RELIABILITY STUDIES OF THICK FILM COMPONENTS

FINAL REPORT

JUNE 19, 1970

PREPARED BY:

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PREPARED UNDER CONTRACT NAS 12-2122

ELECTRONIC RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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TITLE PAGE

FOREWORD

This is a final report presenting the results obtained from a program designed to develop information about the effect of material, design, and processing variables upon the performance characteristics of thick film products - resistors, capacitors, and conductors.

Salient material presented in previous quarterly reports is included in this report, sometimes in augmented form, sometimes in condensed form, but most often in the same detail in which it was reported earlier. This has been done in order to have results obtained from the complete program collected in one single document. Material entirely new to this final report is presented in Section III-G RESISTOR STABILITY STUDY.

Statistical tests of significance have been used in this report, particularly in the presentation of resistor stability results. The intent has been to make the meaning of the results more clearly discernible to the reader by drawing a distinction between results that are unlikely to have occurred if only pure chance were at work and therefore may be considered "significant", and results that are quite likely to have occurred if only pure chance were at work and therefore are not to be considered "significant". The significance tests used, except for an occasional use of the t test, are based upon methods of order statistics and are relatively simple in underlying theory and in application (these tests are discussed in more detail in Exhibit C).

The program reported here was originally conceived by Henry H. Nester and carried out by D. W. Mason and the writer under the guidance of J. M. Woulbroun, and, subsequently, of J. F. Frissora. The writer is greatly indebted to many people for support, assistance, advice, and counsel in connection with the preparation of this report including J. M. Woulbroun, J. F. Frissora, D. W. Mason, F. Cocca, C. W. Watt, and T. M. Liimatainen. It is the sincere desire of all the people past and present of the Microtek Division of Spacetac Incorporated that whatever is of value in this report shall serve as a memorial to Henry H. Nester who conceived of this program and who would have been currently writing this report had it not been for his untimely, prolonged, and finally, terminal illness of last year.

Maynard S. Renner

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I. OUTLINE OF PROGRAM

I. OUTLINE OF PROGRAM

Purpose of the Program:

To develop information about the effect of material, design, and processing variables upon the performance characteristics of thick film products - resistors, capacitors, and conductors.

Materials:

Pastes - resistor, capacitor, and conductor, were, with a few duly noted exceptions, commercial pastes.

Substrates - standard 95% Al_2O_3 substrates.

Process:

Printing - laboratory screen printers with machine variables controlled to simulate normal production product.

Firing - In accord with manufacturers' specifications in conveyor furnaces capable of $\pm 1°C$ temperature control.

Resistor Variables:

Commercially available paste compositions (five).

Paste resistivity.

Type of glaze.

Laser vs. abrasive correct.

Form factor.

Resistor area.

Firing time.

Firing temperature.

Resistor Performance Characteristics:

Comparative levels and ranges of as-fired resistance values.

Resistance temperature characteristic for the two one-square 0.100 square inch resistors.

Comparative precision of laser vs. abrasive correct.

Power loading to resistor failure for the five commercial compositions.

Current-noise index for R8 of five commercial compositions and 18 resistivity-glaze-correct combinations.

Stability under power loading at 125°C for five commercial compositions and 18 resistivity-glaze-correct combinations.

Capacitor Variables:

Dielectric composition - four commercial compositions plus one doped composition.

Electrodes - palladium gold vs. palladium silver.

Overcoating - none vs. glass vs. solder

Contamination - as noted in a detailed scrutiny of each of 120 substrates (1200 capacitors) at each step of a simulated commercial screening operation.

Capacitor Performance Characteristics:

Dielectric breakdown.

Five-second, 100 volt - 300 volt test.

Conductor Variables:

Commercially available conductor compositions (four).

Film thickness.

Firing temperature.

Conductor Performance Characteristics:

Screening defects.

Adhesion (pull test).

Solderability.

Solder leaching.

II. SUMMARY - VARIABLES FOUND TO HAVE EFFECT ON PERFORMANCE

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Variables found, in this study, to have effect upon performance of thick film products are tabulated below. Variables of major interest that were found to have no effect are noted parenthetically. Related data and discussions are presented in the body of this report.

Performance Characteristic	Variables Found to Have Effect
Resistors	
As-Fired Resistance.	Resistor Area. Type of Glaze. Paste Resistivity. Firing Time. Firing Temperature.
Temperature Coefficient of Resistance.	Paste Composition. Paste Resistivity. Type of Glaze. Firing Time. Firing Temperature. (No effect from type of correct-laser vs. abrasive.)
Precision of Resistor Correct.	Type of Correct (laser vs. abrasive). Paste Resistivity. Area of one-square resistors.
Current-Noise Index.	Paste Composition. Paste Resistivity. (No effect from type of correct-laser vs. abrasive.)

Performance Characteristic	Variables Found to Have Effect
Resistors - continued	
1000 Hour Stability Under Load at 125°C.	Paste Composition. Paste Resistivity. Type of Glaze. Resistor Area (Power Density). Resistor Width (Form Factor). Type of Correct (Abrasive vs. Laser) in interaction with Glaze. (For individual resistors, no correlation between percent increase in resistance and as-fired resistance value or measured width of resistor at correct cut.) (No correlation with current-noise index or TCR.)
Capacitors	
Breakdown Voltage.	Dielectric Composition. Electrode (Pd Au vs. Pd Ag). Overcoating.
Failure under 5-second 100 volt - 300 volt test.	Dielectric composition with electrode (Composition 3 on palladium silver). (No correspondence found between contamination observed at time of screening and capacitor failures.)
Conductors	
Screening Defects.	Film Thickness. (No effect found for paste compositions.)
Pull Test.	Paste Compositions. (No effect found for film thickness-firing temperature.)

III. RESISTOR RESULTS

Performance Characteristic	Variables Found to Have Effect
Conductors - continued	
Solderability.	Paste Composition. (No effect found for film thickness-firing temperature.)
Solder Leaching.	Paste Composition. (No effect found for film thickness-firing temperature.)

III RESISTOR RESULTS

A. Resistor Compositions and Experimental Combinations

1. Five Commercial Compositions.

Comparative performance of five different commercial 1000 ohm per square resistivity resistor pastes was studied. The five compositions were coded 211 through 215. The code numbers are identified in Exhibit D (Composition Codes). Compositions 211 through 214 were screened and fired in accord with vendor's specifications (without glass overcoating). Composition 215 was screened and fired with high temperature (680°C) glass overcoating.

2. Resistivities-Overglaze-Correct Combinations.

Effects of paste resistivity, overglaze, and type of correct were studied. A single paste system was used throughout this study. Resistor pastes formulated from the 215 material system to three different resistivities (100, 1000, and 10,000 ohms) were screened and fired with: (1) no overglaze; (2) co-fired low temperature (550°C) glass; and (3) co-fired high temperature (680°C) glass. This gave nine combinations which were then divided at random into two equal groups. One group of each combination was abrasive trimmed and the other group was laser trimmed. The plan of this study, with code numbers, is shown below (code numbers are also given in Table VI):

(Table follows.)

		Code Numbers		
Overglaze:		None	Low Temperature (550°C)	High Temperature (680°C)
Resistivity	Correct			
100 ohms	abrasive	121	123	125
100 ohms	laser	122	124	126
1000 ohms	abrasive	221	223	225
1000 ohms	laser	222	224	226
10,000 ohms	abrasive	321	323	325
10,000 ohms	laser	322	324	326

3. Firing Time - Firing Temperature Combinations.

Effects of firing time and firing temperature were studied. Composition 215 resistor paste at 1000 ohms per square resistivity was used throughout this study. It was screened and co-fired with high temperature (680°C) glass at three different firing times and peak temperatures. The plan of this study with code numbers is given below:

Firing time (minutes)	72	48	24
Peak temperature			
665	231	234	237
680	232	235	238
695	233	236	239

To obtain a check on reproducibility of results, three different sets of substrates were fired at the "center point" of 48 minutes and the (recommended) peak temperature of 680°. All three sets were coded 235 but distinguishable by the different numbers assigned to the individual substrates. This set of resistors was not tested for current noise index or performance under power loading at 125°C.

4. Form Factor and Resistor Area.

Variations in form factor and resistor area were provided by the resistor design. The design layout and the numbers assigned the various resistors are shown in Figure 1. Resistor dimensions are given in this figure and also in Tables VII and VIII A, B, and C.

Only one composition or combination was screened on any one substrate so that, for example, all resistors on all substrates designated 211 were screened with Composition 211. For another example, all resistors on all substrates designated 325 or 326 were screened with Composition 215 and co-fired with high temperature glass.

B. As-Fired Resistance Values

As-fired resistance values varied quite widely. As might be expected the smaller resistors of a pair (or triplet) of resistors of a given form factor almost universally showed as-fired resistance values at a lower percent of nominal than did the larger resistor (or resistors), and R10,

Note to Figure 10A

The resistors in the photomicrograph of the uni-directional cut in Figure 10A are 100 ohm, no glaze resistors. The various randomly placed white spots appearing in this photograph are caused by titanium dioxide lodging in pits on the resistor surface and thus they show the type of pitting characteristic of this group of resistors.

R11, and R12 tended to have lower values than their counterparts R6, R7, and R8. The no glaze and low temperature glaze samples tended to have lower as-fired values than did the high temperature glaze samples.

The resistors of the firing temperature-firing time experiment gave results which were quite uniform in terms of within lot variability. Averages of 12 readings of as-fired resistor values (ohms) for resistor number 7 are given below as representative of the data obtained.

	Temperature		
	665°C	680°C	695°C
Firing Time (Minutes)		R Ohms	
24	740	1280	1820
48	2140	2560 2390 3030	3230
72	2590	5800	5650

The results of the three different runs made at the "center" condition of 680° - 48 minutes - were in satisfactory agreement for this type of data and adequate to provide assurance that the differences in resistance values obtained under the other eight conditions may be considered real differences and not the result of chance variability.

C. Temperature Coefficient of Resistance

1. Comparison of Five Commercial Compositions.

Temperature coefficient of resistance (after correct) of resistors 6 and 10 was measured at -55°C, 50°C, and 125°C, from the 25°C reference point. The values obtained as parts per million per degree Centigrade are shown in Table I.

Resistors 6 and 10 had been uniformly corrected to a resistance value very close to 1050 ohms. Consequently, the nature of the resistance temperature characteristic for each paste can perhaps best be seen by examining the actual resistance readings at the reference temperature of 25°C and the three test temperatures of -55°, 50°, and 125°. Figure 2 shows a plot of these readings for Resistor 6 for each of the five pastes tested.

Composition 211 shows the least amount of resistance change over the range of testing temperatures. Composition 214 shows the second smallest change, approximately twice that of Composition 211. Composition 212 shows approximately twice the change of Composition 214, and Compositions 213 and 215, twice the change of Composition 212.

As indicated by the TCR values of Table I the slopes of different segments of the resistance temperature curves vary noticeably and this can also be seen graphically from Figure 2. For Compositions 211 and

214 the slope is negative from -55° to 25°, quite flat from 25° to 50°, and considerably steeper (more marked for Composition 214) from 50° to 125°. Compositions 212 and 213 show practically a linear resistance temperature relationship with almost constant slope over the entire range. Composition 215 shows a greater slope for the 25-125° segment than for the -55° to 25° portion of the curve.

2. Laser vs. Abrasive Correct.

TCR data (ppm/0°C) for resistors 6 and 10 comparing abrasive with laser correct are shown in Table II. As can be seen from Table II, for the composition used in this experiment, TCR varied little with type of correct (laser vs. abrasive). The TCR values averaged across all resistors show this point also:

Correct	Abrasive			Laser		
Temperature	125°	50°	-55°	125°	50°	-55°
R-6	272.2	229.9	-45.6	272.1	240.6	-43.7
R-10	269.9	224.1	-30.9	248.0	235.5	-30.2
Average	271.6	227.0	-38.3	260.1	238.1	-36.9

3. Effect of Glaze and Resistivity.

TCR, however, did vary with resistivity and type of glaze, as can be seen from Figure 3 in which 125°, 50°, and -55° TCR's are plotted for each of the three types of glaze at each of the three resistivities.*

*In Figures 3 and 4, for convenience of plotting, temperatures of TCR measurement are plotted not to scale but as discrete points.

At resistivities of 100 ohms and 1K ohms, TCR values were markedly higher with the high temperature overglaze than with either no glaze or low temperature glaze with neither of the latter being greatly different from one another. At the 10K resistivity, TCR values for all three types of glaze are very close together.

4. Effect of Firing Time and Firing Temperature.

The TCR values obtained are shown in Table III and charted for Resistor 6 in Figure 4.* (To provide a check on reproducibility of results, three different runs were made at the "center" condition of 48 minutes, 680°.)

For the firing conditions of this test and for the chemically dynamic paste used in this experiment, time of firing is seen to have had a much greater effect upon TCR than firing temperature. As Figure 4 shows there is little difference between any of the six sets of TCR data at 48 minutes and 72 minutes firing time with TCR values being slightly lower at the higher firing temperatures. TCR values of the 24 minute samples are different and quite high as compared with the 48 or 72 minutes samples, with the 665°-24 minute sample being definitely highest of all the values.

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*In Figures 3 and 4, for convenience of plotting, temperatures of TCR measurement are plotted not to scale but as discrete points.

D. Precision of Resistor Correct

1. Laser vs. Abrasive Correct.

Practically any required degree of precision can be obtained from the correct process depending upon the amount of effort that is put into obtaining and maintaining precision. For the purposes of this study, however, a high degree of precision of correct was not considered to be needed. Consequently, the decision was made to request an operating correct tolerance of ±1% with the understanding that all of the output from both processes, laser or abrasive, would be accepted with no rejection or reworking of units.

Upon completion of the correct operation, each resistor was again measured for resistance and the resulting values classified as higher than, lower than, or within the ±1% tolerance limits. The resulting data showed no marked superiority of one correct process over the other, although, as the summary below shows, the proportion of resistors within the ±1% tolerance limits was somewhat greater for the abrasive correct process than for the laser correct process.

Distribution	Laser	Abrasive
>1%	34.7%	13.1%
1% to -1%	55.7%	69.0%
<-1%	9.6%	17.9%
Total Resistors	1167	1154

2. Effect of Resistivity and Resistance Value.

The data were then examined in detail to find out if there were differences in behavior with different resistors or resistivities. The results are given in Table IV with sums and percentages across all resistors for each resistivity and method of correct shown in the two columns at the right of the table. Markedly fewer within tolerance resistors were obtained from the resistors made with the 100 ohm paste, as compared with the resistors made with the 1K and 10K pastes. In particular, the 20 ohm resistors appeared to give a good deal of trouble. With the 1K and 10K pastes the number and percent of resistors that tested within the $\pm 1\%$ tolerance limits was substantially lower for the laser correct than for the abrasive correct (68.2 and 46.0% vs. 82.8 and 88.1%). The number of resistors in the less than -1% category decreased as resistivity increased and dropped to zero or nearly zero for the 10K paste.

3. Effect of Resistor Width.

The one-square resistors varied in design width from 100 mils (R6 and R10) to 30 mils (R8 and R12). Coincident with this variation in width was there any variation noted in proportion of within tolerance resistors? The number of within tolerance resistors varied greater from condition to condition, but when the overall results are examined, 290 of the 100 mil width resistors fell within the $\pm 1\%$ tolerance vs. 219 of the 50 mil width resistors vs. 182 of the 30 mil width resistors. These differences are highly significant ($\chi^2 = 26.5$). When the laser vs. abrasive results are compared by resistor, it is seen that although the proportion of within tolerance resistors decreases with decreasing resistor width for both the abrasive and laser correct resistors the effect is much more marked for the laser correct than for the abrasive correct, as the following summary table of number of resistors corrected within $\pm 1\%$ tolerance limits shows:

Resistor	R6	R10	R7	R11	R8	R12
Design width (mils)	100	100	50	50	30	30
Laser correct	75	55	52	41	42	41
Abrasive correct	68	94	63	63	43	56

It should be noted, however, that this effect as seen in these data is also associated with resistance value since the same effect was not nearly so marked with the five square resistors, R4 (60 mils width) and R5 (25 mils width), as the summary of numbers of R4 and R5 resistors corrected within $\pm 1\%$ of tolerance limits shows:

Resistor	R4	R5
Design width (mils)	60	25
Laser correct	92	75
Abrasive correct	92	90

To sum up, these results point to the conclusion, obvious beforehand, that for precise correct results, low value narrow resistors require more care in the correct operation than high value wide resistors and suggest the possibility that this care may need to be intensified when the laser correct process is used to correct resistors.

E. Power Loading to Resistor Failure

The power loading to resistor failure results reported in Quarterly Report No. 3, February 15, 1970, could not be duplicated upon re-checking, are therefore to be considered suspect, and for this reason are not included in this current report.

F. Current-Noise Test

Current-noise index of Resistor 8 (.0009 sq. in.) was measured in accord with Mil-Std-202C, Method 308 using a Quan-Tech Model 315 Resistor-Noise Test Set. Current-noise index is a measure of small fluctuations in resistance values under a steady d-c potential as a result of inhomogeneities in the resistor film and in resistor-conductor interfaces. It is measured in decibels and the lower the noise level, i.e. the more negative the current noise index, the more desirable the performance. Average readings (12 resistors per average) and minimum and maximum values are tabulated in Tables V-A and V-B.

Note to Figure 17A

The photomicrographs of Figure 17A were taken at different times and at somewhat different magnifications. The resistor sizes shown in these photomicrographs are therefore not precisely comparable. (White areas in photomicrographs are caused by reflection of light from glazed non-planar resistor edges.)

1. Comparison of Five Commercial Compositions (Table V-A).

Of these five compositions, Composition 213 showed the lowest average noise index (-12.46) and also the least spread of results (-14.5 to -10.0). Composition 215 was next with an average noise index of -5.75 but a greater spread of individual values (-10.0 to 0). Compositions 211 and 212 were close together with average noise index values of -2.29 and -3.79 respectively although Composition 212 showed the greater spread (-5.5 to 0 vs. -11.0 to 1.0). Composition 214 was highest in noise index with an average value of 0.08 but a narrow spread (-1.5 to 3.0).

2. Laser vs. Abrasive Correct (Table V-B).

No clean-cut overall difference in noise index between the abrasive and laser correct resistors was noted. The abrasive correct resistors were higher in noise index in 4 out of the 9 combinations tested; the laser correct resistors were higher in 5 out of the 9 combinations. The 10K resistivities showed the highest average noise indexes, the 100 ohm resistivities were intermediate, and the 1K were lowest.

G. Resistor Stability Study

1. Test Procedure.

Eight substrates, eleven resistors each, from each composition of the five commercial compositions (211 through 215) and from each of the resistivity-overglaze-correct combinations (121 through 326) were put under power load in an oven maintained at 125-126°C for a total period of 1000 hours. Two resistors, R1 and R13, on each substrate were designed for high temperature storage only.

All loaded resistors having the same form factor and resistivity were connected in parallel to receive the same voltage and, hence, subject to variation in individual resistor values, the same amount of power. As a consequence, power densities between two resistors of the same form factor but of different areas were greatly different, thus providing a means for assaying the effect of a range of power densities upon resistor performance.

Applied rms voltages were controlled to produce calculated power densities (based upon as-fired resistance values) in the range of 20 watts per square inch on the large resistors (R2, R4, R6, R10, and on R9 the only 20-square resistor.

(Calculated power densities in the range of 20 to 40 watts per square inch have been used historically in the thick film industry as a design objective and have been considered to provide adequate de-rating to ambient temperatures up to 100 - 125°C.* There has been no feedback at this firm indicating occurrence of power problems with military systems using thick films designed in accordance with this practice but specific data indicating appropriate correction factors to be used in de-rating thick films are not known to be available.)

Readings were taken: (1) after correct; (2) after baking substrates, without load for 24 hours at 125°C (the readings taken at this time were considered the reference or time zero readings in calculating ΔR values); (3) after 24 hours power loading at 125°C; (4) after a total of 155 hours power loading at 125°C; and (5) after a total of 1000 hours power loading at 125°C. The middle time of 155 hours was chosen to provide a geometric progression of reading times, i.e. the ratio 24:155 is the same as the ratio 155:1000. Two substrates of each composition and combination were held at room temperature and read at the same time intervals.

Readings were taken manually directly at each resistor using four point probing. (Original plan had been to use a test fixture in combination with a rotary switch but problems in getting reproducibility of readings with this combination led to abandonment of this approach). A Dana 5400 series

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*For space applications, Spacetac Incorporated experience has been that intrinsic weight considerations limit power dissipation to a level well below the level at which reliability considerations become relevant. Typical power densities run one watt per in^2 or less, maximum is approximately 10 watts per in^2.

digital voltmeter with ohms converter was used for taking readings. This instrument had been calibrated by an outside testing laboratory before taking the initial readings and again before taking the 1000 hour readings and was also checked periodically against in-house resistance standards.

The Dana 5400 series instrument has full scale range of 1.0999 times scale value with a 1K minimum scale. The one-square resistors had been corrected to 1.05 times nominal value. Therefore five place readings were obtained for the 1K and 10K one-square resistors - except for the resistors which had changed so greatly in resistance value as to exceed the limits of the 1.0999 (or 10.999) overrange. For these latter resistors only four place readings were obtainable, but for resistors that had changed as much as this, a high degree of accuracy was not considered essential. The instrument provided four place readings for all other resistors except the 0.2 square 100 ohm paste resistors for which it provided three place readings.

All readings that were considered unusually high or low were rechecked and in most cases found to be correct as read initially. In the few cases where errors were found, the proper corrections were made. With many of the smallest, one-square, 100 ohm resistors (R8 and R10) that had shown great, essentially catastrophic resistance changes, it was impossible to obtain a stable resistance reading. Resistance readings were noted in the original data sheets for these resistors, but the readings noted were averages of a number of readings or, more often, selections of the most frequently appearing reading for the given resistor. Resistance data for these resistors have not been reported in the tables of ΔR values partly because of this instability but also because with the many high values and the wide range of values found, it was considered that it would be more meaningful to characterize these results by means of a footnote as "very high, widely varying often unstable readings". (Results for selected individual resistors from this group are reported in a later discussion of the performance of this group of resistors.)

2. Presentation of 1000 Hour Test Results.

Tables VII and VIII A, B, and C summarize the results of 1000 hour tests at 125°C. Average %|ΔR| values are average absolute values of ΔR as percent of average initial (after bake) resistance values. Each minimum and maximum %ΔR value is percent of the individual resistor's intial (after bake) resistance value.

To conserve space the various compositions have been referenced by code numbers in this table. Code numbers are identified in Section III A and in Table VI, but for the reader's convenience are given again below:

1. Table VII: Five commercial compositions, 1000 ohms per square resistivity, coded 211 through 215.
2. Table VIII A, B, and C: Resistivity-overglaze-correct combinations (Composition 215 material system) coded as follows:

			Code Numbers		
Overglaze:			None	Low Temperature (550°C)	High Temperature (680°C)
Table	Resistivity	Correct			
VIII A	100 ohms	abrasive	121	123	125
	100 ohms	laser	122	124	126
VIII B	1000 ohms	abrasive	221	223	225
	1000 ohms	laser	222	224	226
VIII C	10,000 ohms	abrasive	321	323	325
	10,000 ohms	laser	322	324	326

Minimum and maximum calculated power-densities applied to each set of resistors (with the exception of Resistors 1 and 13 which received no power) are included in Tables VII and VIII since one of the purposes of the test was to determine how variation in applied power-density might affect resistor performance. Substantial variations in applied power-densities were obtained in two different ways: (1) all resistors of a given form factor were given the same power loading even though resistor areas were designed to be greatly different (in the extreme by a factor of 11.1:1.0, specifically 0.010 sq. in. to 0.009 sq. in. for the one-square resistors); and (2) in accord with commercial practice all resistors of a given form factor and resistivity were corrected to the same resistance value within the limits of precision of the resistor-correct process with the result that the effective area of each resistor under test becomes approximately an inverse function of the initial as-fired value of each resistor.

The calculated power density values will serve the purpose for which they have been calculated; namely, they afford an indication of gross range of power-densities which each set of resistors has received. They have been calculated upon the basis of certain commonly made assumptions. The assumptions made and the rationale of the calculations are given in Exhibit A.

Outliers, i.e., rejected values, are also shown in Tables VII and VIII. Cursory examination of the data showed that some resistance change values would need to be rejected in order to avoid excessively biasing average values. It would be desirable to have a method of rejection that would be consistent, objective, and free from the need for judgemental decision: hence, it was decided to use the W. J. Dixon test for rejection of outliers. The Dixon test is discussed in more detail in Exhibit B.

As is clearly evident from a quick look, Tables VII and VIII contain a considerable amount of data. Table VII has 390 data entries and Table VIII A, B, and C each have 478 data entries representing summary and consolidation of data from eight substrates per data entry or a total of 2,392 resistors. Multiple operations: differencing, averaging, selecting minimum and maximum as-fired resistance values from the as-fired resistance data, calculating power-densities, and testing for outliers bring the total number of operations on individual items of data required to produce Tables VII and VIII very close to the 20,000 figure. The following sections will be concerned with discussion of various facets of the data not immediately apparent from a study of Tables VII and VIII.

3. Effects of Resistor Composition

(a) Five commercial compositions (Table VII)

Clearly under the conditions of this test there are marked performance differences among the five commercial compositions. If grand averages of average % $|\Delta R|$ values across all resistors are calculated, the following results, arranged in order of increasing value, are obtained:

Composition	% $\lvert\Delta R\rvert$ (Grand Average)
214	0.26
215	0.79
213	1.73
212	2.17
211	2.83

Another way of analyzing the results of Table VII especially useful for evaluating consistency of performance is to ask, for each composition, on how many resistors did it give the lowest average resistance increase, second lowest, third lowest, fourth lowest and highest and to quantify these results by assigning rank numbers to each composition according to its order of performance on each resistor: from 1 for lowest increase to 5 for highest increase. For example, Composition 214 gave the lowest increase of the five compositions on 11 out of 13 resistors (including both loaded and unloaded resistors) and second lowest on the other two of the 13 resistors, and therefore eleven times would be ranked 1 and twice would be ranked 2. Composition 211, on the other hand, gave the highest increase of the five compositions nine times, second highest once, and third highest (or third lowest) three times and therefore nine times would be ranked 5, once would be ranked 4, and three times ranked 3. Adding the 13 rank numbers obtained in this way for each composition will then give a set of rank sums that show the relative performance of each composition compared with each other composition. For example, the rank sum for Composition 214 is 11 times 1 plus 2 times 2 or 15 and the rank sum for Composition 211 is 9 times 5 plus 1 times 4 plus 3 times 3 or 58. By proceeding in this way, the following table of rankings and rank sums, arranged in order of increasing rank sums, has been developed:

	Rank					
Composition	1	2	3	4	5	Rank Sums
214	11	2				15
215	2	10	1			25
213		1	9	2	1	42
212				10	3	55
211			3	1	9	58
Sum						195

From the above table it can be seen that Compositions 214 and 215 consistently gave lower resistance increase values than either of the other three compositions. Significance tests, easily applied to rank sum data of this type (for discussion of these tests see Exhibit B), show that Composition 214 is significantly different at the 1% probability level from Compositions 211, 212, and 213. Composition 215 is significantly different at the 1% probability level from Compositions 211 and 212. There is not sufficient evidence at the 5% probability level to say that Composition 214 is significantly different from 215 or that Composition 215 is significantly different from Composition 213 or that Compositions 211, 212, and 213 are significantly different from one another.

The largest or maximum percent resistance change shown by each of the five compositions on each of the 13 resistors was also considered a performance characteristic that merited evaluation. These data are shown in Table VII, but to present them in a more compact summary form, arbitrary groups or classes of maximum ΔR values were established. These groups, with sign of resistance change disregarded, were: (1) $>0 \leq 0.5\%$ (includes all maximum ΔR values shown in Table VII that were equal to or less than 0.5%; (2) $>0.5\% \leq 1.0\%$ (includes all maximum ΔR values that were greater than 0.50% but equal to or less than 1%; (3) $>1\% \leq 2\%$; (4) $>2\% \leq 4\%$; (5) $>4\%$. The frequency of occurrence of maximum ΔR values within each of these groups for each composition was then counted to give the following table of frequencies:

(Table follows.)

Composition	Group				
	>0 ≤ 0.5%	>0.5% ≤ 1.0%	>1.0% ≤ 2.0%	>2.0% ≤ 4.0%	>4.0%
214	8	4	1		
215		6	6	1	
213		2	2	6	3
212		1	3	5	4
211			1	5	7

All of the compositions showed maximum resistance changes greater than 1%, but in only one case (1.04%) for Composition 214. Compositions 213, 212, and 211 showed 9, 9, and 12 occurrences respectively of maximum resistance changes greater than 2% versus 1 for Composition 215 (2.04%) and Composition 214 showed no resistance changes that were greater than 2%.

(b) Overglaze

In each of the Tables VIII A, B, and C it can be clearly seen that high temperature glaze gives lower average resistance increases than low temperature glaze which in turn gives lower average resistance increases than no glaze. Grand averages (over all resistors for each combination) are tabulated below:

(Table follows.)

Resistivity	Percent $\lvert\Delta R\rvert$ (Grand Averages) 100 ohms	1K ohms	10K ohms
No glaze abrasive	3.50	4.86	3.89
No glaze laser	2.77	3.50	1.50
Low temp. glaze abrasive	0.92	1.61	1.22
Low temp. glaze laser	1.10	1.68	1.10
High temp. glaze abrasive	1.00	0.81	0.41
High temp. glaze laser	1.86*	0.85	0.16

*This average is inflated by the 9.11% % $\lvert\Delta R\rvert$ of R11. Omitting this value would give an average for eight remaining resistors of 0.95%. (The high and variable 100 ohm R8 and R12 values are not included in the calculation of the 100 ohm grand average values.)

The calculated power-densities, however, fall in the same order as the increase values, which might at first sight indicate that the differences noted are effects of power-density rather than effects of glaze. But, going further, it can also be seen from the tables that in almost every case the average increase for the smaller resistor of a given form factor (with high calculated power-density) is lower for the high temperature overglaze resistor than the average increase for the larger low temperature overglaze resistor of the same form factor. This comparison also holds true for the smaller low temperature overglaze resistor versus the larger no glaze resistor of the same form factor. These comparisons would appear to rule out the possibility that the effects seen here can be attributed to differences in power-density and indicate rather that the effects are real and are caused by the variations in glaze.

(c) Paste Resistivity

The effect of paste resistivity is not nearly so pronounced as is the effect of glaze although the data clearly show that the 10K-high temperature overglaze combination gives lower increase values than any other combination. The failures of the 100 ohm paste on R8 and R12, the smallest one-square resistors, are also very obvious. If the effect of resistivity is studied separately for each type of glaze, rank sum significance tests show that with no glaze the 10K paste is significantly different at the 1% probability level from the 1K paste, and with the high temperature glaze the 10K paste is significantly different from both the 1K and the 100 ohm paste, again at the 1% probability level. There is not enough evidence at the 5% probability level to say that any of the other differences are significant.

The catastrophic failures of the 100 ohm smallest one-square resistors (R8 and R12) merit further discussion. At first sight this result might perhaps be attributable to the fact that many of these small resistors had very low as-fired resistance values, were necessarily corrected to very small effective resistor areas (minimum as-fired resistance was 26 ohms), and consequently received correspondingly high power-densities. On the other hand, examination of the data shows that calculated power-densities for many of the 1K and 10K R8 and R12 resistors were higher than calculated power-densities for some of the failing 100 ohm resistors as the following sample 100 and 1K ohm R8 data show:

(Table follows.)

Substrate	100 ohm Paste Calculated Power-Density*	1000 hr. % Δ R	Substrate	1K Paste Calculated Power-Density*	1000 hr. % Δ R
12101	335	52.	22102	411	7.73
12208	382	141.	22208	420	4.48
12303	440	267.	22307	428	1.72
12403	439	67.	22401	498	2.42
12506	259	63.	22505	235	1.08
12602	412	235.	22503	227	0.93

Although percent resistance increases for some of the 1K paste resistors were quite high, all were very much lower than the percent resistance increases for the 100 ohm resistors receiving comparable calculated power-densities. It would appear from these results that, for this material system, the 100 ohm paste has much less tolerance for high power-densities than the higher resistivity pastes.

4. Effect of Power-Density.

Study of the 1000 hour data of Table VII indicates that there are marked differences in the reaction of the five commercial compositions to power loading. Composition 211 had average increase values that were the highest of the five compositions at minimum power-densities. Average values decreased with increasing power-densities (R4 vs. R5, R6 vs. R8, R10 vs. R11, and R12) but with no consistent tendency toward a decrease in the spread or range from minimum to maximum of individual values. Compositions 212, 213, and 215 all show a consistent tendency for average

*Watts/square inch.

values to increase with increasing power-density, 215 least, and 212 greatest. Composition 214, within the limits of the power-densities applied here, shows no evidence of sensitivity to power-density. In fact, in the Composition 214 series the resistor (R8) that received second highest power-density came up with the second lowest average resistance increase (0.10%). From the data it would appear that maximum power-densities applied to this composition in this test were not great enough to exceed the limit of this composition's tolerance for power loading. It is interesting to note that the percent increase in resistance averaged across all eleven loaded 214 resistors was less (0.25%) than the average increase for the two unloaded 214 resistors (0.31%).

The resistors of the resistivity-glaze-correct experiment, with the exception of the 10K high temperature overglaze combination, all displayed definite sensitivity to increasing power-densities. Resistance increases were consistently greater for the smaller than for the larger resistor of each pair of resistors of the same form factor. The effect was most marked with no glaze, least marked with high temperature glaze, most marked with the 100 ohm paste, as evidenced by the performance of the two small 100 ohm one-square resistors (R8 and R12), and least marked with the 10K paste. The 10K high temperature overglaze resistors showed little sensitivity to increased power-density, i.e. the resistance increases for the smaller resistor of each pair of resistors of the same form factor were quite small and in fact in four cases out of 12 were negative.

The data were also examined to see if within each set of eight resistors of a given composition or combination, variations in resistance changes of individual resistors could be correlated with variations in calculated power-densities. If there were a power-density correlation, and the correlation were positive, as might be expected within each set of eight substrates, and for each of the eleven loaded resistors, the resistor with the lowest as-fired resistance value (and hence highest calculated power-density) could be expected to show the largest increase in resistance. The resistor with the highest as-fired resistance value (and hence lowest calculated power-density) could be expected to show the smallest increase in resistance. In this way a very neat explanation for the sometimes substantial differences of Tables VII and VIII between minimum and maximum resistance increases within sets of eight resistors could be developed.

A table of minimum and maximum calculated power densities within each group of eight resistors (based upon as-fired resistance values) had already been prepared. The next step was to compare the resistance increases found for the maximum-power-density-resistor with the resistance increase found for the minimum-power-density-resistor within each eight-resistor group and count the number of times that the maximum-power-density-resistor showed a greater resistance increase than its corresponding minimum-power-density-resistor. This was done, and somewhat surprisingly the count showed that the minimum-power-density-resistor in 120 out of 241 cases (omitting the 100 ohm R8 and R12 resistors) showed a greater percent increase in resistance than its corresponding maximum-power-density-resistor. In other words, the data showed no evidence of correlation for individual resistors within each set of eight resistors between calculated power-density and 1000 hour resistance increase under load.

Some sample data that illustrate the lack of correlation between applied power-density and resistance increase are shown below.

Substrate Code	Resistor	As-Fired Resistance (% of Nominal)	Calculated Power-Density	% Δ R
22105	R2	43.2	33.5	2.46
22103	R2	75.5	19.1	3.49
12101	R4	26.4	373	1.41
12105	R4	48.6	206	1.83
22108	R6	46.5	31.8	2.72
22103	R6	78.1	19.0	4.52
32507	R8	74.5	194	0.10
32503	R8	91.4	158	0.24

The possibility that variation in film thickness of resistors may cause variation in resistor performance also merits examination. It is entirely reasonable to believe that within any group of eight resistors all screened at the same time with the same paste (and where applicable, the same glaze) the resistor with the highest as-fired resistance is the resistor with the thinnest film and the resistor with the lowest as-fired resistance value is the resistor with the thickest film. Any chemical changes that occurred in the resistor film under load would tend to occur more rapidly and more severely in the thinner films than in the thicker films, and the resistor with the highest as-fired resistance value, because of its thinner film, would tend to show a greater resistance change under load than the resistor with the lowest as-fired resistance value.

As noted immediately above, however, maximum 1000 hour increases were divided exactly equally between minimum and maximum as-fired resistance resistors. Possibly the two effects, power-density and film thickness, may tend to counteract one another. However, it may be concluded that within the limits of this experiment, as-fired resistance value is not a reliable indicator of 1000 hour performance under load and, more specifically, the resistor with the lowest as-fired resistance value is not necessarily the resistor that will show the greatest resistance change under load.

5. Effect of Form Factor.

Examination of Tables VII and VIII indicate that there are differences in performance with resistors of different form factor. The data can be put in more compact summary form by use of ranking methods. If the smaller resistors of each form factor are omitted from consideration because applied power-densities are not entirely comparable for these resistors, five large resistors are left for consideration: R2, R4, R6, R9, and R10. These five resistors on each composition and combination have been ranked according to the relative values of resistance increases shown by each resistor, assigning the rank of 1 to the lowest increase of the five resistors and the rank of 5 to the largest increase. When this is done for each of the five compositions and the 18 overglaze-resistivity combinations, the following table results:

Resistor	L	W	Squares	Rank 1	2	3	4	5	Rank Sums
R2	60	300	0.2	13	3	2	2	3	48
R10	100	100	1.0	4	9	5	4	1	58
R6	100	100	1.0	1	5	11	3	3	71
R4	300	60	5.0	1	3	4	10	5	84
R9	500	25	20.0	4	3	1	4	11	84

R2 has given the smallest resistance increase 13 times, and R9 has given the largest increase 11 times. There is quite a bit of variation since R2 gave the largest increase three times and R9 gave the smallest increase four times. The rank sums, however, show that the narrower resistors tend to have the higher rankings. Rank sum significance tests show that R2 is significantly different from R4 and R9 and the 1% probability level, but none of the other differences can be considered significant at the 5% probability level. The conclusion is clear: the wider the resistor, the less the resistance increase, but the differences in width must be great to produce important effects.

6. Calculated Width vs. Measured Width of Resistor at Correct Cut.

When the smallest resistors (R8 and R12) were examined under the microscope, actual effective resistor widths when measured from the furthest point of the correct cut to the outside edge of the effective resistor area were found in a number of samples to be surprisingly small. This finding raised the possibility that actual effective resistor widths might differ from calculated resistor widths.*
If this were so, actual power-densities would differ from calculated power-densities, and this might explain the lack of correspondence that has been noted between minimum and maximum calculated power-densities and minimum and maximum resistance increases under load.

To check this point, a number of actual effective resistor width measurements were obtained by measuring, with a micrometer stage microscope, the distance from the furthest point of the correct cut to the outside edge of the effective resistor area. This was done for resistors R6, R7, and R8 of four combinations: 121, 122, 225, and 226. 121 and 122 were chosen as representative of combinations that had shown relatively large resistance increases and 225 and 226 as representatives of relatively better performing combinations. Combinations 121 and 225 were abrasive correct and 122 and 226 were laser corrected.

Measured widths were plotted against calculated widths (basis as-fired resistance values). The results are shown in Figures 5, 6, and 7 for the

* Calculated resistor width = $\frac{\text{as-fired resistance}}{\text{after correct resistance}}$ X Design Width, Appendix A (4).

abrasive correct samples and Figures 8, 9, and 10 for the laser correct samples. If there were complete one-to-one correspondence between measured and calculated widths, the plotted points would be expected to fall on a straight line passing through the origin at an angle of 45° with the two axes of the chart.

The plotted points for the abrasive correct samples fit this pattern quite well - except for the 100 ohm R8 samples (Figure 7) for which there appears to be no relationship between measured and calculated width. The plotted points for the laser cut samples show somewhat more scatter for all resistors and in almost every case all to the left of the line of one-to-one relationship showing that actual measured width is less than calculated width. This latter result is to be expected since for all of these laser corrected samples the laser cut was a direct uni-directional cut perpendicular to the resistor length. This type of cut would be expected to require a greater reduction in resistor width to obtain a given increase in resistance than the deep wide abrasive-correct cut would require.

Figure 10A shows photographs illustrating the difference between the abrasive cut and the uni-directional laser cut. (The laser correct samples have been washed with a titanium dioxide paste in order to get contrasting white lines indicating locations of the laser cut.) Figure 10A also shows a photograph of a set of resistors (Substrate 22403) in which a right-angled rather than uni-directional correct was used. For these resistors measured width was in very good agreement with calculated width.

From these results it was concluded that, with the possible exception of the very small R8 low resistivity resistors, calculated resistor width provides a satisfactorily accurate estimate of actual width for abrasive correct resistors and probably for resistors that have been laser-corrected with a right-angled cut. For laser correct resistors corrected with a uni-directional transverse cut, measured width will tend to be less than calculated width.

The next step was to compare 1000 hour percent increases in resistance with measured widths. These results are shown in Figures 11, 12, 13, 14, 15, and 16 (100 ohm R8 data not plotted). There is no apparent relationship between measured width and resistance increase, and the lesser measured widths of the laser samples has not affected the performance of these resistors. Large differences in resistance width can have an important effect upon resistor performance as shown by the results of the form factor study, but small differences such as the difference examined here apparently have no relationship to resistor performance.

7. Laser vs. Abrasive Correct

Differences (abrasive-laser) in average absolute percent resistance increases between abrasive correct and laser correct combinations of the resistivity-overglaze-correct experiment are tabulated in Table IX for each resistor of each combination. From Table IX it can be seen that for the no glaze combination the differences (abrasive minus laser) are preponderantly positive indicating that for these combinations laser correct tends to give smaller resistance increases than abrasive correct. When rank sum significance tests are applied to the no glaze data, the differences are found to be highly significant for the 10K paste (significance level less than 1%), significant at the 5% probability level for the 1K paste, but not great enough to be significant (when tested with either rank sum tests or the t test) for the 100 ohm paste.

For the glazed combinations - low temperature and high temperature - the average differences are small, fluctuating from positive to negative, and not significant at the 5% probability level - except for the 10K high temperature glaze combination for which the small difference in favor of laser correct is significant at the 2% (t test) probability level. Average differences (abrasive-laser) across all resistors for each combination are given below:

Resistivity	100 ohms	1K ohms	10K ohms
No glaze	0.82	1.36	2.39
Low temperature glaze	-0.19	0.02	0.12
High temperature glaze	0*	-0.04	0.25

*Value of -7.75 for R2 rejected as an outlier.

The sharp contrast between the large and significant differences in favor of laser correct on the no glaze 1K and 10K samples and the very small differences between the two types of correct on the glazed samples is noteworthy. One possible and reasonable hypothesis suggested by these results is that a glaze helps to protect the integrity of the resistor surface against the random scatter of abrasive material that occurs as part of the abrasive correct process. Microscopic examination of resistor surfaces shows that there are many more fine pits on the surface of the abrasive correct resistors than on the surface of the laser correct resistors, but the degree of pitting could not be correlated with resistor performance.

If the hypothesis that stability of unglazed resistors is adversely affected by the random scatter of abrasive material that occurs during abrasive correct is valid, then it might hold generally true that unglazed resistors will show greater resistance stability when laser corrected than when abrasive corrected. From these test results it is clear that additional quite valuable composition information could have been obtained if the abrasive vs. laser correct experiment had been widened to include the 211 - 214 compositions.

The small but highly significant difference in favor of laser correct on the 10K high temperature paste merits notice, but it is difficult to develop any satisfactory physical explanation for this difference.

8. Study of Possible Failure Mechanisms.

Much work was done in attempting to find, by examination under the microscope, a physical explanation for "failures" - not only the catastrophic failures of the smallest one-square 100 ohm resistors but also the high resistance increases noted for certain compositions and combinations. Some qualitative differences were noted. Resistors of compositions that had shown no substantial change in resistance were in general characterized by a smooth level surface with no or few craters or bubbles--resistors of compositions that had shown marked resistance changes showed more pits, bubbles, and, particularly on the smaller resistors, a tendency to develop a shiny glassy surface.

Many of the 100 ohm no glaze resistors were badly pitted over as much as 50% of the effective resistor area; the smallest one-square (.0009 square inch) laser correct 100 ohm no glaze resistors showed, in addition, deep crevices extending from the tip of the laser cut to the outer edge of the effective resistor area.* Overall, however, no appearance pattern that would consistently and meaningfully distinguish high increase from low increase resistors could be found. For example, the glazed resistors R8 and R12 of the 100 ohm series (123 - 126) which showed equally as catastrophic failures as the unglazed resistors showed little or no visible loss of resistor material.

Figure 17A shows photomicrographs of the smallest one-square resistors (R8 or R12) after 1000 hours under load - and shows also the lack of consistent relationship between surface appearance and resistor stability. The high increase (932%) 122 sample might be explained by surface appearance. But the low increase 225 - 226 and 325 - 326 resistors are little different in appearance except for glaze from the quite high increase 221 - 222 resistors or from the very high (3038%) 126 resistor.

Table X serves to preserve for the record a description of the nuances of surface appearance that could not be preserved by photography because of lack of contrast of the resistor material. This table summarizes general appearance differences noted during examination of several samples substrates from each composition and combination.

*In Figure 10A the laser correct uni-directional cross-resistor cut substrate is from the 100 ohm, no glaze series. The titanium dioxide wash shows part but not all of the surface pitting. A very faint white line at the location of the crevice from the end of the laser cut to the resistor edge can also be seen on R8 of this substrate.

When viewed by transmitted light, the high increase resistors tended in general to show more voids than did the low increase resistors. When voids occurred, they occurred either randomly throughout the resistor area or in clusters that in turn were spread randomly over the resistor area. But some of the high increase resistors failed to show this characteristic to nearly as great an extent as some of the resistors with relatively low increase values. For example, Resistor R8 of substrate 12605, with a 1000 hour resistance increase of 1038%, when viewed with transmitted light was seen to have only one very medium size very deep pit and in this respect to look very much better than many other resistors which had showed very much lower increases. Thus it was concluded that apart possibly from the pitted, bubbly, often partly glassy resistor surface no visual characteristic could be found that was consistently typical of high percent change resistors.

The possibility that surface profile analysis might yield clues to the differences in behavior of the various resistor composition was considered. Surface profiles were taken of the five commercial compositions using R2 because this resistor gave the widest range of values of resistance increase of all the resistors. Sample sections of these profiles are shown in Figure 17. Composition 211 shows the greatest variation in surface profile but not much more than the lower increase Composition 213. Composition 214 showed the least variation in surface irregularity but was hardly better than Composition 213 despite the difference in performance.

Composition 215 which on this resistor gave the lowest resistance change of all five compositions had a surface definitely less regular than the Composition 213 surface. Consequently it was concluded that this line of attack held little promise and no further work was done with the surface analysis approach.

9. Room Temperature Stability.

Two substrates of each combination were stored at room temperature over the 1000 hour period and read at 24, 155, and 1000 hours. Of the five commercial compositions only one resistor (Composition 211 - R9) showed a change of greater than 0.5%. For the overglaze-resistivity experiment the number of resistors showing 1000 hour resistance changes of greater than 0.5% are summarized below:

Resistivity	100 ohms	1K ohms	10K ohms
Overglaze			
None	22	3	2
Low temperature	5	6	4
High temperature	2	0	0

The 100 ohm-no glaze combination gave many more resistance changes of greater than 0.5% than any of the other combinations. There is little difference between the no glaze at 1K and 10K ohms and the low temperature glaze at all three resistivities of the three glazes. The high temperature glaze gave fewest increases of greater than 0.50% at all three resistivities.

The 24 hour and the 155 hour data for both the commercial compositions and the resistivity-overglaze combinations were examined to see if increases at either time period would provide a reliable indicator of 1000 hour increases. Of the 47 resistors showing 1000 hour resistance increases of greater than 0.5% only 11 and 20 respectively showed increases of greater than 0.5% at the 24 and 155 hour readings. Further, many of the resistors increasing less than 0.50 at 1000 hours showed increases of greater than 0.5% at 24 hours and 155 hours. Consequently it was concluded that short term room temperature resistance readings cannot safely and consistently be used as reliable predictors of long term room temperature resistor stability.

10. Time Trends.

In Figures 18 through 25 average percent ΔR values at 24, 155, and 1000 hours are charted by resistors (R4, R5, R6, R7, R8, and R9) for the five commercial compositions and in Figures 26 through 33 for the 1K resistivity-glaze-correct combinations. The charted average values are not average absolute values but rather are averages calculated from the algebraic sums of resistance changes for the individual resistors of each composition or combination. Therefore, wherever a negative minimum % ΔR value appears in Tables VII or VIII, the 1000 hour value plotted in the corresponding figures will differ from the tabulated 1000 hour $\%|\Delta R|$ value. (The figures are presented to show actual pattern of resistance changes whereas the tables are presented to show absolute magnitude of resistance changes.)

Of the five commercial compositions, Composition 211 shows the most variable pattern of resistance change. With increasing power-densities 155 hour resistance changes for this composition tend to become negative but become strongly positive at 1000 hours. Compositions 212 and 213 (except for the unexplainedly anomalous behavior of Composition 212 on R3) show a consistently positive resistance change over the 24-1000 hour period, tending to be linear with log of time.

Composition 214 resistance changes, although always small, are often negative at 155 hours, becoming positive at 1000 hours. In this respect they are much like but always much smaller than Composition 211 resistance changes. Composition 215, although it does not have the same tendency to give negative values at 155 hours as Composition 214, is otherwise much like Composition 214 in behavior.

For the overglaze-resistivity-correct experiments, results are quite alike for all three resistivities and are adequately represented by the 1K resistivity data of Figures 26 through 33. No glaze, with all three resistivities, shows marked increases over the 1000 hour period. There is variation in slope between samples and resistors over different time periods but no consistent pattern. The low temperature glaze shows lesser increases than the no glaze and the high temperature glaze shows still smaller increases with in each case, the increases being smallest for the 10K paste.

11. Pattern of Variation of Within-Group Resistance Changes.

From Tables VII and VIII it can be seen that wherever a large average percent resistance change appears in the tables the difference between the corresponding minimum and maximum percent changes will also be large. Conversely, wherever a small percent change appears in the tables, the differences between the corresponding minimum and maximum changes will be small. For example (Table VII) R4 of Composition 211 had an average percent change of 4.00% and a range, i.e. a difference between maximum and minimum values, of 7.61% (9.21% - 1.60%) and R4 of Composition 214, with an average percent change of 0.35% had a range of 0.36% (0.54% - 0.18%).

Figure 34 in which minimum, maximum, and average (based on algebraic sum of individual values) 1000 hour resistance changes are plotted shows this point very clearly. Composition 211 with high average percent change showed a wide spread between minimum and maximum values. Composition 214 with low average percent change showed little spread.

Now this pattern of behavior is perhaps not entirely unexpected. Nevertheless, there is a salient point to be made. The salient point, generalized from the data presented here: groups of resistors that under an applied stress show small average changes in resistance will also show extreme values, i.e., minimum and maximum values, that are quite close together and little different from the group averages; groups of resistors that under an applied stress show large average changes in resistance will show extreme values that are far apart and widely different from the group averages.

12. Screening Tests.

As the data presented here were being studied and analyzed, the possibility was kept in mind that these results might be utilized to develop, or to point the way to developing, a reliable screening test for early detection of failing resistors. Obvious possibilities considered and rejected, after testing, were microscopic examination of resistors, and surface profile analysis. Power loading at a high multiple of rated power for a specified time is an obvious possibility but was not included in the current program; and such a study, to have meaning, would probably required a program on at least the scale of the current program.

Low current-noise index is often considered an accurate predictor of good resistor stability under load when dealing with types of resistors other than thick film resistors. The data presented here, however, indicate that this relationship does not hold for thick film resistors. Of the five commercial compositions, Composition 214 that consistently showed the lowest resistance increase had the highest current-noise index. The 10K resistors that had relatively small resistance increases consistently showed high current-noise index values. A portion of the current-noise index data is compared with grand average %|ΔR| values below to show the lack of relationship of the two sets of data.

Code Number	Current-Noise Index (Average)	%|ΔR| Grand Average
211	-2.29	2.83
212	-3.79	2.17
213	-12.46	1.73
214	0.08	0.26
215	-5.75	0.79
225	-6.21	0.81
226	-6.00	0.85
325	6.21	0.41
326	8.71	0.16

Temperature coefficient of resistance was also ruled out as an indicator of resistor stability. Compositions 214 and 215 with lowest and highest resistance increases of the five commercial compositions were the two lowest of the five compositions in TCR values.

As-fired resistance value as a possible indicator of resistance performance was scrutinized closely. This measurement is dependent upon

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resistor thickness and also is an indicator of width of effective resistor after correct. But, as reported above, no correlation, positive or negative, could be found between as-fired resistance value of individual resistors and amount of resistance change under load. The reason for this lack of correlation may well be that as thickness of resistor film decreases (and as-fired resistance correspondingly increases) the amount of correct cut required to produce the desired resistance value decreases and therefore the effective volume of resistor material will remain relatively constant. At any rate, within the bound of this study (as-fired resistance values from 26.8% to 121.6% of nominal) no consistent relationship between as-fired resistance and subsequent tendency to change resistance under load has been found.

The 155 hour results were examined for possible correlation with 1000 hour results. But study of Figures 18 - 33 clearly show that 155 hour results can be an uncertain indicator of 1000 hour results. It is true that the greater 155 hour resistance changes of combinations 221 and 222 as compared with combinations 225 and 226 forecast the comparative 1000 hour results; but the moderate 155 hour resistance changes of Composition 211 fail to forecast this composition's large 1000 hour resistance changes. This lack of reliable correspondence between the 24 - 155 hour results and 1000 hour results is indicated by the charts of Figures 35 and 36 in which R6 resistance changes at 24, 155, and 1000 hours of individual resistors are plotted for Compositions 211 and 214 respectively. The 155 hour results do not clearly forecast the marked differences in stability between the two compositions at 1000 hours.

The discussion of variation of resistance changes of individual resistors within groups of resistors may point the way to a more precise definition of the thick film resistor screening (for failures) problem. It was pointed out in this discussion that large average changes are accompanied by large variations in individual resistor values and small average changes are accompanied by small variations in individual values.

This pattern of behavior is seen throughout the data presented here. Consequently, it would appear that stability of thick film resistors is a characteristic associated with type of resistor and/or resistor lot rather than with individual resistors. It may depend upon a variety of factors. The factors studied in this program - paste composition, paste resistivity, form factor, glaze, method of correct - have all been seen to influence resistor stability to varying degrees in different combinations. Other factors not studied here including degree of electrode separation and electrode composition are no doubt also important.

Quality of the silk screening process by which the thick film pastes are applied to the substrates will of course always be important. Close visual inspection of finished substrates to remove all substrates that might have an adverse effect upon resistor performance is essential.

The point of view advanced here, however, is that only in the inspection of resistors for visual defects due to processing or handling is screening of individual resistors for potential failures important. Beyond this visual inspection, attention needs to be turned not to the individual resistor but instead to selection of a resistor type as determined by composition, processing and design factors that will give the required level of performance with respect to both average and degree of variation. Figures 35, 36, 37, and 38 all show plots of percent resistance changes at 24, 155, and 1000 hours of individual resistors. Lines cross and re-cross and it is clear that in only one case (Substrate 06, Figure 37) would it be possible to predict unfailingly the ranking of a resistor's performance at the next reading period by its performance at the previous reading period. The case of Substrate 06 might be seen as undermining what has been said here, but rather it is seen as reinforcing--given a high resistance change combination like 222, screening of individual resistors may be necessary, but the important step is to select a low resistance change resistor type for which screening of individual resistors will not be needed.

(This discussion is not meant to imply that screening of modules in which thick film resistors are assembled is not necessary. This type of screening is necessary; but at least one firm's experience has been that when moldule failures occur, as they do, upon failure analysis, the cause of the failure has never been found to be traceable to a thick film resistor failure.)

The material presented in this report should help in selection of low resistance change, i.e. high stability resistor types. For certain high stress or other unusual applications, actual testing of resistors under conditions of simulated or increased stress may be desirable or needed.

Another approach to this problem, inexpensive and quite fast and appearing to merit consideration, is suggested by the behavior under 125°C storage of the two unloaded resistors, R1 and R13. The average %ΔR values at 155 hours for these two resistors, when arranged in order of value tend to fall in the same order as the order of 1000 hour performance of the loaded resistors* as can be seen from the following 155 hour results for R1 and R13 of the five commercial compositions:

	R1	R13
214	0.10	0.08
215	0.18	0.29
213	0.27	0.37
212	0.38	0.54
211	0.82	0.87

*Page 25.

Figure 38A shows a plot of average percent resistance increase of R1 after 155 hours of 125°C storage versus average 1000 hour (absolute value) resistance increases of the comparable loaded five square resistor, R4, for each of the five compositions and the resistivity glaze combinations. Clearly there is a definite relationship between the two sets of measurements.

These results suggest the possibility that storage at an elevated temperature for a period of, say, seven days might provide a quick, not very costly test that could be used to screen out resistor types that are likely to show a substantial resistance change under stress, but much more work would be needed to establish with a high degree of confidence that resistors showing small changes under storage will also show small change under high loading stresses.

13. Questions Bearing Further Investigation.

(a) Suggested by the Current Study.

Consideration of this program as a whole suggests further questions which have not been answered here because they have not been within the scope of the current program but which would nevertheless bear further investigation.

(1) On unglazed resistors will laser correct give greater resistor stability than abrasive correct for all types of resistor compositions? Laser corrected Composition 215 resistors with no glaze showed greater resistance stability than the comparable resistors when abrasive corrected. Will this hold true for all resistor compositions for some of which there are no glazes available?

(2) Composition 215 showed a marked pattern of lesser resistance stability for the 100 ohms paste and greater resistance stability for 10K ohms paste as compared with the 1K ohms paste. Is this pattern characteristic of all resistor pastes or are there pastes which might be preferred for low resistance resistors because they do not show this pattern?

(3) Will Composition 215 resistor pastes of less than 100 ohms per square resistivity have even less stability than the 100 ohm Composition 215? Will Composition 215 resistor pastes of greater than 10K ohms resistivity have greater stability than the 10K ohms Composition 215? Will this same pattern hold true for other compositions?

(4) Will the high temperature glaze impart the same or greater proportionate degree of increased resistance stability to other resistor compositions (where compatible) as it did to Composition 215? Are there other glazes which might give a greater degree of improvement: (a) for all compositions; (b) for specific compositions?

(5) Are there power loading tests which can be used to obtain reliable low cost, fast evaluations of long term resistor stability? If so, is there a type or are there types of power loading tests which are most efficient in the sense of yielding the greatest amount of reliable information for the least application of effort? Is there a universal test or must the tests be tailored to the individual patterns of stress application encountered in actual use of the resistors?

(6) What are the actual levels of temperature and patterns of temperature that develop in resistors of various form factors and resistance values under the application of various power densities? It is recognized that some valuable work has been done in this area, but it also appears likely that there is much more possibly valuable information that could be obtained.

(7) What is the nature of the effect that causes a resistor to change substantially in resistance value under load? Is it a "field" effect due to current flow, a pure temperature effect, or a combination of the two effects? A consideration of the data obtained in the course of this program raises the possibility that resistor instability may be purely a temperature effect. If temperature could be definitively established as the cause of thick film resistor instability, a remarkable simplification of thinking about the problem of thick film resistor stability could be achieved. Resistor evaluation would then require only the

relatively low cost storage of resistors for pre-determined times and temperatures and the need for the much more costly power loading now considered to be necessary and so often by-passed because of its high cost would be eliminated.

(8) Can high temperature storage for relatively short periods of time (without power loading) be used to provide reliable evaluations of long term resistor stability under load? The R1 and R13 155 hour results presented above indicate that this may be a possibility. Such a test, if it could be developed, would yield substantial reductions in costs of testing as compared with testing resistors under long term power loading and because of the reduced testing costs make it possible to obtain much added information about resistor stability. In line with the point of view presented in this report, namely that resistor stability is a design or lot characteristic, it is suggested that this test might find its greatest value, first as a design qualification test and then as a lot acceptance test, to select designs (and lots) of satisfactory stability and to reject designs (and lots) of unsatisfactory stability. It is also suggested that evaluation of the data obtained from this type of test would depend equally as much upon variability of results as measured by range or spread as upon averages of results.

(9) Are the benefits of "screening" individual resistors on the basis of their short term stability performance great enough to justify the cost of this screening where cost includes both cost of screening effort and cost of rejected units? The point of view presented in this study is that resistor stability is a design or lot characteristic. Thus average resistance change under high temperature storage without loading is proposed above as a measure of design or lot performance. When individual resistors are considered, however, the indications are that there is enough randomness in the behavior pattern of individual resistors to make resistance change at one time period an uncertain indicator of resistance change at another time period - for the individual resistor. This is why the high temperature-short term storage test is proposed above (Question 8) as a design qualification or lot acceptance test but is not proposed as a screening test.

The data of this study indicate that the lack of correspondence between resistance changes of individual resistors at different time periods is great enough to raise serious questions about the value of "screening" individual resistors by means of any type of short term resistance measurement of individual resistors.

Certainly based upon the data of this study there is a very real possibility that in screening any given lot of resistors, the resistors "screened" out, i.e. rejected because of unsatisfactory short term stability, may actually be at least as good or perhaps better on long term stability than the accepted resistors of the same lot. Further study of this question is indicated because of the substantial cost-savings that might be obtained through elimination of testing effort but more particularly through elimination of unwarranted rejection of resistors.

(10) Will extremely low temperatures or cycling from extremely low to extremely high temperature have an effect on resistor stability that is different from the effect of high temperature only? This study has been concerned with high temperature effects only. It may be that extremely low temperatures or cycling from low to high temperatures will have quite different effects.

(11) What is the physical or chemical change that causes resistor instability? This is an essentially basic rather than applied question at the present moment. On the other hand, it is conceivable that identifying and describing the nature of this change might make available the most powerful tool of all possible tools for pre-evaluating resistor performance.

(b) Extrinsic to this Study.

A group of questions which are related to, but not included within the scope of this study are posed below.

(1) What is the effect of atmospheric purity during processing upon resistor stability?

(2) How does the nature of the substrate surface with respect (a) to finish, (b) to glass content, (c) to cleanliness affect resistor stability?

(3) How is stability of corrected resistors affected by different types of encapsulation? Do different compositions react differently to different encapsulants?

(4) What is the effect of humidity upon resistor stability with or without glaze or encapsulation?

(5) What is the nature of the relationship between resistor micro-structure and resistor stability?

IV. CAPACITOR RESULTS

IV CAPACITOR RESULTS

A. Description of Capacitor Experiments

1. Commercial Compositions.

Four commercial dielectric compositions (one of which has since become obsolete) designated Compositions 1 through 4 plus one doped flux composition (designated Composition 5) were screened and fired:

a. on Pd Au

b. on Pd Ag

2. Overcoating Variables.

Composition 1 was also screened, fired, and processed to produce the three following over-coating variables: (1) no overcoat; (2) solder over top conductors; (3) low temperature overglaze on top conductor.

3. Study of Screening Contamination.

Composition 2 was used to screen 120 substrates under conditions intended to simulate a commercial process in which control of contamination during the screening process was at a level such as to permit some contamination of the product. After each screening (five screenings in all: bottom and top electrodes of palladium-gold and three dielectric screenings of Composition 212) the presence or absence of contaminants was recorded.

Ten capacitors were screened on each substrate: four at 0.010 square inches; four at 0.023 square inches; two at 0.100 square inches. The layout of the design is shown in Figure 39.

B. Dielectric Breakdown

1. Five Dielectric Compositions on Pd Au and Pd Ag.

Results of dielectric breakdown tests (averages of three readings) for the five dielectric compositions on Pd Au and Pd Ag are given in Table XI. It can be seen from the data that Composition 4 gives higher readings for every capacitor than any other composition on both Pd Au and Pd Ag electrodes. Composition 2 is second highest for every capacitor on both types of electrodes. Composition 3 gives the third highest readings for eight out of ten capacitors with palladium gold electrodes and seven out of ten with palladium silver electrodes. Composition 1 tends to give higher reading than Composition 5 (uniform doped flux) on palladium gold but lower on palladium silver.

When performance of each composition on the two different electrodes is compared, the higher values shown by Compositions 1 and 3 on Pd Au electrodes as compared with Pd Ag are found to be significantly different at the 1% probability level. The higher values shown by Compositions 2 and 4 on Pd Ag as compared with Pd Au are found to be significantly different at the 1% level. The Pd Au - Pd Ag differences for Composition 5 was not significant at the 5% probability level.

2. No Overcoat vs. Glaze vs. Solder.

Table XII gives the result of this experiment. The solder gave definitely lower dielectric breakdown values than either of the other two coatings. No glass is significantly better than the solder coating at the 5% level and glass coating at the 1% level. The average difference between glass and no glass is not quite significant when tested either by a non-parametric test or the standard test.

C. Five-Second 100 Volt - 300 Volt Test

This test consisted of first subjecting capacitors to 100 volts for five seconds and then, for all capacitors on half of the substrates, to 300 volts for five seconds. Number of substrate failures as indicated by "blowing" or sparking of capacitors was noted.

1. Five Dielectric Compositions on Pd Au and Pd Ag Electrodes.

On palladium gold electrodes (Table XIII) Composition 213 gave zero failing substrates, the other compositions from one to three failing substrates, but with these sample sizes none of the palladium gold differences can be considered significant. On palladium silver Composition 213 gave a total of 14 failures - significantly more than the total failures of Compositions 211 and 212 of palladium silver. The particle size of the silver metal (approximately 10 microns) used in the palladium silver electrodes was considerably greater than the particle size of the gold (2 to 4 microns) used in the palladium gold electrodes. This difference combined with the recognizedly greater porosity of the Composition 213 dielectric is believed to account for the marked differences in performance of Composition 213 on the two different electrodes. The particle size effect probably accounts also for the 100% failure at 300 volts of Composition 215 which was made with a specially doped glass that was intended to block alkali migration.

2. No Overcoat vs. Glaze vs. Solder Coating.

This experiment was a test of relative performances of no overcoat vs. glaze vs. solder, all on palladium silver electrodes using as dielectric Composition 211. Numbers of substrates passing and failing are tabulated below -- the solder coated capacitors showed more failures than the other two.

Combination		100V	300V
No Overcoat	Pass	20	10
	Fail	5	2
Glaze	Pass	20	10
	Fail	3	7
Solder	Pass	2	-
	Fail	30	-

3. Effect of Contamination During Screening.

Each capacitor on each substrate was tested for five seconds at 100 volts and then each capacitor on the odd-numbered substrates (one half of the total substrates) was tested for five seconds at 300 volts. Failures found, as evidenced by "blowing" of the capacitor are tabulated, by capacitor, in Table XIV. In this table, failures at 100 volts that occurred again at 300 volts have been counted only once - as failures at 100 volts.

As can be seen from Table XIV the .100 square inch capacitors show substantially more failures than the smaller capacitors. At 100 volts the .010 square inch capacitors showed zero failures. At 300 volts, however, the .010 square inch Number 1 capacitor showed three failures, but this number of failures is not significantly greater than the zero failures of capacitors 2 or 3.

The major purpose of this experiment was to try to relate types and degrees of contamination noted at the time of screening to the subsequent performance of the finished capacitors in order to develop criteria for control of the screening process that would help to eliminate or reduce capacitor failures. When the records of contamination, as noted at the time of screening, are compared with the 100 volt - 300 volt failure data, however, it is seen that the capacitors noted as showing contamination during screening far outnumber the capacitors that failed on the 100 volt - 300 volt test. For example, of the large capacitors (.100 square inches), 238 out of 240 were noted as showing contamination during screening. Of these 238 capacitors, 228 passed the 100 volt test (the two capacitors noted as having no contamination at screening passed both tests). Of the 117 capacitors which passed the 100 volt test and were tested at 300 volts, 103 passed this test also.

The screening records were examined further to see if there were any correlation between capacitor failure and frequency of occurrence or type of defect (pits, lumps, or thread voids) but none could be found. These results would appear to justify the conclusion that within the limits of this experiment the type of contamination encountered here is not sufficient of itself to explain failures on the 100 volt - 300 volt test.

V. CONDUCTOR RESULTS

V. CONDUCTOR RESULTS

A. Conductor Compositions and Experimental Compositions

1. Four Commercial Compositions.

Four commercial Pd Au conductor pastes were screened and fired:
(1) on 1 x 2 inch substrates in a difficult commercial pattern; and
(2) on 1/2 x 1/2 inch substrates in the form of 100 mil diameter dots.

2. Film Thickness - Firing Time Experiment.

Film thickness-firing temperature effects were studied. A standard palladium gold conductor composition was screened on a difficult commercial pattern: (1) to a very thin film - 325 mesh screen, 6 mil emulsion tape; (2) to standard processing conditions - 230 mesh screen, 6 mil emulsion tape; and (3) to a very thick film - 150 mesh screen, 9 mil emulsion tape. Substrates from each screening were then fired at constant belt speed at three different firing temperatures: (1) 50°C below vendor's specified temperatures (825°C); (2) vendor's specified temperature (875°C); and (3) 50°C above vendor's specified temperature (925°C).

B. Screening Defects

1. Four Commercial Compositions.

Results of inspection for screening defects showed much wider variation in the proportion of screening defects of the same paste than between the various pastes. Consequently it was concluded that for the four pastes studied here proportion of screening defects is independent of the paste used.

2. Film Thickness-Firing Time Experiment.

The 150 mesh screen was found to have deposited an excessive amount of material causing enough flow of the paste to reduce the interconductor spacings to less than permitted tolerances on all substrates of this screening. The proportion of "stringers" - short strings of conductor material protruding from design areas and caused by failure of the screen to break clearly from the substrate after screening - was greater for the 325 mesh samples than for the 230 mesh samples.

C. Pull Test Results

1. Four Commercial Compositions.

Pull tests were run on 12 substrates from each screening of the commercial substrates. The test was a standard "pull" test using a Hunter tester with the force being applied perpendicular to the substrate surface. For this program a 50 pound maximum reading gage was used. Averages of 12 pull strength readings for each of the pastes tested on the commercial substrate (and the order in which the pastes were screened) are shown below.

Paste Number	Order of Screening	Average of 12 Gage Readings	Average Pounds/sq. in.
1	1	17.7	3360
1	3	21.2	4070
2	2	13.9	2680
2	5	12.3	2360
3	4	16.8	3240
3	6	14.8	3840
4	7	18.5	3550

The results show good reproducibility for repeated screenings of the same paste and also show small but real differences among the various pastes.

2. Film Thickness-Firing Time Experiment

Pull test results as averages of 10 tests per condition are given below:

Firing Temperature	Screen Mesh 150	230	325
	Average gage readings at break (.0052 sq. in. pad):		
825	20.05	20.50	19.75
875	22.25	22.70	17.10
925	22.15	17.70	21.60
	Average gage readings at break (pounds per square inch):		
825	3856	3942	3798
875	4279	4365	3288
925	4260	3403	4154

All of the above averages are well within the commercially acceptable range for pull test values. The two low averages (230 mesh - 925° and 325 mesh - 875°) might be interpreted as indicating some special effect under these specific conditions but it is more likely that they rather indicate the substantial amount of variability inherent in the pull test.

D. Solderability Tests

Solderability tests were run on 25 substrates from each of the screenings by giving each substrate three 5-second dips in a solder pot maintained at standard production conditions. After the solder dipping each substrate was examined for roughness of surface, sharpness of definition of edges of conductor paths, and amount of conductor pads showing under back lighting. Each substrate was graded according to a scoring system of 1 to 5 (1 excellent, 5 poor).

1. Four Commercial Compositions.

No real differences were found among three of the pastes, but paste number 3 scored substantially higher (poorer) than the other three pastes as shown below:

Paste Number	Order of Screening	Average Solderability Score
1	1	1.7
	3	1.5
2	2	1.6
	5	1.4
3	4	3.3
	6	4.1
4	7	1.6

2. Film Thickness-Firing Time Experiment.

No major differences among the combinations were found as is shown by the following average scores:

Firing Temperatures	Screen Mesh		
	150	230	325
825	1.92	2.15	1.92
875	1.92	1.90	1.92
925	1.96	2.15	1.96

E. Solder-Leaching

1. Four Commercial Compositions.

Solder-leaching tests were run on the 25 substrates previously tested for solderability by giving each substrate 25 3-second dips in a standard production solder pot. Each substrate was then examined for estimated percent of conductor paths leached. The following results were obtained:

Paste Number	Order of Screening	Average % Leached
1	1	10.2
	3	11.9
2	2	5.8
	5	5.4
3	4	15.6
	6	28.4
4	7	0.3

2. Film Thickness-Firing Time Experiment.

Ten substrates from each condition were given 25 successive 3-second dips in a solder pot at standard production temperature and then examined for amount of leaching. All samples showed severe leaching on some conductor paths, leaching so severe as to be well beyond commercially acceptable limits but no clear-cut marked difference in degree or amount of leaching could be discerned among any of the samples.

VI. TABLES I THROUGH XIV

TABLE I

Resistance Temperature Characteristics (TCR) of Resistors 6 and 10 of Five Commercial Compositions

Composition		TCR (ppm/°C) 125°C	50°C	-55°C
211	R-6	49	29	- 8
	R-10	42	22	-15
212	R-6	129	103	65
	R-10	136	114	72
213	R-6	229	207	192
	R-10	258	233	236
214	R-6	97	40	-17
	R-10	83	25	-32
215	R-6	335	268	113
	R-10	334	252	111

TABLE II

TCR Values (ppm/0^{o}C) for Resistors 6 and 10; Laser Vs. Abrasive Correct with Three Glazes

100 Ohm Resistivity

Resistor	Glaze	Abrasive Correct Temperature 125°	Abrasive Correct Temperature 50°	Abrasive Correct Temperature -55°	Laser Correct Temperature 125°	Laser Correct Temperature 50°	Laser Correct Temperature -55°
R-6	None	144	110	-102	160	104	-113
R-10		111	29	-131	141	105	-118
R-6	Low Temp.	145	77	- 85	157	111	- 84
R-10		144	116	-128	129	111	- 91
R-6	High Temp.	260	225	- 2	246	287	- 12
R-10		264	225	- 1	254	227	- 8

1K Resistivity

Resistor	Glaze	Abrasive Correct Temperature 125°	Abrasive Correct Temperature 50°	Abrasive Correct Temperature -55°	Laser Correct Temperature 125°	Laser Correct Temperature 50°	Laser Correct Temperature -55°
R-6	None	346	310	9	326	295	- 2
R-10		316	291	- 32	325	313	- 17
R-6	Low Temp.	360	344	23	349	316	3
R-10		363	345	22	344	318	11
R-6	High Temp.	460	405	141	414	386	105
R-10		478	423	151	416	385	108

10K Resistivity

Resistor	Glaze	Abrasive Correct Temperature 125°	Abrasive Correct Temperature 50°	Abrasive Correct Temperature -55°	Laser Correct Temperature 125°	Laser Correct Temperature 50°	Laser Correct Temperature -55°
R-6	None	247	237	-101	254	286	- 87
R-10		247	202	-103	282	219	- 97
R-6	Low Temp.	234	179	-125	180	188	-125
R-10		242	190	- 93	249	244	- 94
R-6	High Temp.	254	182	- 68	263	192	- 78
R-10		264	196	- 63	268	197	- 66

TABLE III

TCR Values of Resistors 6 and 10
When Fired 24, 48, and 72 Minutes -
At Temperatures of 665, 680, and 695° Centigrade

	R-6			R-10		
	Firing Temperature			Firing Temperature		
Firing Time	665	680	695	665	680	695
-55° TCR						
24 min.	- 54	-143	-151	- 44	-158	-151
48 min.	-288	-314 -293 -318	-331	-294	-322 -293 -326	-328
72 min.	-302	-330	-356	-306	-331	-368
50° TCR						
24 min.	+198	+100	+ 98	+199	+ 78	+103
48 min.	- 85	-122 - 87 -123	-128	-100	-128 - 85 -131	-128
72 min.	-127	-160	-162	-119	-161	-168
125° TCR						
24 min.	+254	+158	+165	+261	+133	+168
48 min.	- 46	- 69 - 39 - 71	- 71	- 55	- 73 - 36 - 77	- 70
72 min.	- 87	-106	-116	- 82	-108	-123

TABLE IV

Number of Resistors Greater Than, Within and Less Than ±1% Tolerance Limits by Individual Resistor for Laser vs. Abrasive Correct and at Three Different Paste Resistivities (100 Ohm, 1K, and 10K)

	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	R-11	R-12	All	All (%)
Length	.060	.025	.300	.125	.100	.050	.030	.500	.100	.050	.030	-	-
Width	.300	.125	.060	.025	.100	.050	.030	.025	.100	.050	.030	-	-
Area	.018	.0032	.018	.0032	.010	.0025	.0009	.0125	.010	.0025	.0009	-	-
No. Squares	0.2	0.2	5	5	1	1	1	20	1	1	1	-	-
						100 Ohm Laser							
1%	0	0	11	8	10	4	19	4	36	25	18	135	34.9
1% to -1%	0	12	25	28	25	18	13	32	0	11	8	172	44.6
-1%	36	24	0	0	1	4	4	0	0	0	10	79	20.5
						100 Ohm Abrasive							
1%	3	3	9	11	2	1	2	3	3	8	4	49	13.1
1% to -1%	2	0	24	23	0	4	2	31	31	10	2	129	34.5
-1%	29	31	1	0	32	29	30	0	0	16	28	196	52.4
						1K Laser							
1%	0	6	2	13	4	17	14	0	0	23	14	93	23.5
1% to -1%	22	30	33	23	24	17	19	36	36	12	18	270	68.2
-1%	14	0	1	0	8	2	3	0	0	1	4	33	8.3
						1K Abrasive							
1%	0	3	3	3	0	6	13	3	2	13	11	57	14.8
1% to -1%	35	31	32	31	32	27	20	32	33	22	23	318	82.8
-1%	0	1	0	0	3	2	2	0	0	0	1	9	2.4
						10K Laser							
1%	12	12	1	12	9	18	25	35	16	17	20	177	46.0
1% to -1%	23	23	34	23	26	17	10	0	19	18	15	208	54.0
-1%	0	0	0	0	0	0	0	0	0	0	0	0	0
						10K Abrasive							
1%	1	8	0	0	2	4	15	0	6	5	4	45	11.4
1% to -1%	35	28	36	36	34	32	21	35	30	31	31	349	88.1
-1%	0	0	0	0	0	0	0	1	0	0	1	2	0.5

TABLE V-A

Average Minimum and Maximum Current-Noise Index of Resistor 8 (12 Resistors per Composition) of Five Commercial Compositions

Composition	Index	Minimum	Maximum
211	- 2.29	- 5.5	0.0
212	- 3.79	-11.0	+ 1.0
213	-12.46	-14.5	-10.0
214	+ .08	- 1.5	3.0
215	- 5.75	-10.0	0.0

TABLE V-B

Average, Minimum, and Maximum Current-Noise Index Value of Resistor 8 (12 Resistors per Average with Three Glazes, Laser and Abrasive Correct)

		Laser Correct			Abrasive Correct		
Resistivity	Glaze	Avg.	Min.	Max.	Avg.	Min.	Max.
100 ohm	None	- .42	-3.0	4.0	1.54	-4.0	5.0
	Low Temp.	.31	-2.5	8.5	-1.65	-4.5	5.0
	High Temp.	-2.87	3.5	-5.7	-3.92	-6.5	1.0
1K	None	-2.37	-9.0	6.0	-7.13	-8.0	-2.5
	Low Temp.	-3.75	-7.0	4.5	-2.22	-9.5	4.0
	High Temp.	-6.0	-8.5	-1.5	-6.21	-9.5	-0.5
10K	None	4.21	2.5	6.0	6.21	2.5	10.0
	Low Temp.	4.29	-2.0	9.5	5.67	2.5	10.5
	High Temp.	8.71	7.0	14.0	6.21	4.0	8.0

TABLE VI

Relationship of Code Number of Tables VII and VIII A, B and C to Various Resistor Compositions and Combinations

Table VII:	Five commercial compositions, 1000 ohms per square resistivity, coded 211 through 215. (Compositions 211, 212, 213, 214 unglazed. Composition 215 glazed with high temperature (680°C) overglaze.)
Table VIII A, B and C:	Resistivity-overglaze-correct combinations (Composition 215 material system) coded as follows:

			Code Numbers		
		Overglaze:	None	Low Temp. (550°C)	High Temp. (680°C)
Table	Resistivity	Correct			
VIII A	100 ohms	abrasive	121	123	125
	100 ohms	laser	122	124	126
VIII B	1,000 ohms	abrasive	221	223	225
	1,000 ohms	laser	222	224	226
VIII C	10,000 ohms	abrasive	321	323	325
	10,000 ohms	laser	322	324	326

TABLE VII. Average Percent ΔR (Absolute Value), Minimum and Maximum % ΔR and Minimum and Maximum Calculated Power Densities - Five Commercial Compositions

		R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	R-11	R-12	R-13
DESIGN LENGTH (Mils):		300	60	25	300	125	100	50	30	500	100	50	30	300
DESIGN WIDTH (Mils):		60	300	125	60	25	100	50	30	25	100	50	30	60
NOMINAL RESISTANCE: (Ohms):		5000	200	200	5000	5000	1000	1000	1000	20000	1000	1000	1000	5000
211	%|ΔR| (Avg.)	1.84	4.63	4.71	4.00	2.79	3.32	3.51	1.97	1.79	2.97	1.16	2.14	1.98
	% ΔR (Min.)	1.12	2.7	2.91	1.60	-4.75	1.66	1.79	-8.05	0.45	0.80	-0.64	-3.96	1.09
	% ΔR (Max.)	2.70	7.5	6.98	9.21	-1.83	5.55	4.59	3.17	3.22	4.57	2.28	2.11	3.62
	W/in.^{2}(Min.)	-	17.1	108.	17.5	109.	17.5	74.2	243.	16.3	18.0	80.9	255.	-
	W/in.^{2}(Max.)	-	20.2	132.	19.2	128.	19.6	85.2	275.	18.2	20.0	88.9	284.	-
	Outliers (% ΔR)	-	-	-	-	-	-	-	-	-	-	-	-	-
212	%|ΔR| (Avg.)	0.76	1.04	4.96	1.81	2.57	1.60	2.34	3.76	1.42	1.60	2.42	2.95	1.05
	% ΔR (Min.)	0.45	0.74	2.91	1.16	1.66	1.16	1.46	2.06	0.70	0.99	1.42	0.95	0.66
	% ΔR (Max.)	0.97	1.80	8.18	3.24	4.05	1.91	3.25	6.91	2.24	2.23	3.34	4.76	1.79
	W/in.^{2}(Min.)	-	15.6	117.	14.5	112.	15.1	69.2	223.	15.6	16.5	69.2	221.	-
	W/in.^{2}(Max.)	-	28.4	238.	26.8	173.	26.3	107.	298.	21.9	27.6	108.	301.	-
	Outliers (% ΔR)	-	-	47.9	-	-	-	-	-	-	-	-	-	-
213	%|ΔR| (Avg.)	0.53	1.03	2.23	1.20	1.77	1.27	1.72	3.18	1.24	1.35	2.00	4.35	0.70
	% ΔR (Min.)	0.34	0.50	0.96	0.58	0.77	0.77	0.99	1.66	0.70	0.73	1.16	2.86	0.40
	% ΔR (Max.)	0.75	2.10	4.14	2.05	2.84	1.44	2.38	4.90	1.51	2.10	2.58	5.56	0.91
	W/in.^{2}(Min.)	-	17.7	157.	15.8	115.	16.3	83.4	227.	15.8	18.4	82.0	245.	-
	W/in.^{2}(Max.)	-	20.4	174.	19.4	142.	18.8	99.3	313.	18.4	21.8	113.	322.	-
	Outliers (% ΔR)	-	-	-	-	-	-	-	-	-	-	-	-	-
214	%|ΔR| (Avg.)	0.36	0.48	0.41	0.35	0.20	0.35	0.29	0.10	0.09	0.19	0.09	0.22	0.25
	% ΔR (Min.)	0.24	0.20	0.20	0.18	-0.46	0.22	0.04	-0.18	-0.15	0.11	-0.07	-0.56	0.04
	% ΔR (Max.)	0.60	0.74	1.04	0.54	-0.02	0.46	0.53	0.21	0.10	0.32	0.24	0.25	0.35
	W/in.^{2}(Min.)	-	15.0	118.	14.7	115.	14.7	75.5	230.	14.6	14.7	78.3	280.	-
	W/in.^{2}(Max.)	-	20.9	150.	16.7	141.	17.2	87.1	269.	17.0	16.0	87.0	302.	-
	Outliers (% ΔR)	-	-	-	-	-	-	-	-	-	-	-	-	-
215	%|ΔR| (Avg.)	0.29	0.36	0.51	0.69	1.35	0.51	1.01	1.17	1.39	0.51	0.85	1.35	0.32
	% ΔR (Min.)	0.14	0.20	-0.2	0.58	0.50	0.43	0.64	0.92	1.10	0.33	0.41	0.90	0.15
	% ΔR (Max.)	0.52	0.64	1.01	0.90	2.04	0.66	1.93	1.38	1.80	0.66	1.18	1.81	0.66
	W/in.^{2}(Min.)	-	17.6	133.	15.3	92.4	15.4	68.3	191.	13.1	16.5	84.3	212.	-
	W/in.^{2}(Max.)	-	24.5	175.	21.5	139.	23.9	98.3	290.	18.9	25.3	100.	321.	-
	Outliers (% ΔR)	-	-	-	-	-	-	-	-	-	-	-	-	-

FOLDOUT FRAME 2

FOLDOUT FRAME 1

TABLE VIII-A. Average Percent ΔR (Absolute Value), Minimum and Maximum % ΔR and Minimum and Maximum Calculated Power Densities - 100 Ohm Resistivity Paste, Three Glazes, Laser and Abrasive Correct

		R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	R-11	R-12	R-13
DESIGN LENGTH:		300	60	25	300	125	100	50	30	500	100	50	30	300
DESIGN WIDTH:		60	300	125	60	25	100	50	30	25	100	50	30	60
NOMINAL RESISTANCE:		500	20	20	500	500	100	100	100	2000	100	100	100	100
121	% |ΔR| (Avg.)	3.06	1.46	1.74	3.47	7.06	3.34	3.03	*	4.26	2.76	4.38	*	2.52
	% ΔR (Min.)	1.76	1.00	0.51	2.91	2.70	2.55	2.41	*	2.46	2.63	3.23	*	1.35
	% ΔR (Max.)	5.37	1.99	3.12	4.26	11.91	4.63	3.50	*	6.85	2.93	5.60	*	4.21
	$W/in.^2$ (Min.)	–	19.4	136.	17.5	186.	18.3	102.	335.	17.3	20.1	110.	359.	–
	$W/in.^2$ (Max.)	–	21.4	171.	19.8	231.	21.2	117.	408.	22.7	23.2	125.	454.	–
	Outliers (% ΔR)	–	–	–	–	–	–	-1.37	*	–	4.27	–	*	–
122	% |ΔR| (Avg.)	1.77	1.30	1.68	1.90	2.01	3.34	4.09	*	2.47	2.36	5.82	*	1.24
	% ΔR (Min.)	1.27	0.50	1.02	1.39	1.06	1.21	1.99	*	0.70	1.50	2.00	*	.82
	% ΔR (Max.)	2.73	2.43	3.08	2.96	3.37	2.92	7.05	*	2.30	2.59	10.11	*	2.01
	$W/in.^2$ (Min.)	–	17.7	120.	17.2	206.	17.1	89.9	382.	17.8	19.7	110.	358.	–
	$W/in.^2$ (Max.)	–	21.8	142.	28.7	373.	25.2	176.	459.	23.2	26.2	142.	491.	–
	Outliers (% ΔR)	–	–	–	–	–	–	–	*	–	–	–	*	–
123	% |ΔR| (Avg.)	.75	0.37	1.10	0.73	0.98	0.65	1.19	*	1.20	0.65	1.39	*	.70
	% ΔR (Min.)	.45	-0.99	-2.59	0.14	0.66	0.29	0.38	*	0.70	-0.29	-0.39	*	.41
	% ΔR (Max.)	.90	0.50	1.04	1.17	1.38	1.48	1.64	*	3.10	1.45	2.81	*	.84
	$W/in.^2$ (Min.)	–	22.4	143.	18.3	195.	21.9	118.	440.	21.8	22.7	138.	506.	–
	$W/in.^2$ (Max.)	–	25.8	187.	23.7	269.	26.3	145.	593.	26.0	27.0	159.	615.	–
	Outliers (% ΔR)	–	–	–	–	–	–	–	*	–	–	–	*	–
124	% |ΔR| (Avg.)	.46	0.56	0.50	1.13	0.89	0.95	1.92	*	0.54	1.02	2.43	*	.66
	% ΔR (Min.)	.26	-0.99	-0.98	-0.12	0.52	0.75	1.05	*	0.30	0.19	0.74	*	.25
	% ΔR (Max.)	.80	1.51	.51	2.48	1.32	1.21	3.25	*	0.70	1.70	5.27	*	1.03
	$W/in.^2$ (Min.)	–	18.9	114.	20.8	214.	21.4	80.2	439.	21.6	34.4	145.	608.	–
	$W/in.^2$ (Max.)	–	24.2	145.	24.8	286.	27.6	150.	641.	27.4	28.3	174.	749.	–
	Outliers (% ΔR)	–	–	–	–	–	2.27	–	*	–	–	–	*	–
125	% |ΔR| (Avg.)	.61	0.50	0.39	0.62	1.36	0.66	1.27	*	2.04	0.79	1.36	*	.67
	% ΔR (Min.)	.55	-1.49	-0.58	0.56	0.90	0.49	0.87	*	1.15	0.58	0.99	*	.52
	% ΔR (Max.)	.73	–	1.03	0.69	2.12	1.08	1.84	*	3.69	1.17	1.98	*	.80
	$W/in.^2$ (Min.)	–	18.2	148.	16.7	132.	16.8	102.	253.	15.2	18.3	112.	314.	–
	$W/in.^2$ (Max.)	–	21.1	205.	17.9	160.	20.7	185.	629.	22.5	22.3	253.	506.	–
	Outliers (% ΔR)	–	–	–	–	–	–	6.50	*	–	-0.19	2185.32	*	–
126	% |ΔR| (Avg.)	.66	0.36	0.71	0.72	1.01	0.65	2.44	*	1.00	0.74	9.11	*	.64
	% ΔR (Min.)	.50	-0.50	-1.02	0.56	0.68	0.57	0.96	*	0.65	0.48	2.96	*	.47
	% ΔR (Max.)	.78	1.03	1.04	0.96	1.26	0.75	3.62	*	1.40	0.95	19.63	*	.76
	$W/in.^2$ (Min.)	–	18.0	123.	14.7	114.	17.6	99.4	412.	18.0	17.8	108.	391.	–
	$W/in.^2$ (Max.)	–	19.5	169.	17.6	169.	19.4	129.	568.	21.2	19.7	146.	521.	–
	Outliers (% ΔR)	–	–	–	–	–	–	–	*	–	–	–	*	–

*High, widely varying, often unstable readings

FOLDOUT FRAME 1

FOLDOUT FRAME 2

TABLE VIII-B. Average Percent ΔR (Absolute Value), Minimum and Maximum % ΔR and Minimum and Maximum Calculated Power Densities - 1000 Ohm Resistivity, Three Glazes, Laser and Abrasive Correct

		R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	R-11	R-12	R-13
DESIGN LENGTH:		300	60	25	300	125	100	50	30	500	100	50	30	300
DESIGN WIDTH:		60	300	125	60	25	100	50	30	25	100	50	30	60
NOMINAL RESISTANCE:		5000	200	200	5000	5000	1000	1000	1000	20000	1000	1000	1000	5000
221	% |ΔR| (Avg.)	3.07	2.70	2.85	3.98	6.02	3.65	4.45	6.59	6.71	3.73	5.34	7.43	2.93
	% ΔR (Min.)	1.40	1.14	0.29	2.23	4.73	2.47	2.11	5.66	5.28	2.40	8.98	5.53	1.80
	% ΔR (Max.)	5.19	3.72	4.74	5.20	8.26	5.79	7.31	7.73	8.18	6.69	3.81	9.74	4.20
	W/in.^{2} (Min.)	-	19.1	125.	18.9	123.	19.0	83.4	219.	15.3	18.3	83.1	240.	-
	W/in.^{2} (Max.)	-	33.5	211.	29.2	208.	31.8	14.7	411.	26.5	30.6	142.	434.	-
	Outliers (% ΔR)	-	-	-	-	-	-	-	-	-	-	-	-	-
222	% |ΔR| (Avg.)	3.14	2.93	4.64	2.72	2.70	2.44	4.01	6.19	2.04	2.50	3.95	4.42	2.41
	% ΔR (Min.)	2.63	2.40	3.88	1.59	1.14	0.99	2.80	4.48	1.00	1.15	1.80	2.98	2.03
	% ΔR (Max.)	5.23	3.74	7.60	3.14	3.83	3.39	6.92	7.76	2.85	3.70	5.24	6.54	3.48
	W/in.^{2} (Min.)	-	29.7	204.	28.4	200.	30.4	129.	351.	23.0	30.3	133.	391.	-
	W/in.^{2} (Max.)	-	34.9	268.	34.4	234.	37.0	168.	420.	30.3	36.1	165.	481.	-
	Outliers (% ΔR)	-	-	-	-	-	5.91	-	-	-	-	-	-	-
223	% |ΔR| (Avg.)	1.06	1.05	1.92	1.54	1.93	1.13	1.52	1.58	1.54	1.07	1.18	3.26	0.78
	% ΔR (Min.)	0.79	0.84	1.34	1.07	0.89	0.97	0.88	0.83	1.35	0.80	0.88	2.07	0.64
	% ΔR (Max.)	1.10	1.24	3.19	1.74	2.57	1.23	2.60	2.04	1.89	1.23	1.54	4.63	1.01
	W/in.^{2} (Min.)	-	27.3	197.	28.4	201.	28.8	133.	324.	23.8	27.3	130.	342.	-
	W/in.^{2} (Max.)	-	34.9	226.	30.2	217.	31.4	147.	428.	27.0	300.	139.	439.	-
	Outliers (% ΔR)	2.11	-	-	-	-	1.76	-	-	0.15	-	-	-1.98	-
224	% |ΔR| (Avg.)	1.04	1.37	2.65	1.48	1.16	1.14	1.57	3.42	1.09	0.87	1.29	2.46	0.78
	% ΔR (Min.)	0.75	0.96	1.74	-2.64	0.96	0.67	0.87	1.73	0.65	0.43	0.96	2.10	-0.08
	% ΔR (Max.)	1.25	1.80	4.11	2.93	2.08	1.51	2.19	5.64	1.40	1.19	1.58	3.13	1.32
	W/in.^{2} (Min.)	-	20.5	134.	20.2	138.	20.4	99.2	261.	18.9	18.2	85.5	226.	-
	W/in.^{2} (Max.	-	34.4	248.	34.7	242.	36.7	172.	498.	29.2	34.1	164.	534.	-
	Outliers (% ΔR)	-	-	-	-	∞	-	-	-	-	-	-	-	-
225	% |ΔR| (Avg.)	0.42	0.21	0.75	0.60	1.42	0.57	0.84	1.09	0.95	0.53	0.69	1.24	0.31
	% ΔR (Min.)	0.02	0	0.25	0.22	0.68	0.37	0.48	0.68	0.55	0.27	0.38	0.57	0.07
	% ΔR (Max.)	0.72	0.35	1.95	0.88	1.84	0.75	1.25	1.65	1.19	0.68	0.87	1.71	0.48
	W/in.^{2} (Min.)	-	16.8	112.	16.0	101.	16.9	69.0	190.	12.7	16.4	69.9	206.	-
	W/in.^{2} (Max.)	-	20.1	140.	17.9	123.	19.6	81.3	235.	16.4	19.6	84.8	266.	-
	Outliers (% ΔR)	-	0.70	-	-	2.81	-	-	-	-	-	-	-	-
226	% |ΔR| (Avg.)	0.47	0.51	0.87	0.63	0.98	0.67	0.87	1.23	0.88	0.43	0.99	1.26	0.56
	% ΔR (Min.)	0.43	0.30	0.65	0.12	0.69	0.42	0.58	0.86	0.50	0.28	0.51	0.59	0.46
	% ΔR (Max.)	0.58	0.70	1.15	0.91	1.60	0.91	1.76	1.33	1.30	0.61	1.82	0.59	0.72
	W/in.^{2} (Min.)	-	16.3	108.	15.0	101.	16.0	69.5	185.	13.8	16.1	67.6	199.	-
	W/in.^{2} (Max.)	-	19.1	129.	18.8	138.	22.8	79.1	227.	18.6	19.4	86.5	294.	-
	Outliers (% ΔR)	1.36	-	-	-	-1.02	-	-	-	-	-	-	377.3	-

FOLDOUT FRAME 2

FOLDOUT FRAME 1

TABLE VIII-C. Average Percent ΔR (Absolute Value), Minimum and Maximum % ΔR and Minimum and Maximum Calculated Power Densities - 10,000 Ohm Resistivity, Three Glazes, Laser and Abrasive Correct

		R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	R-11	R-12	R-13
DESIGN LENGTH:		300	60	25	300	125	100	50	30	500	100	50	30	300
DESIGN WIDTH:		60	300	125	60	25	100	50	30	25	100	50	30	60
NOMINAL RESISTANCE:		50000	2000	2000	50000	50000	10000	10000	10000	200000	10000	10000	10000	50000
321	% |ΔR| (Avg.)	1.84	2.24	3.63	2.73	6.01	2.80	3.69	5.05	5.60	2.92	3.74	4.37	2.12
	% ΔR (Min.)	1.16	1.30	2.57	1.49	5.27	2.18	2.62	1.89	3.53	1.93	1.63	1.54	0.97
	% ΔR (Max.)	3.00	2.92	4.13	4.43	6.83	3.95	4.80	6.46	7.43	4.31	6.33	7.17	3.02
	W/in.^{2} (Min.)	–	22.4	132.	23.7	136.	23.5	98.	252.	23.5	24.1	164.	231.	–
	W/in.^{2} (Max.)	–	24.2	152.	24.5	150.	25.9	116.	303.	24.8	26.2	182.	315.	–
	Outliers (% ΔR)	–	–	–	–	–	–	–	–	–	–	–	–	–
322	% |ΔR| (Avg.)	1.68	1.27	1.88	1.31	1.20	1.36	1.30	2.67	0.97	0.92	1.61	2.00	1.36
	% ΔR (Min.)	0.95	0.80	1.20	0.48	0.16	0.60	0.77	1.25	0.20	0.67	0.71	0.68	0.62
	% ΔR (Max.)	2.11	1.80	2.52	2.65	1.89	2.46	1.95	4.49	1.67	2.58	2.00	3.64	1.87
	W/in.^{2} (Min.)	–	22.8	136.	22.8	140.	23.6	112.	290.	23.5	25.0	170.	305.	–
	W/in.^{2} (Max.)	–	24.4	148.	25.3	151.	26.0	126.	307.	24.7	26.3	215.	356.	–
	Outliers (% ΔR)	–	–	–	–	–	–	–	–	–	–	–	–	–
323	% |ΔR| (Avg.)	0.58	0.67	0.68	0.86	1.22	0.76	1.07	1.43	3.29	0.60	1.35	1.44	0.74
	% ΔR (Min.)	0.43	0.59	0.20	0.70	0.62	0.54	0.52	0.57	2.10	0.40	0.89	0.19	0.50
	% ΔR (Max.)	0.68	0.69	1.93	1.16	1.60	1.03	1.63	2.48	4.87	0.75	1.98	3.72	0.93
	W/in.^{2} (Min.)	–	22.9	136.	23.9	1.41	24.4	116.	2.97	22.7	24.8	182.	302.	–
	W/in.^{2} (Max.)	–	25.9	151.	26.9	1.79	27.7	125.	342.	26.0	28.1	197.	351.	–
	Outliers (% ΔR)	–	0.84	–	–	–	–	–	–	–	–	–	–	–
324	% |ΔR| (Avg.)	0.69	0.66	0.62	1.01	1.22	0.94	1.48	1.74	1.05	0.92	1.43	1.01	0.79
	% ΔR (Min.)	0.60	0.50	0.30	0.82	0.67	0.64	1.00	1.30	0.83	0.64	0.67	0.00	0.72
	% ΔR (Max.)	0.79	1.05	1.04	1.16	1.95	1.28	2.17	2.73	1.28	1.33	3.21	2.24	0.87
	W/in.^{2} (Min.)	–	22.3	123.	24.5	1.03	23.0	105.	271.	22.7	25.2	181.	300.	–
	W/in.^{2} (Max.)	–	35.1	210.	27.1	2.06	35.7	166.	332.	32.7	36.7	264.	447.	–
	Outliers (% ΔR)	–	–	–	1.71	–	–	–	[illegible]	–	–	–	–	-0.49/-8.65
325	% |ΔR| (Avg.)	0.29	0.12	0.08	0.29	0.77	0.22	0.46	0.37	1.02	0.21	0.48	0.48	0.34
	% ΔR (Min.)	0.19	0.05	-0.30	0.16	0.50	0.06	0.05	0.10	0.55	0.11	0.06	-0.25	0.16
	% ΔR (Max.)	0.48	0.25	0.10	0.60	1.17	0.31	1.18	0.84	1.61	0.30	0.99	1.88	0.56
	W/in.^{2} (Min.)	–	12.3	80.7	13.44	80.6	13.9	65.	158.	12.9	14.0	103.	185.	–
	W/in.^{2} (Max.)	–	13.1	97.3	13.9	97.	16.3	74.	194.	14.5	16.9	118.	201.	–
	Outliers (% ΔR)	–	–	–	–	–	–	–	–	–	–	–	–	–
326	% |ΔR| (Avg.)	0.08	0.05	0.12	0.10	0.18	0.13	0.28	0.19	0.11	0.09	0.22	0.26	0.06
	% ΔR (Min.)	-0.06	-0.05	-0.20	0.02	-0.44	0.03	0.01	-0.12	0.00	0.03	-0.02	-0.67	0.09
	% ΔR (Max.)	0.16	0.10	0.15	0.18	0.36	0.30	0.64	0.40	0.24	1.90	0.59	0.27	0.00
	W/in.^{2} (Min.)	–	14.2	84.5	13.7	65.8	13.9	68.	1.81	14.4	14.5	110.	183.	–
	W/in.^{2} (Max.)	–	15.1	94.9	15.7	111.	15.8	76.	2.04	150.	18.1	125.	221.	–
	Outliers (% ΔR)	–	–	–	–	–	–	–	–	–	–	–	–	–

FOLDOUT FRAME 1

FOLDOUT FRAME 2

TABLE IX Differences Between Percent Increase at 1000 Hours Under Load for Abrasive and Laser Correct Resistors (Abrasive - Laser) at Three Resistivities and Three Glazes at Each Resistivity.

Differences in Percent Increase of Resistance at 1000 Hours (Abrasive-Laser)

Glaze:	None			Low Temperature			High Temperature		
Resistivity (ohm):	100	1000	10000	100	1000	10000	100	1000	10000
Resistor									
2	.16	-.23	.97	-.19	-.32	.01	.14	-.30	.07
3	.06	-1.79	1.75	.60	-.73	.06	-.32	-.12	-.04
4	1.57	1.26	1.42	-.40	.06	-.15	-.10	-.03	.19
5	5.05	3.32	4.81	.09	.77	0	.35	.44	.59
6	0	1.21	1.44	-.30	-.01	-.18	.01	-.10	.09
7	-1.06	.44	2.39	-.73	-.05	-.41	-1.17	-.03	.18
8	-	.40	2.38	-	-1.84	-.31	-	-.14	.18
9	1.79	4.67	4.63	.66	.45	2.24	1.04	.07	.91
10	.40	1.23	2.00	-.37	.20	-.32	.05	.10	.12
11	-1.44	1.39	2.13	-1.04	-.11	-.08	-7.75*	-.30	.26
12	-	3.01	2.37	-	.80	.43	-	.02	.22
Averages	0.82	1.36	2.39	-0.19	0.02	0.12	0	-0.04	0.25

*Outlier - Rejected

TABLE X

Description of Appearance Differences of Resistors after 1000 Hour under Load and As Seen under 40X Magnification with Reflected Light

214	Very smooth velvet-like surface, R8 and R12 (.0009 sq. in.) glassy shiny surface.
215 123-126 223-226 323-326	Smooth surfaces, some pits, frequently velvet-like but to a lesser extent than 214 surfaces. No differences noted between small resistors and large resistors.
213	Slightly rough surface, R8 and R12 very slightly glassy, with small pits.
212	Slightly rough surface. All resistors glassy around edges, R8 and R12 glassy surfaces - pitted.
211	All surfaces in active areas of resistors slightly glassy. Glassy characteristic more marked on smaller resistors, particularly R8 and R12, and showing some definite loss of resistor material.
321-322 221-222	Slightly glassy in effective resistor areas, some pits and bubbles, no differences between large resistors and small resistors.
121-122	All surfaces rough, badly pitted. On abrasive correct samples, R8 and R12 showed loss of as much as 50% or more of resistor material around correct cut. On laser correct samples, a deep crevice in effective resistor area running to outer edge of area.

TABLE XI Average Dielectric Breakdown Values in Volts of Capacitors Made from Five Dielectric Compositions and Screened on (a) Palladium-Gold and (b) Palladium-Silver Electrodes.

			Palladium-Gold					Palladium-Silver				
	Composition # ---		1	2	3	4	5	1	2	3	4	5
Capacitor Number	Capacitor Length	Capacitor Width										
1	100	100	824	1201	791	1921	611	606	1323	746	2K	713
2	100	100	706	1069	774	1594	639	610	1254	572	1829	794
3	200	115	709	901	707	1870	756	538	1097	640	2K	658
4	200	115	750	1079	759	1570	605	577	1082	599	2K	562
5	400	250	624	756	693	2139	541	498	740	588	2K	488
6	400	250	599	777	732	959	464	462	741	526	2K	432
7	200	115	773	1071	648	1894	556	524	1099	638	2K	559
8	200	115	693	1042	785	1890	565	496	1092	503	2K	611
9	100	100	821	1052	843	1613	654	624	1319	718	2K	712
10	100	100	824	1149	849	1470	717	623	1276	736	2K	627

TABLE XII Breakdown Voltage of Capacitors Using Composition 1, Palladium-Silver Electrodes and Glass, Solder and Nothing Over the Top Electrode.

Capacitor Number Area	Glass Over Top	Soldered	Nothing
1	768	323	598
2	798	414	647
3	598	315	551
4	517	385*	587
5	521	197*	551
6	559	81	509
7	635	505*	504
8	580	464	529
9	668	313	642
0	551	567*	638

* One reading of 30 or less discarded from each of these averages

TABLE XIII

Numbers of Substrates with (a) No Failing Capacitors ("Pass") and (b) One or More Failing Capacitors When Tested for Five Seconds at 100 and 300 Volts (Five Dielectric Compositions Screened on Pd-Au and Pd-Ag Electrodes)

		Pd-Au		Pd-Ag	
Composition		100 V	300 V	100 V	300 V
1	Pass	20	10	20	10
	Fail	3	0	2	2
2	Pass	20	10	20	10
	Fail	1	0	1	0
3	Pass	20	10	12	4
	Fail	0	0	8	6
4	Pass	20	10	20	10
	Fail	2	1	2	0
5	Pass	20	10	20	0
	Fail	0	2	1	10

TABLE XIV

Number of Failing and Passing Capacitors, by Capacitor When Tested for Five Seconds at 100 Volts and Capacitors on Half of the Substrates then Tested for Five Seconds at 300 Volts

Capacitor	Area (in.^{2})	100 Volt Test		300 Volt Test*	
		Failing	Passing	Failing	Passing
1	.010	0	120	3	57
2	.010	0	120	0	60
3	.010	0	120	0	60
4	.010	0	120	1	59
5	.023	1	119	2	58
6	.023	1	119	1	58
7	.023	0	120	3	57
8	.023	2	118	3	56
9	.100	3	117	6	53
10	.100	7	113	6	52
		14	1,186	25	570

*Excluding capacitors failing at 100 volts.

VII. FIGURES 1 THROUGH 39

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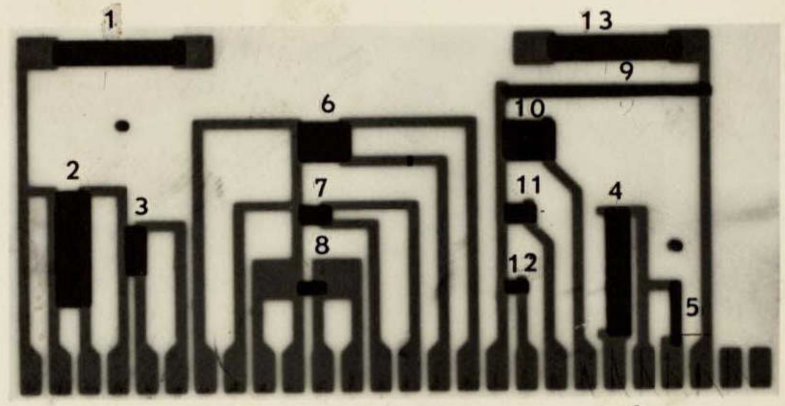

Resistor:	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13
Design Length (Mils)	300	60	25	300	125	100	50	30	500	100	50	30	300
Design Width (Mils)	60	300	125	60	25	100	50	30	25	100	50	30	60

Note: R1 and R13 are designed for high temperature storage.

Figure 1, Layout of Resistor Test Pattern (Enlarged 2:1) with Resistor Designations and Dimensions

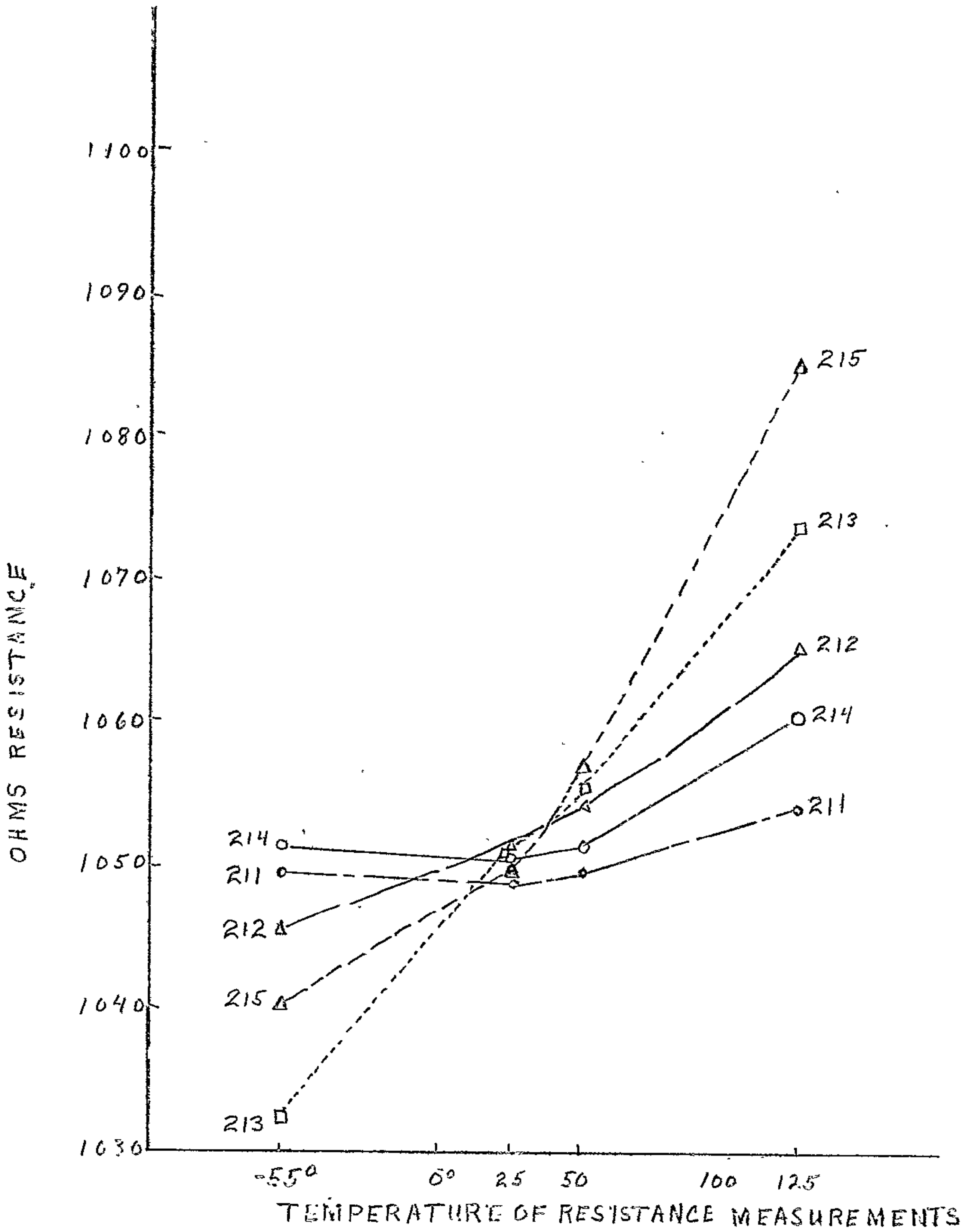

FIGURE 2: RESISTANCE TEMPERATURE RELATIONSHIP FOR FIVE COMMERCIAL 1K/SQUARE PASTES, RESISTOR 6 ~~(0.100 X 0.100 INCHES)~~

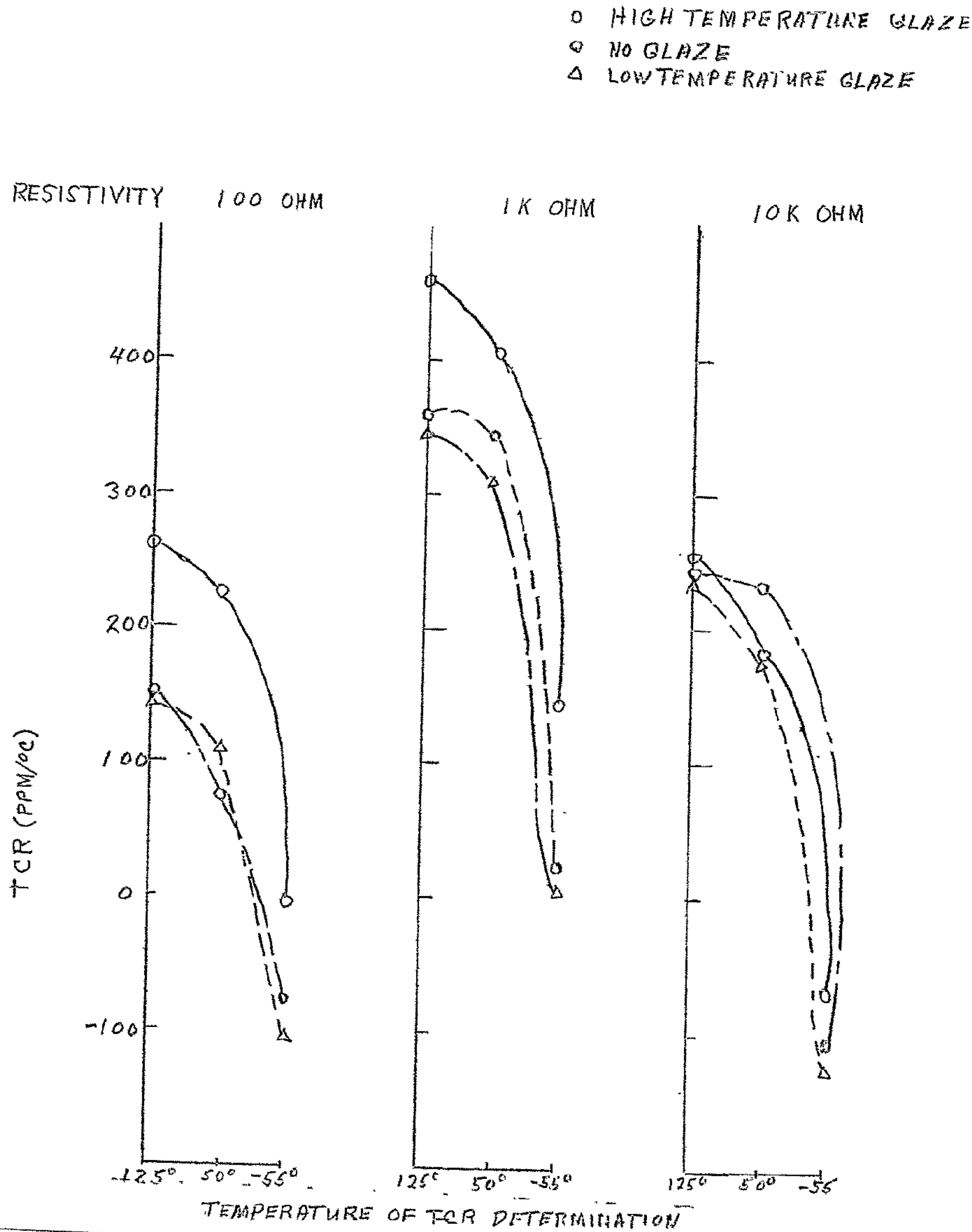

FIGURE 3: TCR VALUES (PPM/°C) AT 125, 50, AND -55°C OF ONE PASTE FORMULATION AT RESISTIVITIES OF 100, 1K, AND 10K OHMS WITH THREE OVERGLAZES (RESISTOR 6, 0.100 X 0.100 INCHES) (ABRASIVE CORRECT)

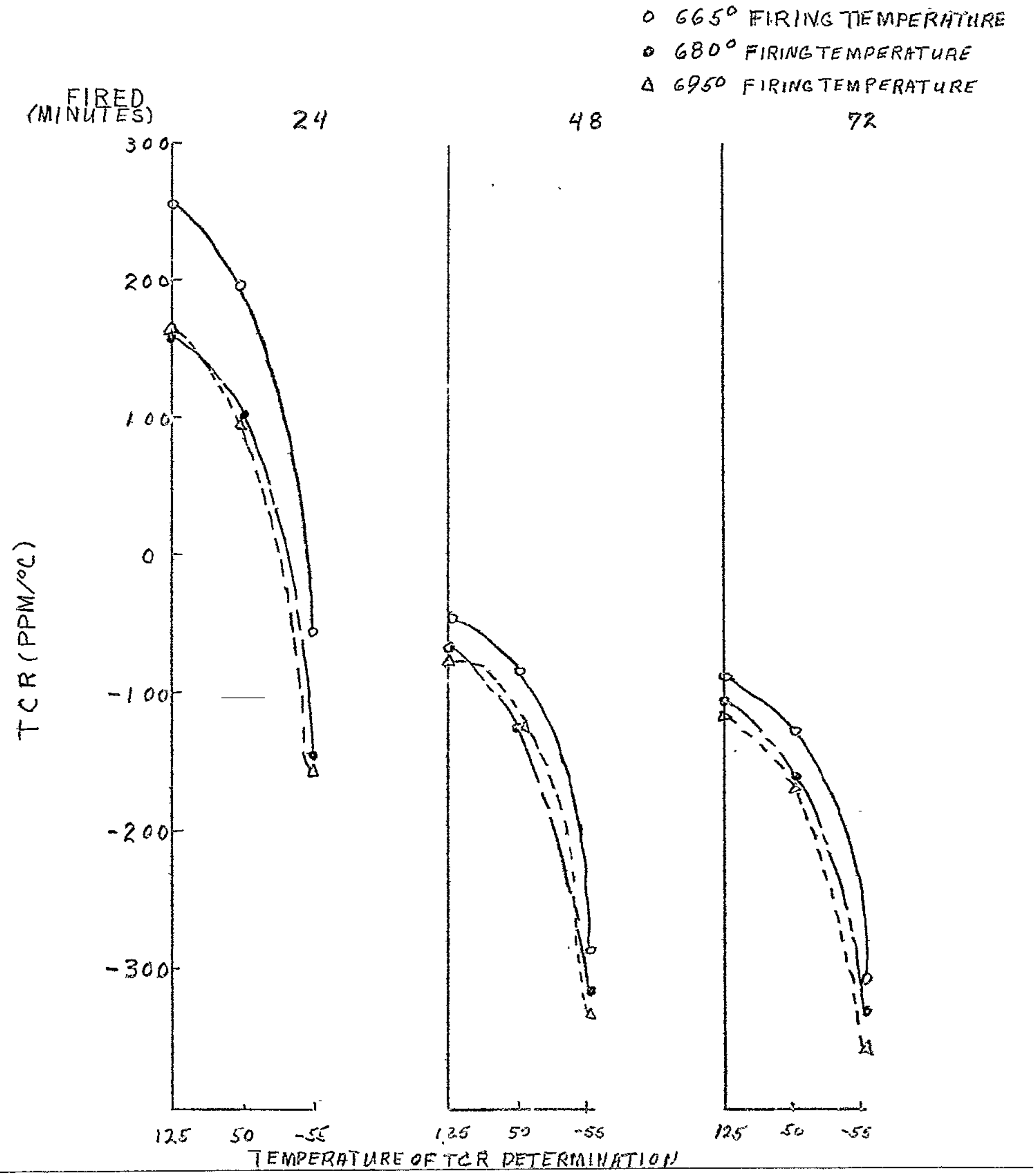

FIGURE 4: TCR VALUES (PPM/°C) AT 125, 50, AND -55°C OF RESISTORS FIRED AT 665°, 680°, AND 695°C AND FOR 24, 48, AND 72 MINUTES (RESISTOR 6, 0.100 X 0.100 INCHES)

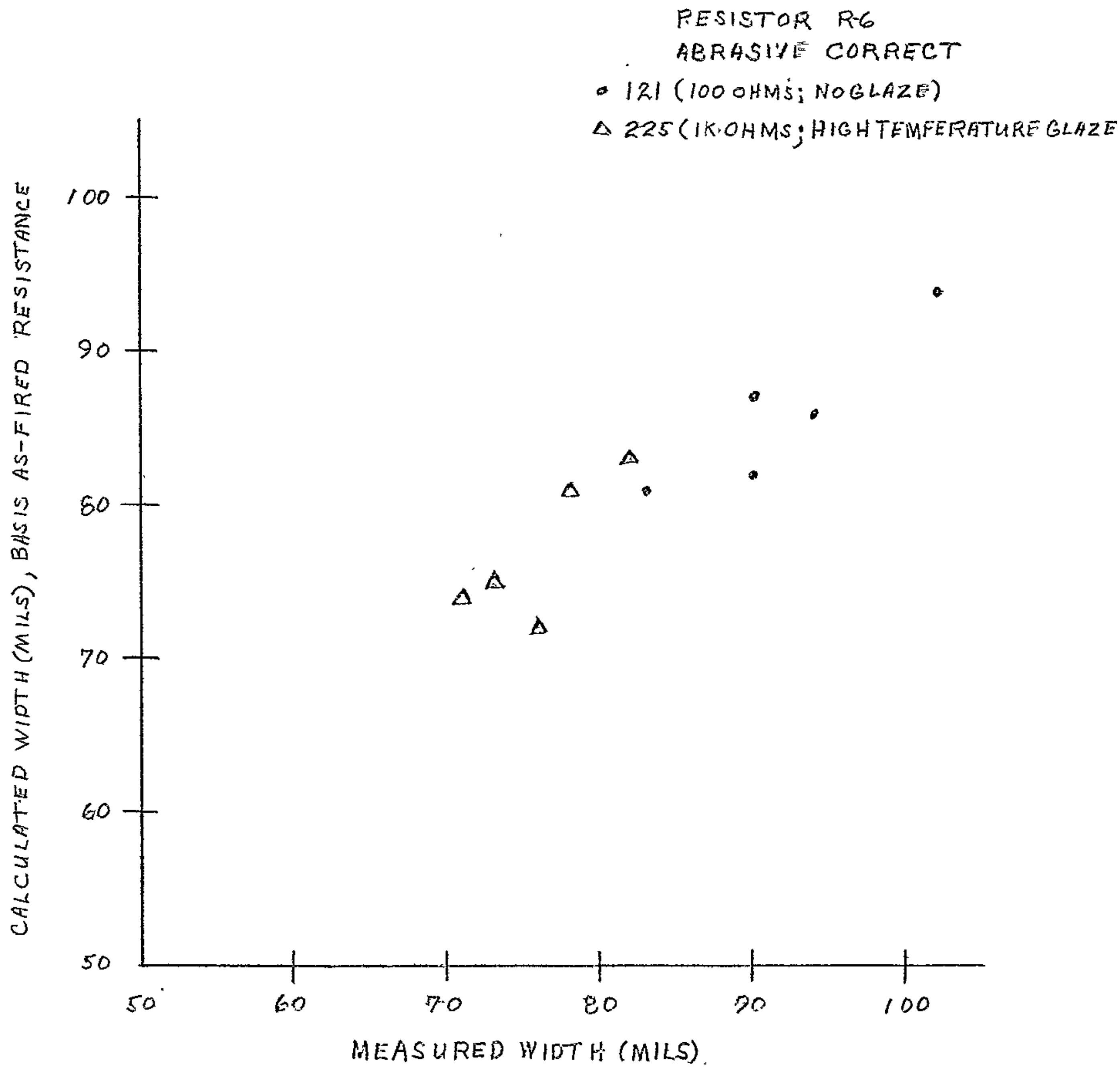

FIGURE 5: MEASURED WIDTH VERSUS CALCULATED WIDTH, ABRASIVE CORRECT, RESISTOR R6

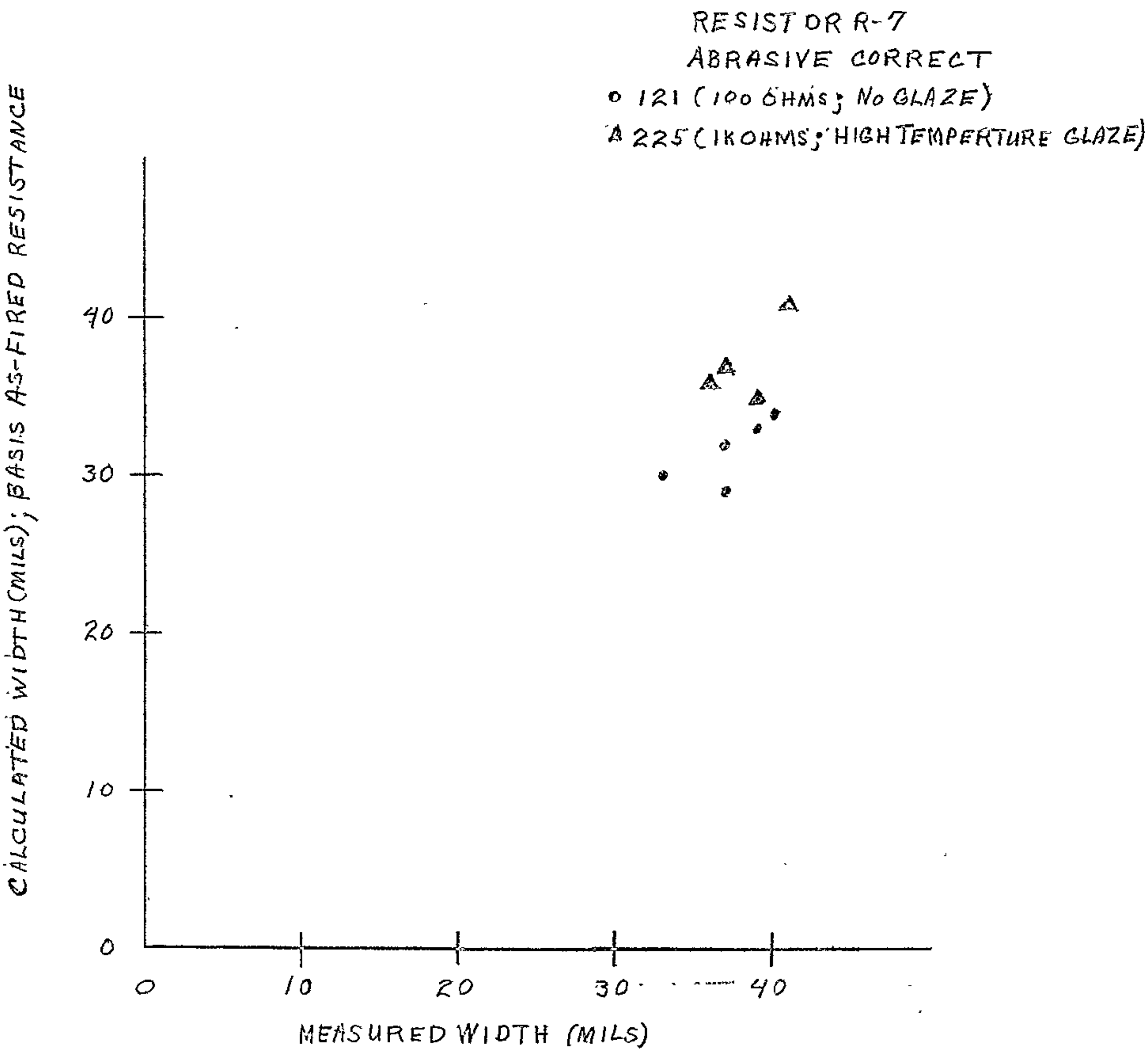

FIGURE 6: MEASURED WIDTH VERSUS CALCULATED WIDTH, ABRASIVE CORRECT, RESISTOR R7

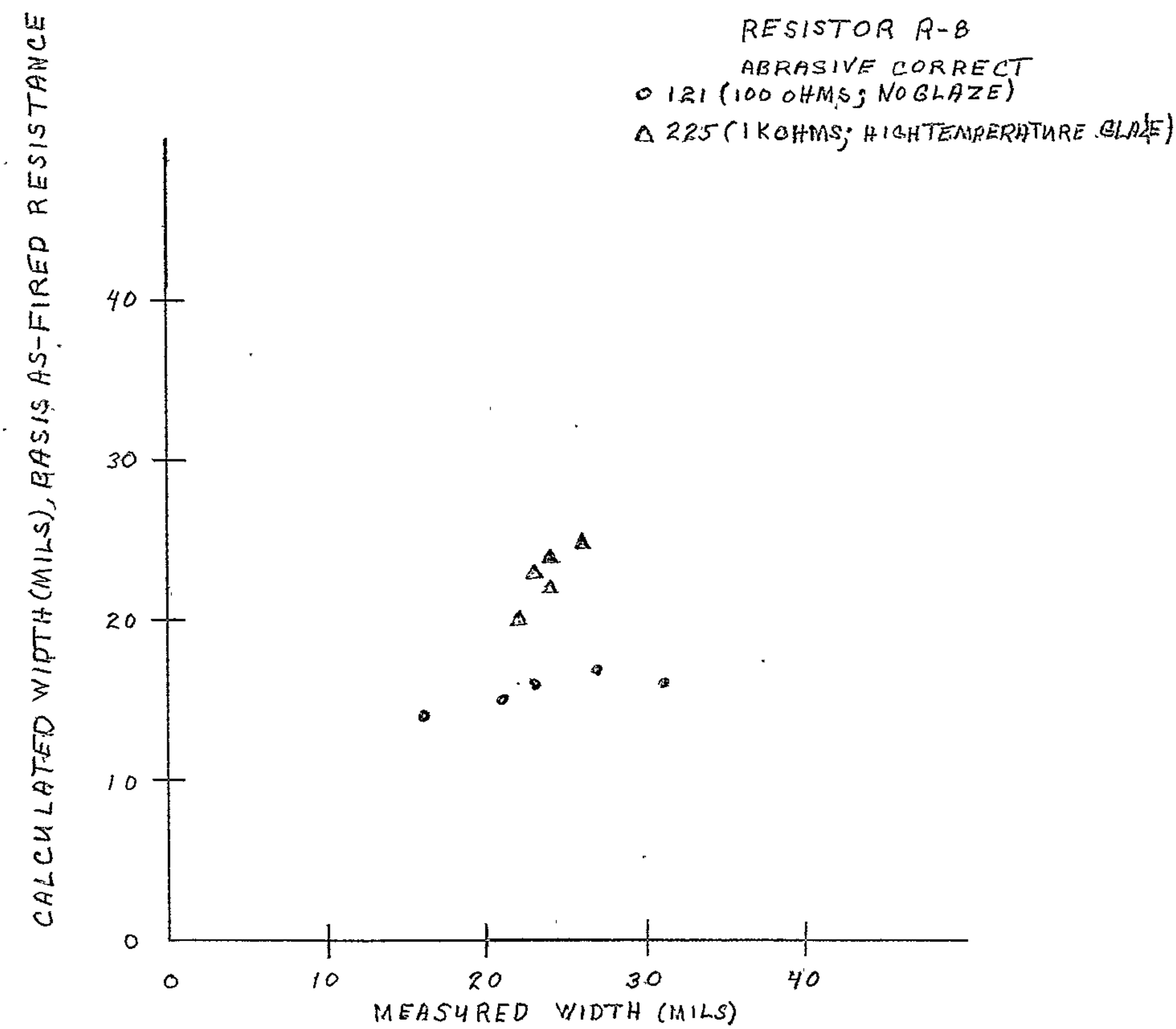

FIGURE 7: MEASURED WIDTH VERSUS CALCULATED WIDTH
ABRASIVE CORRECT, RESISTOR R8

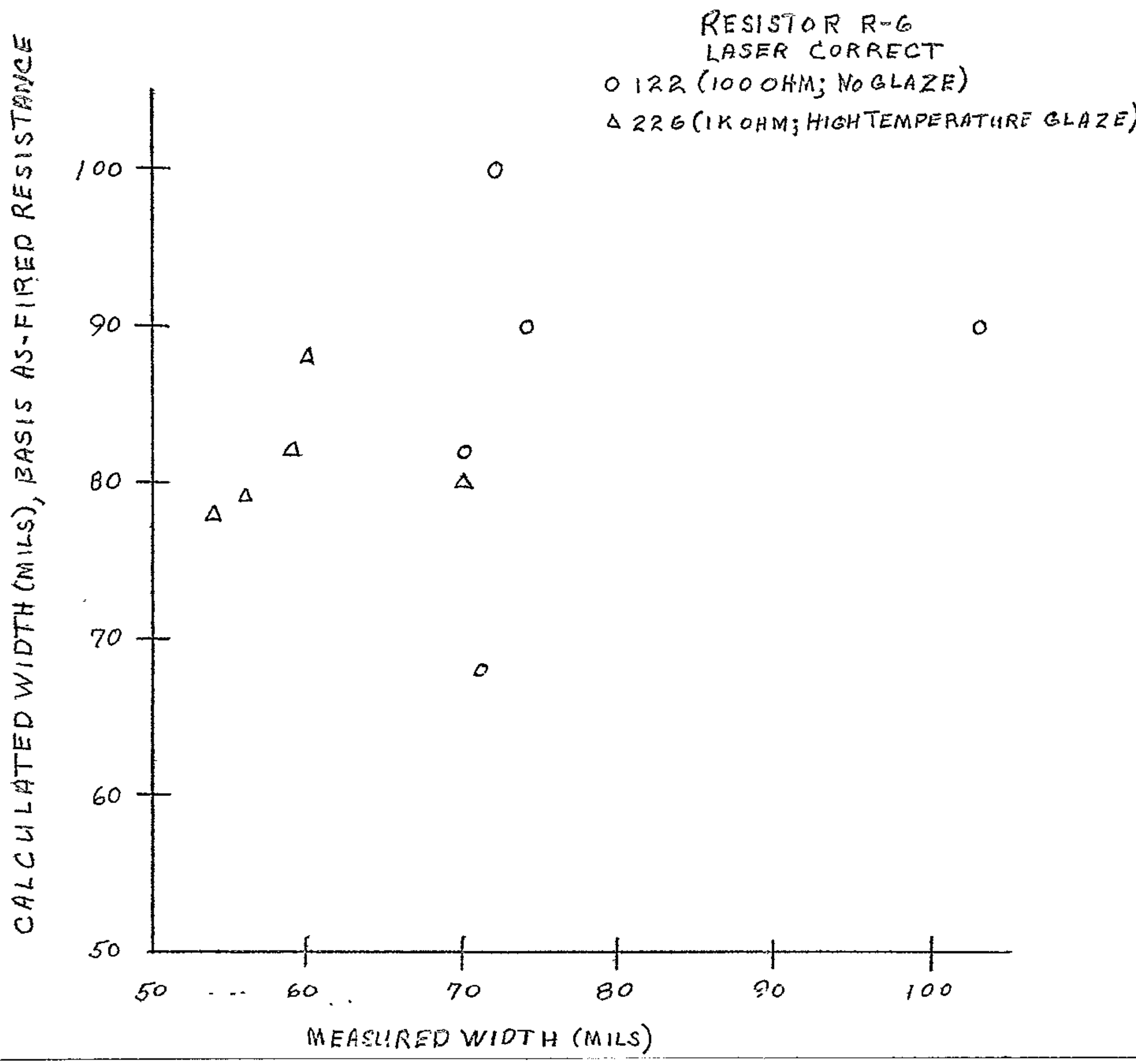

FIGURE 8: MEASURED WIDTH VERSUS CALCULATED WIDTH
LASER CORRECT, RESISTOR R6

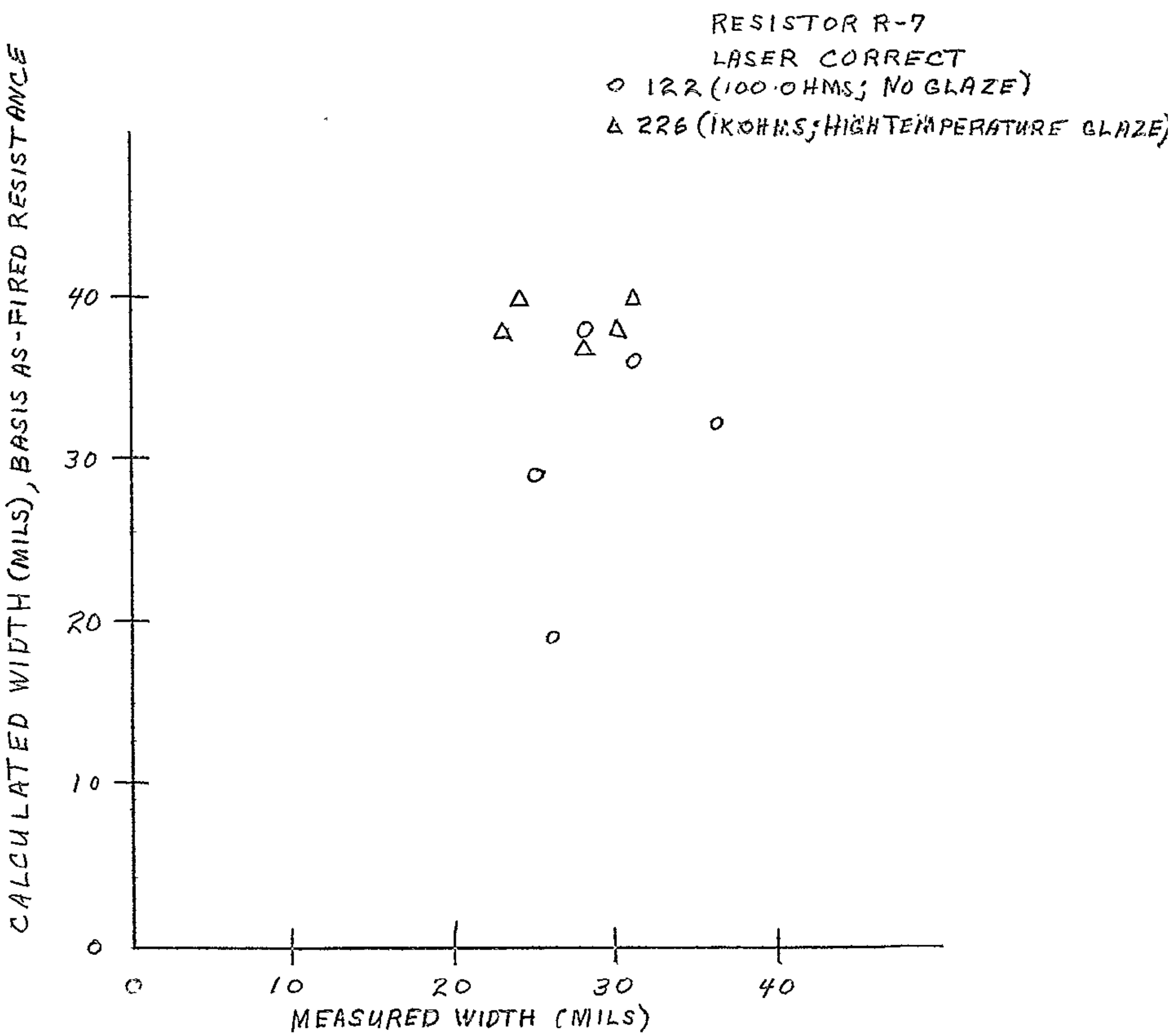

FIGURE 9: MEASURED WIDTH VERSUS CALCULATED WIDTH, LASER CORRECT, RESISTOR R7

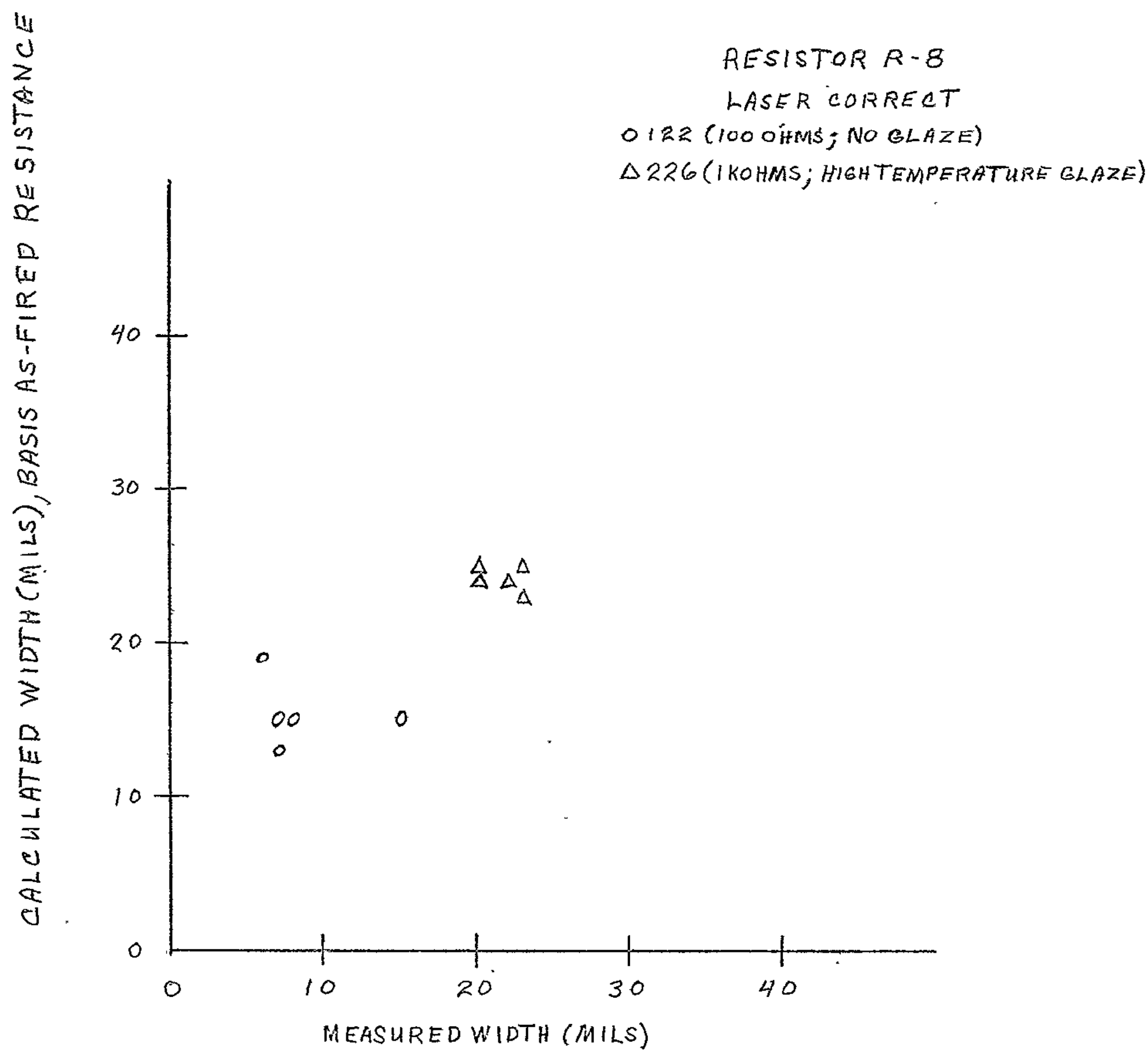

FIGURE 10: MEASURED WIDTH VERSUS CALCULATED WIDTH, LASER CORRECT, RESISTOR R8

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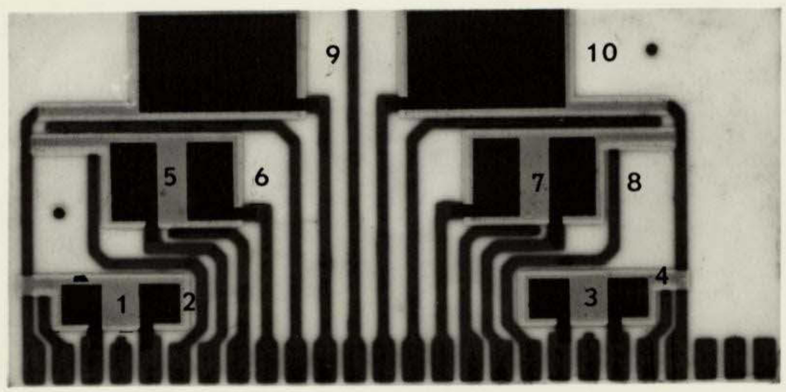


Capacitor	Length (Mils)	Width (Mils)
1, 2, 3, 4	100	100
5, 6, 7, 8	200	115
9, 10	400	250

Figure 39, Layout of Capacitor Test Pattern (Enlarged 2:1) with Capacitor Designations and Dimensions

VIII. EXHIBITS

EXHIBIT A

CALCULATED POWER DENSITY

1. Method of Calculation.

Calculated power densities were developed to afford an indication of the gross range of power densities which each set of resistors received. The basis for the calculation involves certain simplifying assumptions and is as follows:

(1) $R_1 = \frac{\rho l}{w_1 h}$ and $\rho = \frac{w_1 h R_1}{l}$

where R_1 is the as-fired resistance value, ρ is the inherent resistivity of the given resistor, l and w_1 are design length and width respectively, and h is thickness or height of resistor film. Then, where R_2 is the after-correct resistance value and w_2 is the after-correct resistor width required to produce the after-correct value R_2:

(2) $R_2 = \frac{\rho l}{w_2 h}$

or (substituting for ρ)

(3) $R_2 = \frac{w_1 h R_1}{l} \cdot \frac{l}{w_2 h} = \frac{w_1 R_1}{w_2}$

(4) $w_2 = \frac{w_1 R_1}{R_2}$

and effective area is then w_2 times effective length, i.e.

$$(5)\quad w_2 l = \frac{w_1 R_1}{R_2} \cdot l$$

But $w_1 l$ is design area (A) and therefore effective area is:

$$(6)\quad w_2 l = \frac{R_1}{R_2} A$$

and power density in watts per square inch is calculated as

$$(7)\quad W/in^2 = \frac{W}{\frac{R_1 A}{R_2}} = \frac{R_2 W}{R_1 A}$$

2. Assumptions Involved Are:

(a) before-correct resistor width assumed to be uniformly the design width

(b) effective after-correct resistor width assumed to be uniform and reduced from design width by the ratio of before-correct to after-correct resistance value

(c) effective after-correct resistor length assumed to be design value and unchanged by the correct operation

(d) resistor height (of the individual resistor) assumed to be uniform over entire area of resistor

EXHIBIT B

OUTLIERS

The nature of the data indicated that in order to avoid reporting and tabulating average results that might be misleading, at least a few erratic outlying individual ΔR values would need to be rejected before making calculations of average ΔR values. The need for a consistent, objective method of detecting such outlying observations, free from dependence upon arbitrary judgement, was clearly indicated. Therefore the W. J. Dixon test was used to detect and reject outliers. This is a standard, frequently used, quick test, often referenced in statistical texts and literature. (For a discussion of this subject with bibliography, see Grubb, Frank E., Detecting Outlying Observations in Samples, Technometrics, Vol. 11, No. 1, pp. 1-23.)

To use the test, the set of numbers containing a high (or low) value which is to be tested are arranged in order, the smallest number in the standard notation of the test is given the designation "X_1" and the largest number "X_n". Ratios are then calculated as shown below, and if the calculated ratio exceeds a certain initial value, the value in question is rejected as an outlier. (For these resistance stability data the 1% critical level was used - i.e. a number was rejected only when the probability that it should not be rejected was 1% or less.) The composition of the ratios and their 1% critical values are given below:

Ratio			n	1% Critical Value
$r_{10} =$	$\frac{X_2-X_1}{X_n-X_1}$	if smallest value is suspected	6	.698
$=$	$\frac{X_n-X_{n-1}}{X_n-X_1}$	if largest value is suspected	7	.736
$r_{11} =$	$\frac{X_2-X_1}{X_{n-1}-X_1}$	if smallest value is suspected	8	.683
$=$	$\frac{X_n-X_{n-1}}{X_n-X_2}$	if largest value is suspected		

Clearly the way the test works is to compare the difference X_n-X_{n-1} (when the largest value is suspect) with (for eight values) the difference X_n-X_2. If X_n-X_2 is large, then X_n-X_{n-1} will also have to be large for X_n to be considered an outlier. Two examples are given below. One is an example of wide differences (R4 of Composition 211) where there was a wide spread of results but no outlier was detected, and the other an example of small differences (R6 of Combination 124) where an outlier was detected and rejected.

(a) R4 - Composition 211, ordered 1000 hour ΔR values (ohms):

81, 114, 117, 152, 154, 265, 268, 465

$$R_{11} = \frac{465-268}{465-114} = 0.56 \text{ (less than .683, do not reject)}$$

(b) R6 - Combination 124, ordered 1000 hour values (ohms):

0.8, 0.8, 1.0, 1.0, 1.1, 1.1, 1.3, 2.4

$$R_{11} = \frac{2.4-1.3}{2.4-0.8} = 0.687 \text{ (greater than .683, reject)}$$

EXHIBIT C

SIGNIFICANCE TESTING

In examining the 1000 hour resistance stability data, there appeared to be a particular and definite need to be able to point to a set of data and to say "these differences can be considered real differences that are not the result of pure chance" and contrary-wise, to say "these differences cannot be considered real differences because they might well have occurred through the workings of pure chance".

The usual way of dealing with this problem is to apply the statistics of the normal distribution by calculating averages and standard deviations which then serve as estimates of the true means or standard deviations (parameters) of the populations under study. But these 1000 hour data show wide variations in averages of different resistors even within the same experimental combinations, and also wide variations in spread. For example, (Table VII) Composition 212, R2 had an average of 1.04% and a spread of 1.06% (0.74% to 1.80%) whereas R3 of the same composition had an average of 4.96% and a spread of 5.27% (2.91% to 8.18%). To have calculated averages and standard deviations from data of this type might have masked real differences and risked, with some of the data, drawing conclusions that were invalid or, at least, of questionable validity.

Consequently the decision was made to use the methods of order or non-parametric statistics (non-parametric because these methods do not require reference to the usual parameters of mean and standard deviation). The non-parametric methods used here are discussed perhaps most completely and understandably in the booklet SOME RAPID APPROXIMATE STATISTICAL PROCEDURES, Frank Wilcoxon and Roberta A. Wilson, Lederle Laboratories, Pearl River, New York.

The way order statistics work can perhaps best be illustrated by some examples. Suppose for example that each of the compositions of Table VII happened to be greatly different from every other so that, say, 214 gave for every resistor, values in the neighborhood of 0.25%, 215 in the neighborhood of 1.00% and 213, 212, and 211 in the neighborhood of 2.00%, 3.00%, and 4.00% respectively. Then if the results for each resistor were ranked from 1 to 5, 1 for lowest or best value and 5 for the highest or poorest value (the other way round, 5 for the lowest and 1 for the highest would work equally as well) then the sum of ranks (rank sum) for 214 for 13 resistors would be 13 x 1, or 13, and for 211 would be 13 x 5, or 65. Intuitively it should be clear had this clean-cut type of result occurred that, since 214 was best all of the time and 215 worst all of the time, probably the difference between 214 and 215 was a real difference and not a difference that was the result of pure chance.

Suppose, on the other hand, that there were no real differences between any of the compositions. Then if the results were ranked, 214 would be best sometimes and 215 best sometimes and the same for 211, 212, and 213 so that all compositions would come out with about the same rank sum, i.e. all would have a rank sum very close to 39. Intuitively it should be clear that had this occurred that there really could not be very much difference among any of the five compositions.

Of course results do not often come out as clearly as described in either of the two examples immediately above. Instead results are likely to come out as they actually did for the five compositions in Table VII. Composition 215 on R1 and R2 had the lowest increase of all five compositions and ranked 1 on these two resistors but Composition 214 ranked 1 on the other 11 resistors. Composition 213 had the highest increase on R12 and ranked 5 on this resistor. Composition 211 ranked 3 on this resistor although it ranked 5 on nine other resistors. What can be done about this type of result?

To deal with this type of result, tables have been prepared to show the kind of result that might be expected to occur with different frequencies or different percentages of the time when there are no real differences among the compositions or "treatments" as they are often called. For example, if there were no real differences among the five compositions of Table VII, then only 5% of the time, for 13 resistors and five compositions, would the difference between the highest and lowest rank sums be 22.0 or greater; 1% of the time the difference would be 26.2 or greater (Table V of the Wilcoxon-Wilson booklet). People who use significance tests are usually willing to run a 5% or 1 in 20 chance of being wrong although in extreme cases they may want to reduce the risk to 1% or 1 in 100. A chance of 1 in 20 may at first sight seem rather a large risk, but 19:1 odds are pretty big odds in a horse race, and an executive has recently been defined as "a man who makes decisions promptly and is sometimes right."

How this method works can be shown by using the data from Table VII. Rank sums were 15, 25, 42, 55, and 58. Reversing the order, rearranging and calculating all possible differences in scores between pairs of compositions we get the following:

		211	212	213	215	214
		58	55	42	25	15
211	58					
212	55	3				
213	42	16	13			
215	25	33**	30**	17		
214	15	43**	40**	27**	10	

It is quite clear from the above table that Compositions 211 and 212 with rank sums of 58 and 55 respectively and a difference between rank sums of 3 are probably very much alike in performance. The rank sum (42) of Composition 213 differs from the rank sum of Composition 211 (58) by 13.

There may be a real difference in performance between 213 and 211, but the difference in rank sums is not 22 or less, therefore one cannot say on the basis of this amount of evidence that the difference between 211 and 213 is significant at the 5% probability level.

The rank sum of Composition 214, however, differs from the rank sums of Compositions 211, 212, and 213 by 43, 40, and 27 respectively. Since for 13 resistors and five compositions (Table V of the Wilcoxon-Wilson booklet) a difference in rank sums equal to or greater than 26.2 would occur only once in a hundred times we conclude at the 1% probability level that the 214 is significantly different from 211, 212, and 213 (very much less than 1% for the 211, 212 differences of 43 and 40). The differences which are greater than 26.2 are given a double asterisk to show that they are significant at the 1% level (a single star would show significance at the 5% level).

One argument that might be raised against use of this method is that it makes no allowance for very small differences, i.e. 0.96%, 0.97%, 0.98%, 0.99%, and 1.00% would be scored 1, 2, 3, 4, 5 in no way differently from 1.00%, 3.00%, 5.00%, 7.00%, and 9.00%. To this argument there are two reassuring answers: (1) most of the differences found in these data are quite large; and (2) if the small differences were not real differences one composition would be best on one resistor and another best on another resistor etc., and the rank sums would come out about even with no significant differences shown, or, if there were real but very small differences among the five compositions and the data were capable of showing the differences, the rank sums would also show the differences in performance.

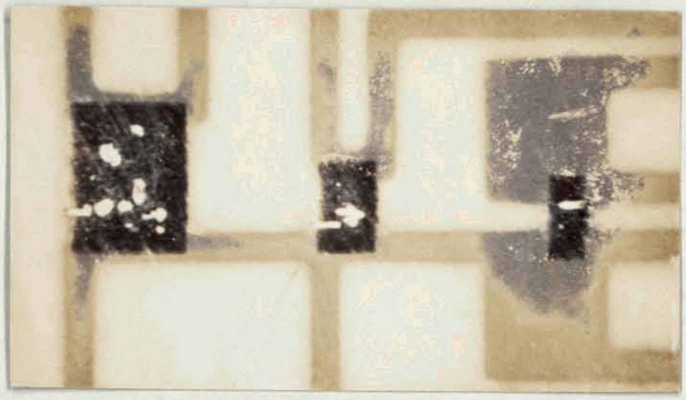
EXHIBIT D

COMPOSITION CODES

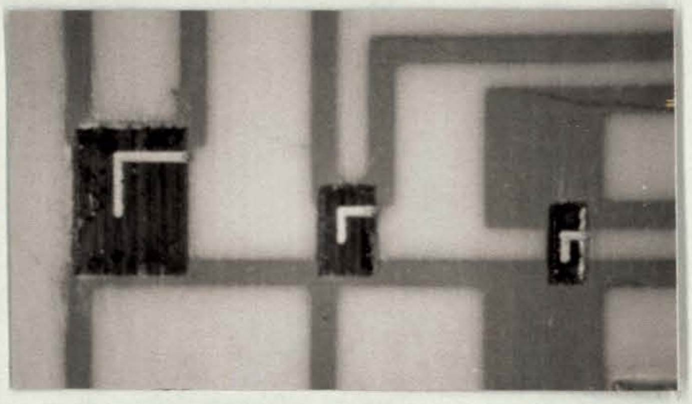
	Composition Code Number	Composition
A. Resistors*	211	Alloys Unlimited, R-13A
	212	Blend-ohm Methode 44R102
	213	Bournes Incorporated
	214	Dupont Birox DP1031
	215	Dupont 8000 series blended in-house to produce appropriate resistivities
B. Capacitors	1	Microtek Composition 6
	2	Owens-Illinois Capacitor Dielectric 06275-S
	3	Owens-Illinois Capacitor Dielectric 06220-S
	4	Owens-Illinois Insulating Dielectric 06201-S
	5	Composition 2 silver doped at Microtek
C. Conductors	1	Owens-Illinois Pd/Au 06140-S
	2	Engelhard A-1927
	3	Bourne CC-6000
	4	Dupont EX8451

*Compositions 211, 212, 213, 214 screened at 1K per square only; 215 screened at 100, 1K and 10K per square with overglaze as noted in body of report.

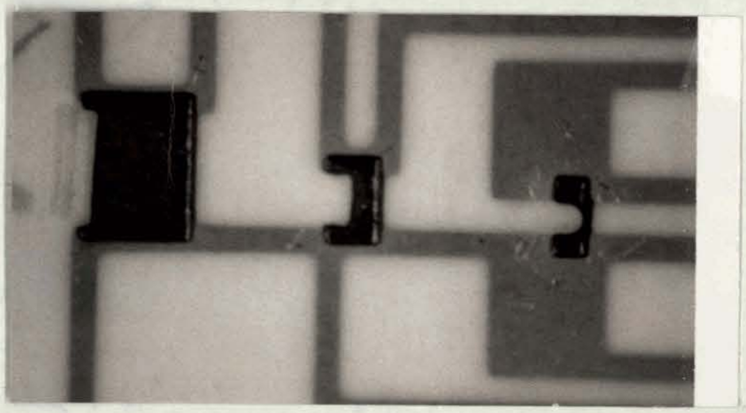
Resistor: R6 R7 R8



Laser Correct - Uni-Directional Cross-Resistor Cut



Laser Correct - Right Angle Cut



Abrasive Correct

FIGURE 10A: PHOTOMICROGRAPHS SHOWING CROSS-RESISTOR LASER CORRECT RIGHT-ANGLE LASER CORRECT AND ABRASIVE CORRECT, R6, R7, R8. (LASER CORRECT SAMPLES RUBBED WITH TITANIUM DIOXIDE PASTE TO OBTAIN CONTRAST.)

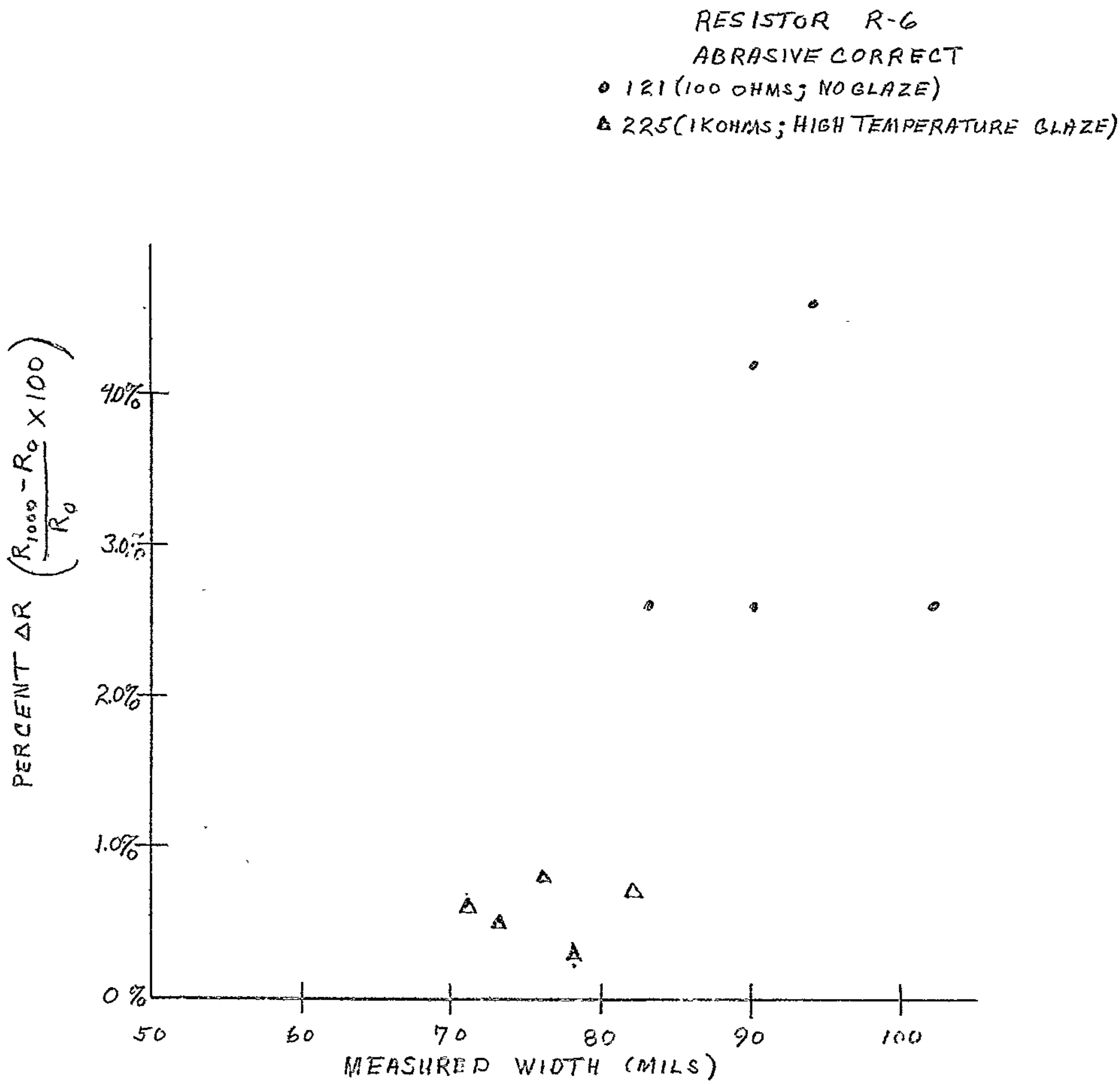


FIGURE 11: PERCENT CHANGE IN RESISTANCE AT 1000 HOURS ON LOAD VERSUS MEASURED RESISTOR WIDTH, ABRASIVE CORRECT, RESISTOR R6

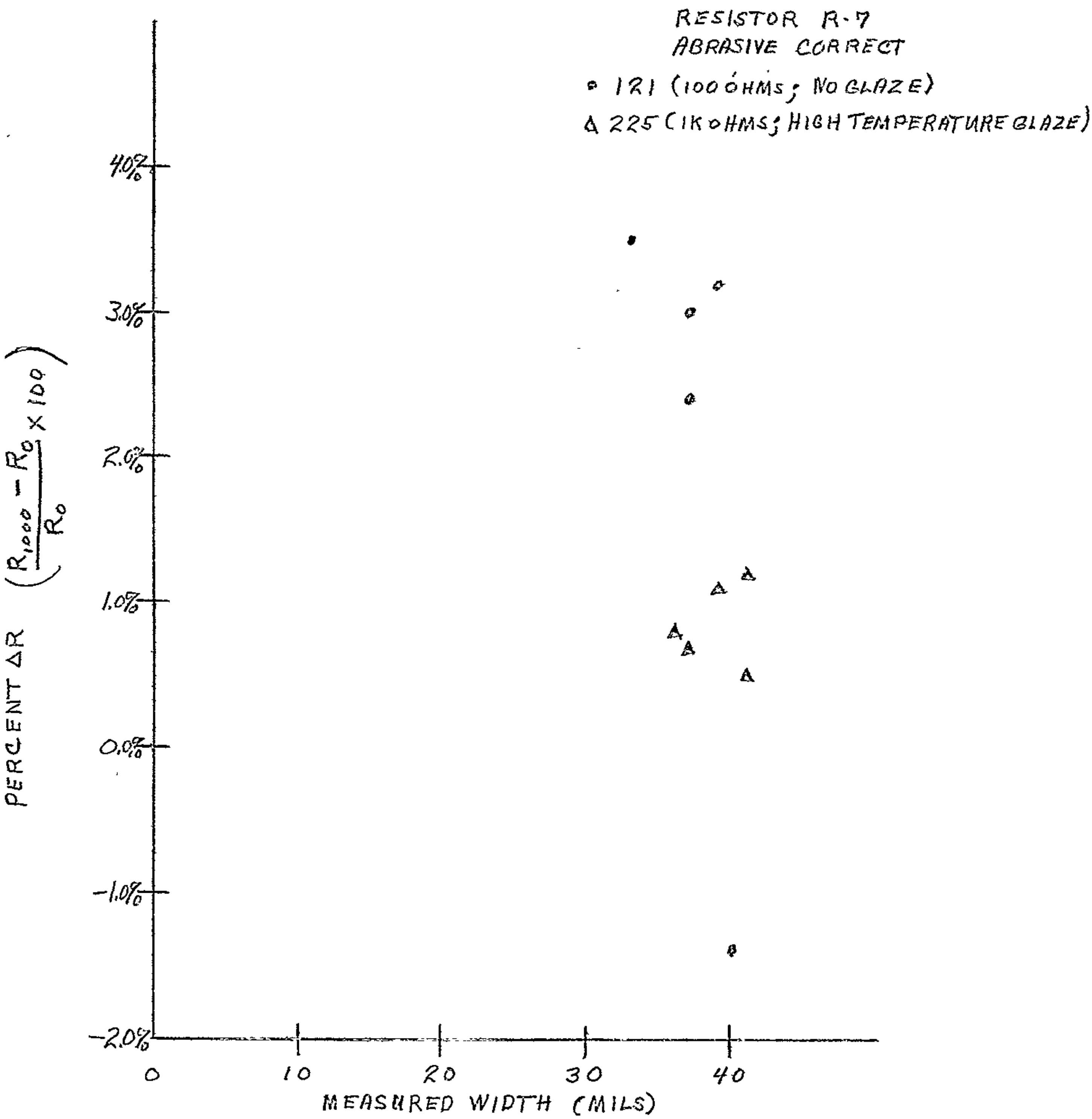


FIGURE 12: PERCENT CHANGE IN RESISTANCE AT 1000 HOURS ON LOAD VERSUS MEASURED RESISTOR WIDTH, ABRASIVE CORRECT, RESISTOR R7

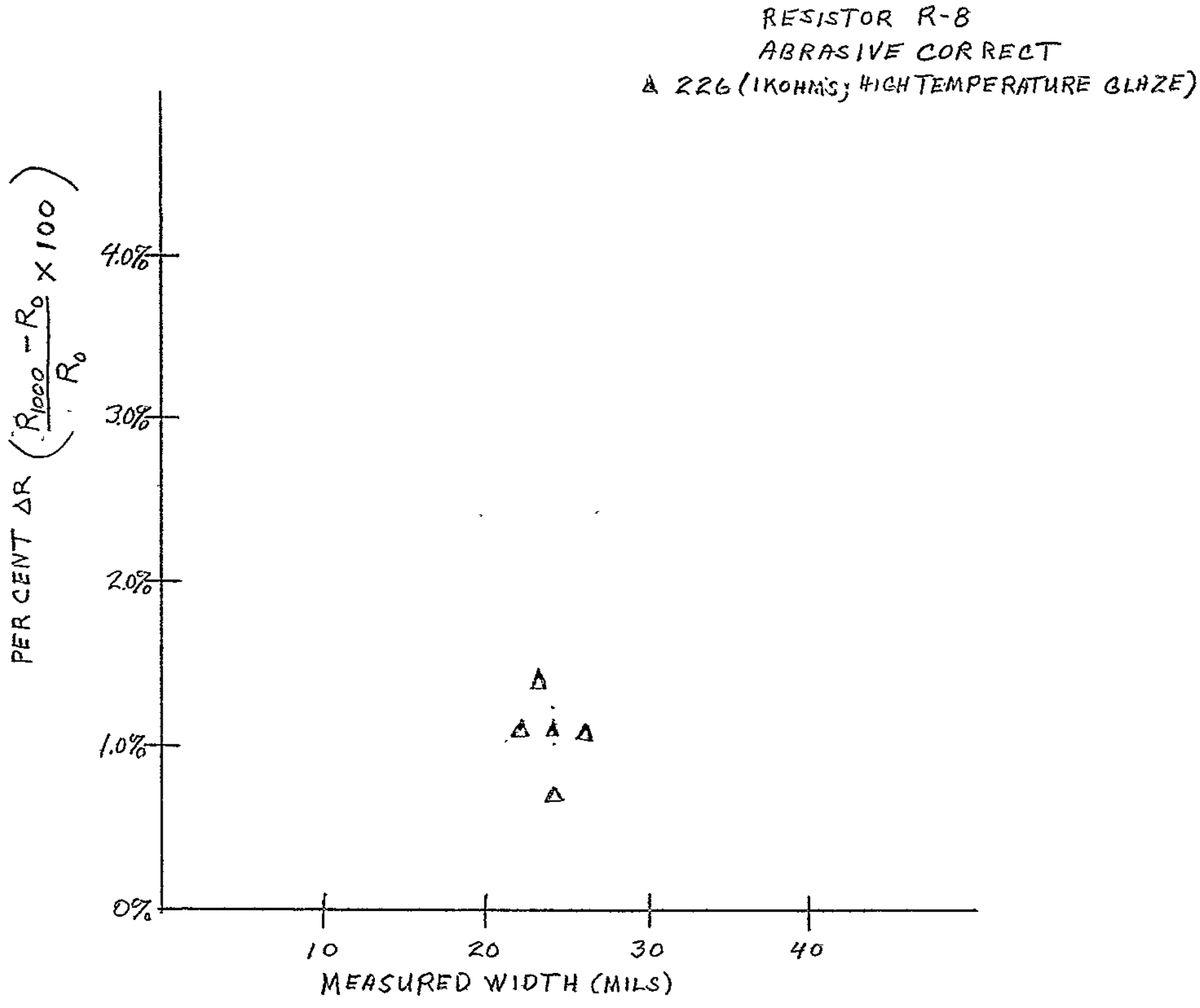


FIGURE 13: PERCENT CHANGE IN RESISTANCE AT 1000 HOURS ON LOAD VERSUS MEASURED RESISTOR WIDTH, ABRASIVE CORRECT, RESISTOR R8

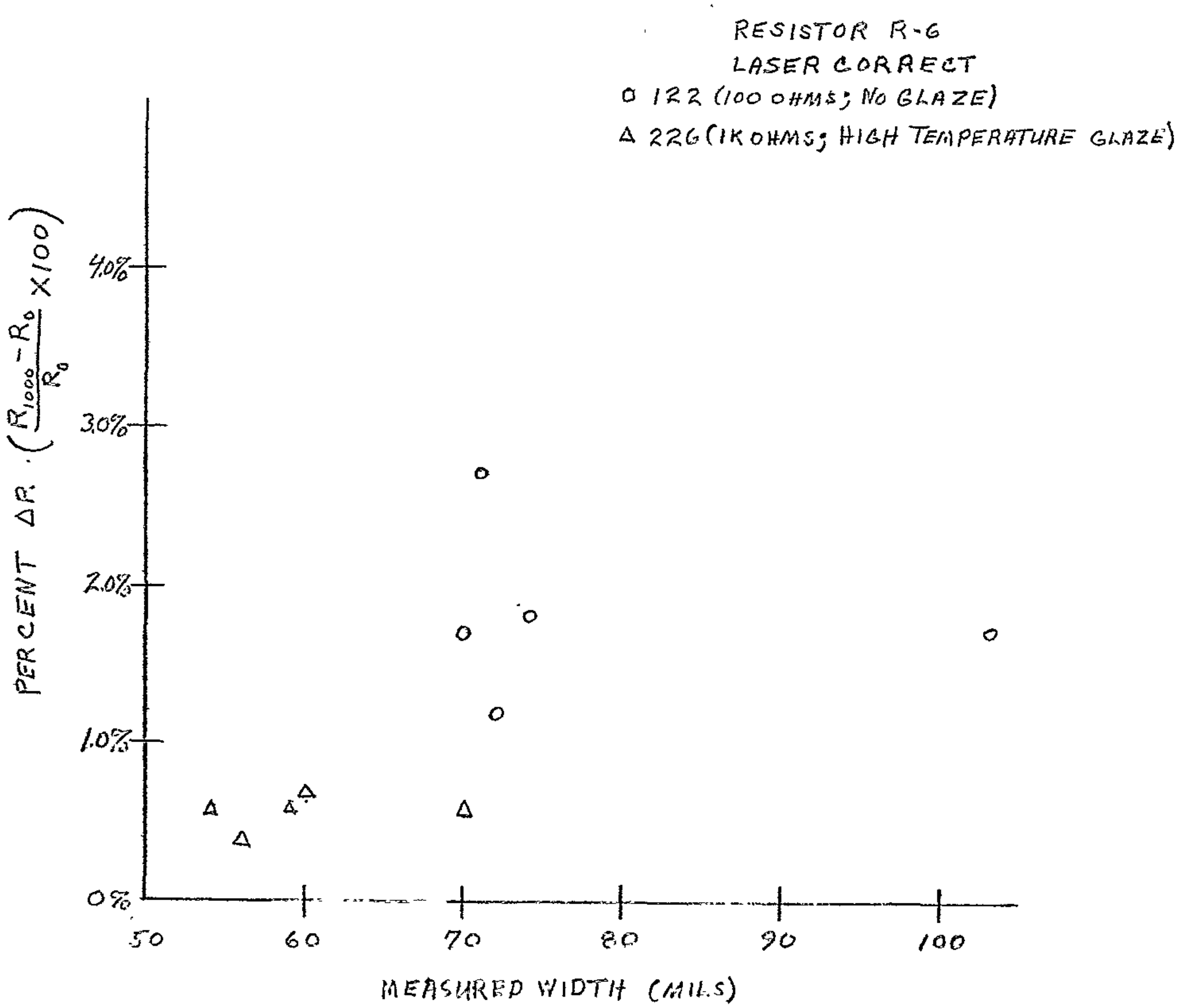


FIGURE 14: PERCENT CHANGE IN RESISTANCE AT 1000 HOURS ON LOAD VERSUS MEASURED RESISTOR WIDTH, LASER CORRECT, RESISTOR R6

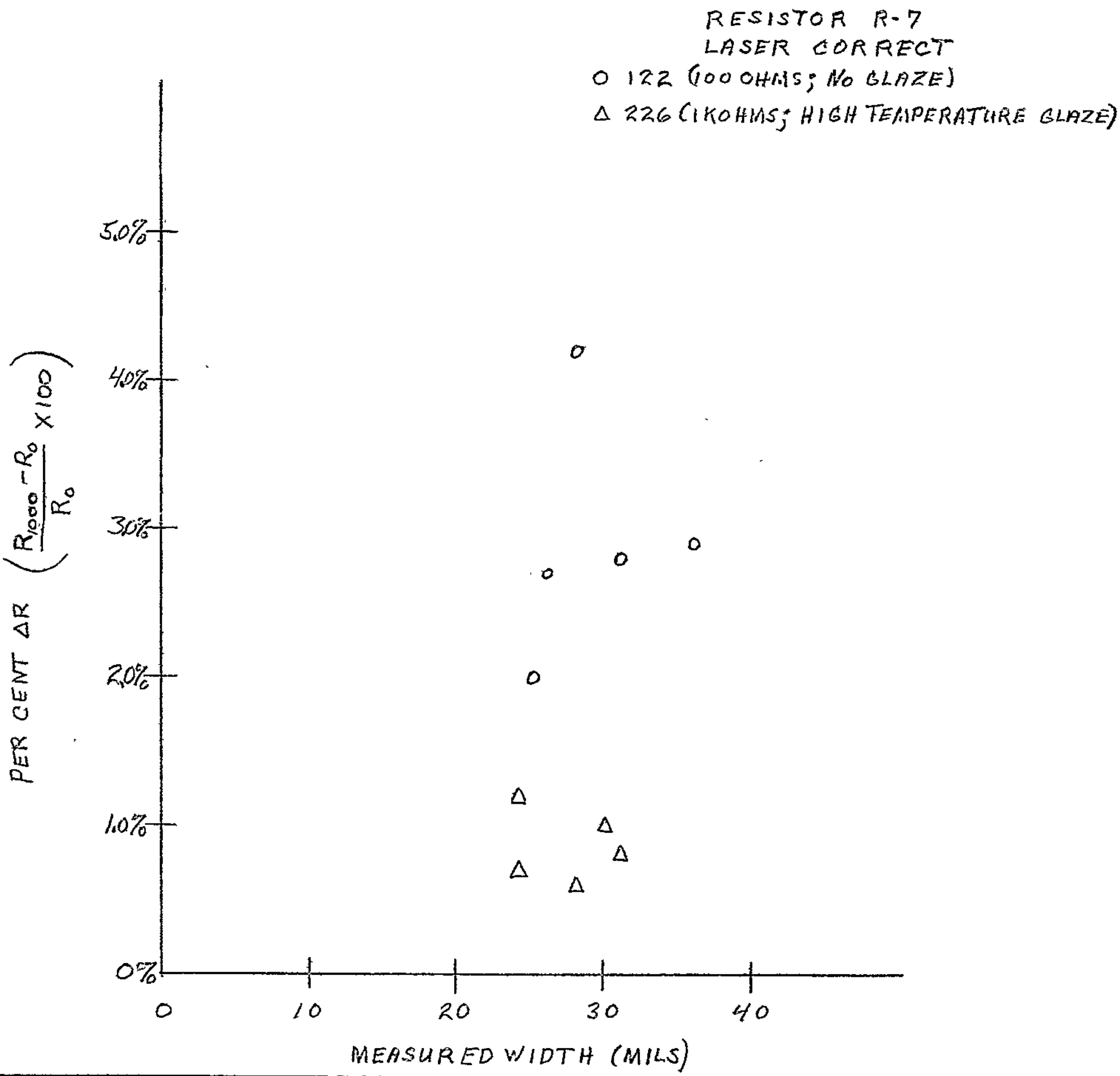


FIGURE 15: PERCENT CHANGE IN RESISTANCE AT 1000 HOURS ON LOAD VERSUS MEASURED RESISTOR WIDTH, LASER CORRECT, RESISTOR R7

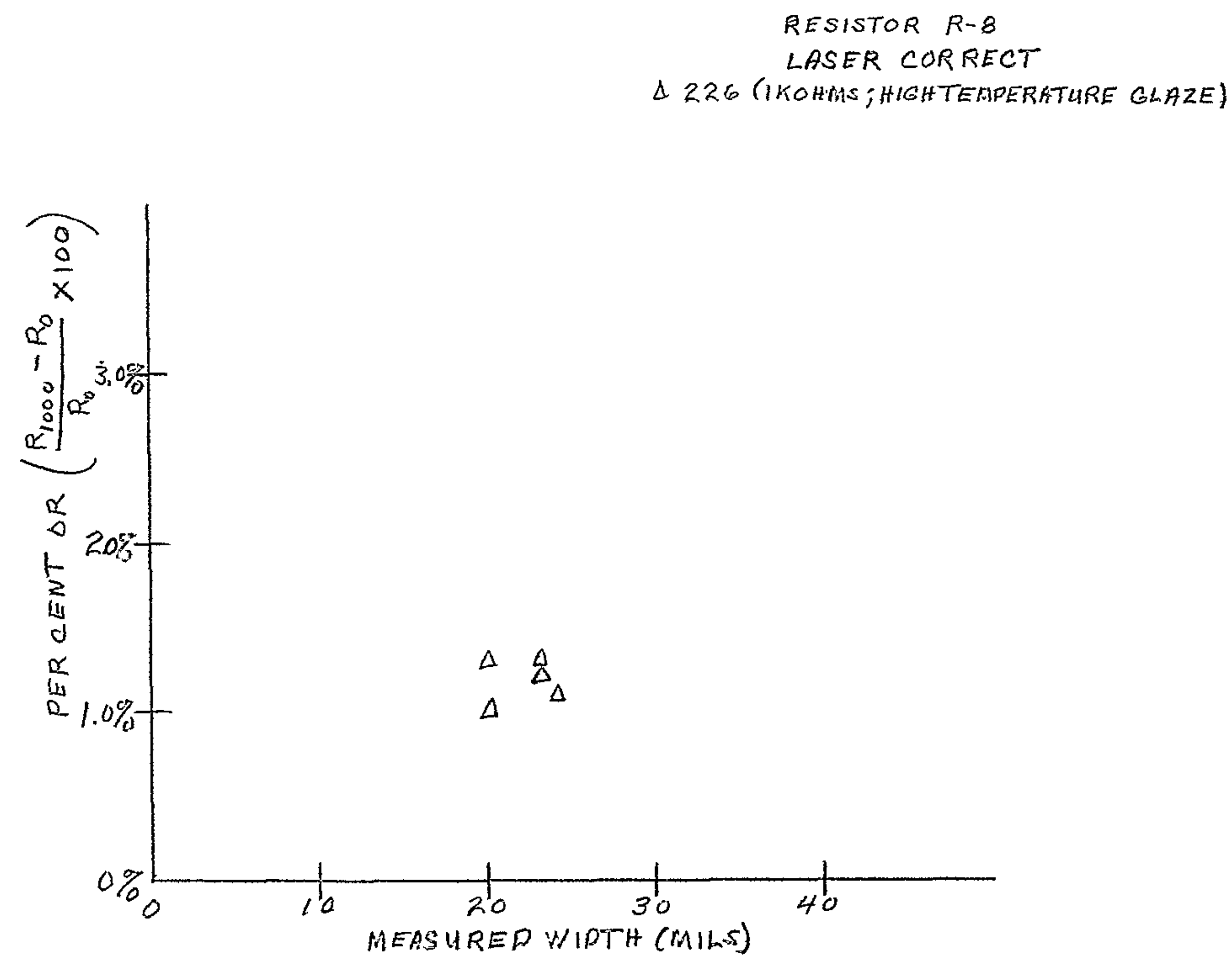


FIGURE 16: PERCENT CHANGE IN RESISTANCE AT 1000 HOURS ON LOAD VERSUS MEASURED RESISTOR WIDTH, LASER CORRECT, RESISTOR R8

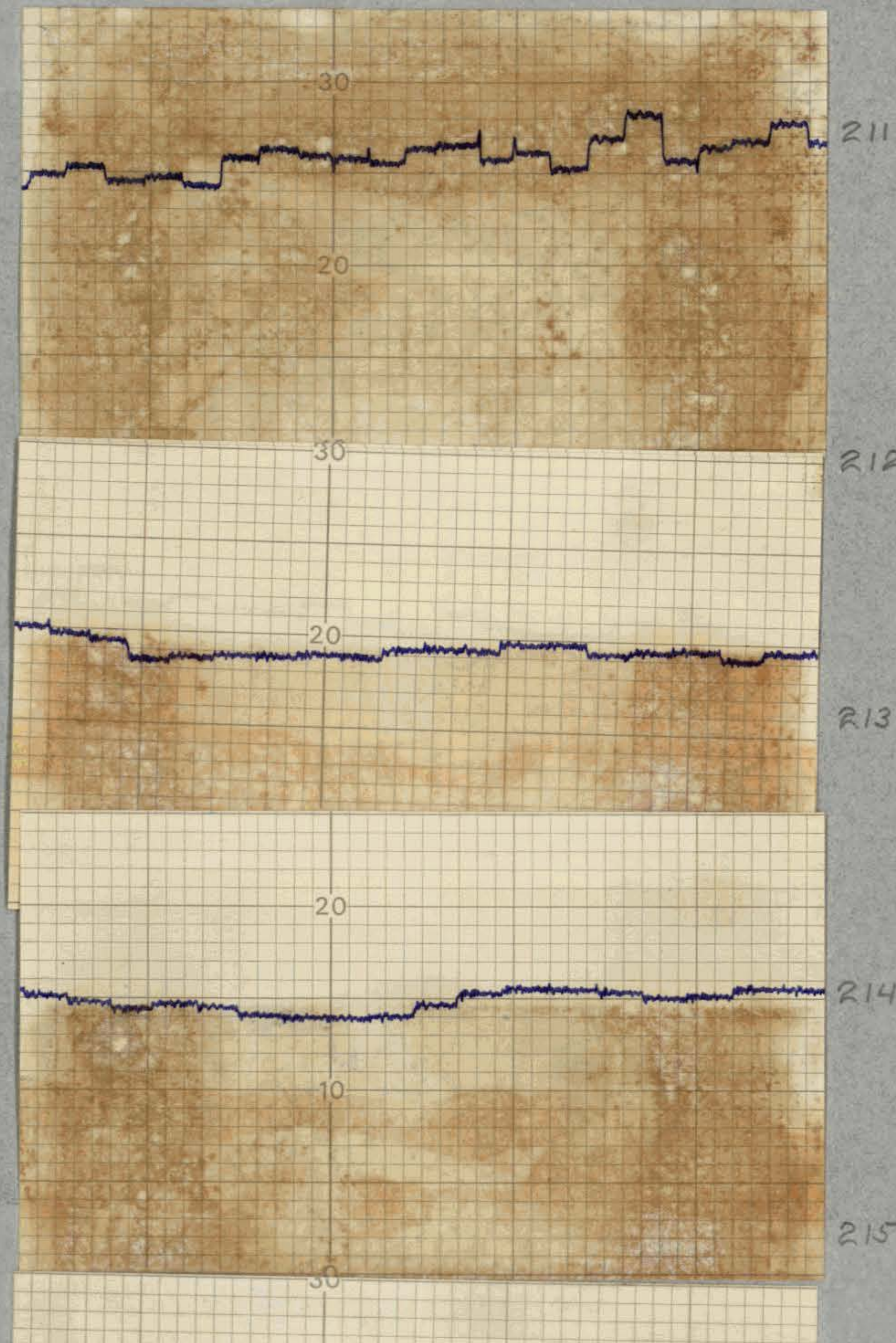
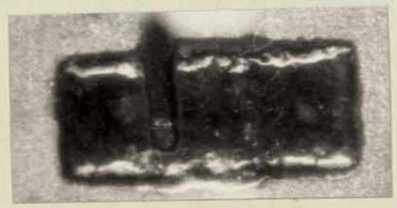
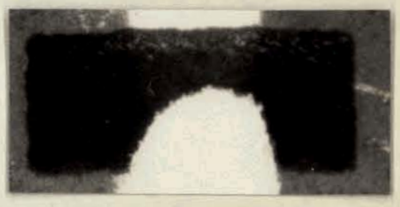


FIGURE 17: SAMP
OF F
10 MICROINCHES)

122-06 (ΔR = 932%)



126-06 (ΔR = 3038%)



221-08 (ΔR = 6.6%)

222-07 (ΔR = 6.5%)

225-06 (ΔR = 1.14%)

226-04 (ΔR = 1.07%)

325-03 (ΔR = 0.24%)

326-08 (ΔR = 0.56%)

FIGURE 17A. SAMPLE PHOTOMICROGRAPHS OF THE SMALLEST ONE-SQUARE RESISTOR (R8 OR R12) AFTER 1000 HOURS LOADING AT 125°C (ΔR VALUES NOTED).

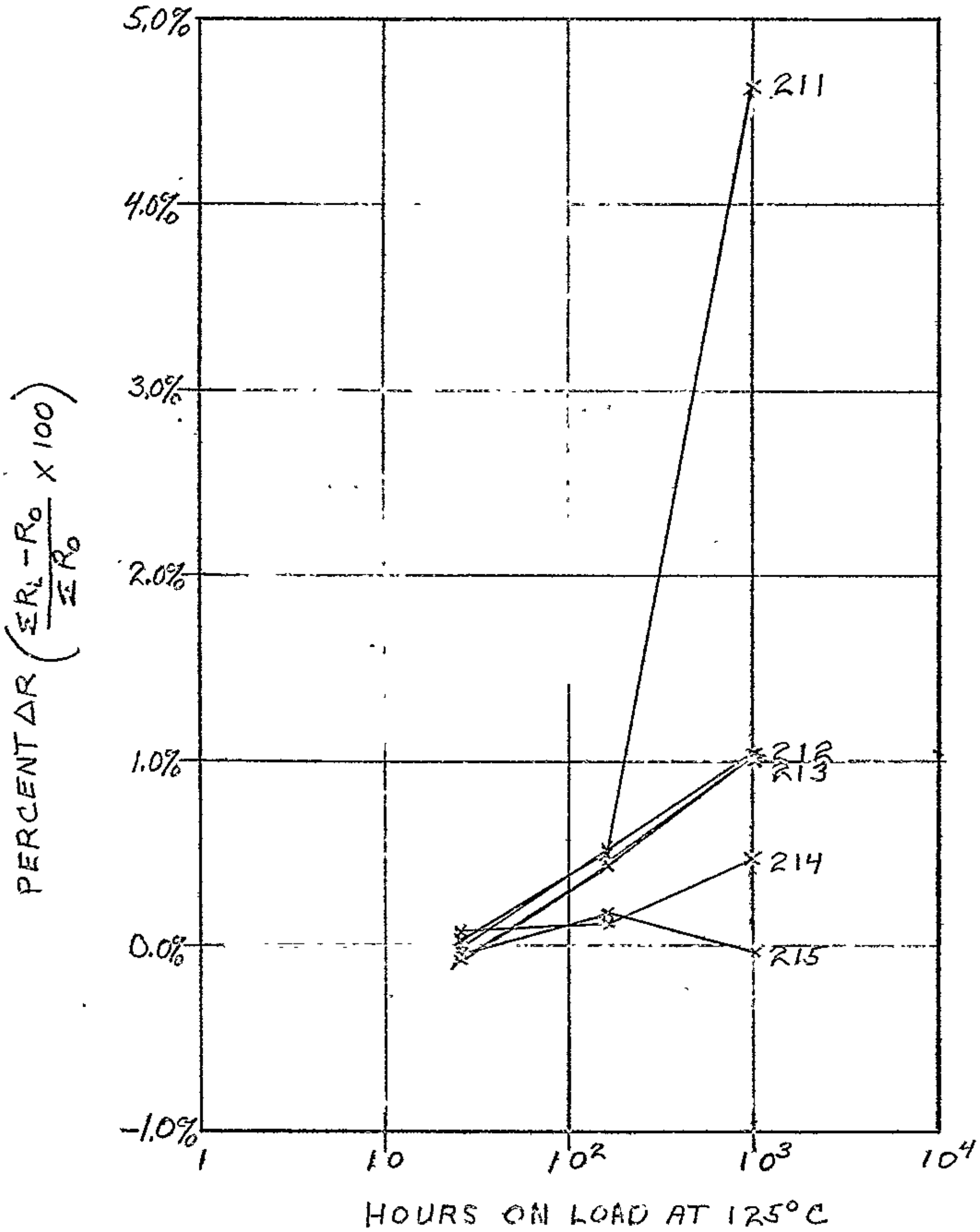


FIGURE 18: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R2

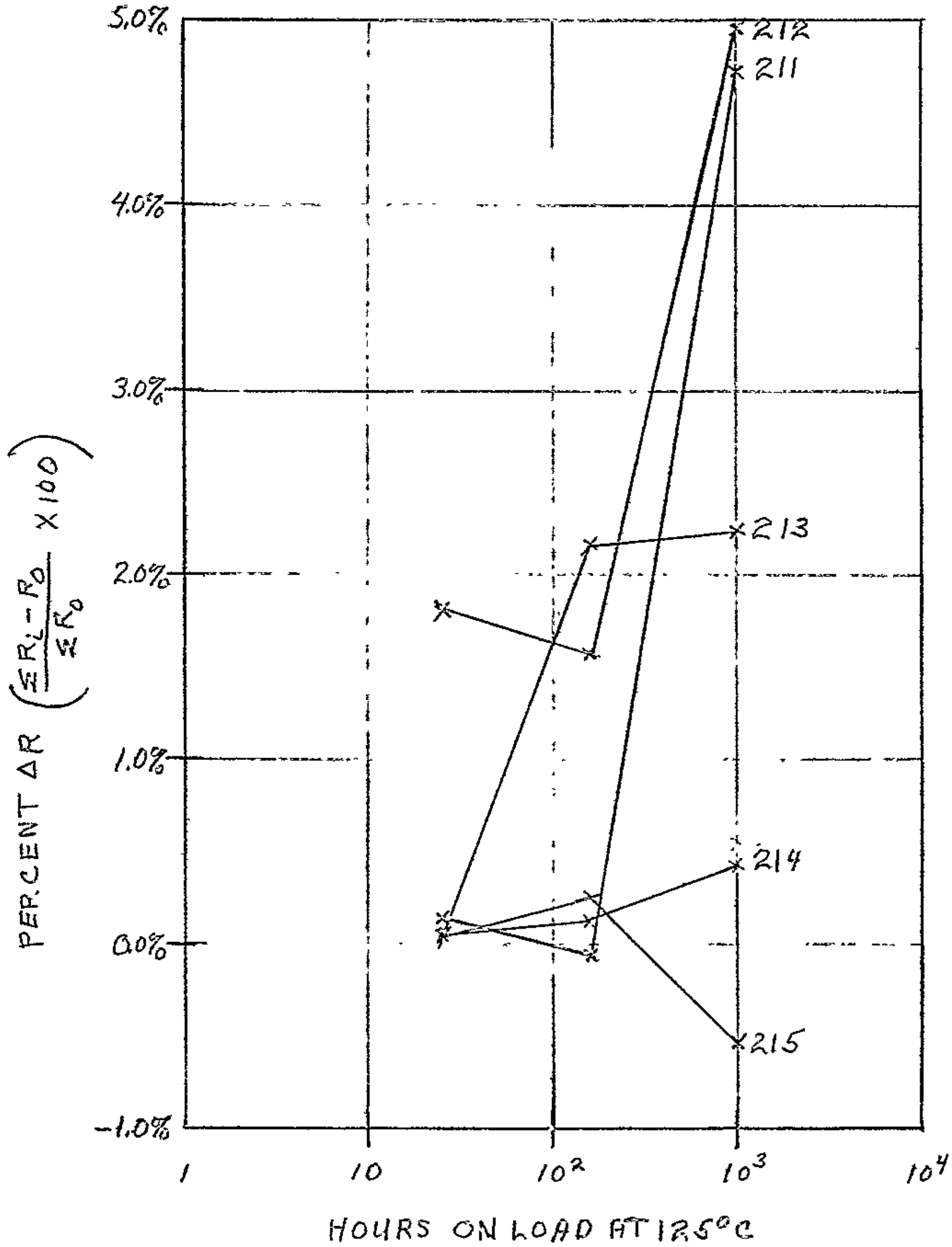


FIGURE 19: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R3

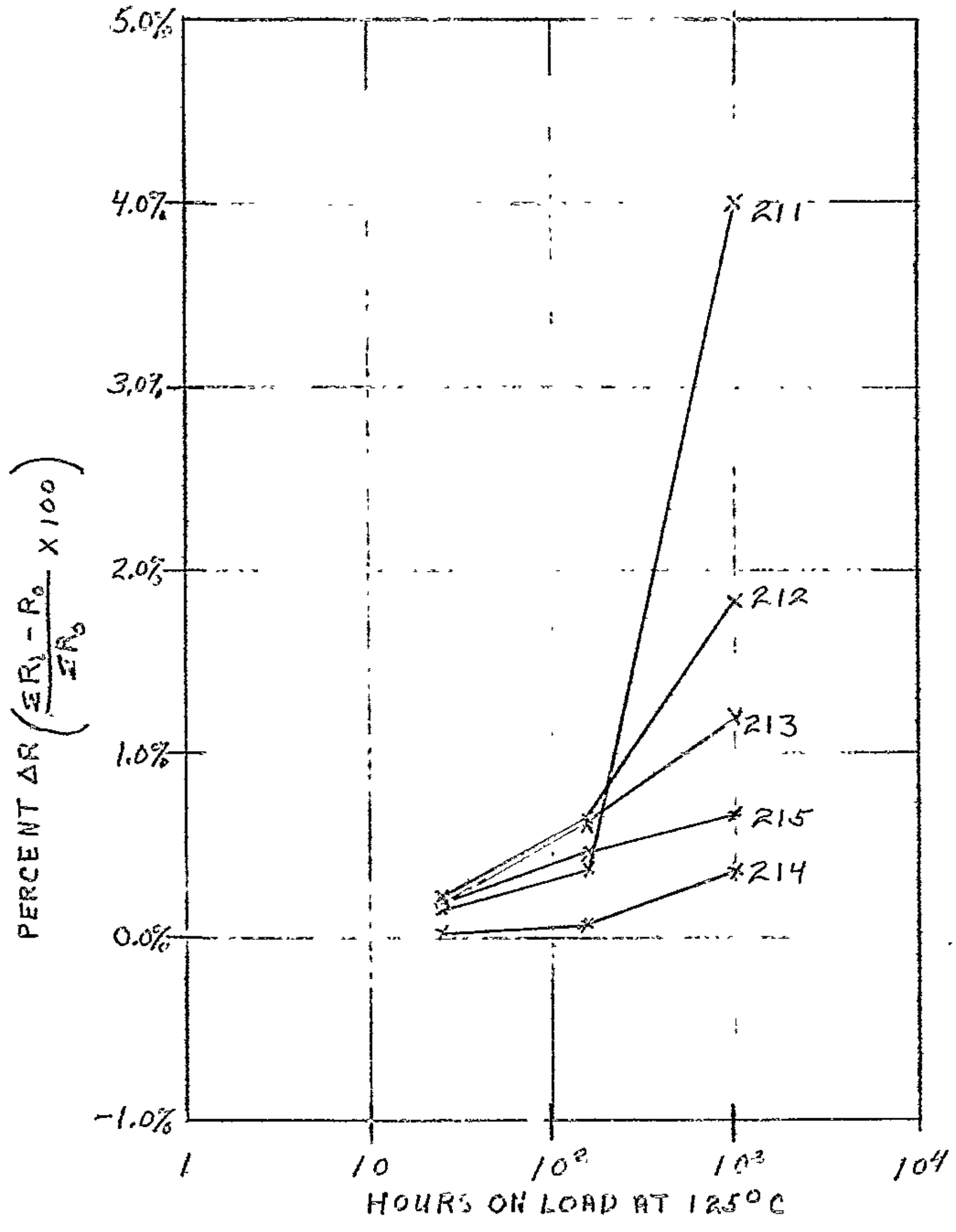


FIGURE 20: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R4

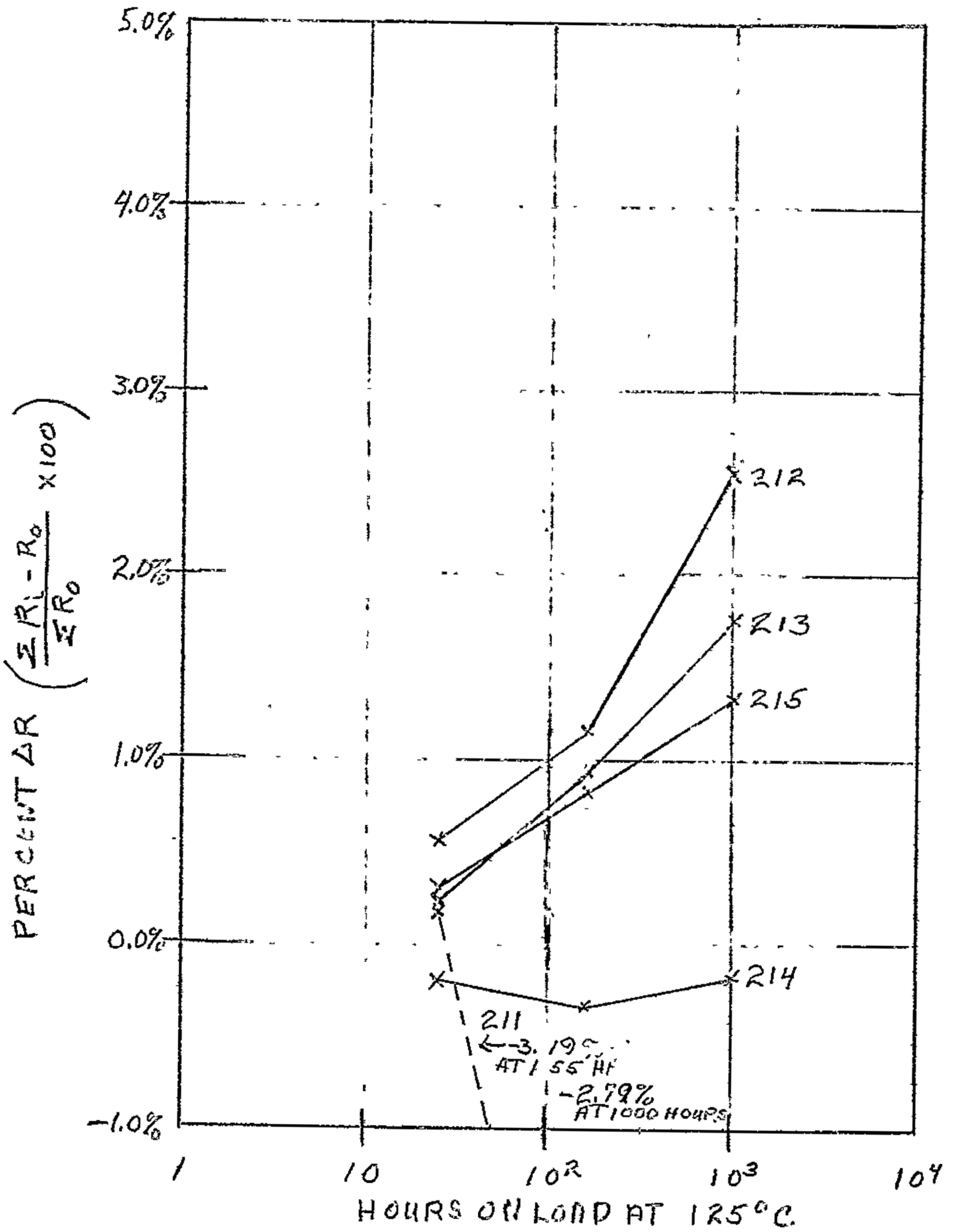


FIGURE 21: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R5

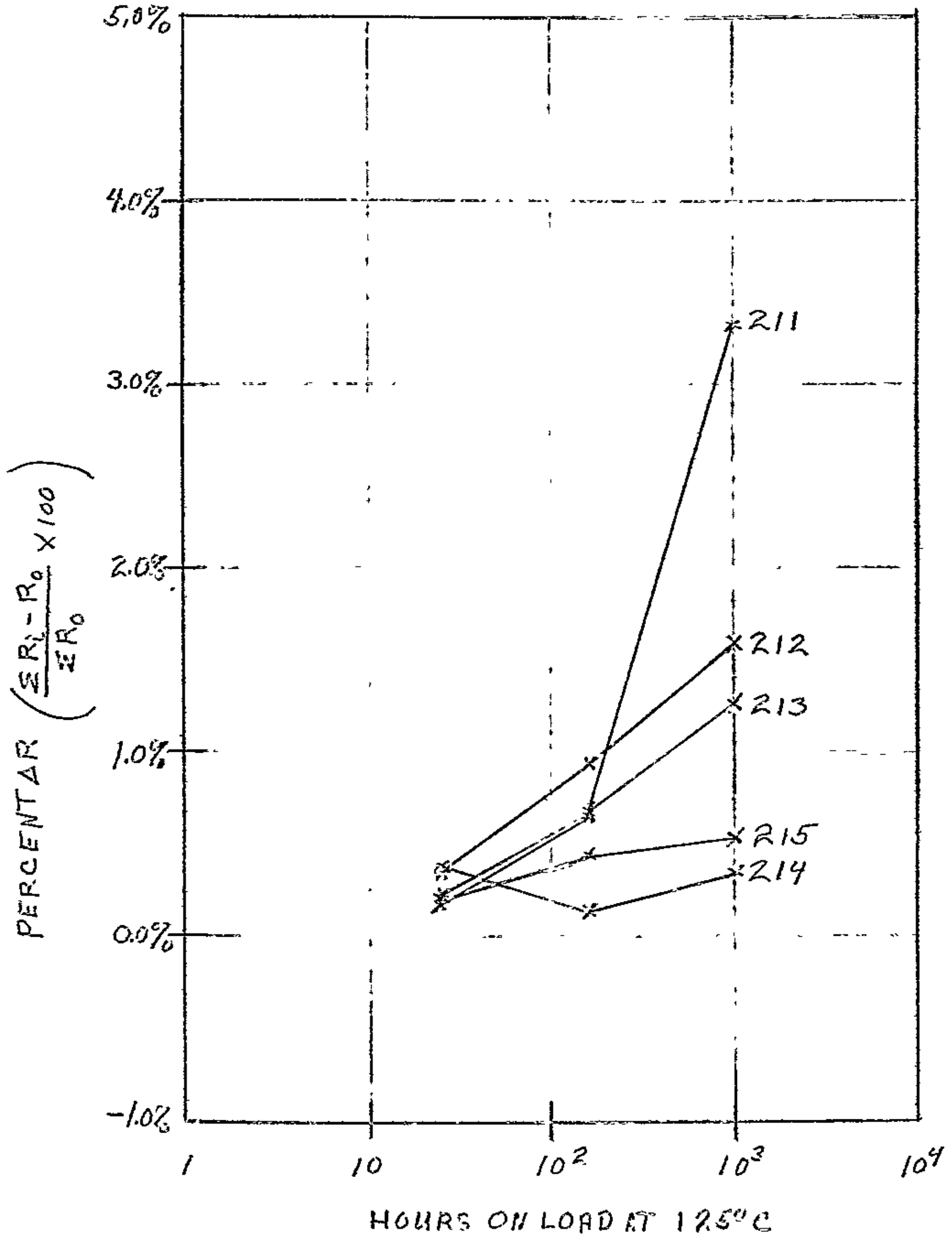


FIGURE 22: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R6

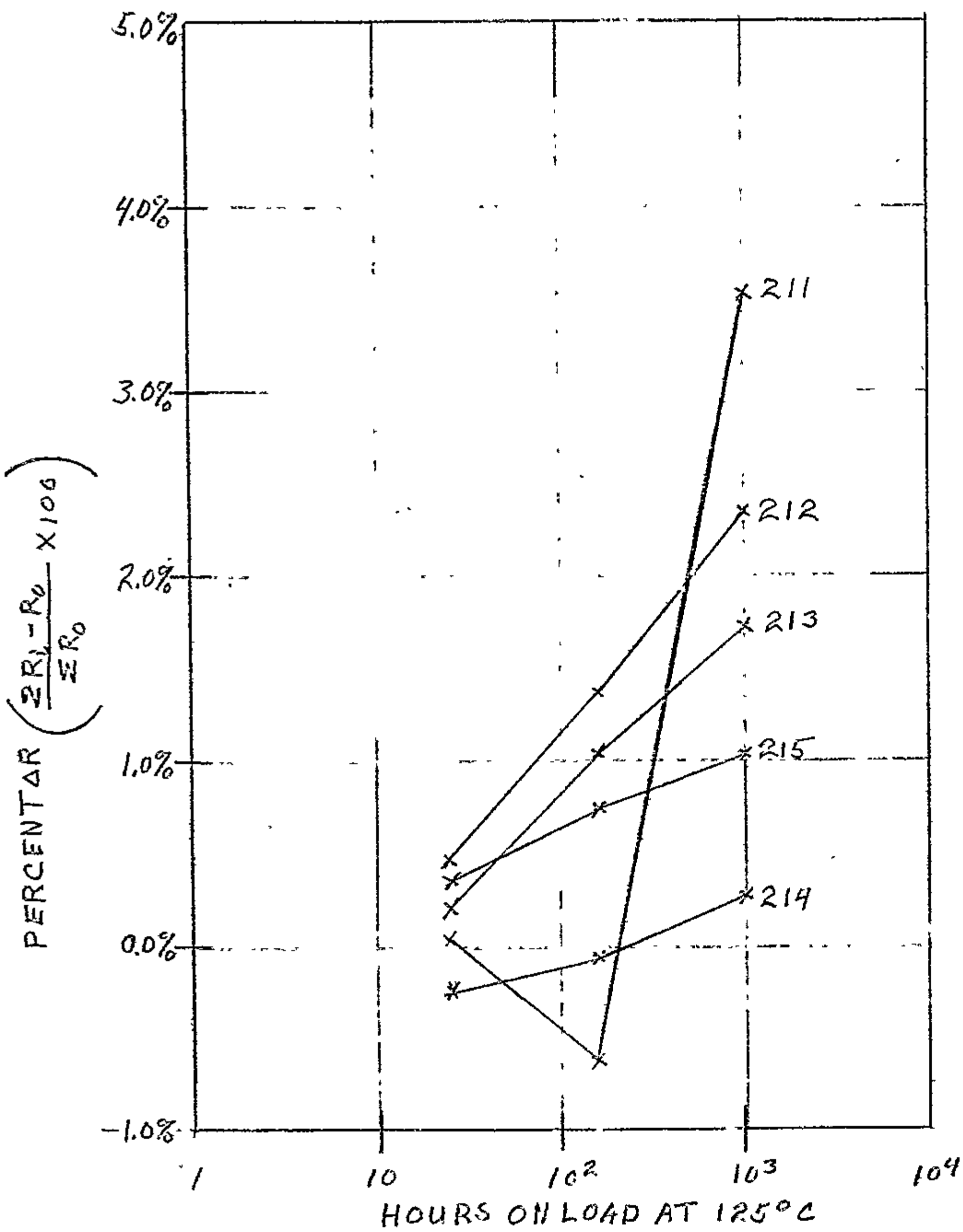


FIGURE 23: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R7

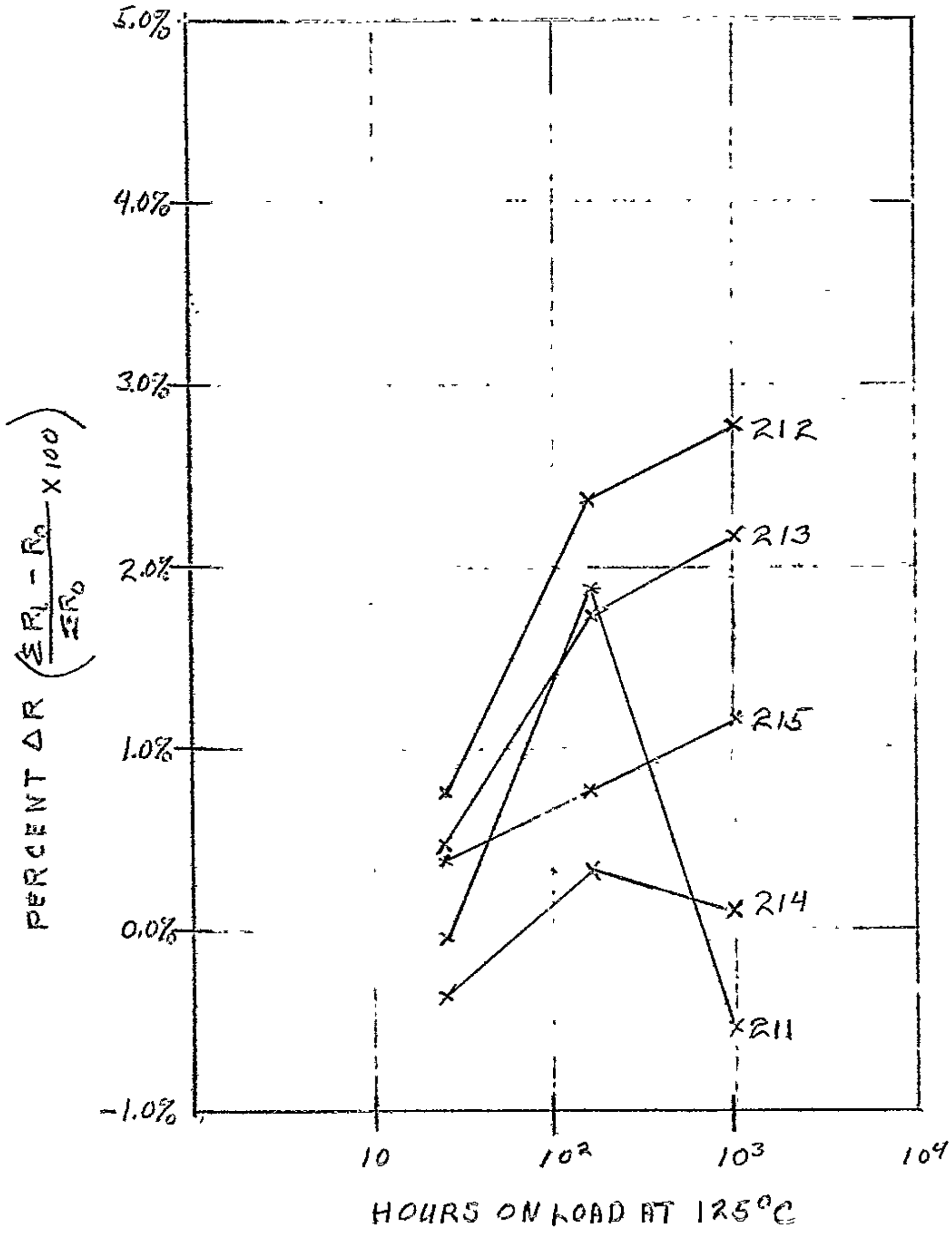


FIGURE 24: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R8

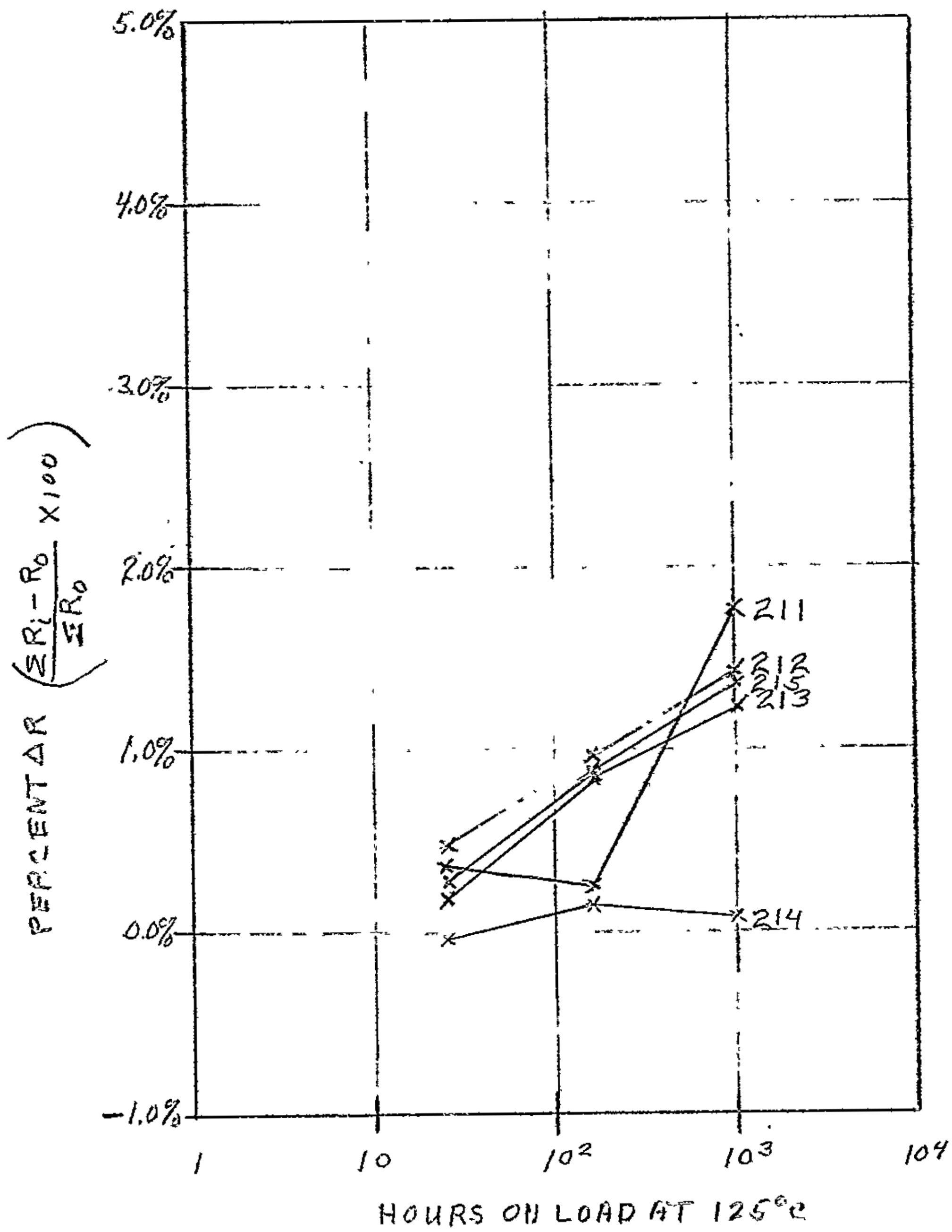


FIGURE 25: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMPOSITIONS 211-215, RESISTOR R9

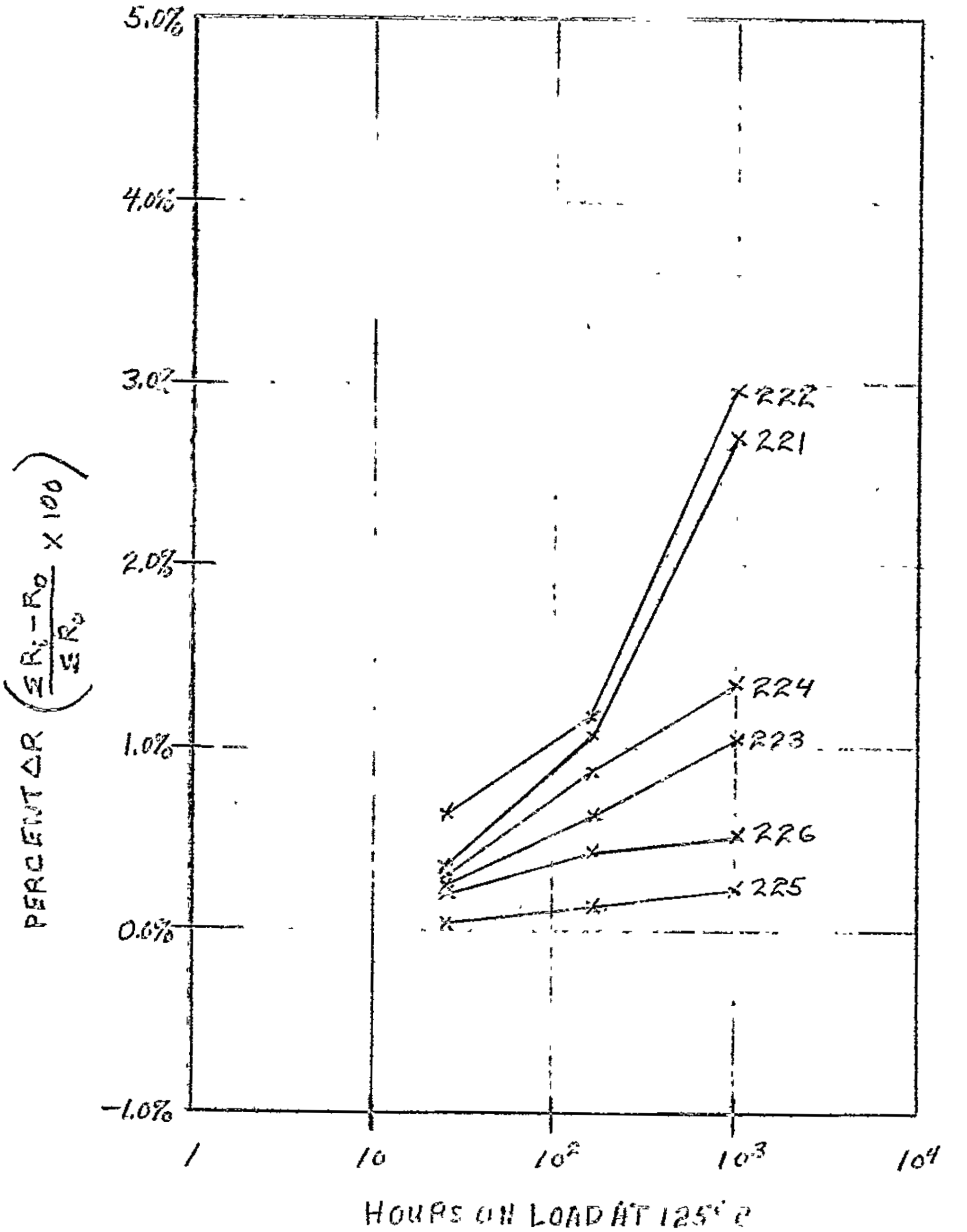


FIGURE 26: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 221-226, RESISTOR R2

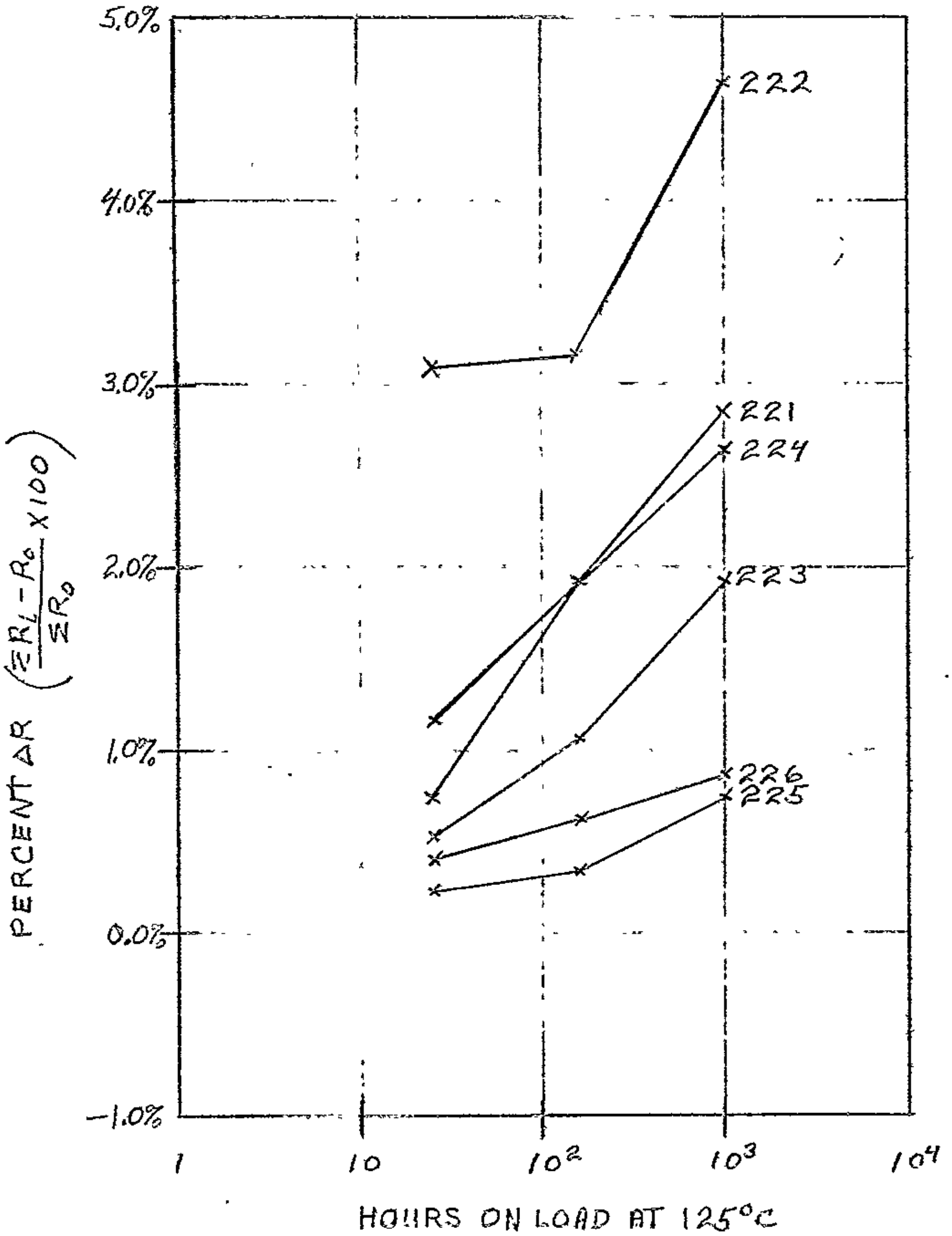


FIGURE 27: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 221-226, RESISTOR R3

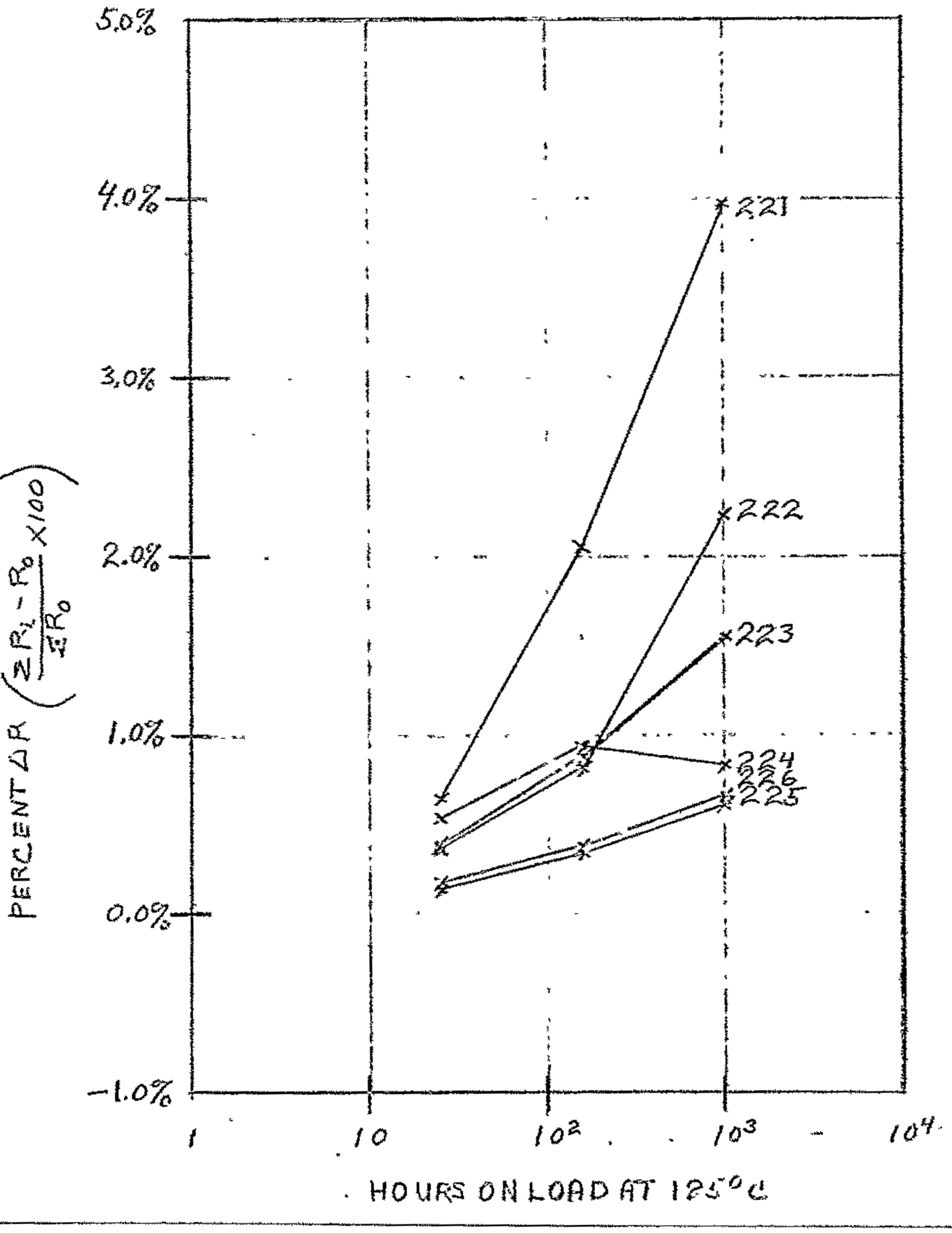


FIGURE 28: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 221-226, RESISTOR R4

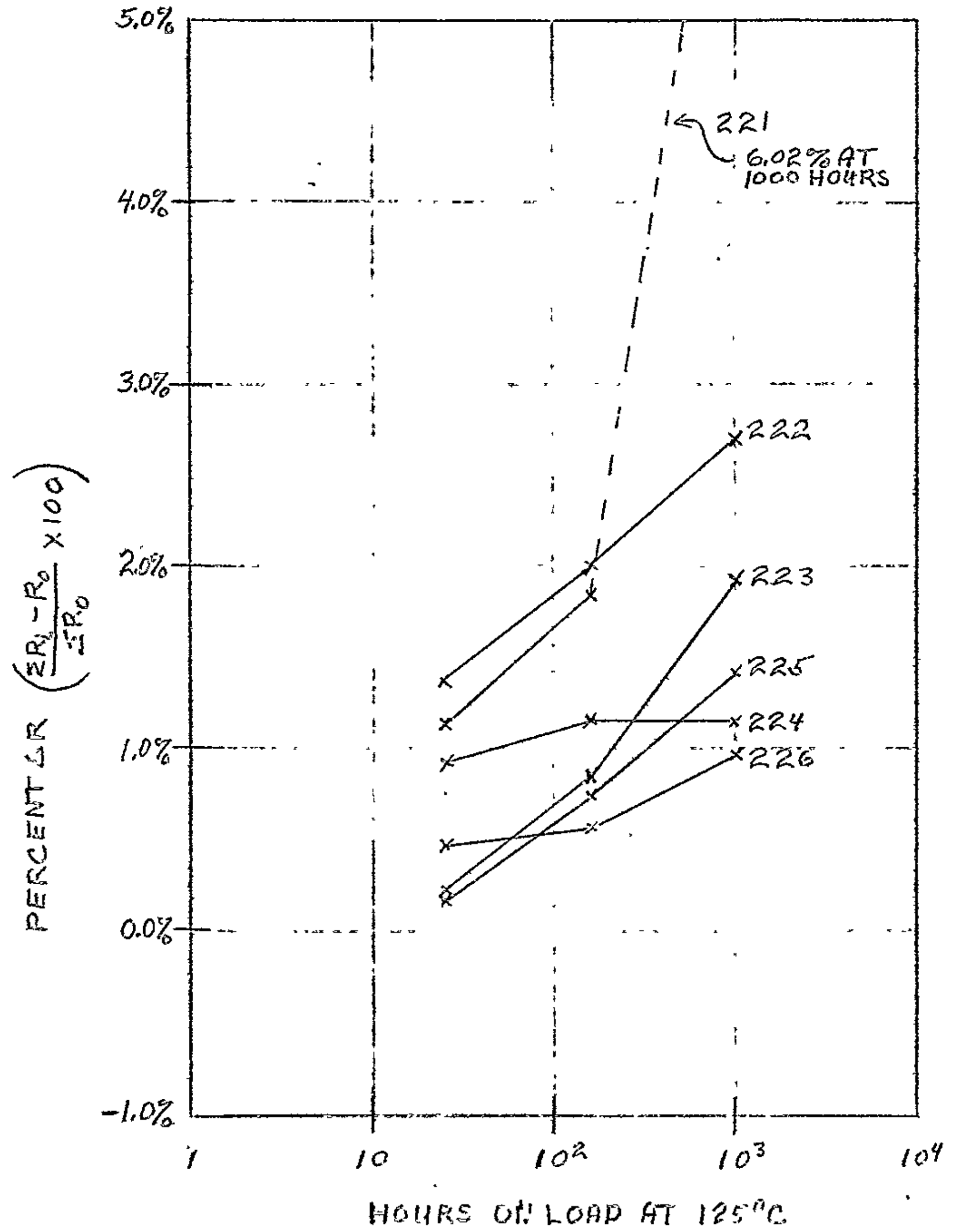


FIGURE 29: AVERAGE PERCENT CHANGES IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 221-226, RESISTOR R5

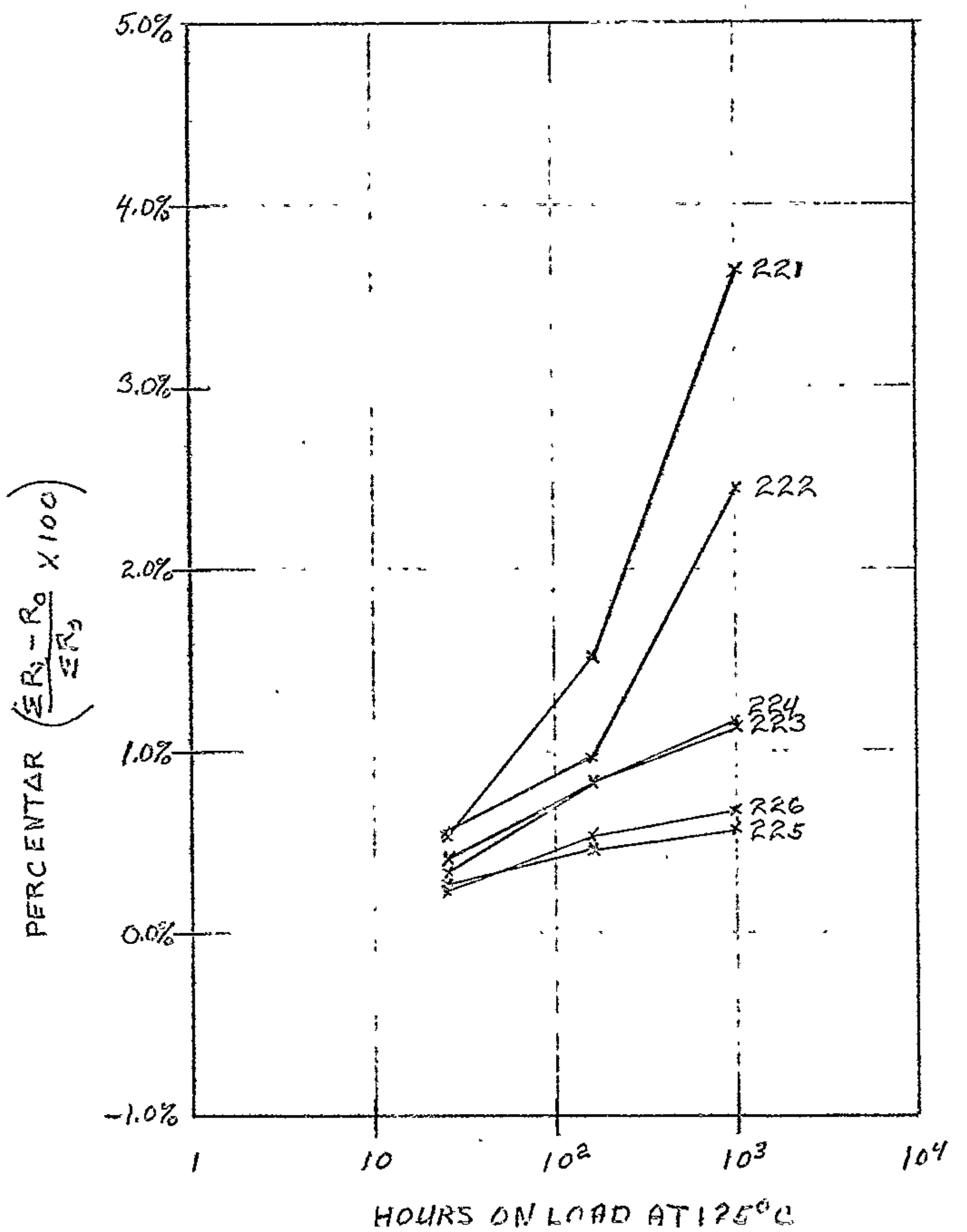


FIGURE 30: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 221-226, RESISTOR R6

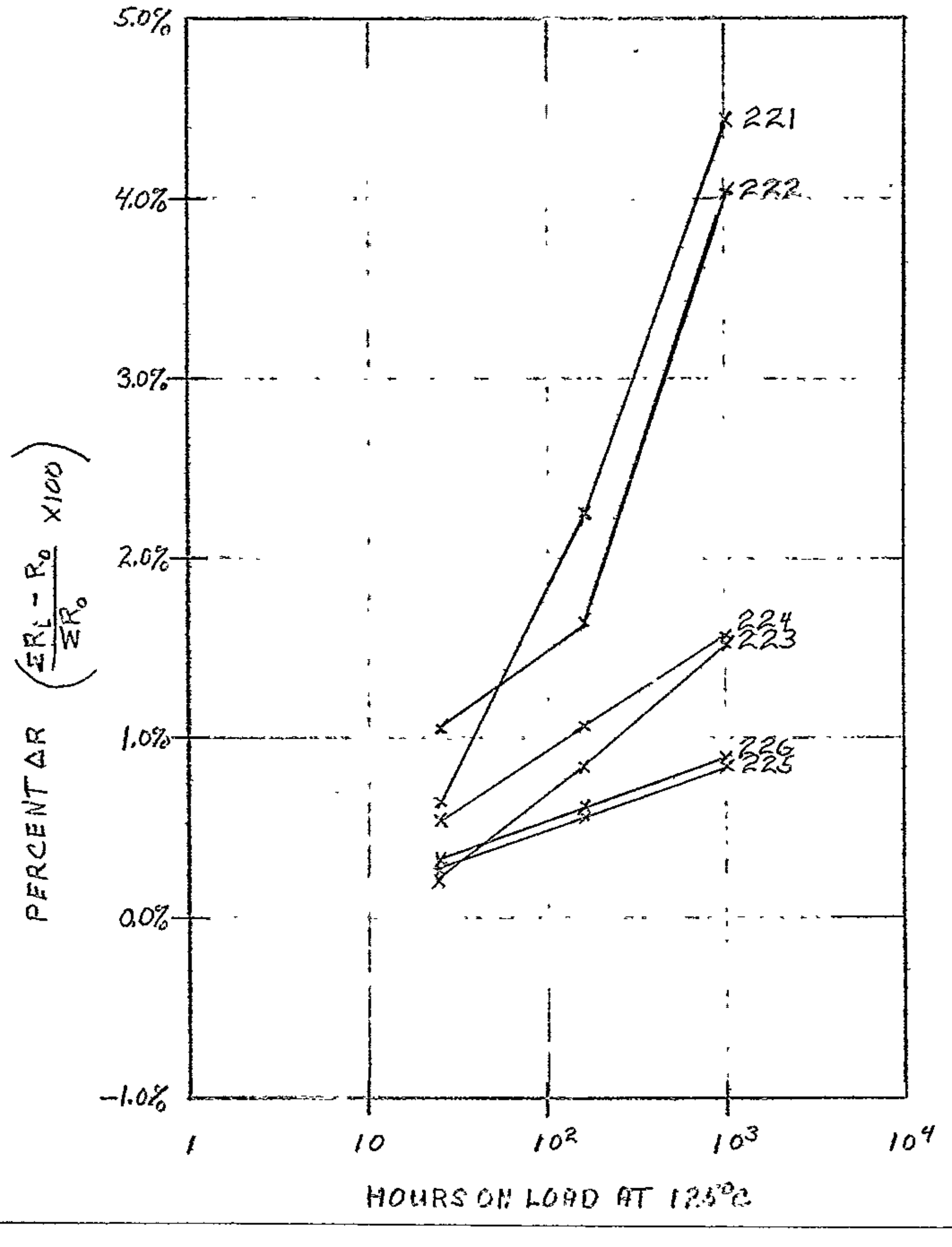


FIGURE 31: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 221-226, RESISTOR R7

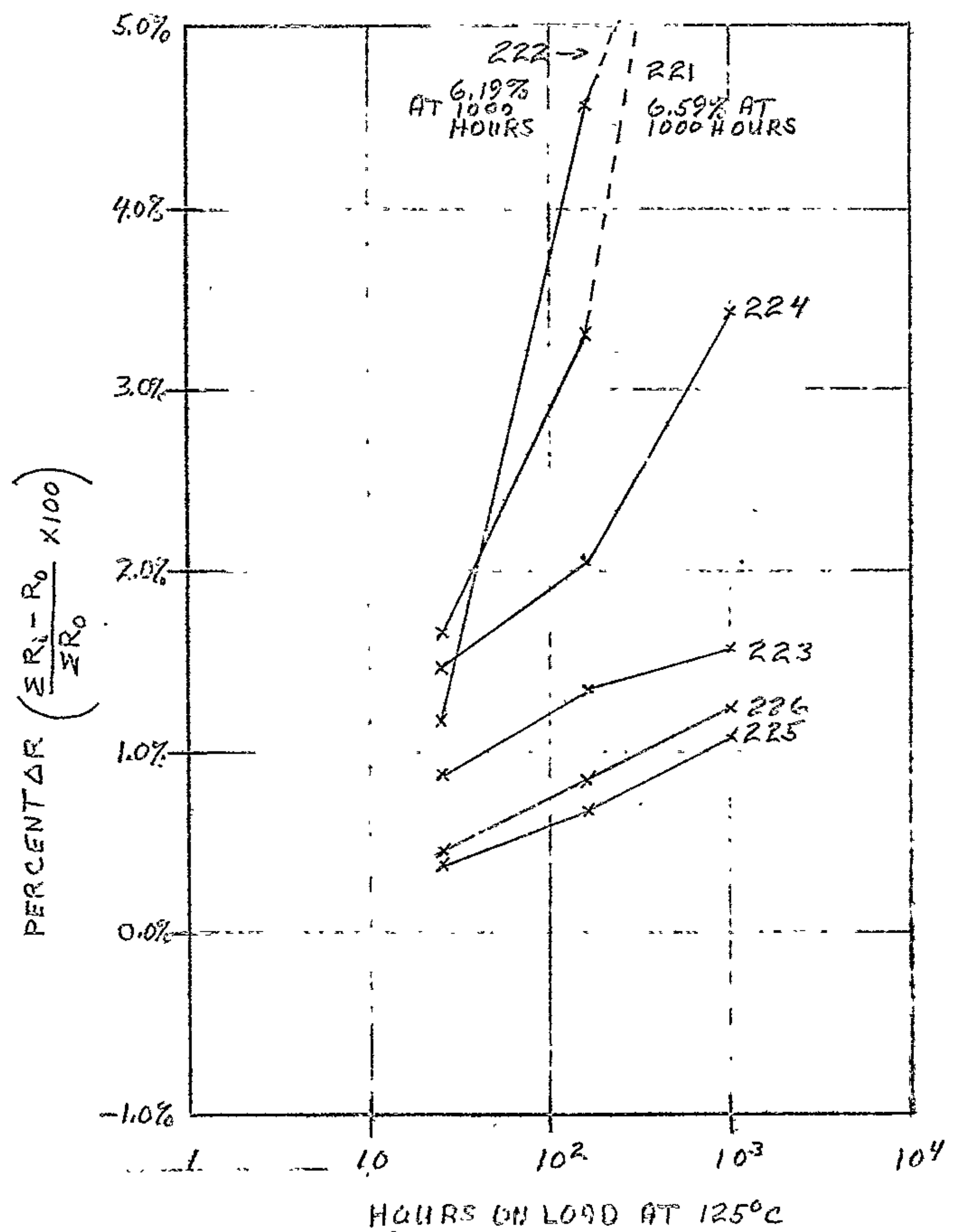


FIGURE 32: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 211-226, RESISTOR R8

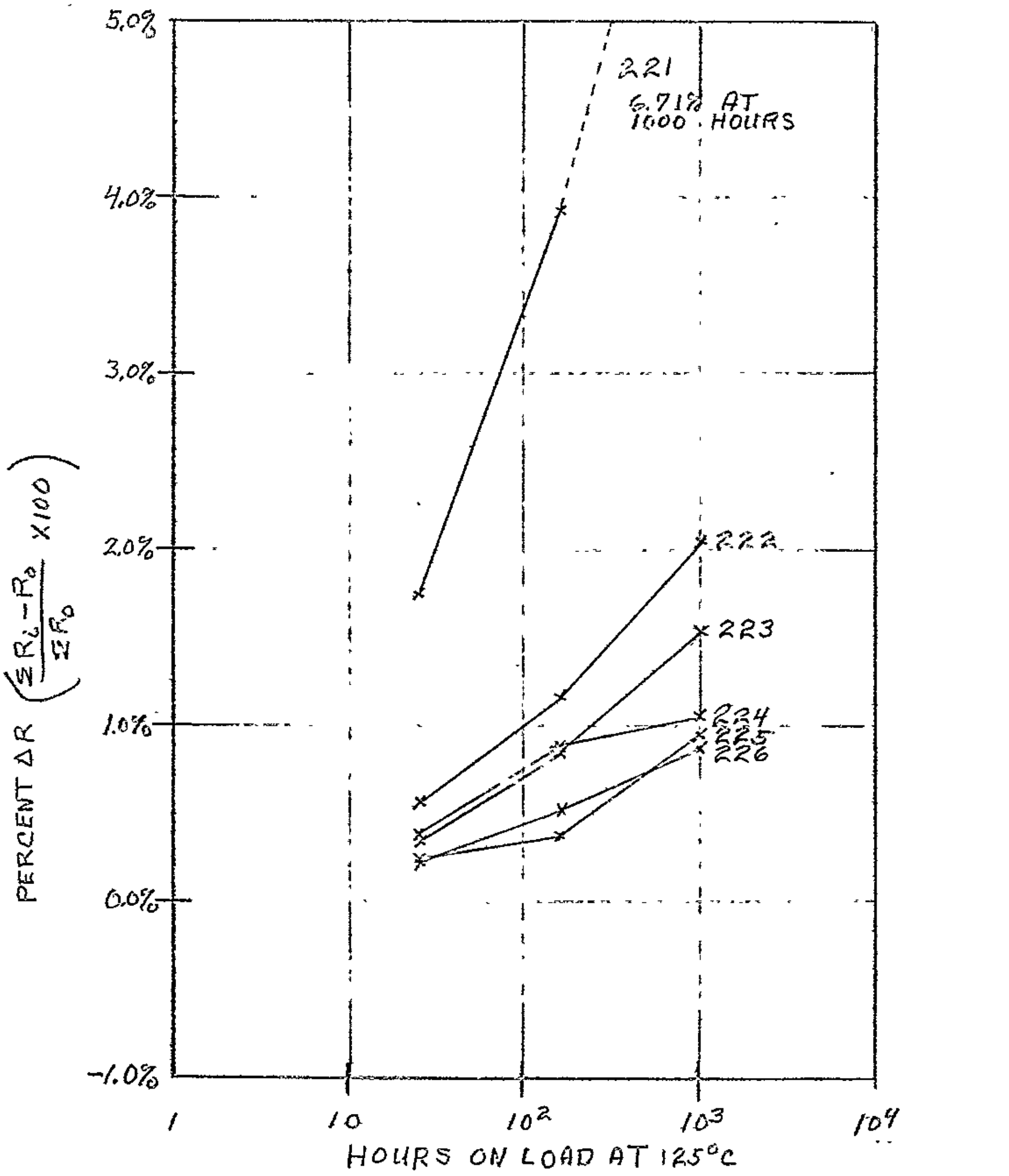


FIGURE 33: AVERAGE PERCENT CHANGE IN RESISTANCE AT 24, 155, AND 1000 HOURS UNDER LOAD AT 125°C, COMBINATIONS 221-226, RESISTOR R9

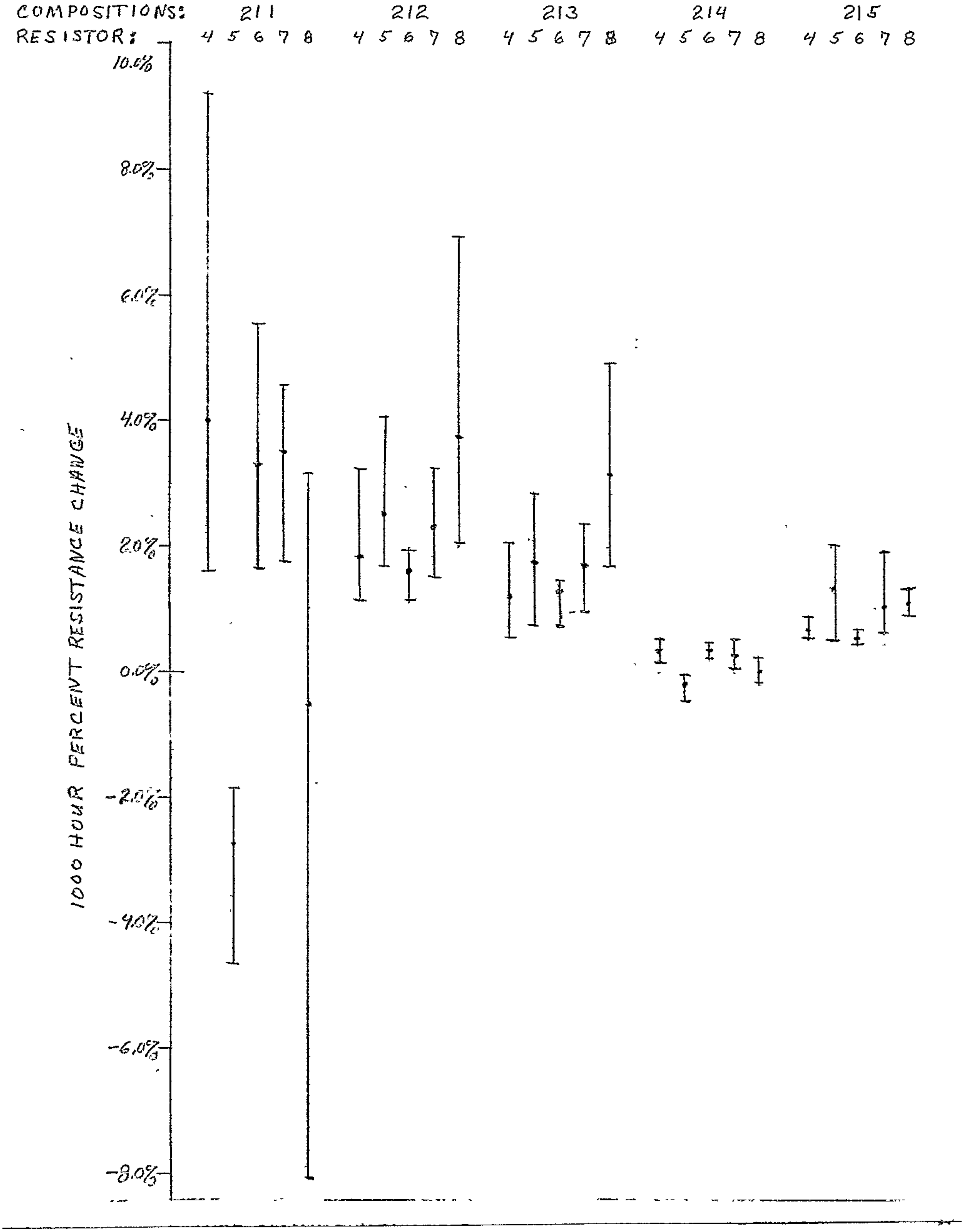


FIGURE 34: MULTIVARI CHART SHOWING MINIMUM, MAXIMUM, AND AVERAGE PERCENT 1000 HOUR RESISTANCE CHANGE FOR R4, R5, R6, R7, AND R8 OF FIVE COMMERCIAL COMPOSITIONS

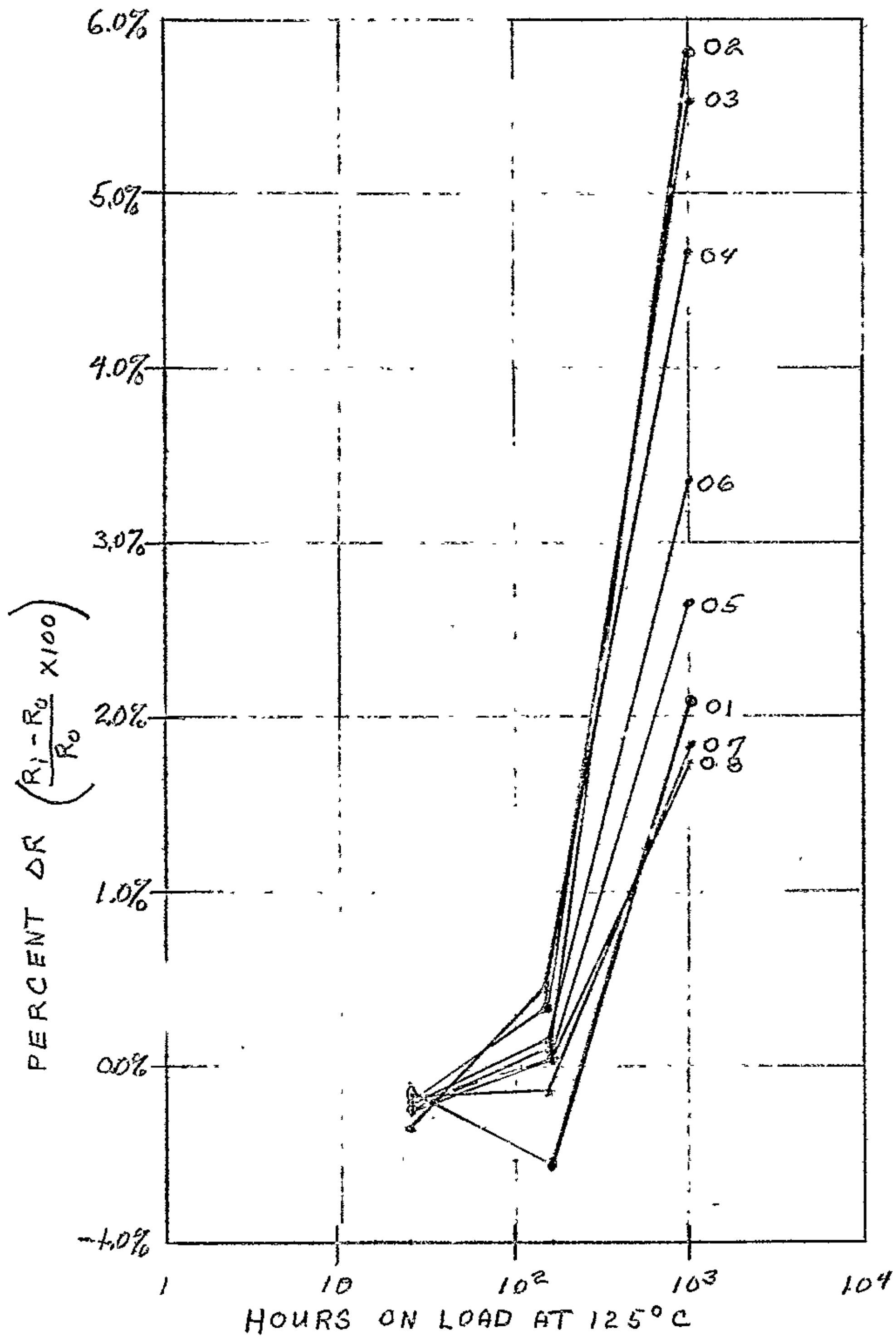


FIGURE 35: PERCENT RESISTANCE CHANGE OF INDIVIDUAL RESISTORS AT 24, 155, AND 1000 HOURS, COMPOSITION 211, RESISTOR R6

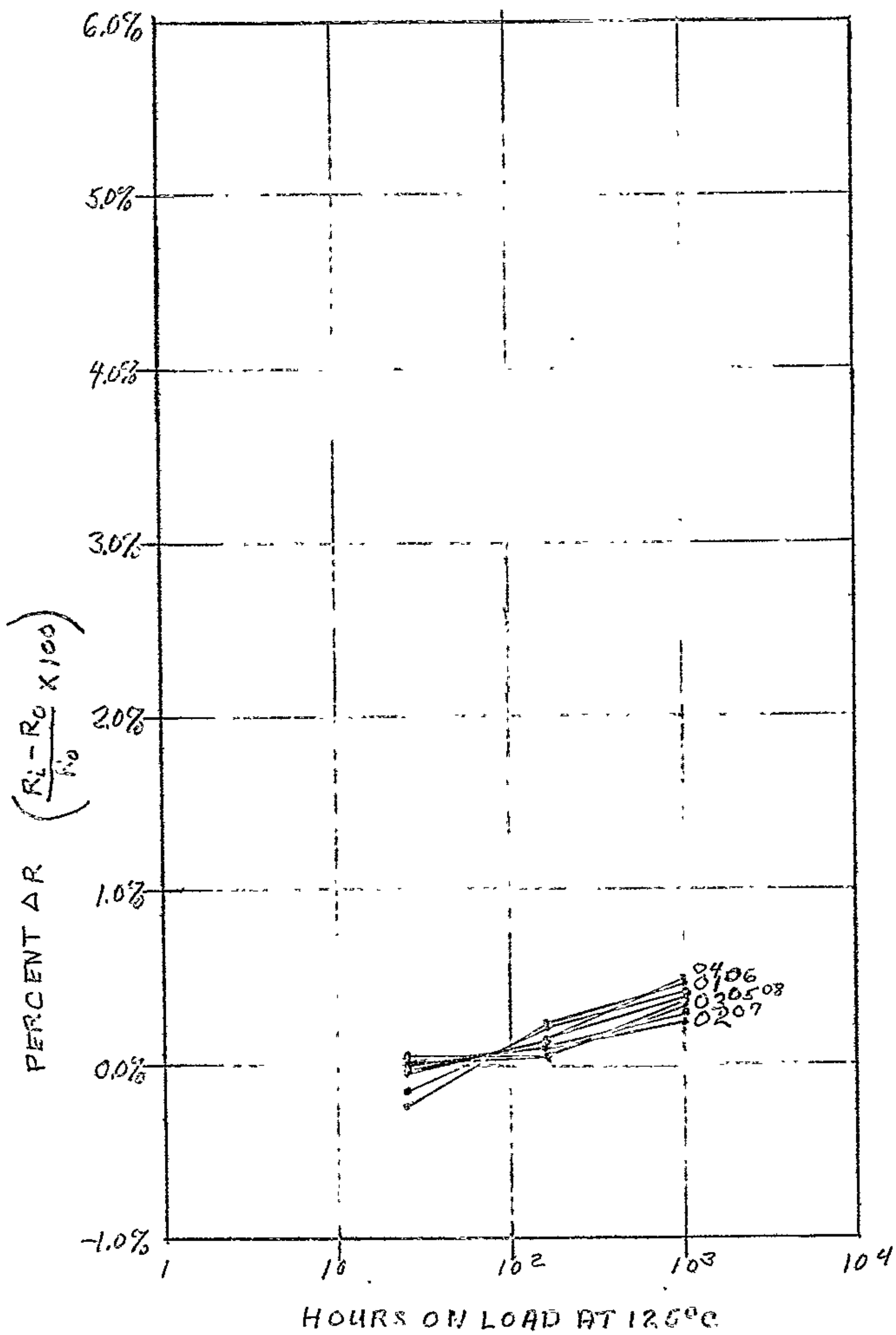


FIGURE 36: PERCENT RESISTANCE CHANGE OF INDIVIDUAL RESISTORS AT 24, 155, AND 1000 HOURS, COMPOSITION 214, RESISTOR R6

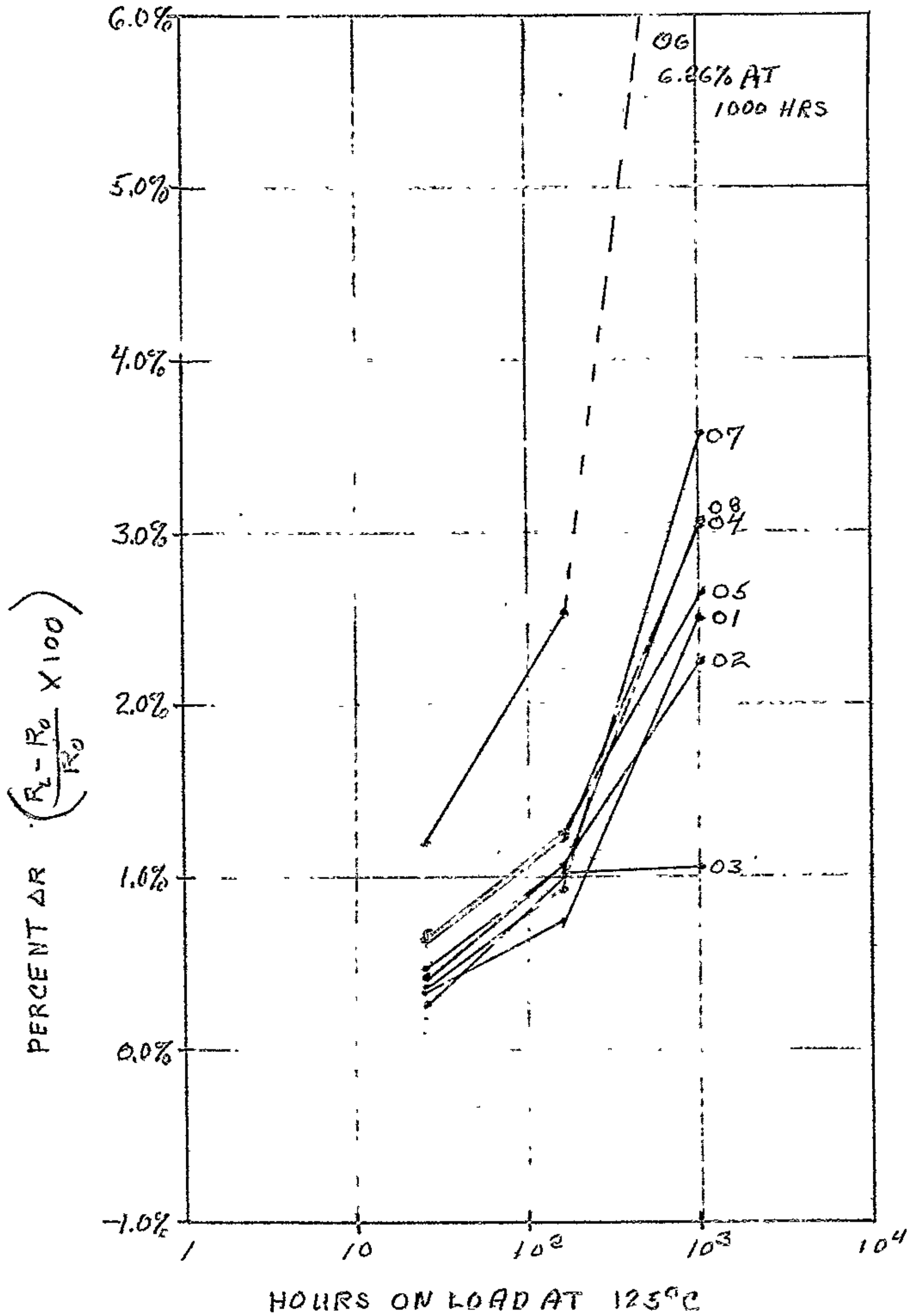


FIGURE 37: PERCENT RESISTANCE CHANGE OF INDIVIDUAL RESISTORS AT 24, 155, AND 1000 HOURS, COMBINATION 222, RESISTOR R6

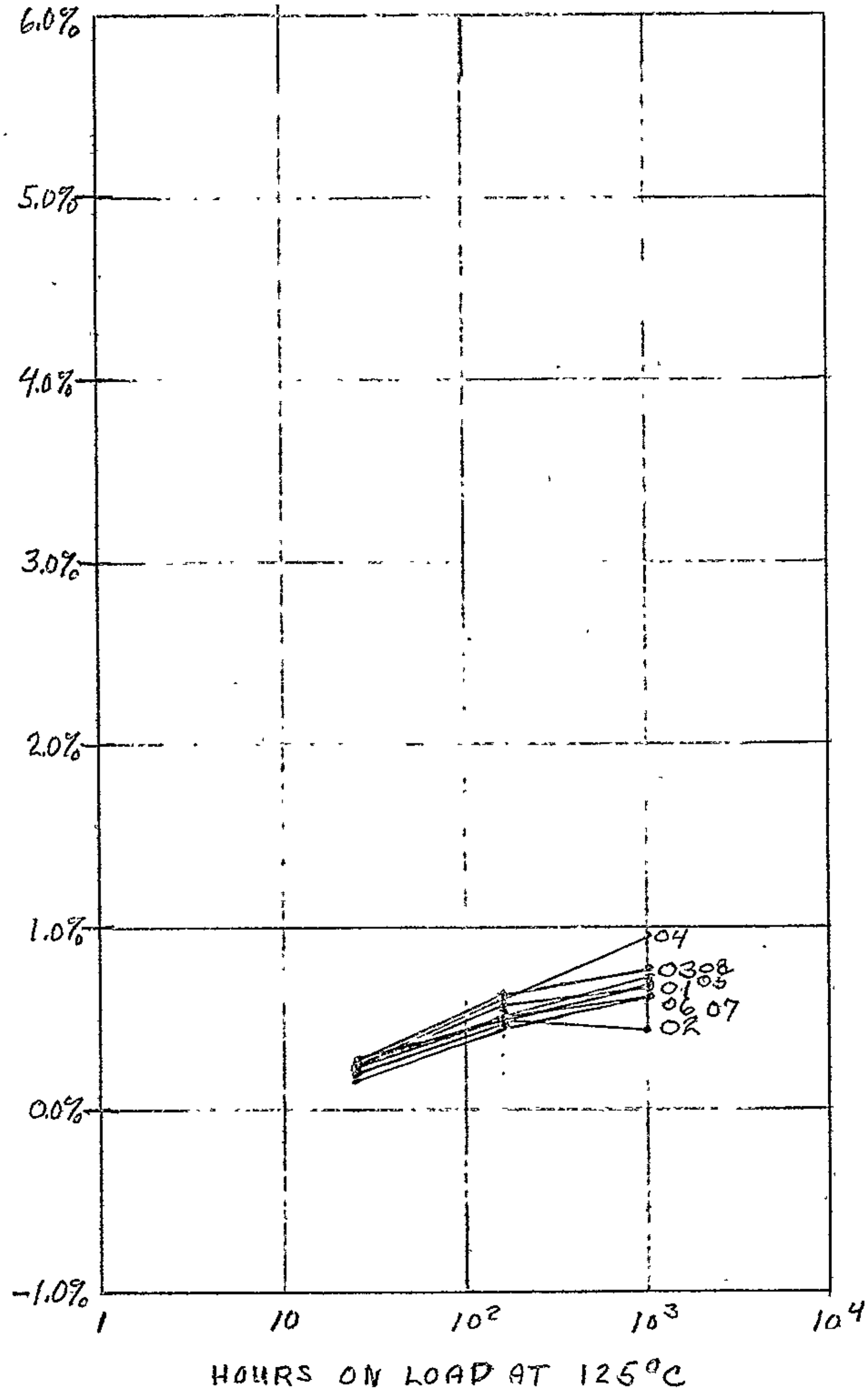


FIGURE 38: PERCENT RESISTANCE CHANGE OF INDIVIDUAL RESISTORS AT 24, 155, AND 1000 HOURS, COMBINATION 226, RESISTOR R6

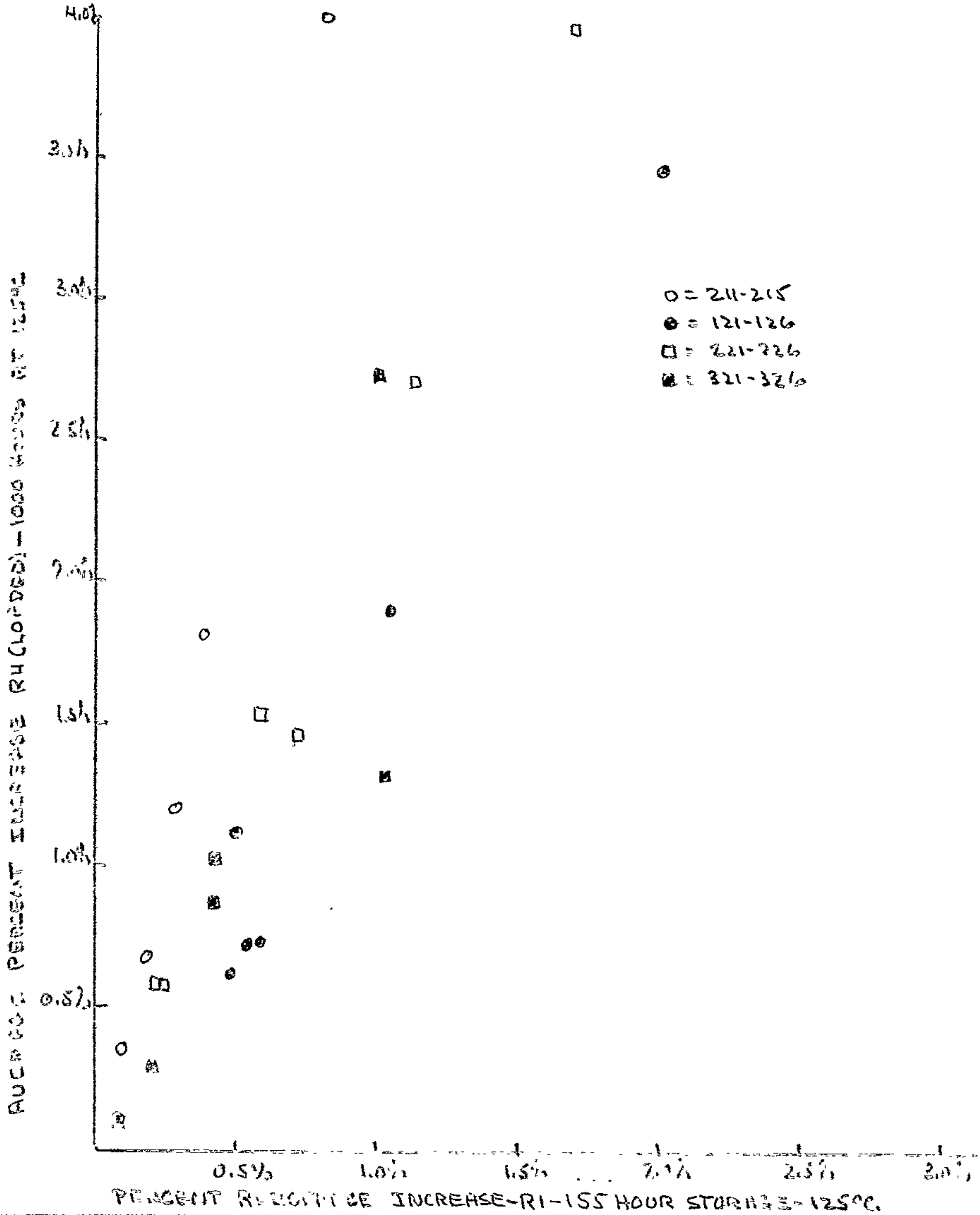


FIGURE 38A: AVERAGE 1000 HOUR PERCENT INCREASE OF R4 (LOADED) VERSUS AVERAGE 155 HOUR PERCENT INCREASE OF R1 (NOT LOADED) - BOTH AT 125°C.