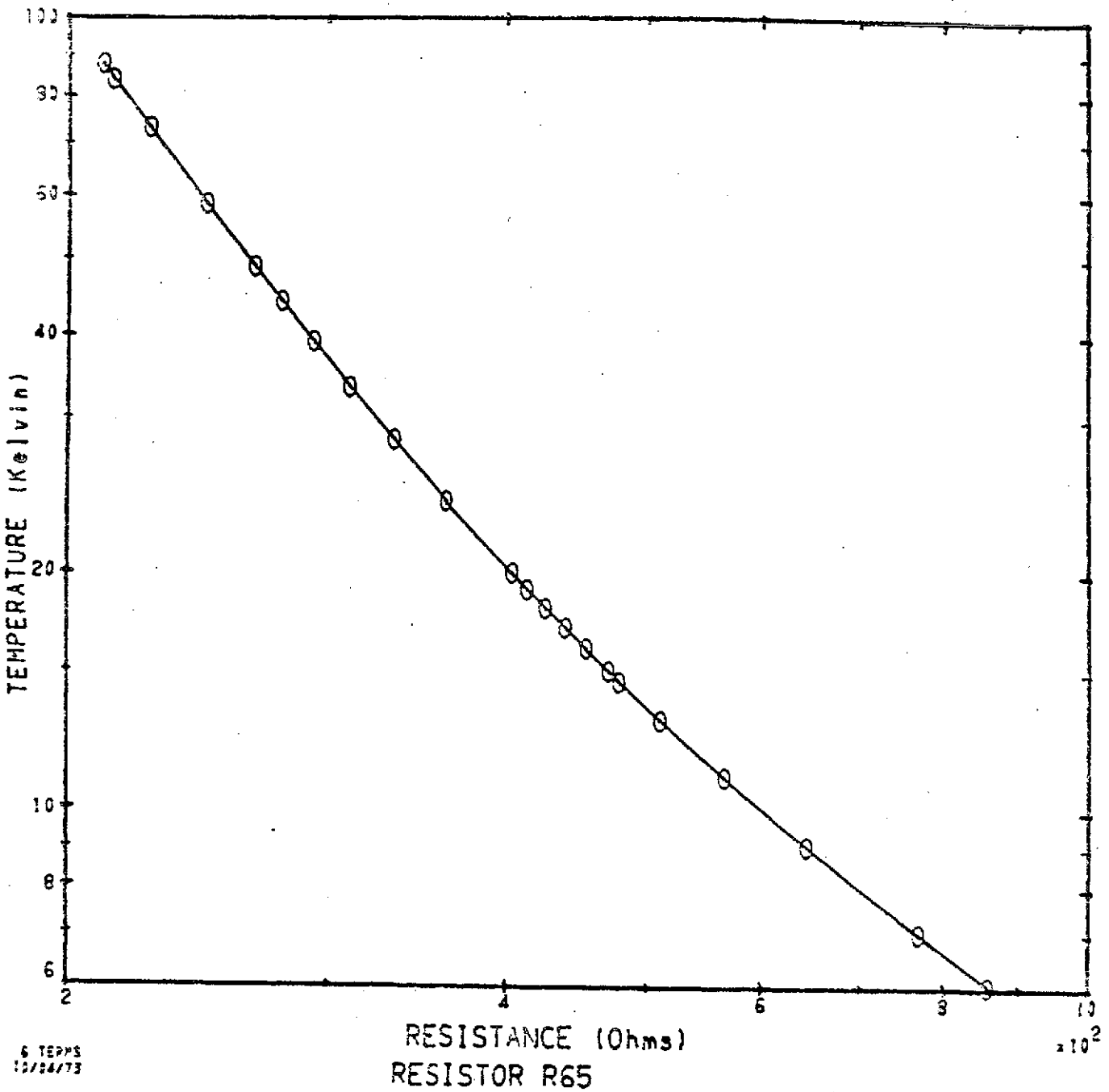

100
80
60
40
20
10
8
6
TEMPERATURE (Kelvin)
1
2
4
6
x10^2
RESISTANCE (Ohms)
6 TERMS
10/24/73
RESISTOR R31

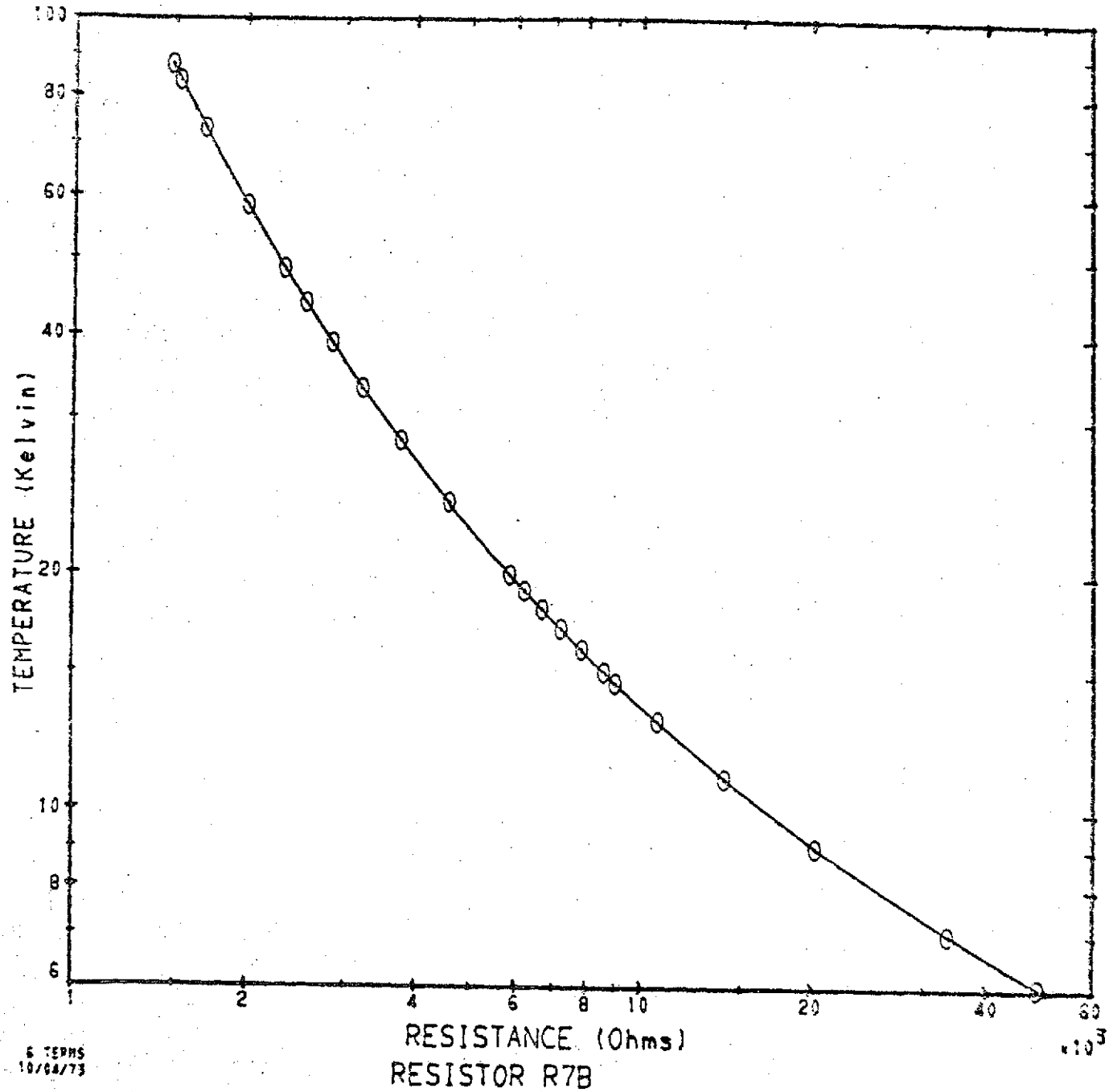

100
80
60
40
20
10
8
6
TEMPERATURE (Kelvin)
1
2
4
6
8
10
x10²
RESISTANCE (Ohms)
6 TERMS
10/06/73
RESISTOR R32

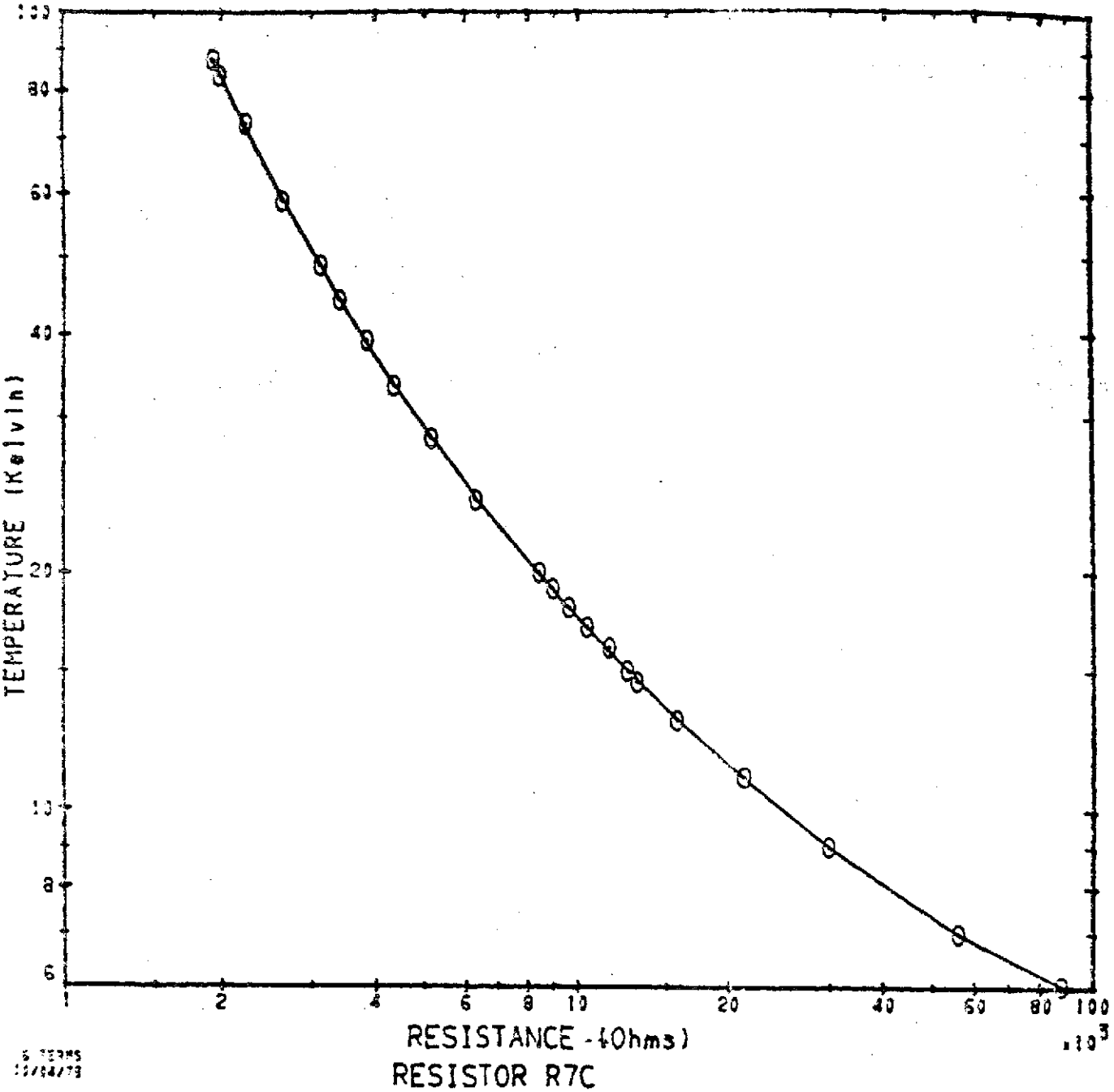

100
80
60
40
20
10
8
6
TEMPERATURE (Kelvin)
60
80
100
200
RESISTANCE (Ohms)
RESISTOR R51
6 TERMS
12/14/75

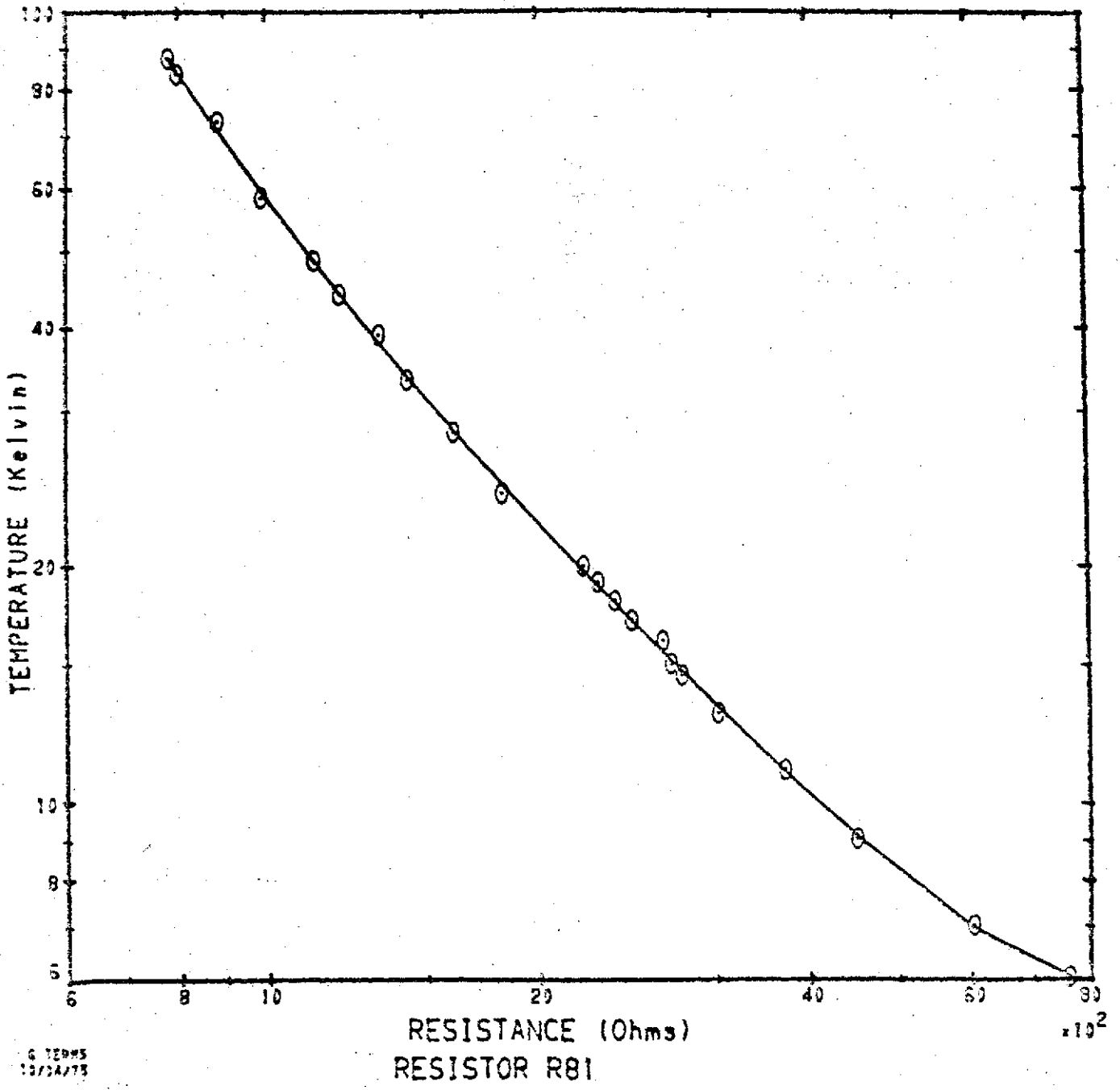

100
90
60
40
20
10
8
6
TEMPERATURE (Kelvin)
60
80
100
200
RESISTANCE (Ohms)
RESISTOR R52

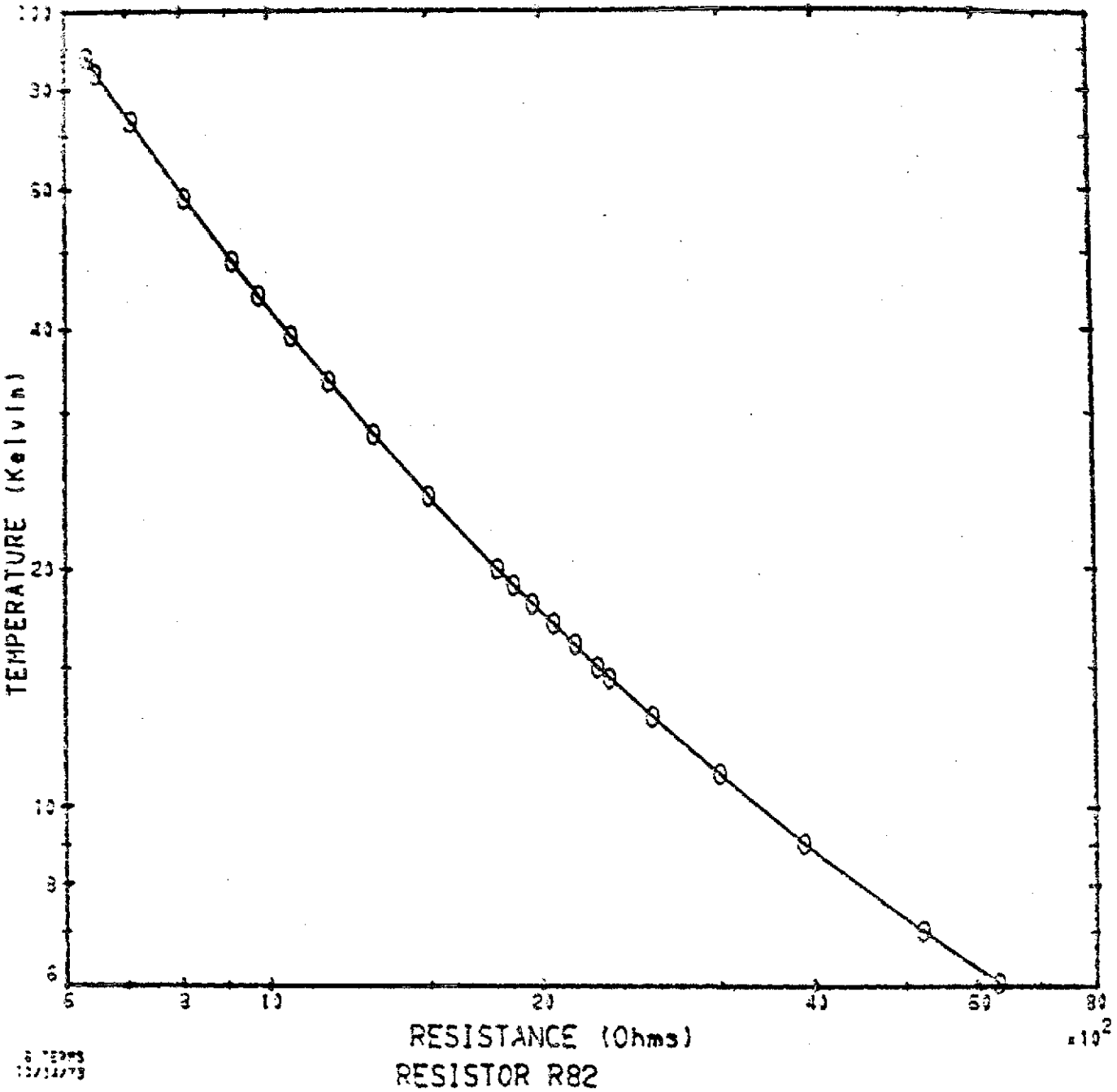

TEMPERATURE (Kelvin)
80
60
40
20
10
8
6
2
4
5
8
10
20
RESISTANCE (Ohms)
x10²
RESISTOR R63


TEMPERATURE (Kelvin)
100
80
60
40
20
10
8
6
2
4
6
8
10
x10²
RESISTANCE (Ohms)
RESISTOR R65
6 TEPPS
10/24/73


100
80
60
40
20
10
8
6
TEMPERATURE (Kelvin)
1
2
4
6
8
10
20
40
60
RESISTANCE (Ohms)
x10^3
6 TEPHS
10/04/73
RESISTOR R7B


TEMPERATURE (Kelvin)
80
60
40
20
10
8
6
2
4
6
8
10
20
40
50
80
100
RESISTANCE - (Ohms)
x10³
RESISTOR R7C


TEMPERATURE (Kelvin)
100
80
60
40
20
10
8
6
6
8
10
20
40
60
80
RESISTANCE (Ohms)
x10²
RESISTOR R81


TEMPERATURE (Kelvin)
RESISTANCE (Ohms)
x10²
RESISTOR R82

APPENDIX B

DATA AND CURVE FITTING FOR THE CALIBRATED FILMS

The following tables give the measured values of resistance and temperature as well as the coefficients and calculated values of the temperature in terms of

$$\log T = A + B \log R + C (\log R)^2 + D (\log R)^3 + E (\log R)^4 + F (\log R)^5$$

THIN FILM CARBON THERMOMETER R31-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R31

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.371JJ12666+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

5.51113634J0+000	CONSTANT
-1.7422326455+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

9.7057719203+000	CONSTANT
-5.2744037115+000	X**1
7.38d51J8967-001	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.690409329d+001	CONSTANT
-1.6820747946+001	X**1
5.5473615761+000	X**2
-6.6465960323-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

4.11033663739+001	CONSTANT
-5.4125964739+001	X**1
2.697773[1]39+001	X**2
-7.1843076622+000	X**3
6.781343[811]-001	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A =	-2.971322903[7]+002	CONSTANT
B =	6.5355934441[+002	X**1
C =	-5.61[4233297+002	X**2
D =	2.3[5]4[0]0582+002	X**3
E =	-5.042410311[+001	X**4
F =	4.23[5]3[0]9236+000	X**5

THIN FILM CARBON THERMOMETER RS1-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
5.6601+002	5.000000+000	6.014322+000	-1.532245-002
5.0551+002	7.000000+000	6.961524+000	4.647550-002
4.1899+002	9.000000+000	9.076797+000	-7.179677-002
3.6905+002	1.100400+001	1.095896+001	5.504402-002
3.2900+002	1.298300+001	1.305450+001	-7.150446-002
3.0646+002	1.454600+001	1.457531+001	-2.931236-002
3.0061+002	1.502300+001	1.502269+001	3.094971-004
2.8988+002	1.592300+001	1.591068+001	1.123194-001
2.7808+002	1.702000+001	1.700299+001	1.700961-002
2.6839+002	1.801300+001	1.800650+001	6.500265-003
2.5979+002	1.901700+001	1.898982+001	2.717742-002
2.5242+002	1.994100+001	1.991442+001	2.657789-002
2.2219+002	2.460200+001	2.474375+001	-1.417503-001
2.0134+002	2.950100+001	2.951880+001	-1.779575-002
1.8545+002	3.439100+001	3.443118+001	-4.018172-002
1.7367+002	3.922800+001	3.911711+001	1.028931-001
1.6358+002	4.412700+001	4.412173+001	5.270180-003
1.5602+002	4.866800+001	4.865415+001	1.384630-002
1.4303+002	5.852400+001	5.859219+001	-6.818933-002
1.2971+002	7.303300+001	7.285702+001	1.759761-001
1.2192+002	8.330100+001	8.401244+001	-2.114374-001
1.1985+002	8.751100+001	8.743130+001	7.969902-002

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 9.696964+002

THIN FILM CARBON THERMOMETER R31-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R31

log X	log Y	log YCALC	log Y - log YCALC
2.752621+000	7.730789-001	7.791667-001	-1.107847-003
2.703726+000	8.455941-001	8.427044-001	2.869736-003
2.622201+000	9.544837-001	9.579326-001	-3.448895-003
2.567088+000	1.041945+000	1.039769+000	2.175892-003
2.517193+000	1.113375+000	1.115760+000	-2.385334-003
2.486375+000	1.162744+000	1.163618+000	-8.742874-004
2.476007+000	1.176757+000	1.176748+000	8.947216-006
2.462226+000	1.194744+000	1.191389+000	3.355076-003
2.444172+000	1.230960+000	1.230525+000	4.342463-004
2.428759+000	1.255586+000	1.255429+000	1.567505-004
2.414623+000	1.279142+000	1.278521+000	6.210993-004
2.402118+000	1.299747+000	1.299168+000	5.792252-004
2.346729+000	1.390970+000	1.393466+000	-2.495110-003
2.303923+000	1.469637+000	1.470099+000	-2.618984-004
2.268217+000	1.536445+000	1.536952+000	-5.071243-004
2.239736+000	1.593508+000	1.592367+000	1.140863-003
2.213733+000	1.644704+000	1.644653+000	5.187182-005
2.193192+000	1.687243+000	1.687120+000	1.235766-004
2.155433+000	1.767334+000	1.767840+000	-5.057243-004
2.112983+000	1.853519+000	1.852471+000	1.047714-003
2.086070+000	1.923249+000	1.924344+000	-1.094394-003
2.078630+000	1.942063+000	1.941667+000	3.957056-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 1.629-003
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 0.0013

THIN FILM CARBON THERMOMETER R32-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R32

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.3710312666+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

4.8396048482+000	CONSTANT
-1.4211992530+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

8.9736358826+000	CONSTANT
-4.7959736224+000	X**1
6.8258709403-001	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.4564258369+001	CONSTANT
-1.1580215630+001	X**1
3.4034400063+000	X**2
-3.6266432159-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

1.0561523255+002	CONSTANT
-1.5938916010+002	X**1
9.2381939038+001	X**2
-2.4378544107+001	X**3
2.4036044443+000	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A = -3.6301982824+002	CONSTANT
B = 7.8807157783+002	X**1
C = -6.7053117117+002	X**2
D = 2.8214463591+002	X**3
E = -5.8913522633+001	X**4
F = 4.8836863126+000	X**5

THIN FILM CARBON THERMOMETER R32-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R32

log X	log Y	log YCALC	log Y - log YCALC
2.938695+000	7.730789-001	7.793544-001	-1.275501-003
2.840110+000	8.455941-001	8.403375-001	5.256588-003
2.727363+000	9.544837-001	9.652082-001	-1.072449-002
2.672654+000	1.041945+000	1.033536+000	8.409006-003
2.604414+000	1.113375+000	1.120528+000	-7.153072-003
2.569380+000	1.162744+000	1.165442+000	-2.698503-003
2.559565+000	1.176757+000	1.178056+000	-1.299438-003
2.546337+000	1.204744+000	1.195089+000	9.655136-003
2.519291+000	1.230960+000	1.230071+000	8.880800-004
2.500657+000	1.255586+000	1.254354+000	1.232433-003
2.483219+000	1.279142+000	1.277260+000	1.881669-003
2.468015+000	1.299747+000	1.297417+000	2.329995-003
2.394205+000	1.390970+000	1.398849+000	-7.878660-003
2.345025+000	1.469837+000	1.471217+000	-1.380317-003
2.302818+000	1.536445+000	1.537473+000	-1.028008-003
2.270950+000	1.593508+000	1.590466+000	3.041290-003
2.240323+000	1.644704+000	1.644017+000	6.873042-004
2.217043+000	1.687243+000	1.686515+000	7.268414-004
2.174410+000	1.767334+000	1.768390+000	-1.055640-003
2.128696+000	1.853519+000	1.851746+000	1.773066-003
2.099178+000	1.923249+000	1.924722+000	-1.473247-003
2.091233+000	1.942063+000	1.941979+000	8.353562-005

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 5.373-003
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 0.0054

THIN FILM CARBON THERMOMETER K32-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
6.6835+002	5.999000+000	6.016645+000	-1.764466-002
6.9201+002	7.008000+000	6.923688+000	8.431174-002
5.3373+002	9.005000+000	9.230138+000	-2.251384-001
4.7060+002	1.101400+001	1.080279+001	2.112067-001
4.3217+002	1.298300+001	1.319861+001	-2.156080-001
3.7101+002	1.454600+001	1.463666+001	-9.066343-002
3.6271+002	1.502300+001	1.506802+001	-4.501712-002
3.5183+002	1.602300+001	1.567071+001	3.522910-001
3.3059+002	1.702000+001	1.698523+001	3.476829-002
3.1671+002	1.811300+001	1.756196+001	5.104449-002
3.0424+002	1.901700+001	1.893478+001	8.221679-002
2.9377+002	1.994100+001	1.983430+001	1.066972-001
2.4786+002	2.460200+001	2.505238+001	-4.503848-001
2.2132+002	2.950100+001	2.959491+001	-9.391208-002
2.0083+002	3.439100+001	3.447250+001	-8.150254-002
1.8662+002	3.922000+001	3.894631+001	2.736916-001
1.7391+002	4.412700+001	4.405722+001	6.977912-002
1.6483+002	4.866800+001	4.858639+001	8.160708-002
1.4942+002	5.552400+001	5.866643+001	-1.424274-001
1.3449+002	7.393300+001	7.273544+001	2.975593-001
1.2565+002	8.350100+001	8.408576+001	-2.847589-001
1.2338+002	8.751100+001	8.749417+001	1.683093-002

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 2.236708-001

THIN FILM CARBON THERMOMETER R51-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R51

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.3710012666+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

7.5674085355+000	CONSTANT
-3.0445644480+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

1.4305327496+001	CONSTANT
-9.7955443976+000	X**1
1.6712213497+000	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

5.0433445878+000	CONSTANT
3.9444907503+000	X**1
-5.1065236901+000	X**2
1.1127661433+000	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

-2.7722643207+002	CONSTANT
5.6366637036+002	X**1
-4.2371268526+002	X**2
1.3806440597+002	X**3
-1.6833552034+001	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A = 2.6623670343+002	CONSTANT
B = -6.3153273916+002	X**1
C = 7.5965252873+002	X**2
D = -4.4432366319+002	X**3
E = 1.2659365434+002	X**4
F = -1.4126514323+001	X**5

THIN FILM CARBON THERMOMETER R51-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R51

log X	log Y	log YCALC	log Y - log YCALC
2.226604+000	7.780789-001	7.788543-001	-7.753936-004
2.201060+000	8.455941-001	8.439406-001	1.653460-003
2.156905+000	9.544837-001	9.552228-001	-7.390836-004
2.123040+000	1.041945+000	1.042662+000	-7.171956-004
2.096480+000	1.113375+000	1.113865+000	-4.896680-004
2.078722+000	1.162744+000	1.163076+000	-3.328238-004
2.074105+000	1.176757+000	1.176098+000	6.582031-004
2.064376+000	1.204744+000	1.203858+000	8.861779-004
2.055094+000	1.230960+000	1.230744+000	2.154560-004
2.046560+000	1.255586+000	1.255819+000	-2.325942-004
2.038776+000	1.279142+000	1.278983+000	1.586298-004
2.031767+000	1.299747+000	1.300080+000	-3.331474-004
2.002619+000	1.390970+000	1.390176+000	7.942306-004
1.977752+000	1.469837+000	1.469835+000	1.447625-006
1.957367+000	1.536445+000	1.536800+000	-3.549521-004
1.940312+000	1.593508+000	1.593770+000	-2.627305-004
1.925065+000	1.644704+000	1.645284+000	-5.796740-004
1.912625+000	1.687243+000	1.687615+000	-3.716975-004
1.889347+000	1.767334+000	1.767248+000	8.612961-005
1.861785+000	1.863519+000	1.861544+000	1.974816-003
1.843111+000	1.923249+000	1.924935+000	-1.685714-003
1.838151+000	1.942163+000	1.941616+000	4.464811-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 9.503-004
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS

THIN FILM CARBON THERMOMETER RS1-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
1.6850+002	5.999000+000	6.009720+000	-1.072024-002
1.5888+002	7.008000+000	6.981370+000	2.663036-002
1.4352+002	9.005003+000	9.020338+000	-1.533778-002
1.3275+002	1.101400+001	1.103220+001	-1.820359-002
1.2486+002	1.298300+001	1.299765+001	-1.465260-002
1.1987+002	1.454600+001	1.455715+001	-1.115168-002
1.1861+002	1.502300+001	1.500025+001	2.275115-002
1.1598+002	1.602300+001	1.599034+001	3.266160-002
1.1353+002	1.702000+001	1.701156+001	8.441627-003
1.1132+002	1.801300+001	1.802265+001	-9.649769-003
1.0934+002	1.901700+001	1.901006+001	6.944855-003
1.0759+002	1.994100+001	1.995630+001	-1.530261-002
1.0606+002	2.080200+001	2.075705+001	4.495062-002
9.5006+001	2.950100+001	2.950090+001	9.833463-005
9.0650+001	3.439100+001	3.441912+001	-2.811951-002
8.7159+001	3.922000+001	3.924373+001	-2.373368-002
8.4152+001	4.412700+001	4.418594+001	-5.893778-002
8.1776+001	4.866800+001	4.870967+001	-4.167107-002
7.7508+001	5.852400+001	5.851239+001	1.160538-002
7.2742+001	7.303300+001	7.270166+001	3.313405-001
6.9680+001	8.380100+001	8.412691+001	-3.259056-001
6.8691+001	8.751100+001	8.742108+001	8.992039-002

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 1.215954-001.

THIN FILM CARBON THERMOMETER R52-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R52

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.3710012666+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

7.4032634120+000	CONSTANT
-2.8933481703+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

1.3501872424+001	CONSTANT
-2.7513161300+000	X**1
1.4024727356+000	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

8.1545688121+000	CONSTANT
-1.0808582741+000	X**1
-2.2571385101+000	X**2
5.8174518904-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

-1.2114150758+002	CONSTANT
2.4682353635+002	X**1
-1.8023134555+002	X**2
5.7281323239+001	X**3
-6.7639150366+000	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A = -6.1535425239+002	CONSTANT
B = 1.4279746611+003	X**1
C = -1.3081359288+003	X**2
D = 5.9518884209+002	X**3
E = -1.3487327646+002	X**4
F = 1.2191963003+001	X**5

THIN FILM CARBON THERMOMETER R52-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R52

log X	log Y	log YCALC	log Y - log YCALC
2.305456+000	7.783789-001	7.782491-001	-1.732260-004
2.277971+000	3.455941-001	3.452279-001	3.662034-004
2.232876+000	9.544637-001	9.546026-001	-1.388691-004
2.198196+000	1.041945+000	1.041934+000	1.126916-005
2.170429+000	1.113375+000	1.114176+000	-8.011666-004
2.152175+000	1.162744+000	1.162922+000	-1.783396-004
2.147136+000	1.176757+000	1.176534+000	2.227425-004
2.137081+000	1.204744+000	1.203973+000	7.706258-004
2.127368+000	1.230960+000	1.230792+000	1.677061-004
2.118426+000	1.255586+000	1.255750+000	-1.643820-004
2.113194+000	1.279142+000	1.278962+000	1.802639-004
2.102925+000	1.299747+000	1.299648+000	9.927712-005
2.071381+000	1.390970+000	1.391455+000	-4.844692-004
2.045341+000	1.469857+000	1.469712+000	1.244737-004
2.023566+000	1.536445+000	1.536776+000	-3.307447-004
2.005526+000	1.593503+000	1.593030+000	4.773447-004
1.989322+000	1.644704+000	1.644866+000	-1.613067-004
1.976145+000	1.687243+000	1.687166+000	7.740222-005
1.951229+000	1.767334+000	1.767911+000	-5.769026-004
1.922243+000	1.863513+000	1.862446+000	1.072776-003
1.903203+000	1.923249+000	1.924400+000	-1.150470-003
1.897918+000	1.942063+000	1.941516+000	5.468579-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 5.761-004
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 0.0006

THIN FILM CARBON THERMOMETER R52-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
2.0251+002	5.999000+000	6.001352+000	-2.351529-003
1.8966+002	7.003000+000	7.002693+000	5.906838-003
1.7095+002	9.005000+000	9.007465+000	-2.465477-003
1.5783+002	1.101400+001	1.101371+001	2.855617-004
1.4806+002	1.298300+001	1.300697+001	-2.397255-002
1.4196+002	1.454600+001	1.455130+001	-5.304297-003
1.4033+002	1.502300+001	1.501530+001	7.703073-003
1.3711+002	1.602300+001	1.599459+001	2.840650-002
1.3408+002	1.702000+001	1.701343+001	6.571132-003
1.3135+002	1.801300+001	1.801982+001	-6.819275-003
1.2888+002	1.901700+001	1.900911+001	7.891804-003
1.2674+002	1.994100+001	1.993644+001	4.557873-003
1.1786+002	2.462200+001	2.462946+001	-2.746075-002
1.1100+002	2.958100+001	2.949255+001	8.454446-003
1.0558+002	3.439100+001	3.441720+001	-2.620105-002
1.0130+002	3.922000+001	3.917692+001	4.308407-002
9.7571+001	4.412700+001	4.414339+001	-1.639281-002
9.4655+001	4.866800+001	4.865933+001	8.673088-003
8.9378+001	5.352400+001	5.360179+001	-7.779303-002
8.3607+001	7.303300+001	7.285282+001	1.801804-001
8.0021+001	8.380100+001	8.402329+001	-2.222877-001
7.9053+001	8.751100+001	8.740088+001	1.101233-001

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 8.116510-002

THIN FILM CARBON THERMOMETER R63-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R63

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.3710012666+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

6.3350330227+000	CONSTANT
-1.8712558773+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

1.3093782611+001	CONSTANT
-6.9553472010+000	X**1
9.5229839925-001	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.8103627836+001	CONSTANT
-1.2584682748+001	X**1
3.0526621835+000	X**2
-2.6037960736-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

-1.7699827705+001	CONSTANT
4.1054450643+001	X**1
-2.7091723344+001	X**2
7.2521762230+000	X**3
-7.0054437400-001	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A =	3.4841538407+001	CONSTANT
B =	-5.7100028549+001	X**1
C =	4.6256004171+001	X**2
D =	-2.0136720602+001	X**3
E =	4.3933324141+000	X**4
F =	-3.7872970384-001	X**5

THIN FILM CARBON THERMOMETER R63-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R63

log X	log Y	log YCALC	log Y - log YCALC
3.010092+000	7.730769-001	7.790838-001	-1.004937-003
2.962980+000	8.455941-001	8.431654-001	2.430690-003
2.883104+000	9.544837-001	9.565544-001	-2.070718-003
2.826895+000	1.041945+000	1.041457+000	4.883661-004
2.780645+000	1.113375+000	1.115210+000	-1.835264-003
2.751643+000	1.162744+000	1.163434+000	-6.906642-004
2.743865+000	1.176757+000	1.176638+000	1.188347-004
2.728807+000	1.204744+000	1.202535+000	2.208530-003
2.712686+000	1.230960+000	1.230401+000	5.583514-004
2.693035+000	1.255586+000	1.255055+000	5.313950-004
2.666108+000	1.278142+000	1.278415+000	7.273539-004
2.674974+000	1.298747+000	1.298808+000	9.389865-004
2.625162+000	1.338970+000	1.341184+000	-2.213192-003
2.566258+000	1.469837+000	1.470443+000	-6.064737-004
2.553828+000	1.536445+000	1.537378+000	-9.436393-004
2.520618+000	1.593508+000	1.592195+000	1.312990-003
2.503828+000	1.644784+000	1.644820+000	-1.154793-004
2.484784+000	1.687243+000	1.687099+000	1.441853-004
2.449182+000	1.767334+000	1.766120+000	-7.856532-004
2.409452+000	1.863519+000	1.861525+000	1.994388-003
2.383359+000	1.923249+000	1.924545+000	-1.296170-003
2.376245+000	1.942063+000	1.941955+000	1.081243-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 1.508-03
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS [illegible]

THIN FILM CARBON THERMOMETER R63-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
1.0235+003	5.999000+000	6.012897+000	-1.389747-002
9.1629+002	7.000000+000	6.963887+000	3.911331-002
7.6402+002	9.005000+000	9.048038+000	-4.303840-002
6.7127+002	1.101400+001	1.100162+001	1.237833-002
6.0345+002	1.298300+001	1.303798+001	-5.498033-002
5.6447+002	1.454600+001	1.456915+001	-2.315110-002
5.5445+002	1.502300+001	1.501839+001	4.110137-003
5.3556+002	1.602300+001	1.594172+001	8.127536-002
5.1626+002	1.702000+001	1.699813+001	2.186773-002
5.0008+002	1.801300+001	1.799097+001	2.202682-002
4.8541+002	1.901700+001	1.898518+001	3.182291-002
4.7312+002	1.994100+001	1.989753+001	4.346773-002
4.2165+002	2.460200+001	2.472769+001	-1.256933-001
3.8573+002	2.950100+001	2.954223+001	-4.122607-002
3.5795+002	3.439100+001	3.446581+001	-7.480634-002
3.3730+002	3.922000+001	3.910161+001	1.183936-001
3.1303+002	4.412700+001	4.413873+001	-1.173494-002
3.0534+002	4.866800+001	4.865184+001	1.615504-002
2.8131+002	5.852400+001	5.862997+001	-1.059677-001
2.5572+002	7.303300+001	7.269838+001	3.346166-001
2.4175+002	8.330100+001	8.405148+001	-2.504812-001
2.3782+002	8.751100+001	8.748922+001	2.178450-002

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 1.220983-001

THIN FILM CARBON THERMOMETER R65-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 T VERSUS LOG10 R FOR RESISTOR R65

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.3710012566+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

6.4272731136+000	CONSTANT
-1.9544315714+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

1.4151635612+001	CONSTANT
-7.9073348814+000	X**1
1.1423009574+000	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.6552480529+001	CONSTANT
-1.2970757128+001	X**1
3.0776107242+000	X**2
-2.4582527339-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

-6.1663309840+001	CONSTANT
1.1043096039+002	X**1
-6.7955533133+001	X**2
1.7886053136+001	X**3
-1.7322660358+000	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A =	7.3394774301+001	CONSTANT
B =	-1.4845624062+002	X**1
C =	1.3021009414+002	X**2
D =	-5.7830602265+001	X**3
E =	1.2710013377+001	X**4
F =	-1.1003729029+000	X**5

THIN FILM CARBON THERMOMETER R65-2
' IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 T VERSUS LOG10 R FOR RESISTOR R65

log X	log Y	log YCALC	log Y - log YCALC
2.933639+000	7.730789-001	7.785894-001	-5.105504-004
2.886513+000	8.455941-001	8.443749-001	1.219164-003
2.839276+000	9.544837-001	9.552361-001	-7.523448-004
2.792356+000	1.041945+000	1.042467+000	-5.216957-004
2.746575+000	1.113375+000	1.114024+000	-6.489874-004
2.680262+000	1.162744+000	1.162657+000	8.704490-005
2.672556+000	1.176757+000	1.176230+000	5.265814-004
2.657088+000	1.204744+000	1.203925+000	8.191013-004
2.642487+000	1.230960+000	1.230622+000	3.375037-004
2.629057+000	1.255586+000	1.255661+000	-7.457062-005
2.616738+000	1.279142+000	1.279036+000	1.056832-004
2.606051+000	1.299747+000	1.299634+000	1.125209-004
2.560258+000	1.390970+000	1.391257+000	-2.864738-004
2.522876+000	1.469837+000	1.470053+000	-2.163992-004
2.492380+000	1.536445+000	1.536927+000	-4.820238-004
2.467368+000	1.593508+000	1.593455+000	5.240462-005
2.445132+000	1.644704+000	1.644934+000	-2.297746-004
2.427238+000	1.687243+000	1.687165+000	7.850572-005
2.394046+000	1.767334+000	1.767308+000	2.556411-005
2.355834+000	1.863519+000	1.862284+000	1.234865-003
2.331410+000	1.923249+000	1.924384+000	-1.134943-003
2.324630+000	1.942063+000	1.941804+000	2.587082-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 6.805-004
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 0.0007

THIN FILM CARBON THERMOMETER R65-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
8.5830+002	5.999000+000	6.006056+000	-7.056485-003
7.7004+002	7.000000+000	6.988355+000	1.964548-002
6.4458+002	9.000500+000	9.020613+000	-1.561322-002
5.6540+002	1.101400+001	1.102724+001	-1.323650-002
5.1118+002	1.298300+001	1.300241+001	-1.941324-002
4.7892+002	1.454600+001	1.454308+001	2.915137-003
4.7050+002	1.502300+001	1.500480+001	1.820432-002
4.5403+002	1.602300+001	1.599281+001	3.019170-002
4.3902+002	1.702000+001	1.700678+001	1.322163-002
4.2565+002	1.801300+001	1.801609+001	-3.093190-003
4.1375+002	1.901700+001	1.901237+001	4.627119-003
4.0369+002	1.994100+001	1.993563+001	5.165826-003
3.6329+002	2.460200+001	2.461823+001	-1.623353-002
3.3333+002	2.950100+001	2.951570+001	-1.470335-002
3.1073+002	3.439100+001	3.442919+001	-3.819179-002
2.9334+002	3.922000+001	3.921527+001	4.732237-003
2.7870+002	4.412700+001	4.415035+001	-2.335269-002
2.6745+002	4.866800+001	4.865920+001	8.796726-003
2.4777+002	5.852400+001	5.852056+001	3.444836-003
2.2690+002	7.303500+001	7.282563+001	2.073658-001
2.1449+002	8.380100+001	8.402028+001	-2.192837-001
2.1117+002	8.751100+001	8.745869+001	5.211457-002

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 7.870544-002

THIN FILM CARBON THERMOMETER R78-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R78 $\log T = P(\log R)$

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.371J012666+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

4.3284982238+000	CONSTANT
-7.8791433184-001	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

9.0588478418+000	CONSTANT
-3.2695004831+000	X**1
3.2143779514-001	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.7052827364+001	CONSTANT
-9.5271763650+000	X**1
1.9356054087+000	X**2
-1.3020591785-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

2.3232337710+001	CONSTANT
-1.5967824204+001	X**1
4.4576159340+000	X**2
-5.7173648020-001	X**3
2.7823803430-002	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A =	2.8073623052+001	CONSTANT
B =	-2.2305391190+001	X**1
C =	7.7362626960+000	X**2
D =	-1.4165233134+000	X**3
E =	1.3665388255-001	X**4
F =	-5.5602565100-003	X**5

THIN FILM CARBON THERMOMETER R78-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R73

log X	log Y	log YCALC	log Y - log YCALC
4.669313+000	7.780789-001	7.782267-001	-1.478465-004
4.536646+000	6.459941-001	6.491820-001	4.121263-004
4.308964+000	9.548437-001	9.548146-001	-3.308374-004
4.148441+000	1.041945+000	1.042203+000	-2.583277-004
4.033112+000	1.113375+000	1.113658+000	-2.827367-004
3.954941+000	1.162744+000	1.162733+000	1.102259-005
3.935084+000	1.176757+000	1.176222+000	5.342866-004
3.894953+000	1.204744+000	1.204199+000	5.451243-004
3.858037+000	1.230950+000	1.230813+000	1.453635-004
3.824464+000	1.255556+000	1.255770+000	-1.836499-004
3.793554+000	1.279142+000	1.279216+000	-7.442784-005
3.767453+000	1.299747+000	1.299958+000	-2.031787-004
3.658798+000	1.390979+000	1.390832+000	1.384170-004
3.572495+000	1.469537+000	1.469936+000	-9.951833-005
3.504741+000	1.536445+000	1.536796+000	-3.512193-004
3.453396+000	1.593503+000	1.593698+000	-1.932031-004
3.403333+000	1.644764+000	1.644920+000	-2.158108-004
3.367026+000	1.687243+000	1.687107+000	1.363865-004
3.300769+000	1.767334+000	1.767034+000	3.003280-004
3.225903+000	1.863519+000	1.863579+000	9.399537-004
3.161675+000	1.923249+000	1.924377+000	-1.128197-003
3.169571+000	1.942063+000	1.941755+000	3.074531-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 4.828-004
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 0.0005

THIN FILM CARBON THERMOMETER R78=2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
4.8900+004	5.999000+000	6.001043+000	-2.042582-003
3.4407+004	7.000800+000	7.001353+000	6.647156-003
2.0369+004	9.005000+000	9.011862+000	-6.862455-003
1.4075+004	1.101400+001	1.102055+001	-6.553312-003
1.0718+004	1.298300+001	1.299146+001	-8.455074-003
9.0145+003	1.454600+001	1.454563+001	3.691611-004
8.0116+003	1.502300+001	1.500453+001	1.847033-002
7.8515+003	1.602300+001	1.600290+001	2.009937-002
7.2117+003	1.702000+001	1.701426+001	5.735020-003
6.6755+003	1.801300+001	1.802062+001	-7.618756-003
6.2209+003	1.901700+001	1.902026+001	-3.259345-003
5.8540+003	1.994100+001	1.995061+001	-9.606933-003
4.5582+003	2.460200+001	2.459416+001	7.839825-003
3.7368+003	2.950100+001	2.950776+001	-6.760947-003
3.1970+003	3.439100+001	3.441832+001	-2.732368-002
2.8210+003	3.922000+001	3.923718+001	-1.718024-002
2.5342+003	4.412700+001	4.414893+001	-2.193316-002
2.3282+003	4.866800+001	4.865266+001	1.533741-002
1.9988+003	5.852400+001	5.848354+001	4.045717-002
1.6862+003	7.303300+001	7.287510+001	1.578960-001
1.5201+003	8.330100+001	8.401898+001	-7.179787-001
1.4776+003	8.751100+001	8.744907+001	6.193033-002

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 7.113360-002

THIN FILM CARBON THERMOMETER R7C-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R7C

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.5710012566+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

4.2277305555+000	CONSTANT
-7.3032431752-001	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

8.8427171151+000	CONSTANT
-3.0504915771+000	X**1
2.8767160148-001	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.5607357344+001	CONSTANT
-8.1202912186+000	X**1
1.5417395790+000	X**2
-1.0238200639-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

3.3606385167+001	CONSTANT
-2.6117740025+001	X**1
8.2478715540+000	X**2
-1.2055349914+000	X**3
6.7616573703-002	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A = 1.8946133413+001	CONSTANT
B =-7.8266671487+000	X**1
C =-8.3417710622-001	X**2
D = 1.0372114197+000	X**3
E =-2.0736666972-001	X**4
F = 1.3463032185-002	X**5

THIN FILM CARBON THERMOMETER R7C-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R7C

log X	log Y	log YCALC	log Y - log YCALC
4.944117+000	7.780789-001	7.783020-001	-2.231788-004
4.745101+000	8.455941-001	8.448957-001	6.983729-004
4.494631+000	9.544857-001	9.551220-001	-6.382482-004
4.328511+000	1.041545+000	1.041270+000	6.747161-004
4.193520+000	1.113375+000	1.115896+000	-2.521263-003
4.119812+000	1.162744+000	1.164482+000	-1.738644-003
4.099373+000	1.176757+000	1.177557+000	-8.004975-004
4.064525+000	1.204744+000	1.200312+000	4.431767-003
4.019219+000	1.230960+000	1.230809+000	1.504491-004
3.984220+000	1.255586+000	1.255115+000	4.714385-004
3.952221+000	1.279142+000	1.277938+000	1.203918-003
3.924693+000	1.299747+000	1.298054+000	1.692903-003
3.801058+000	1.390970+000	1.394419+000	-3.448342-003
3.711772+000	1.469857+000	1.470903+000	-1.045800-003
3.639089+000	1.536445+000	1.538048+000	-1.603599-003
3.586212+000	1.593508+000	1.589935+000	3.573055-003
3.532748+000	1.644704+000	1.645209+000	-5.042808-004
3.493600+000	1.687243+000	1.687590+000	-3.466263-004
3.421622+000	1.767334+000	1.770013+000	-2.679033-003
3.350244+000	1.863519+000	1.857935+000	5.583897-003
3.298773+000	1.923249+000	1.925446+000	-2.196554-003
3.265986+000	1.942063+000	1.942777+000	-7.144518-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 2.599-003
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 0.0026

THIN FILM CARBON THERMOMETER R7C-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
6.7926+004	5.999000+000	6.002064+000	-3.063607-003
5.5603+004	7.008000+000	6.996740+000	1.126025-002
3.1234+004	9.005000+000	9.018244+000	-1.324366-002
2.1306+004	1.101400+001	1.099690+001	1.709797-002
1.5795+004	1.298300+001	1.305859+001	-7.559100-002
1.3177+004	1.454600+001	1.460435+001	-5.834981-002
1.2571+004	1.502300+001	1.505072+001	-2.771613-002
1.1602+004	1.602300+001	1.586032+001	1.626756-001
1.0452+004	1.702000+001	1.701410+001	5.895077-003
9.6432+003	1.801300+001	1.799346+001	1.954300-002
8.9582+003	1.901700+001	1.896436+001	5.264446-002
8.4080+003	1.994100+001	1.986342+001	7.757977-002
6.3250+003	2.460200+001	2.479612+001	-1.961139-001
5.1496+003	2.950100+001	2.957349+001	-7.248718-002
4.3560+003	3.439100+001	3.451822+001	-1.272209-001
3.8567+003	3.922000+001	3.889865+001	3.213496-001
3.4099+003	4.412700+001	4.417827+001	-5.126780-002
3.1160+003	4.866800+001	4.870686+001	-3.885922-002
2.6401+003	5.852400+001	5.888613+001	-3.621329-001
2.2400+003	7.303300+001	7.210000+001	9.330035-001
1.9896+003	8.330100+001	8.422592+001	-4.249184-001
1.9319+003	8.751100+001	8.765506+001	-1.440816-001

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 2.975335-001

THIN FILM CARBON THERMOMETER R81-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R81

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.371001256E+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

5.408837790E+000	CONSTANT
-1.219221445E+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

1.025923373E+001	CONSTANT
-4.141614770E+000	X**1
4.372715839E-001	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.113207381E+001	CONSTANT
-4.924555235E+000	X**1
6.701923198E-001	X**2
-2.298343708E-002	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

1.151786955E+002	CONSTANT
-1.297814782E+002	X**1
5.666557039E+001	X**2
-1.114609776E+001	X**3
8.257391343E-001	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A =-4.725471469E+002	CONSTANT
B = 7.483679635E+002	X**1
C =-4.667771003E+002	X**2
D = 1.444469756E+002	X**3
E =-2.223333443E+001	X**4
F = 1.363377527E+000	X**5

THIN FILM CARBON THERMOMETER R51-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R81

log X	log Y	log YCALC	log Y - log YCALC
3.682472+000	7.736789-001	7.799832-001	-1.304355-003
3.778698+000	9.455941-001	8.414433-001	4.150813-003
3.651408+000	9.544837-001	9.585743-001	-4.090582-003
3.574662+000	1.041945+000	1.039685+000	2.259692-003
3.500385+000	1.113375+000	1.121748+000	-8.373065-003
3.459702+000	1.162744+000	1.167692+000	-4.948163-003
3.448568+000	1.176757+000	1.180376+000	-3.618886-003
3.438428+000	1.204744+000	1.191968+000	1.277584-002
3.404947+000	1.230960+000	1.230541+000	4.189217-004
3.385455+000	1.255586+000	1.253220+000	2.365739-003
3.367062+000	1.279142+000	1.274787+000	4.354684-003
3.351071+000	1.299747+000	1.293682+000	6.065123-003
3.261420+000	1.390970+000	1.402653+000	-1.168269-002
3.206624+000	1.469837+000	1.472507+000	-2.669862-003
3.155841+000	1.536445+000	1.540036+000	-3.590866-003
3.124757+000	1.593508+000	1.582871+000	1.063666-002
3.080945+000	1.644704+000	1.645337+000	-6.330214-004
3.052054+000	1.687243+000	1.687922+000	-6.787412-004
2.995087+000	1.767334+000	1.775163+000	-7.828793-003
2.946365+000	1.863519+000	1.853065+000	1.045431-002
2.902073+000	1.923249+000	1.926178+000	-2.928391-003
2.891918+000	1.942063+000	1.943197+000	-1.134166-003

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 7.177-003
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 6.1072

THIN FILM CARBON THERMOMETER R81-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
7.6291+003	5.999000+000	6.017044+000	-1.804441-002
6.0076+003	7.008000+000	6.941339+000	6.666059-002
4.4813+003	9.005000+000	9.090218+000	-8.521801-002
3.7555+003	1.101400+001	1.095684+001	5.715843-002
3.1651+003	1.298300+001	1.323574+001	-2.527368-001
2.8821+003	1.454600+001	1.471268+001	-1.666785-001
2.6091+003	1.502300+001	1.514871+001	-1.257066-001
2.7443+003	1.602300+001	1.555851+001	4.644904-001
2.5407+003	1.702000+001	1.700359+001	1.640963-002
2.4292+003	1.801300+001	1.791514+001	9.785572-002
2.3284+003	1.901700+001	1.882727+001	1.897312-001
2.2442+003	1.994100+001	1.966445+001	2.765497-001
1.3257+003	2.460200+001	2.527278+001	-6.707843-001
1.6093+003	2.950100+001	2.968292+001	-1.819185-001
1.4317+003	3.439100+001	3.467653+001	-2.855331-001
1.3328+003	3.922000+001	3.827110+001	9.489015-001
1.2049+003	4.412700+001	4.419137+001	-6.436578-002
1.1273+003	4.866800+001	4.874412+001	-7.612071-002
9.3875+002	5.852400+001	5.958855+001	-1.064547+000
8.8382+002	7.303300+001	7.129595+001	1.737054+000
7.9813+002	8.330100+001	8.436797+001	-5.669685-001
7.7968+002	8.751100+001	8.773983+001	-2.288349-001

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 6.354228-001

THIN FILM CARBON THERMOMETER R82-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND UP TO 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R82

THE COEFFICIENTS FOR AN EXPANSION WITH 1 TERMS ARE

1.3710312665+000	CONSTANT

THE COEFFICIENTS FOR AN EXPANSION WITH 2 TERMS ARE

5.2186539168+000	CONSTANT
-1.1907831137+000	X**1

THE COEFFICIENTS FOR AN EXPANSION WITH 3 TERMS ARE

1.0167029362+001	CONSTANT
-4.2533639442+000	X**1
4.6963059639-001	X**2

THE COEFFICIENTS FOR AN EXPANSION WITH 4 TERMS ARE

1.6733667448+001	CONSTANT
-1.0302706213+001	X**1
2.3171658074+000	X**2
-1.8738160342-001	X**3

THE COEFFICIENTS FOR AN EXPANSION WITH 5 TERMS ARE

2.1681449824+001	CONSTANT
-1.6401532265+001	X**1
5.1261459036+000	X**2
-7.5577763492-001	X**3
4.3656422973-002	X**4

THE COEFFICIENTS FOR AN EXPANSION WITH 6 TERMS ARE

A = 5.6632624600+000	CONSTANT
B = 7.8472492252+000	X**1
C = -9.7136172230+000	X**2
D = 3.7715661501+000	X**3
E = -6.4603742465-001	X**4
F = 4.1869924654-002	X**5

THIN FILM CARBON THERMOMETER R82-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.
LOG10 R VERSUS LOG10 T FOR RESISTOR R82

log X	log Y	log YCALC	log Y - log YCALC
3.739999+000	7.780789-001	7.785183-001	-4.394088-004
3.717701+000	8.455941-001	8.444875-001	1.106570-003
3.589159+000	9.544837-001	9.553784-001	-8.947048-004
3.496559+000	1.041945+000	1.041700+000	2.446769-004
3.422940+000	1.113375+000	1.114613+000	-1.238316-003
3.376038+000	1.162744+000	1.163229+000	-4.855160-004
3.363537+000	1.176757+000	1.176488+000	2.682492-004
3.338498+000	1.204744+000	1.203441+000	1.302835-003
3.313741+000	1.230960+000	1.230622+000	3.375386-004
3.291621+000	1.255586+000	1.255371+000	2.147635-004
3.271002+000	1.279142+000	1.278846+000	2.961946-004
3.253285+000	1.299747+000	1.299337+000	4.098721-004
3.176487+000	1.390970+000	1.391750+000	-7.798669-004
3.115099+000	1.469837+000	1.470095+000	-2.579850-004
3.065098+000	1.536445+000	1.537068+000	-6.231999-004
3.024839+000	1.593506+000	1.593174+000	3.337472-004
2.988945+000	1.644704+000	1.644912+000	-2.073550-004
2.960476+000	1.687243+000	1.687137+000	1.060147-004
2.908265+000	1.767334+000	1.767513+000	-1.792700-004
2.849715+000	1.863519+000	1.862003+000	1.516257-003
2.812639+000	1.923249+000	1.924491+000	-1.242260-003
2.802551+000	1.942063+000	1.941851+000	2.111652-004

THE STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 8.434-004
THE WEIGHTED STANDARD DEVIATION IN THE TRANSFORMED VARIABLE IS 0.0008

THIN FILM CARBON THERMOMETER R82-2
Y IS TEMP. IN K ,X IS RESISTANCE IN OHMS
22 EXPERIMENTAL POINTS AND 6 TERMS.

X	Y	YCALC	Y-YCALC
6.3096+003	5.999000+000	6.005073+000	-6.072716-003
5.2204+003	7.006000+000	6.990167+000	1.583345-002
3.8829+003	9.005000+000	9.023571+000	-1.857063-002
3.1373+003	1.101400+001	1.100780+001	6.203424-003
2.6461+003	1.298300+001	1.302007+001	-3.707163-002
2.3770+003	1.454600+001	1.456227+001	-1.627063-002
2.3096+003	1.502300+001	1.501372+001	9.276340-003
2.1802+003	1.602300+001	1.597500+001	4.799518-002
2.0594+003	1.702000+001	1.700678+001	1.322300-002
1.9571+003	1.801300+001	1.800409+001	8.905431-003
1.8664+003	1.901700+001	1.900403+001	1.296542-002
1.7918+003	1.994100+001	1.992219+001	1.881075-002
1.5014+003	2.460200+001	2.464622+001	-4.421774-002
1.3035+003	2.950100+001	2.951853+001	-1.752976-002
1.1617+003	3.439100+001	3.444039+001	-4.938551-002
1.0589+003	3.922000+001	3.918987+001	3.012826-002
9.7487+002	4.412700+001	4.414807+001	-2.107358-002
9.1301+002	4.866800+001	4.865612+001	1.187879-002
8.0948+002	5.852400+001	5.854816+001	-2.416278-002
7.0748+002	7.303300+001	7.277046+001	2.545363-001
6.4959+002	8.380100+001	8.404105+001	-2.400484-001
6.3468+002	8.751100+001	8.746846+001	4.253976-002

THE STANDARD DEVIATION IN THE ORIGINAL VARIABLE IS 9.237923-002

APPENDIX C

DATA ON LONG TERM DRIFT AND THREE POINT CALIBRATIONS OF THE FILMS

Figures C-1 and C-2 show examples of data on long term drift and thermal cycling of the films between room temperature and the boiling point of liquid nitrogen (LN_2). A total of 109 such data sheets were delivered (along with the films) to the sponsor.

In addition, three point calibrations of the films at room temperature and the boiling points of liquid nitrogen and liquid helium were obtained for 100 films and delivered (along with the films) to the sponsor.

MP003(1) S-C

KΩ Readings

Date #	1 Room	2 LN_2	3 Room	4 LN_2	5 Room	6 LN_2
1-9-73 P	.06567	.12012	.06581	.12018	.06572	.11878
Lq. Temp.	22°		21°		20°	
1-17-73 A	.06615	.11605	.06625	.11627	.06647	.11637
	8.5°		8°		7.5°	
2-2-73 A	.06630	.11950	.06671	.11959	.06687	.11969
	22°		20°		18°	
6-13-73	.0684	.1242				
6-14-73	.0682	.1243				
6-15-73	.0678	.1243				

Figure C-1.

Pins 3, 4 Current and Voltage

MP003(2) S-C

KΩ Readings

Date	#	1	2	3	4	5	6
		Room	LN_2	Room	LN_2	Room	LN_2
1-9-73	P	.07048	.14088	.07062	.14147	.06870	.12779
Lq. Temp °C		20°		20°		19°	
1-17-73	P	.06794	.12096	.06799	.12136	.06835	.12185
		9°		9°		8°	
2-5-73	P	.06929	.12550	.06970	.12586	.06978	.12573
		15°		14°		13°	
6-13-73		.0702	.1293				
6-14-73		.0697	.1296				
6-15-73		.0695	.1294				

Figure C-2.

APPENDIX D

LIQUID-GAS DISCRIMINATION SET POINTS

The liquid-gas discrimination set point is based on the transient response of the carbon film to a constant current pulse of amplitude, I_o. A differentiating circuit measures the initital voltage transient $\frac{dV}{dt}$ given by

$$\frac{dV}{dt} \approx I_o \frac{dR}{dt}$$

$\frac{dR}{dt}$ is large in gas and small in liquid, and the set point is some intermediate point which can be set in an electronic comparator.

For peak voltages on the order of 20 V the liquid initial transients for all films at 20 kelvin is on the order of 10 volts/sec; and in gas just above the boiling point the initital transients are on the order of 1000 volts/sec; therefore a sufficient set point for all the films anywhere near 100 volts/sec will give rapid liquid-gas discrimination using circuits outlined in reference [2].

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7. AUTHOR(S)

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8. Performing Organization

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS, Boulder Labs.
DEPARTMENT OF COMMERCE
Boulder, Colorado 80302

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This is a summary of work done on NASA(Marshall Space Flight Center) purchase order H-92167A concerning Carbon Thin Film Thermometry. Optimum film deposition parameters were sought on an empirical basis for maximum stability of the films. One hundred films were fabricated for use at the Marshall Space Flight Center; 10 of these films were given a precise quasi-continuous calibration of temperature vs. resistance with 22 intervals between 5 and 80 K using primary platinum and germanium thermometers. Sensitivity curves were established and the remaining 90 films were given a three point calibration and fitted to the established sensitivity curves. Hydrogen gas-liquid discrimination set points are given for each film.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Calibration; carbon films; low temperature; thermometry; vacuum deposition.

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