Characterization of DuPont 1900 Series Resistors Applied to DuPont 5704 Dielectric on Alumina Substrates

Federal Manufacturing & Technologies

Gregg E. Barner

KCP-613-5890

Published June 1997

Topical Report

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**CHARACTERIZATION OF DUPONT 1900 SERIES
RESISTORS APPLIED TO DUPONT 5704 DIELECTRIC
ON ALUMINA SUBSTRATES**

Gregg E. Barner

Published June 1997

Topical Report
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ABSTRACT

Existing thick film hybrid microcircuit (HMC) production utilizing integral thick film resistors requires that thick film resistors be deposited via screen printing directly on the base alumina substrate material. This requirement, when coupled with circuits of moderate to high density and associated layer buildup prior to resistor application, results in printing on surfaces with significant topography surrounding the resistor, compared to required as-printed resistor thicknesses. Due to the technological requirement to print resistors after most other thick film processing has been completed, resistor printing is seldom performed on a flat surface. The surface topography of the substrate surrounding the resistor area prohibits the printing process from maintaining a relatively uniform printed resistor thickness across the substrate. Although resistors are, in most cases, adjusted to final electrical values by physically modifying the length-to-width ratio through laser trimming, the resistors must be within certain resistance ranges. This variation in thickness translates into potential scrap product through extreme variation in as-fired resistor electrical values and/or product incapable of being laser trimmed due to excessive resistor thickness. The development of a thick film resistor application process compatible with existing conductor and dielectric materials and enabling more planarization of the print surface was needed to enhance production yields on products of moderate complexity.

SUMMARY

Development of Characterization Methodology. In an effort to establish a planarized surface for thick film resistor application on HMCs, an evaluation was performed to establish design and manufacturing parameters for integral thick film resistors utilizing DuPont 1900 series resistor compositions printed on DuPont 5704 dielectric material on 96% alumina ceramic. These materials were selected based on DuPont's recommendation for compatibility with existing production technology at AlliedSignal Federal Manufacturing & Technologies (FM&T). This evaluation was performed on two layers of dielectrics for six resistivity compositions: 10 ohms/square (DuPont 1911), 100 ohms/square (DuPont 1921), 1K ohms/square (DuPont 1931), 10K ohms/square (DuPont 1939), 100K ohms/square (DuPont 1949), and 1 M ohms/square (DuPont 1959). The characterization effort focused on two main areas: (1) application (screen printing) and sintering (firing) and (2) final resistor electrical adjustment (laser trimming).

Test Procedures. The test samples were subjected to a series of environmental and electrical tests which included the following: as-fired resistance, trimmed resistance, isolation resistance, 24 hour drift, temperature shock, temperature cycle, 1000 hour aging, and temperature coefficient of resistance (TCR) determination.

Test Results. Based on the testing that was done, the test results indicated that integral thick film resistors printed on dielectric, using otherwise existing thick film technology, perform comparably to thick film resistors printed directly on alumina.

DISCUSSION

SCOPE AND PURPOSE

The purpose of this project was to evaluate and characterize thick film resistor materials suitable for application via screen printing on dielectric materials used in existing thick film production at FM&T. This capability is needed to facilitate the manufacture of moderate to high density hybrid microcircuits containing integral thick film resistors that are not candidates for low temperature cofired ceramic (LTCC) technology. The advantage of printing the resistor materials on dielectric — versus the currently used process of printing directly on the ceramic substrate — is the reduced effect of surface topography on print thickness, resulting in less resistor thickness variation. The reduced variation in as-printed thickness should result in less scrap product caused by the effects of excessive variability of resistor electrical properties and thickness on subsequent manufacturing processes. The ultimate result is improved producibility of moderate to high density thick film microelectronic products. Refer to Figure 1 for a visual comparison of the two resistor printing methodologies.

PRIOR WORK

Thick film technology was refined to meet the requirements of RF applications and multilayer circuits utilizing thick film resistors (specifically DuPont 1400 series resistor compositions) printed on the base ceramic substrate. Additionally, in support of the development of low temperature cofired ceramic technology (LTCC) at FM&T, DuPont 1931 and 1949 resistor compositions have been used in the fabrication of trimmed resistors on DuPont 851 LTCC and DuPont 951 LTCC. All six DuPont 1900 Series resistor compositions have been printed on DuPont 951 LTCC. All six DuPont 2000 series resistor compositions have been printed on DuPont 951 LTCC.

RESISTORS PRINTED ON ALUMINA SUBSTRATE

RESISTORS PRINTED ON DIELECTRIC

Figure 1. Resistor Printing Methodologies

The electrical properties and associated environmental tests used to evaluate these resistors included:

- Untrimmed resistor stability (24 hour resistance change)
- Post laser trim stability (24 hour resistance change)
- Post temperature cycle resistance change (-125 to +150°C)
- Temperature shock resistance change (ambient to +300°C)
- Resistance change at 150°C (200, 600, and 1000 hours)
- Hot TCR (+25 to +125°C)
- Cold TCR (-55 to +25°C)

ACTIVITY

Test Plan

A plan was developed to characterize the materials and manufacturing processes used in printing integral thick film resistors on dielectric materials and to ensure similar performance from existing production technology.

The plan utilized a test sample design that has been used at FM&T in the evaluation of other resistor systems and that provides a method of data comparison between resistor systems.

Prior to determining the electrical performance of the screen-printed resistors on different dielectric thicknesses (2, 6, and 10 dielectric prints with corresponding dielectric thicknesses of 0.0015, 0.0045 and 0.0075 inch), the manufacturing parameters for printing, sintering, and laser trimming of the materials were determined using test samples with double-printed dielectric.

Although processes were centered around DuPont recommendations where applicable, sensitivity to processing parameter variation was evaluated for resistor geometry, resistor orientation, print thickness, firing temperature, and laser trimming parameters.

Test Sample Configuration and Fabrication

Each test sample contained 12 resistors each with a two-to-one length to width aspect ratio. The test sample shown in Figure 2 provided resistors of 0.025 , 0050, and 0.100 inch widths oriented with the resistor lengths parallel and perpendicular to the direction of squeegee travel to simulate actual production.

Figure 2. Two Square Resistor Test Pattern

The initial evaluation consisted of printing 72 test samples for each resistor composition, encapsulation, and firing combination, generating a total of 288 resistors for each geometry. Test samples were printed to the dried target thickness range recommended by DuPont which is 25 microns, the same as for the DuPont 1400 series compositions. Test samples were prepared both with and without glass encapsulation for comparison of laser trim parameter determination. Sintering was performed using the time/temperature profiles listed in Table 1.

Table 1. Sintering Profiles for DuPont 1900 Series Resistors

Time (min)	Peak Temperature (°C)	Profile Description
60	850	Current production
30	850	DuPont recommendation
30	825	Process sensitivity evaluation
30	875	Process sensitivity evaluation

The 60 minute profile maintained approximate ascent and descent rates of 50°C per minute, and the 30 minute profiles maintained ascent and descent rates of approximately 100°C per minute as illustrated in Figure 3. The test sample matrix for the initial material evaluation is shown in Table 1.

Testing

Initial electrical testing of as-fired resistors was performed after the test samples had been printed and fired and again after encapsulation to determine the encapsulation effects.

In order to eliminate the effects of print thickness and print width variations on fired sheet resistivity determinations, the untrimmed resistance measurements are normalized to account for these variations. This calculation is used to determine typical as-fired sheet resistivities for each resistor composition and, subsequently, the resistor nominal design values incorporated into product definitions. The following equation is used for this determination:

$$R_{Normalized} = \frac{\left(\frac{\bar{R}_M}{2} \right) \times \bar{T}_D}{T_R} \times \frac{\bar{W}_F}{W_R}$$

where

- $\bar{R}_M$ = The Average As-Measured Resistance
- $\bar{T}_D$ = Average Dried Thickness
- T_R = Reference Dried Thickness (25 microns)
- $\bar{W}_F$ = Average Fired Width
- W_R = Reference Fired Width (0.025, 0.050, or 0.100 inch)

Figure 3. Resistor Sintering Time/Temperature Profiles

Additionally both trimmed and untrimmed test samples were subjected to tests to determine the optimum laser trim parameters and the effects of optimized laser trimming on future resistor performance. These tests were as follows:

- Isolation resistance.
- 24 hour short term drift.
- Temperature shock (solder pot shock test): 25°C to 268°C, 268°C for 15 seconds, and back to 25°C.
- Temperature cycle: -50°C to 125°C with approximately 5 seconds ramp time, ten cycles, 15 minutes minimum at each temperature extreme.
- Temperature coefficient of resistance (TCR) measured and calculated at -55°C, 25°C, and 125°C.
- 1000 hour aging test at 150°C, ambient humidity.

Resistance was measured after each test, and the change in resistance was calculated.

Data and Analysis

The evaluation data established the following recommendations and observations regarding material characteristics, design criteria, and manufacturing parameters for the six DuPont 1900 series resistor compositions:

1. DuPont 1900 series thick film resistors printed on two layers of DuPont 5704 dielectric should be designed to 70% of trimmed nominal value.
2. The minimum resistor dimension should be 0.050 inch.
3. DuPont 1911 (10 ohm/square) paste should not be used because of paste cracking after firing, which leads to poor resistor stability.
4. Target print thicknesses for each of the six pastes ranged from 41 to 46 microns to yield the DuPont recommended dried thickness of 25 microns, resulting in optimum as-fired resistivities and maximum post-trim resistor stability.
5. Firing of DuPont 1900 series resistors should be performed using a 30 minute - 850°C profile in which average as-fired resistivities for all six DuPont 1900 series pastes ranged from 29% above nominal to 30% below nominal, which is a range similar to DuPont 1400 series resistors (23% above nominal to 23% below nominal) used on existing thick film production designs.
6. Resistors should be encapsulated (overglazed) with DuPont 9137 encapsulant to maximize stability and minimize changes in TCR due to laser trimming. Resistivities for all six pastes were unaffected by encapsulation.
7. Resistivities were virtually unaffected by resistor orientation but were dependent on resistor geometry.
8. Overall print lot capability (+/- 3 sigma) was +/- 30% from average fired values for all pastes.
9. Preliminary estimates for encapsulated samples indicate that resistor tolerances as tight as 1% are possible with 100% yield for resistors made with DuPont 1921 through 1959 pastes. Since this is preliminary, it is recommended initially that tolerances should not be tighter than 2%.

Results

The test samples demonstrated that a capability for printing thick film resistors on dielectric can be incorporated into existing FM&T thick film production, thereby providing enhanced producibility for moderate to high density microelectronic products.

ACCOMPLISHMENTS

In an effort to provide improved producibility of moderate to high density thick film microelectronic products utilizing integral thick film resistors, a capability was developed to apply thick film resistors directly on dielectric, thereby minimizing variations in thickness caused by the effects of surface topography.

FUTURE WORK

Future work to be done to maintain the state-of-the-art capability could include the evaluation of the DuPont 1900 series resistor compositions on additional dielectric layers.

Future work to be done to enhance the state-of-the-art capability at FM&T will include the evaluation of the DuPont 2000 series resistor compositions for use with existing thick film processes and materials. The intent will be to minimize the number of different thick film resistor technologies required to support a variety of thick film and low temperature cofired ceramic (LTCC) product types.

Future work to be done to develop additional capabilities will include evaluating the compatibility of DuPont 2000 series resistors with different thick film processes and materials not in use at FM&T.

APPENDIX A

Characterization of Printing, Drying, and Firing of DuPont 1900 Series Resistors on Two Layers of DuPont 5704 Dielectric

By Gregg E. Barner

August 1996

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SUMMARY

An evaluation was performed to establish design and manufacturing parameters for integral thick film resistors utilizing DuPont 1900 Series Resistor Compositions printed on DuPont 5704 Dielectric material. This evaluation was performed for (6) resistivity compositions (10, 100, 1K, 10K, 100K and 1 Meg Ohm per square) in conjunction with the evaluation of laser trimming DuPont 1900 Series Resistors printed on DuPont 5704 Dielectric material. Both evaluations support an effort to develop a production capability to utilize integral thick film resistors on thick film hybrid microcircuit products.

Test samples were fabricated using a 2 square test pattern configuration consisting of resistors with length to width aspect ratios of 2:1 and minimum dimensions of .025", .050", and .100". The test pattern configuration is illustrated in Figure 1. The test samples were printed on (2) layers of DuPont 5704 Dielectric both with and without encapsulation. The test samples were fired using 850 (nominal), 825, and 875 degree C - 30 minute, and 850 degree C - 60 minute firing profiles.

The evaluation established the following material characteristics, design criteria, and manufacturing parameters for the (6) DuPont 1900 Series Resistor compositions:

1. Target print thicknesses for each of the six pastes ranged from 41 to 46 microns to yield the DuPont recommended dried thickness of 25 microns resulting in optimum as-fired resistivities and maximum post-trim resistor stability.
2. DuPont 1900 Series thick film resistors printed on (2) layers of DuPont 5704 dielectric should be designed to 70% of trimmed nominal value.
3. Average resistivities for all (6) DuPont 1900 Series pastes ranged from 29% above nominal to 30% below nominal which is a similar range to DuPont 1400 Series resistors (23% above nominal to 23% below nominal) used on existing thick film production designs.
4. Resistivities for all (6) pastes were unaffected by encapsulation (overglaze).
5. Resistivities were virtually unaffected by resistor orientation, however were more dependent on resistor geometry.
6. Overall print lot capability (± 3 sigma) was $\pm 30\%$ from average fired values for all pastes.

DISCUSSION

SCOPE AND PURPOSE

The objective of this printing and firing evaluation was to determine the following characteristics for all (6) DuPont 1900 Series Resistor Compositions printed on 2 layers of DuPont 5704 Dielectric material on alumina substrates in an effort to develop a production fabrication capability utilizing integral thick film resistors printed on dielectric:

1. Target print thicknesses consistent with manufacturer's recommendations and compatible with subsequent resistor firing and trimming processes.
2. Resistor physical design requirements compatible with manufacturing processes.
3. Sensitivity of resistance to variations in manufacturing processes including firing, encapsulation (overglaze) and print thickness.
4. Effects of geometry variations on untrimmed resistance.

PRIOR WORK

Thick film technology was refined to meet the requirements of RF applications and multilayer circuits utilizing thick film resistors (specifically DuPont 1400 Series Resistor Compositions) printed on the base 96% aluminum oxide substrate. Additionally, another project is currently examining the DuPont 2000 Series Resistor Compositions for printing on DuPont 951 Low Temperature Cofired Ceramic.

ACTIVITY

Test Sample Configuration and Fabrication

The evaluation consisted of printing test samples using a two square resistor test pattern with each resistor having a length to width ratio of two. The test pattern shown in Figure 1 provided resistors of .025 inch, .050 inch, and .100 inch widths oriented with the resistor lengths parallel and perpendicular to the direction of squeegee travel to simulate actual production. The two square test patterns provide resistors which have nominal untrimmed resistances of twice the nominal

as-fired sheet resistance. Each test pattern contained two resistors of each width in each orientation. Test patterns were printed on substrates containing nine test patterns each. The test sample substrates were comprised of .025 inch thick 96% alumina with 2 layers of DuPont 5704 fired to a final thickness of 35 - 40 microns.

Test samples for each resistor composition were prepared as follows:

With Encapsulation

825 Degree C Fire

850 Degree C Fire

875 Degree C Fire

Without Encapsulation

825 Degree C Fire

850 Degree C Fire

875 Degree C Fire

The complete sample size for each resistor composition, encapsulation, and firing combination was eight substrates (72 test samples) generating a total of 288 resistors for each geometry.

Figure 1 Two Square Resistor Test Pattern

The test samples were printed to the dried target thickness range recommended by DuPont of 23 to 27 microns which is the same for DuPont 1400 Series Compositions. Test samples were prepared both with and without glass encapsulation for comparison of laser trim parameter determination.

Figure 2 Resistor Sintering Time/Temperature Profiles

Sintering (firing) was performed using a 30 minute, 850 degree C, time and temperature profile compared to a 60 minute, 850 degree C, time and temperature profile currently used in thick film production utilizing DuPont 1400 Series resistors. Both profiles provide a peak temperature of 850 degrees C with a time at peak temperature of 10 minutes. The 30 minute and 60 minute profiles maintain approximate ascent and descent rates of 100 and 50 deg. C per minute, respectively as illustrated in Figure 2. Sensitivity of the resistor compositions to firing process variations was further evaluated using 825 degree C and 875 degree C, 30 minute profiles.

Print Thickness

The manufacturer's recommended target dried thickness for DuPont 1900 Series Resistors is 23 to 27 microns. The evaluation established target wet printed thicknesses needed to obtain a dried thickness of 23 to 27 microns. Figures 1-5 and 1-6 illustrate the comparison between wet (as-printed), dried, and fired thickness and resistivity for each paste composition.

Untrimmed Resistance Measurements

As part of the overall evaluation of the sensitivity of DuPont 1900 Series Resistor Compositions to variations in manufacturing processes, such as firing, encapsulation, thickness, and geometry, electrical resistance measurements were made on as-fired (untrimmed) resistors. The untrimmed resistance data is shown for each resistor composition in the appropriate appendix both as a percent from nominal and actual resistance.

Normalized Sheet Resistance and Design Considerations

In order to eliminate the effects of print thickness and print width variations on fired sheet resistivity determinations, the untrimmed resistance measurements are normalized to account for these variations. This calculation is used to determine typical as-fired sheet resistivities for each resistor composition and subsequently the resistor nominal design values incorporated into product definitions. The following equation is used for this determination:

$$R_{Normalized} = \frac{\left(\frac{\bar{R}_M}{2}\right) \times \bar{T}_D}{T_R} \times \frac{\bar{W}_F}{W_R}$$

$\bar{R}_M$	=	The Average As-Measured Resistance
$\bar{T}_D$	=	Average Dried Thickness
T_R	=	Reference Dried Thickness (25 microns)
$\bar{W}_F$	=	Average Fired Width
W_R	=	Reference Fired Width (.025, .050, or .100 inch)

The normalized resistance data is shown for each resistor composition in the appropriate appendix both as a percent from nominal and actual resistance.

Firing Sensitivity

Figure 1-1 illustrates the untrimmed sheet resistance as a percent of the nominal sheet resistance for each resistivity and firing profile combination. This data indicates DuPont 1900 Series Resistors printed to a dried target thickness of 23-27 microns, range from 29 percent below nominal to 29 percent above nominal when fired using a 30 minute, 850 degree C profile. These values shift by typically 10-20 percent when fired using 825 or 875 degree C profiles depending on the specific resistor composition.

Figure 1-2 illustrates the normalized sheet resistivity as a percent of the nominal sheet resistance for each resistivity and firing profile. This data indicates DuPont 1900 Series Resistors normalized to a dried target thickness of 25 microns, range from 10 percent above nominal to 30 percent below nominal when fired using a 30 minute, 850 degree C profile. These values shift by up to 20 percent when fired using 825 or 875 degree C profiles.

Encapsulation Effects

Virtually no difference in resistivities was observed between encapsulated and unencapsulated resistors for all six resistor compositions. Figure 1-4 shows sensitivity to overglaze for untrimmed resistance and Figure 1-5 for normalized resistance. Trim parameters yielding acceptable visual and electrical results were significantly reduced with encapsulated samples.

Thickness Sensitivity

Figure 1-5 illustrates variations in untrimmed resistance as a percent from nominal for various dried thicknesses. The relationship shows typically that thickness is inversely proportional to resistance for all resistor compositions. Figure 1-6 shows the relationship between wet, dried, and fired thicknesses for each resistor composition. The dried thickness target range of 18 to 20 microns was maintained by printing the wet thickness within the range of 32 to 38 microns for each resistor composition.

Effects of Resistor Geometry and Orientation

Figure 1-11 illustrates untrimmed resistance as a percent from nominal for each resistor geometry and orientation combination. The geometries tested were .025 inch, .050 inch, and .100 inch minimum resistor dimensions (resistor width) and the orientation refers to the direction of the resistor length compared to the direction of the squeegee travel. The chart shows for each paste composition the effect of resistor orientation was negligible with all geometries exhibiting a spread of typically less than 10 percent between resistors parallel and perpendicular to the squeegee travel. The inherent lack of surface topography on this substrate material would contribute to this consistency. Resistor geometry, however, can be seen to have more of an effect on resistance with most paste compositions displaying a 10 percent spread between the .025 inch and .050 inch geometries compared to a 20 - 25 percent spread between .050 inch and .100 inch resistor geometries. The larger resistor geometries tend to print thinner resulting in higher resistivities.

Overall Printing/Firing Capability

The within print lot variability of as-fired resistance is shown in Figures 1-7 through 1-10 for .025, .050, and .100 inch resistors. The data presented in these figures is a composite of both parallel and perpendicular orientations. The 3 sigma limits were typically +/- 25% except for the 10 Ohm and 100 Ohm compositions which were +/- 50%.

Resistor Series Comparisons

Figures 2-1 and 2-2 illustrate relative resistivities (as a percent from nominal) for DuPont 1900 Series Resistor Compositions versus DuPont 1400 and DuPont 2000 Series Resistor Compositions. DuPont 1400 is currently used in thick film production on aluminum oxide substrate material. DuPont 2000 is used in LTCC production at AlliedSignal Federal Manufacturing & Technologies. DuPont 1900 can be seen to be comparable to the 1400/2000 Series in terms of percent from nominal for untrimmed resistivities. Additionally DuPont 1900 Series Resistor Compositions printed on DuPont 951 LTCC versus 2 layers of DuPont 5704 on alumina yielded fired values typically within 10-15% of each other.

Resistivity Specific Data

10 Ohm - DuPont 1911 (Reference Appendix 3 for data)

1. Average untrimmed resistances were centered 25% above nominal for 50 mil geometries with a spread of approximately +/- 20% when fired using the 850 degree C - 30 minute profile. Normalized resistance was centered at nominal with a spread of 5-10%.
2. Composite print lot capabilities (+/- 3 sigma for all geometries) ranged from -15% to +85% from nominal.
3. Firing sensitivities indicated a 10% upward shift between 850 degree C - 30 minute & 850 degree C - 60 minute profiles compared to a 10-15% downward shift between 850 degree C - 30 minute & 825 or 875 degrees C - 30 minute profiles.
4. Encapsulation resulted in no significant change in as-fired resistivity (+/- 1%).
5. Thickness sensitivity indicated a +/- 20% shift in resistivities between dried thicknesses of 25 microns and 28 or 22 microns.
6. The target wet print thickness for DuPont 2011 is 41 microns yielding a dried thickness of 25 microns.
7. Resistance sensitivity to substrate material when comparing DuPont 951 LTCC and AlO₂ with 2 dielectric prints indicated a 7% increase for resistors printed on LTCC substrates.
8. Resistances were effected by resistor geometry as follows; 25 mil resistors were approximately nominal value and 50 & 100 mil resistors 15% & 40% above nominal respectively.
9. Resistances were effected by orientation as follows; resistors parallel to squeegee travel were 10-15% lower than resistors perpendicular to squeegee travel.

100 Ohm - DuPont 1921 (Reference Appendix 4 for data)

1. Average untrimmed resistances were centered 30% below nominal for 50 mil geometries with a spread of approximately +/- 10% when fired using the 850 degree C - 30 minute profile. Normalized resistance was centered 20% below nominal with a spread of 5 -10%.
2. Composite print lot capabilities (+/- 3 sigma for all geometries) ranged from 5 to 96% above nominal.
3. Firing sensitivities indicated no change between 850 & 825 degrees C - 30 minute profiles with a 15 -20% upward shift between 850 degrees C - 30 minute and 875 degrees C - 30 minute & 850 degrees C - 60 minute profiles.

4. Encapsulation resulted in no significant change in as-fired resistivity (+/- 1%)
5. Thickness sensitivity indicated a +/- 5% shift in resistivities between dried thicknesses of 25 microns and 22 or 28 microns.
6. The target wet print thickness for DuPont 1921 is 41 microns yielding a dried thickness of 25 microns.
7. Resistance sensitivity to substrate material when comparing DuPont 951 LTCC and AlO₂ with 2 dielectric prints indicated a 40% increase for resistors printed on LTCC substrates.
8. Resistances were effected by resistor geometry as follows; 25 mil resistors were approximately 5% below nominal value and 50 & 100 mil resistors 10% & 35% above nominal respectively.
9. Resistances were effected by orientation as follows; resistors parallel to squeegee travel were 5-10% lower than resistors perpendicular to squeegee travel.

1K Ohm (DuPont 1931) (Reference Appendix 5 for data)

1. Average untrimmed resistances were centered 33% below nominal for 50 mil geometries with a spread of 5-15% when fired using the 850 degree C - 30 minute profile. Normalized resistance was centered 35% below nominal with a spread of 5-15%.
2. Composite print lot capabilities (+/- 3 sigma for all geometries) ranged from - 50% to + 15% from nominal.
3. Firing sensitivities indicated a 1% upward shift between 850 & 875 degrees C with a 20% downward shift between 850 & 825 degrees C.
4. Encapsulation resulted in no significant change in as-fired resistivity (+/- 2%).
5. Thickness sensitivity indicated a +/- 5-10% shift in resistivities between dried thicknesses of 25 microns and 22 or 28 microns.
6. The target wet print thickness for DuPont 1931 is 42 microns yielding 25 microns dried thickness.
7. Resistance sensitivity to substrate material when comparing DuPont 951 LTCC and AlO₂ with 2 dielectric prints indicated a 20% increase for resistors printed on LTCC substrates.
8. Resistances were effected by resistor geometry as follows; 25 mil resistors were approximately 40% below nominal value and 50 & 100 mil resistors 35% & 15% below nominal respectively.
9. Resistances were effected by orientation as follows; resistors parallel to squeegee travel were 0-10% lower than resistors perpendicular to squeegee travel.

10K Ohm - (DuPont 1939) (Reference Appendix 6 for data)

1. Average untrimmed resistances were centered 15% above nominal for 50 mil geometries with a spread of approximately +/- 10% when fired using the 850 degree C - 30 minute profile. Normalized resistance was centered 10% above nominal with a spread of 10-15%
2. Composite print lot capabilities (+/- 3 sigma for all geometries) ranged from nominal to 45% above nominal (+/- 20% from average fired resistance).
3. Firing sensitivities indicated a 15% upward shift between 850 & 875 degrees C with a 10% downward shift between 850 & 825 degrees C.
4. Encapsulation resulted in no significant change in as-fired resistivity (+/- 5%).
5. Thickness sensitivity indicated a +/- 5-10% shift in resistivities between dried thicknesses of 25 microns and 22 or 28 microns.
6. The target wet print thickness for DuPont 1939 is 42 microns yielding 25 microns dried thickness.
7. Resistance sensitivity to substrate material when comparing DuPont 951 LTCC and AIO2 with 2 dielectric prints indicated a 10% decrease for resistors printed on LTCC substrates.
8. Resistances were effected by resistor geometry as follows; 25 mil resistors were approximately 20% below nominal value and 50 & 100 mil resistors 30% & 50% above nominal respectively.
9. Resistances were effected by orientation as follows; resistors parallel to squeegee travel were 0-10% lower than resistors perpendicular to squeegee travel.

100K Ohm (DuPont 1949) (Reference Appendix 7 for data)

1. Average untrimmed resistances were centered 3% below nominal for 50 mil geometries with a spread of 5% when fired using the 850 degree C - 30 minute profile. Normalized resistance was centered 3% below nominal with a spread of 5-10%.
2. Composite print lot capabilities (+/- 3 sigma for all geometries) ranged from -20% to +20% from nominal.
3. Firing sensitivities indicated a 35% upward shift between 850 & 875 degrees C with a 10% downward shift between 850 & 825 degrees C.
4. Encapsulation resulted in no significant change in as-fired resistivity (+/- 2%).
5. Thickness sensitivity indicated a +/- 2-5% shift in resistivities between dried thicknesses of 25 microns and 22 or 28 microns.
6. The target wet print thickness for DuPont 1949 is 45 microns yielding 25 microns dried thickness.
7. Resistance sensitivity to substrate material when comparing DuPont 951 LTCC and AIO2 with 2 dielectric prints indicated a 15% increase for resistors printed on LTCC substrates.

8. Resistances were effected by resistor geometry as follows; 25 mil resistors were approximately 20% above nominal value and 50 & 100 mil resistors 30% & 45% above nominal respectively.
9. Resistances were effected by orientation as follows; resistors parallel to squeegee travel were 3-5% higher than resistors perpendicular to squeegee travel.

1Meg Ohm (DuPont 1959) (Reference Appendix 8 for data)

1. Average untrimmed resistances were centered 25% below nominal for 50 mil geometries with a spread of 5-10% when fired using the 850 degree C - 30 minute profile. Normalized resistance was centered 20% below nominal with a spread of 10%.
2. Composite print lot capabilities (+/- 3 sigma for all geometries) ranged from 45% below nominal to nominal.
3. Firing sensitivities indicated a 30% upward shift between 850 & 875 degrees C with a 15% upward shift between 850 & 825 degrees C.
4. Encapsulation resulted in no significant change in as-fired resistivity (+/- 4%).
5. Thickness sensitivity indicated a +/- 5-10% shift in resistivities between dried thicknesses of 25 microns and 22 or 28 microns.
6. The target wet print thickness for DuPont 1959 is 46 microns yielding 25 microns dried thickness.
7. Resistance sensitivity to substrate material when comparing DuPont 951 LTCC and AlO₂ with 2 dielectric prints indicated a 20% increase for resistors printed on LTCC substrates.
8. Resistances were effected by resistor geometry as follows; 25 mil resistors were approximately 10% below nominal value and 50 & 100 mil resistors 5% & 30% above nominal respectively.
9. Resistances were effected by orientation as follows; resistors parallel to squeegee travel were 0-10% lower than resistors perpendicular to squeegee travel.

ACCOMPLISHMENTS

Target print thicknesses and sintering process parameters were determined for the six DuPont 1900 Series resistor compositions. These target thicknesses and sintering process parameters are consistent with the manufacturer's recommendations and compatible with AlliedSignal manufacturing processes.

Resistor physical design requirements were established for integral thick film resistors in applications utilizing DuPont 1900 Series Resistor Compositions in conjunction with DuPont 5704 Dielectric printed on alumina substrate material.

FUTURE WORK

Future work to be done to maintain state-of-the-art capability will include the evaluation of the DuPont 2000 Series Resistor Compositions for use with existing thick film processes and materials (specifically the DuPont 5704 Dielectric Composition printed on alumina substrates) at AlliedSignal's Federal Manufacturing And Technologies.

Future work to be done to develop additional capabilities will include evaluating the compatibility of DuPont 2000 Series Resistors with different thick film processes and materials not in use at AlliedSignal Federal Manufacturing & Technologies

APPENDIX 1

SUMMARY DATA FOR DUPONT 1900 RESISTOR SERIES

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Firing Sensitivity - 2 Dielectrics (Unglazed)

% from Nominal Resistance

RESISTOR DECADE	DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
825 Degree C - 30 Minute Fire *	13.5	(27.1)	(10.0)	7.0	(14.3)	(7.9)
850 Degree C - 30 Minute Fire —	29.1	(29.2)	(29.6)	18.5	(3.0)	(22.6)
875 Degree C - 30 Minute Fire ○	19.2	13.0	(28.1)	33.0	32.7	7.3
850 Degree C - 60 Minute Fire —	38.0	5.7	(2.1)	26.6	4.9	(9.9)

Value in parenthesis is nominal sheet resistance

Data for All Geometry Combinations

Dried Target Thickness = 25 microns

Figure 1-1

NORMALIZED SHEET RESISTANCE - DUPONT 1900 SERIES

Firing Sensitivity - 2 Dielectrics (Unglazed)

% from Nominal Normalized Sheet Resistance

RESISTOR DECADE	DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
825 Degree C - 30 Minute Fire *	18.8	(24.9)	(6.1)	8.6	(17.4)	(8.2)
850 Degree C - 30 Minute Fire —	2.4	(20.7)	(29.7)	10.5	(3.5)	(18.9)
875 Degree C - 30 Minute Fire ○	18.9	6.1	(30.3)	27.3	24.5	2.7
850 Degree C - 60 Minute Fire —	27.0	(4.3)	(4.8)	18.4	(1.1)	(16.0)

Value in parenthesis is nominal sheet resistance

Data for All Geometry Combinations

Dried Target Thickness = 25 microns

Figure 1-2

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Sensitivity to Overglaze - 2 Dielectrics

% from Nominal Resistance

RESISTOR DECADE	DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
UNGLAZED (850 Deg. - 30 Min.)	29.1	(29.2)	(29.6)	18.5	(3.0)	(22.6)
GLAZED (850 Deg. - 30 Min.)	28.2	(28.2)	(27.0)	13.5	(1.3)	(12.6)

Value in parenthesis is nominal sheet resistance

Data for All Geometry Combinations

Dried Target Thickness = 25 microns

Figure 1-3

NORMALIZED SHEET RESISTANCE - DUPONT 1900

Sensitivity to Overglaze - 2 Dielectrics

% from Nominal Normalized Sheet Resistance

RESISTOR DECADE	DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
UNGLAZED (850 Deg. - 30 Min.)	2.4	(20.7)	(29.7)	10.5	(3.5)	(18.9)
GLAZED (850 Deg. - 30 Min.)	1.6	(19.5)	(27.4)	8.8	(2.0)	(22.2)

Value in parenthesis is nominal sheet resistance

Data for All Geometry Combinations

Dried Target Thickness = 25 microns

Figure 1-4

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Thickness Sensitivity - 2 Dielectrics (Unglazed)

% from Nominal Resistance

RESISTOR DECADE	DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
28 Micron Dried Thickness —	12.2	(33.0)	(35.8)	11.2	(7.5)	(29.8)
25 Micron Dried Thickness —	24.1	(30.7)	(33.4)	16.6	(3.0)	(23.2)
22 Micron Dried Thickness —	51.0	(24.0)	(19.5)	27.6	1.6	(14.9)

Value in parenthesis is nominal sheet resistance

Data Based on 850 Degree C Fire

Figure 1-5

THICKNESS RELATIONSHIP - DUPONT 1900 SERIES

Wet, Dried & Fired Thicknesses

RESISTOR DECADE	DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
WET THICKNESS —	41.0	43.0	42.3	42.7	45.3	46.0
DRIED THICKNESS —	24.6	28.0	25.3	24.3	25.0	24.3
FIRE THICKNESS *	15.7	13.7	14.0	13.3	16.0	17.0

Dried Target Thickness = 25 microns

Figure 1-6

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Print Lot Variability (Unglazed)

% from Nominal Resistance

RESISTOR DECADE		DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
Average(50 mil)	—	24.1	38.6	(33.4)	16.6	(3.0)	(23.2)
Average(25)	—	12.2	33.9	(35.8)	11.2	(7.6)	(30.0)
Average(100)	—	51.1	52.4	(19.5)	27.6	1.6	(15.0)

Fired at 850 Degrees C - 30 Minutes

Average Resistances for All Geometries

Figure 1-7

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Print Lot Variability (Unglazed)

% from Nominal Resistance

RESISTOR DECADE		DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
-3 Sigma(25)	—	(15.5)	7.1	(54.0)	1.6	(18.9)	(44.0)
Average(25)	—	12.2	33.9	(35.8)	11.2	(7.6)	(30.0)
+3 Sigma(25)	—	40.0	60.6	(17.4)	20.8	3.8	(16.0)

Average +/- 3 Sigma Resistances

Fired at 850 Degrees C - 30 Minutes

Based on 25 mil Geometry

Figure 1-8

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Print Lot Variability (Unglazed)

% from Nominal Resistance

RESISTOR DECADE		DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
-3 Sigma (50 mil)	—	(13.7)	5.5	(49.8)	6.3	(20.5)	(45.0)
Average(50 mil)	—	24.1	38.6	(33.4)	16.6	(3.0)	(23.2)
+3 Sigma(50 mil)	⊕	61.9	71.8	(17.2)	26.8	14.2	(1.4)

Average +/- 3 Sigma Resistances
 Fired at 850 Degrees C - 30 Minutes
 Based on 50 mil Geometry

Figure 1-9

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Print Lot Variability (Unglazed)

% from Nominal Resistance

RESISTOR DECADE		DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
-3 Sigma (100)	—	14.6	8.4	(52.6)	10.4	(19.0)	(32.5)
Average(100)	—	51.1	52.4	(19.5)	27.6	1.6	(15.0)
+3 Sigma(100)	⊕	87.5	96.5	13.5	44.9	22.3	2.6

Average +/- 3 Sigma Resistances
 Fired at 850 Degrees C - 30 Minutes
 Based on 100 mil Geometry

Figure 1-10

RESISTOR GEOMETRY & ORIENTATION AFFECTS

DUPONT 1900 SERIES

% from Nominal Resistance

RESISTOR DECADADE	DUPONT 1911 (10)	DUPONT 1921 (100)	DUPONT 1931 (1K)	DUPONT 1939 (10K)	DUPONT 1949 (100K)	DUPONT 1959 (1Meg)
25 MIL PARALLEL	(3.8)	(6.8)	(39.6)	17.3	24.1	(5.2)
25 MIL PERPENDICULAR	5.8	(2.4)	(40.1)	19.7	21.0	(14.7)
50 MIL PARALLEL	7.6	4.7	(35.3)	25.5	32.6	4.0
50 MIL PERPENDICULAR	20.2	12.6	(35.4)	34.2	31.6	4.5
100 MIL PARALLEL	35.6	32.3	(19.3)	46.2	49.7	31.2
100 MIL PERPENDICULAR	43.8	38.9	(9.4)	53.7	43.3	35.4

Samples were Fired at 850 deg. C & Unglazed

Orientation Refers to Resistor Length Direction

Orientation is Relative to Squeegee Travel

Figure 1-11

APPENDIX 2

DUPONT 1400, 1900, & 2000 RESISTOR SERIES COMPARATIVE DATA

UNTRIMMED SHEET RESISTANCE

DUPONT 1400 1900 & 2000 SERIES RESISTORS

% from Nominal

Data for Unglazed Samples

Data for All Geometry Combinations

Data Format indicates Substrate & Firing Profile

Figure 2-1

UNTRIMMED SHEET RESISTANCE

DUPONT 1400 & 1900 SERIES RESISTORS

% from Nominal

DuPont 1400 Fired @ 850 Deg. C - 60 Minutes

DuPont 1900 Fired @ 850 Deg. C - 30 Minutes

Data for All Geometry Combinations

Figure 2-2

UNTRIMMED SHEET RESISTANCE - DUPONT 1900 SERIES

Substrate Comparison - LTCC vs. 2 Layers of Die.

RESISTOR DECADE	10 OHM	100 OHM	1K OHM	10K OHM	100K OHM	1 MEGOHM
1900 SERIES (2 DIE.) - 850/30 *	29.1	(29.2)	(29.6)	18.5	(3.0)	(22.6)
1900 SERIES (LTCC) -850/30 ○	36.9	14.5	(9.8)	7.2	9.8	(4.7)

Data for Unglazed Samples

Data for All Geometry Combinations

Data Format indicates Substrate & Firing Profile

Figure 2-3

APPENDIX 3

DUPONT 1911 RESISTOR PRINT DATA

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1911 (10 OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	4.4	9.8	26.3
825/30 GLAZED	3.0	8.2	24.4
850/30 UNGLAZED	12.2	24.1	51.0
850/30 GLAZED	9.5	23.2	51.9
875/30 UNGLAZED	3.0	14.0	40.5
875/30 GLAZED	1.4	13.1	39.7
850/60 UNGLAZED	21.9	32.9	59.2
850/60 GLAZED	20.6	31.3	57.6

Nominal as-fired resistance is 20 ohms.

Target Dried Thickness is 25 Microns

Figure 3-1

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1911 (10 OHMS PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	20.9	22.0	25.3
825/30 GLAZED	20.6	21.6	24.9
850/30 UNGLAZED	22.4	24.8	30.2
850/30 GLAZED	21.9	24.6	30.4
875/30 UNGLAZED	20.6	22.8	28.1
875/30 GLAZED	20.3	22.6	27.9
850/60 UNGLAZED	24.4	26.6	31.8
850/60 GLAZED	24.1	26.3	31.5

Nominal as-fired resistance is 20 ohms.

Target Dried Thickness is 25 Microns

Figure 3-2

NORMALIZED SHEET RESISTANCE

DUPONT 1911 (10 OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	36.3	15.0	5.0
825/30 GLAZED	30.8	13.3	3.0
850/30 UNGLAZED	9.5	(2.3)	0.0
850/30 GLAZED	6.7	(3.0)	1.0
875/30 UNGLAZED	16.6	15.1	24.9
875/30 GLAZED	15.0	14.0	24.0
850/60 UNGLAZED	28.3	20.7	32.1
850/60 GLAZED	26.8	19.3	30.8

Nominal as-fired resistance is 20 ohms.

Target Dried Thickness is 25 Microns

Figure 3-3

NORMALIZED SHEET RESISTANCE

DUPONT 1911 (10 OHMS PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	13.6	11.5	10.5
825/30 GLAZED	13.1	11.3	10.3
850/30 UNGLAZED	10.9	9.8	10.0
850/30 GLAZED	10.7	9.7	10.1
875/30 UNGLAZED	11.7	11.5	12.5
875/30 GLAZED	11.5	11.4	12.4
850/60 UNGLAZED	12.8	12.1	13.2
850/60 GLAZED	12.7	11.9	13.1

Nominal as-fired resistance is 20 ohms.

Target Dried Thickness is 25 Microns

Figure 3-4

THICKNESS & RESISITIVITY COMPARISON

DUPONT 1911 (10 OHMS PER SQUARE)

Actual Values - 2 Dielectrics

DRIED THICKNESS	29 Microns	25 Microns	21 Microns
825/30 UNGLAZED	20.9	22.0	25.3
825/30 GLAZED	20.6	21.6	24.9
850/30 UNGLAZED	22.4	24.8	30.2
850/30 GLAZED	21.9	24.6	30.4
875/30 UNGLAZED	20.6	22.8	28.1
875/30 GLAZED	20.3	22.6	27.9
850/60 UNGLAZED	24.4	26.6	31.8
850/60 GLAZED	24.1	26.3	31.5

Figure 3-5

THICKNESS RELATIONSHIP

DUPONT 1911 (10 OHMS PER SQUARE)

Printed on 2 Dielectrics

GEOMETRY	25 MIL	50 MIL	100 MIL
WET THICKNESS	47	41	35
DRIED THICKNESS	29	25	20
FIRE THICKNESS	19	16	12

Figure 3-6

APPENDIX 4

DUPONT 1921 RESISTOR PRINT DATA

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1921 (100 OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 ML	50 ML	100 ML
825/30 UNGLAZED	(33.0)	(29.5)	(18.7)
825/30 GLAZED	(34.6)	(30.8)	(21.0)
850/30 UNGLAZED	(33.0)	(30.7)	(24.0)
850/30 GLAZED	(33.0)	(29.5)	(22.0)
875/30 UNGLAZED	(4.4)	8.5	35.0
875/30 GLAZED	(5.0)	8.0	34.5
850/60 UNGLAZED	(9.0)	1.5	25.0
850/60 GLAZED	(9.0)	1.5	24.5

Nominal as-fired resistance is 200 ohms.

Target Dried Thickness is 25 microns

Figure 4-1

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1921 (100 OHMS PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 ML	50 ML	100 ML
825/30 UNGLAZED	134	141	162
825/30 GLAZED	131	138	158
850/30 UNGLAZED	134	139	152
850/30 GLAZED	134	141	156
875/30 UNGLAZED	191	217	270
875/30 GLAZED	190	216	269
850/60 UNGLAZED	162	203	250
850/60 GLAZED	162	203	249

Nominal as-fired resistance is 200 ohms.

Target Dried Thickness is 25 microns

Figure 4-2

NORMALIZED SHEET RESISTANCE

DUPONT 1921 (100 OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 ML	50 ML	100 ML
825/30 UNGLAZED	(15.2)	(27.7)	(31.8)
825/30 GLAZED	(16.7)	(28.4)	(33.2)
850/30 UNGLAZED	(12.1)	(23.8)	(26.2)
850/30 GLAZED	(11.8)	(22.3)	(24.5)
875/30 UNGLAZED	10.3	7.4	0.7
875/30 GLAZED	9.8	8.5	0.3
850/60 UNGLAZED	(7.0)	(8.8)	3.0
850/60 GLAZED	(7.2)	(8.8)	2.6

Nominal as-fired sheet resistance is 100 ohms.

Figure 4-3

NORMALIZED SHEET RESISTANCE

DUPONT 1921 (100 OHMS PER SQUARE)

Actual Values (Ohms/Square) - 2 Dielectrics

RESISTOR GEOMETRY	25 ML	50 ML	100 ML
825/30 UNGLAZED	85	72	68
825/30 GLAZED	83	72	67
850/30 UNGLAZED	88	76	74
850/30 GLAZED	88	78	76
875/30 UNGLAZED	110	107	101
875/30 GLAZED	110	108	100
850/60 UNGLAZED	93	91	103
850/60 GLAZED	93	91	103

Nominal as-fired sheet resistance is 100 ohms.

Figure 4-4

THICKNESS & RESISITIVITY COMPARISON

DUPONT 1921 (100 OHMS PER SQUARE)

Actual Values - 2 Dielectrics

DRIED THICKNESS	29 Microns	25 Microns	21 Microns
825/30 UNGLAZED	134	141	162
825/30 GLAZED	131	138	158
850/30 UNGLAZED	134	139	152
850/30 GLAZED	134	141	156
875/30 UNGLAZED	191	217	270
875/30 GLAZED	190	216	269
850/60 UNGLAZED	182	203	250
850/60 GLAZED	182	203	249

Figure 4-5

THICKNESS RELATIONSHIP

DUPONT 1921 (100 OHMS PER SQUARE)

Printed on 2 Dielectrics

GEOMETRY	25 MIL	50 MIL	100 MIL
WET THICKNESS —	48	43	38
DRIED THICKNESS —	32	28	24
FIRE THICKNESS —	16	14	11

Figure 4-6

APPENDIX 5

DUPONT 1931 RESISTOR PRINT DATA

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1931 (1K OHM PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 ML	50 ML	100 ML
825/30 UNGLAZED	(17.6)	(13.6)	1.0
825/30 GLAZED	(18.9)	(14.4)	0.0
850/30 UNGLAZED	(35.8)	(33.4)	(19.5)
850/30 GLAZED	(35.2)	(30.8)	(15.0)
875/30 UNGLAZED	(38.2)	(32.5)	(13.6)
875/30 GLAZED	(38.5)	(32.6)	(13.9)
850/60 UNGLAZED	(12.7)	(9.9)	16.4
850/60 GLAZED	(13.4)	(10.6)	15.6

Nominal as-fired resistance is 2,000 ohms.

Target Dried Thickness is 25 microns

Figure 5-1

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1931 (1K OHM PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 ML	50 ML	100 ML
825/30 UNGLAZED	1,647	1,727	2,020
825/30 GLAZED	1,622	1,711	1,993
850/30 UNGLAZED	1,285	1,331	1,610
850/30 GLAZED	1,296	1,345	1,700
875/30 UNGLAZED	1,236	1,350	1,729
875/30 GLAZED	1,230	1,348	1,722
850/60 UNGLAZED	1,746	1,802	2,328
850/60 GLAZED	1,731	1,787	2,311

Nominal as-fired resistance is 2,000 ohms.

Target Dried Thickness is 25 microns

Figure 5-2

NORMALIZED SHEET RESISTANCE

DUPONT 1931 (1K OHM PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	5.9	(10.4)	(13.9)
825/30 GLAZED	4.3	(11.2)	(15.1)
850/30 UNGLAZED	(14.9)	(34.2)	(39.9)
850/30 GLAZED	(14.2)	(31.6)	(36.5)
875/30 UNGLAZED	(29.2)	(34.0)	(27.7)
875/30 GLAZED	(29.5)	(34.1)	(28.0)
850/60 UNGLAZED	(4.8)	(13.7)	4.2
850/60 GLAZED	(5.6)	(14.5)	3.4

Nominal as-fired resistance is 2,000 ohms.

Target Dried Thickness is 25 microns

Figure 5-3

NORMALIZED SHEET RESISTANCE

DUPONT 1931 (1K OHM PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	1,059	896	861
825/30 GLAZED	1,043	888	849
850/30 UNGLAZED	851	658	601
850/30 GLAZED	858	654	635
875/30 UNGLAZED	708	660	723
875/30 GLAZED	705	659	720
850/60 UNGLAZED	952	863	1,042
850/60 GLAZED	944	855	1,034

Nominal as-fired resistance is 2,000 ohms.

Target Dried Thickness is 25 microns

Figure 5-4

THICKNESS & RESISITIVITY COMPARISON

DUPONT 1931 (1K OHM PER SQUARE)

Actual Values - 2 Dielectrics

Figure 5-5

THICKNESS RELATIONSHIP

DUPONT 1931 (1K OHM PER SQUARE)

2 Dielectrics

GEOMETRY	25 MIL	50 MIL	100 MIL
WET THICKNESS —	48	43	36
DRIED THICKNESS —	32	25	19
FIRED THICKNESS —	16	14	12

Figure 5-6

APPENDIX 6

DUPONT 1939 RESISTOR PRINT DATA

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1939 (10K OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	1.8	5.4	13.7
825/30 GLAZED	1.0	4.5	12.6
650/30 UNGLAZED	11.2	16.6	27.6
650/30 GLAZED	6.3	12.3	21.6
875/30 UNGLAZED	17.4	30.0	51.4
875/30 GLAZED	16.3	29.0	50.4
650/60 UNGLAZED	19.7	24.1	36.0
650/60 GLAZED	18.7	23.0	34.9

Nominal as-fired resistance is 20,000 ohms.

Target Dried Thickness is 25 microns

Figure 6-1

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1939 (10K OHMS PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	20,366	21,083	22,741
825/30 GLAZED	20,183	20,908	22,518
650/30 UNGLAZED	22,246	23,316	25,529
650/30 GLAZED	21,258	22,458	24,366
875/30 UNGLAZED	23,475	26,000	30,275
875/30 GLAZED	23,258	25,791	30,083
650/60 UNGLAZED	23,931	24,821	27,203
650/60 GLAZED	23,733	24,599	26,975

Nominal as-fired resistance is 20,000 ohms.

Target Dried Thickness is 25 microns

Figure 6-2

NORMALIZED SHEET RESISTANCE

DUPONT 1939 (10K OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	23.0	5.6	(2.7)
825/30 GLAZED	22.3	4.7	(3.5)
850/30 UNGLAZED	27.4	9.8	(5.7)
850/30 GLAZED	21.7	5.8	(1.0)
875/30 UNGLAZED	28.9	24.8	28.1
875/30 GLAZED	27.7	23.8	27.3
850/60 UNGLAZED	22.4	16.3	16.6
850/60 GLAZED	21.4	15.3	15.6

Nominal as-fired resistance is 20,000 ohms.

Target Dried Thickness is 25 microns

Figure 6-3

NORMALIZED SHEET RESISTANCE

DUPONT 1939 (10K OHMS PER SQUARE) - ON LTCC

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	12,339	10,560	9,728
825/30 GLAZED	12,228	10,473	9,650
850/30 UNGLAZED	12,737	10,979	9,434
850/30 GLAZED	12,171	10,575	9,004
875/30 UNGLAZED	12,887	12,477	12,813
875/30 GLAZED	12,768	12,377	12,732
850/60 UNGLAZED	12,240	11,630	11,660
850/60 GLAZED	12,139	11,526	11,562

Nominal as-fired resistance is 20,000 ohms.

Target Dried Thickness is 25 microns

Figure 6-4.

THICKNESS & RESISITIVITY COMPARISON

DUPONT 1939 (10K OHMS PER SQUARE)

Actual Values - 2 Dielectrics

DRIED THICKNESS	28 Microns	25 Microns	22 Microns
825/30 UNGLAZED	20,366	21,083	22,741
825/30 GLAZED	20,183	20,908	22,518
850/30 UNGLAZED	22,246	23,316	25,529
850/30 GLAZED	21,258	22,458	24,366
875/30 UNGLAZED	23,475	26,000	30,275
875/30 GLAZED	23,258	25,791	30,083
850/60 UNGLAZED	23,931	24,821	27,203
850/60 GLAZED	23,733	24,599	26,975

Figure 6-5

THICKNESS RELATIONSHIP

DUPONT 1939 (10K OHMS PER SQUARE)

Printed on 2 Dielectrics

GEOMETRY	25 MIL	50 MIL	100 MIL
WET THICKNESS —	49	42	37
DRIED THICKNESS —	30	24	19
FIRE THICKNESS —	15	13	12

Figure 6-6

APPENDIX 7

DUPONT 1949 RESISTOR PRINT DATA

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1949 (100K OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	(21.0)	(16.0)	(6.0)
825/30 GLAZED	(21.7)	(16.2)	(6.6)
850/30 UNGLAZED	(7.5)	(3.0)	1.6
850/30 GLAZED	(7.0)	(1.6)	4.8
875/30 UNGLAZED	20.0	30.0	48.0
875/30 GLAZED	19.1	29.2	46.8
850/60 UNGLAZED	(1.2)	3.4	12.5
850/60 GLAZED	(1.9)	2.7	11.8

Nominal as-fired resistance is 200,000 ohms.

Target Dried Thickness is 25 microns

Figure 7-1

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1949 (100K OHMS PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	158,025	168,963	187,700
825/30 GLAZED	156,691	167,608	186,317
850/30 UNGLAZED	184,916	194,000	203,333
850/30 GLAZED	185,916	196,750	209,500
875/30 UNGLAZED	240,075	260,341	296,658
875/30 GLAZED	238,225	258,391	293,633
850/60 UNGLAZED	197,508	206,917	225,084
850/60 GLAZED	196,191	205,440	223,491

Nominal as-fired resistance is 200,000 ohms.

Target Dried Thickness is 25 microns

Figure 7-2

NORMALIZED SHEET RESISTANCE

DUPONT 1949 (100K OHMS PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	(9.9)	(18.0)	(24.2)
825/30 GLAZED	(10.7)	(18.6)	(25.3)
850/30 UNGLAZED	4.2	(2.8)	(11.9)
850/30 GLAZED	4.7	(1.4)	(9.2)
875/30 UNGLAZED	26.7	25.1	21.7
875/30 GLAZED	25.7	24.1	20.9
850/60 UNGLAZED	2.3	(3.7)	(2.0)
850/60 GLAZED	1.6	(4.4)	(2.7)

Nominal as-fired resistance is 200,000 ohms.

Target Dried Thickness is 25 microns

Figure 7-3

NORMALIZED SHEET RESISTANCE

DUPONT 1949 (100K OHMS PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	90,059	82,046	75,784
825/30 GLAZED	89,299	81,379	74,659
850/30 UNGLAZED	104,174	97,193	88,116
850/30 GLAZED	104,737	98,571	90,790
875/30 UNGLAZED	126,716	125,108	121,767
875/30 GLAZED	125,740	124,066	120,872
850/60 UNGLAZED	102,328	96,275	97,964
850/60 GLAZED	101,646	95,566	97,270

Nominal as-fired resistance is 200,000 ohms.

Target Dried Thickness is 25 microns

Figure 7-4

THICKNESS & RESISTIVITY COMPARISON

DUPONT 1949 (100K OHMS PER SQUARE)

Actual Values - 2 Dielectrics

Figure 7-5

THICKNESS RELATIONSHIP

DUPONT 1949 (100K OHMS PER SQUARE)

Printed on 2 Dielectrics

GEOMETRY	25 MIL	50 MIL	100 MIL
WET THICKNESS —	50	46	40
DRIED THICKNESS —	28	25	22
FIRE THICKNESS —	19	16	13

Figure 7-6

APPENDIX 8

DUPONT 1959 RESISTOR PRINT DATA

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1959 (1MEG OHM PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	(21.2)	(11.4)	8.8
825/30 GLAZED	(21.6)	(11.7)	8.5
850/30 UNGLAZED	(29.8)	(23.2)	(14.9)
850/30 GLAZED	(31.5)	(26.3)	(19.9)
875/30 UNGLAZED	(11.7)	2.2	31.3
875/30 GLAZED	(11.8)	2.4	31.2
850/60 UNGLAZED	(20.2)	(13.7)	4.2
850/60 GLAZED	(20.7)	(14.0)	3.6

Nominal as-fired resistance is 2,000,000 ohms.

Target Dried Thickness is 25 microns

Figure 8-1

UNTRIMMED RESISTANCE SUMMARY

DUPONT 1959 (1MEG OHM PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	1,575,833	1,771,666	2,177,500
825/30 GLAZED	1,568,333	1,765,833	2,170,833
850/30 UNGLAZED	1,403,333	1,536,666	1,702,500
850/30 GLAZED	1,370,833	1,474,166	1,601,666
875/30 UNGLAZED	1,766,166	2,043,750	2,627,500
875/30 GLAZED	1,763,833	2,047,500	2,624,583
850/60 UNGLAZED	1,596,666	1,726,666	2,083,333
850/60 GLAZED	1,586,565	1,719,646	2,071,783

Nominal as-fired resistance is 2,000,000 ohms.

Target Dried Thickness is 25 microns

Figure 8-2

NORMALIZED SHEET RESISTANCE

DUPONT 1959 (1MEG OHM PER SQUARE)

Percent from Nominal - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	(8.3)	(10.0)	(6.2)
825/30 GLAZED	(8.7)	(10.3)	(6.5)
850/30 UNGLAZED	(10.2)	(18.9)	(27.6)
850/30 GLAZED	(12.6)	(22.2)	(31.9)
875/30 UNGLAZED	(0.6)	1.1	7.6
875/30 GLAZED	(0.9)	1.4	7.5
850/60 UNGLAZED	(14.0)	(20.2)	(13.7)
850/60 GLAZED	(14.6)	(20.5)	(14.2)

Nominal as-fired resistance is 2,000,000 ohms.

Target Dried Thickness is 25 microns

Figure 8-3

NORMALIZED SHEET RESISTANCE

DUPONT 1959 (1MEG OHM PER SQUARE)

Actual Values - 2 Dielectrics

RESISTOR GEOMETRY	25 MIL	50 MIL	100 MIL
825/30 UNGLAZED	916,718	900,192	937,981
825/30 GLAZED	912,355	897,228	935,109
850/30 UNGLAZED	897,522	810,783	724,044
850/30 GLAZED	874,452	777,807	681,162
875/30 UNGLAZED	994,218	1,011,824	1,075,748
875/30 GLAZED	991,278	1,013,681	1,074,554
850/60 UNGLAZED	859,510	797,973	862,976
850/60 GLAZED	854,072	794,728	858,229

Nominal as-fired resistance is 2,000,000 ohms.

Target Dried Thickness is 25 microns

Figure 8-4

THICKNESS & RESISITIVITY COMPARISON

DUPONT 1959 (1MEG OHM PER SQUARE)

Actual Values - 2 Dielectrics

DRIED THICKNESS	25	25	20
825/30 UNGLAZED	1,575,833	1,771,666	2,177,500
825/30 GLAZED	1,568,333	1,765,833	2,170,833
850/30 UNGLAZED	1,403,333	1,536,666	1,702,500
850/30 GLAZED	1,370,833	1,474,166	1,601,666
875/30 UNGLAZED	1,766,166	2,043,750	2,627,500
875/30 GLAZED	1,763,833	2,047,500	2,624,583
850/60 UNGLAZED	1,596,666	1,726,666	2,083,333
850/60 GLAZED	1,586,565	1,719,646	2,071,873

Figure 8-5

THICKNESS RELATIONSHIP

DUPONT 1959 (1MEG OHM PER SQUARE)

2 Dielectrics

GEOMETRY	25 MIL	50 MIL	100 MIL
WET THICKNESS —	53	45	40
DRIED THICKNESS —	28	25	20
FIRED THICKNESS —	19	17	15

Figure 8-6

APPENDIX B

Characterization of Laser Trimming of DuPont 1900 Series Resistors on Two layers of DuPont 5704 Dielectric

By Sam W. Bandler

July 1996

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SUMMARY

Samples were printed, using Du Pont 1911, 1921, 1931, 1939, 1949 and 1959 resistor pastes, on 2 layers of Du Pont 5704 dielectric on 96% alumina ceramic substrates. The resistivity of the paste is 10 Ohms/square, 100 Ohms/square, 1K Ohms/square, 10K Ohms/square, 100K Ohms/square, and 1M Ohms/square, respectively. The samples were divided into four groups and fired at 825° C for 30 minutes, 850° C for 30 minutes, 850° C for 60 minutes, or 875° C for 30 minutes. The resistors on half the samples of each paste decade were over-coated with Du Pont 5415D glaze.

Samples were trimmed using various laser settings for beam speed, pulse rate, and power to determine the range of acceptable operation.

Samples were subjected to the following tests:

- Isolation resistance.
- 24 hour short term drift.
- Temperature shock (solder pot shock test): 25°C to 268°C, 268°C for 15 seconds and back to 25°C.
- Temperature cycle: -50°C to 125°C with approximately 5 seconds ramp time, ten cycles, 15 minutes minimum at each temperature extreme.
- Temperature coefficient of resistance (TCR) measured and calculated at -55°C, 25°C, and 125°C.
- 1000 hour aging test at 150°C, ambient humidity.

Resistance was measured after each test, and the change in resistance was calculated.

Using visual requirements, isolation resistance, and the results of the above tests, the range for acceptable operation was determined for the 1921 through 1959 pastes. Testing was discontinued on the 1911 paste because the cracks that occurred in the paste after firing were determined to be detrimental to resistor stability.

An operating point for each paste, glazed and unglazed, was selected based on the above results, and additional samples were trimmed at these points. These samples were tested, using the above tests, through the 1000 hour aging test. From this data it was possible to estimate the best possible resistor tolerance and yield.

Based on the results of these tests the following conclusions and recommendations are made:

- 1911 paste should not be used because of paste cracking after firing leading to poor resistor stability.
- The minimum resistor dimension should be 0.050 inches.

- Resistors should be glaze over-coated to maximize stability and minimize changes in TCR due to laser trimming.
- TCR, for trimmed/glazed samples, was determined to be within the manufacturer's specification of $\pm 100 \text{ ppm}^\circ\text{C}$.
- Preliminary estimates, for glazed samples, indicate that resistor tolerances as tight as $\pm 1\%$ are possible with 100% yield for resistors made with 1921 through 1959 pastes. Since this is preliminary, it is recommended initially that tolerances should not be tighter than $\pm 2\%$.

DISCUSSION

Scope and Purpose

The objective of this project was to report on the characterization of laser trimming resistors printed with Du Pont 1900 series resistor pastes on Du Pont 5704 dielectric on 96% alumina substrates.

Prior Work

The results of a study of Du Pont 1700 and 1900 series resistor pastes printed on Du Pont 5704 dielectric was conducted by Du Pont. The results were described in a report entitled "Laser Trimming Resistors Over Dielectric". It was published in the October, 1985 issue of Hybrid Circuit Technology.¹

Du Pont 1700 series resistor pastes have been printed on dielectric at FM&T. These resistors were laser trimmed, and the process characterized in 1989.

A related study was conducted on Du Pont 1900 series resistors printed on Du Pont 951 LTCC substrates. The samples were printed and laser trimmed by CTS Corp. and the testing was conducted by FM&T.

Activity

Test Sample Preparation

Du Pont 1911, 1921, 1931, 1939, 1949, and 1959 resistor pastes were used to print resistors on approximately 720 test samples on 2 layers of Du Pont 5704 dielectric on 96% alumina substrate. The samples were divided into four groups and fired at 825° C for 30 minutes (825/30), 850° C for 30 minutes (850/30), 850° C for 60 minutes (850/60), or 875° C for 30 minutes (875/30). The resistors on half of the samples from each resistor paste decade were over-coated with Du Pont 5415D glaze

Each test sample, shown in Figure 1, contains twelve resistors with a length-to-width aspect ratio of 2:1. There are three different resistor widths, 0.025 inch (25 mil), 0.050 inch (50 mil) and 0.1 inch (100 mil), on the sample.

Figure 1

The resistors on all samples were measured to determine the effects of the four firing profiles on initial resistance.

The 850° C/60 minute profile, initially the preferred profile, was chosen to develop the laser trimming envelope. The resistors on approximately twenty samples from each paste, both glazed and unglazed, were laser trimmed. They were trimmed using various combinations of pulse rate, beam speed, and power. Two resistors were cut using each combination. The 0.025 inch resistor was cut completely in half, and the 0.05 inch resistor was cut to raise its value 1.4 times its original value. The 0.1 inch resistor was left untrimmed to be used for reference. The trimming was accomplished on a Teradyne model W419 laser trim system.

The acceptable operating range of the laser was determined from these samples for the 1921 through 1959 pastes. The laser trims were evaluated using visual criteria, isolation resistance, and stability as determined by tests described later in this report. An acceptable operating range could not be defined for samples printed with the 1911 paste and trimmed using standard trimming techniques. In addition, it was noted that the resistors were cracked. Resistors printed with 1911 paste in another study were also cracked. It was determined, in this study, that cracks in resistors are detrimental to resistor stability. No further tests were conducted on this paste.

Having established the operating range, an operating point was selected, and an additional 36 samples were trimmed at this point. The samples were selected from those fired using the 850° C/30 minute profile. This profile became the preferred profile as the result of initial data from this evaluation and recommendations from Du Pont. The samples were from the 1921 through 1959

paste decades, both glazed and unglazed. Resistor R4 was cut in half while resistors R5, R7, R8, R10, R11, R1 and R2 were trimmed to increase their value approximately 1.4 times. Resistors R6, R9, R12, and R3 were left untrimmed to be used for reference. All resistors were tested and evaluated like the first group to determine the tolerance and yield that might be expected.

Test Descriptions

The samples trimmed for the operating envelope and the samples trimmed at the operating point were subjected to the following tests:

The resistor values on all samples, trimmed and untrimmed, were measured on a Teradyne W419 Laser Trim System within a few seconds of having been laser trimmed. This measurement will hereafter be referred to as $T\emptyset$.

The samples were remeasured again approximately 24 hours later, and the change in resistance was calculated. This was done to determine the ability to repeatably measure them and to obtain some measure of their off-the-shelf stability. In past studies of other resistor pastes, the largest change in resistance typically occurred during the first 24 hours.

Each sample was then subjected to a solder pot shock test. This test involved placing each test sample individually on molten solder heated to approximately 268°C for 15 seconds. The sample was removed and placed on a stainless steel table top at approximately 25°C and allowed to cool. All of the resistors were remeasured, and the change in resistance, compared to $T\emptyset$, was calculated.

The test samples were then subjected to a temperature cycle test. The test apparatus consisted of two interconnected test chambers. One chamber was set to -50°C while the other was set to 125°C. A cycle consisted of moving the test samples from one chamber to the other and then back. The approximate transport time was five seconds. The samples were held at each temperature extreme a minimum of 15 minutes. Upon completion of this test, the resistors were again measured, and the change from $T\emptyset$ was calculated.

One sample from each paste decade was removed from the samples trimmed at the operating point. One trimmed and one untrimmed resistor was tested from each sample. These were used to determine the temperature coefficient of resistance (TCR) for the resistors from each paste decade. The TCR test involved measuring the resistors at 25°C. The samples were then heated to 125°C and allowed to stabilize at that temperature for approximately 30 minutes. The resistors were measured at this temperature. The samples were then cooled to -55°C and allowed to stabilize at this temperature for approximately 30

minutes. The resistors were measured while at this temperature. The following formulas were used:

$$\text{hot TCR(ppm/}^{\circ}\text{C)} = \frac{R_{125^{\circ}} - R_{25^{\circ}}}{R_{25^{\circ}}} \times 10,000$$

$$\text{cold TCR(ppm/}^{\circ}\text{C)} = \frac{(R_{-55^{\circ}}) - R_{25^{\circ}}}{R_{25^{\circ}}} \times (-12,500).$$

The samples were subjected to the 1000 hour aging test. The samples were placed in an oven heated to 150°C. At intervals of 200, 600, and 1000 hours the samples were removed from the oven and allowed to cool to room temperature. The resistors were measured, and the change compared to TØ was calculated.

The results of each of the tests are shown in the graphs in the appendices at the end of this report. The results are arranged by paste decade in Appendices A through F. Appendix G contains the TCR data.

Requirements

There were two main requirements used when considering the ability of a combination of laser parameters to make an acceptable trim. They were visual requirements and isolation resistance.

Visual (Viewed at 30X Magnification)

- Laser kerf free of obvious debris.
- Laser kerf free of bridges (continuous laser kerf).
- No continuous grooving of the dielectric in the kerf.
- The width of reflowed resistor material on either side of the kerf shall be less than the kerf width.

Isolation Resistance

Isolation resistance is the value of the resistor that has been cut completely in half. Depending upon the combination of laser parameters selected and the resistor material, the value of the isolation resistance will range from the design value of the resistor to some greater value (typically greater than 32 Meg Ohms).

As the combination of laser parameters is adjusted to cause increasing energy to be applied to the resistor, the value of the isolation resistance increases from a minimum to some larger value. Increasing laser energy cuts deeper into the

resistor. At some value of laser energy, the resistor material is removed completely from the laser kerf, and there is a several orders of magnitude increase in resistance. This is the minimum laser energy considered sufficient to trim resistors.

Application of Requirements

The lower end of the operating envelope is determined by the combination of laser parameters that result in the minimum energy necessary to produce an isolated trim and meet the visual requirements for kerf cleanliness.

The upper end of the operating envelope is determined by the combination of laser parameters that result in the maximum energy that can produce laser trims that meet all the requirements.

Observations - 1911 Paste

From the data shown in Appendix A the following general observations can be made:

- The 4 firing profiles produced resistors with values above the design value.
- Resistor values did not vary greatly over the 4 profiles.
- Resistor values increased as resistor size increased for each profile.
- The glaze overcoat does not effect post fired resistor values.
- No acceptable operating range was defined using standard trim techniques and visual requirements.
- Resistors, most notably 25 mil wide, contained numerous cracks that were determined in previous studies to be detrimental to resistor stability.

Observations - 1921 Paste

From the data shown in Appendix B the following general observations can be made:

- The 825/30 and 850/30 firing profiles produced resistors with values ranging from approximately -45% to +5% from nominal.
- The 850/60 and 875/30 firing profiles produced resistors with values ranging from -25% to +50% from nominal.
- Resistor values increased as resistor size increased for each profile.
- The glaze overcoat does not effect post fired resistor values.
- An acceptable operating range was established for glazed and unglazed samples.

- Laser trimming resistors, glazed or unglazed, reduces their stability.
- The stability of glazed samples trimmed within the envelope ranged from -.03% to +.38% change in resistance after all tests.
- The stability of unglazed samples trimmed within the envelope ranged from 0% to +.14% change in resistance after all tests.
- An operating point was selected for the glazed samples: a pulse rate of 3 KHz at 550 mW at .375 ips.
- An operating point was selected for the unglazed samples: a pulse rate of 4 KHz at 450 mW at .4 ips.
- The 25 mil wide resistors, both glazed and unglazed, trimmed at the operating point are less stable than the 50 mil wide resistors.
 - Stability for glazed 25 mil resistors ranged from 0% to +.39% change in resistance after all tests.
 - Stability for unglazed 25 mil resistors ranged from 0% to +.26% change in resistance after all tests.
 - Stability for glazed 50 mil resistors ranged from 0% to +.16% change in resistance after all tests.
 - Stability for unglazed 50 mil resistors ranged from -.05% to +.25% change in resistance after all tests.
- Glaze makes little difference in resistor stability.
- Laser trimming and glaze does not effect TCR.
- TCR is within the manufacturer's specification of $\pm 100 \text{ ppm}/^\circ\text{C}$.

Observations - 1931 Paste

From the data shown in Appendix C the following general observations can be made:

- The 825/30 firing profile produced resistors with values ranging from approximately -29% to +48% from nominal.
- The 850/30 firing profile produced resistors with values ranging from approximately -45% to +5% from nominal.
- The 850/60 firing profile produced resistors with values ranging from approximately -29% to +47% from nominal.
- The 875/30 firing profile produced resistors with values ranging from approximately -55% to +5% from nominal.
- Resistor values increased as resistor size increased for each profile.
- The glaze has little or no effect on post fired resistor values.
- An acceptable operating range was established for glazed and unglazed samples.
- Laser trimming resistors, glazed or unglazed, reduces their stability.

- The stability of glazed samples trimmed within the envelope ranged from +.03% to +.31% change in resistance after all tests.
- The stability of unglazed samples trimmed within the envelope ranged from 0% to +.12% change in resistance after all tests.
- An operating point was selected for the glazed samples: a pulse rate of 3 KHz at 550 mW at .375 ips.
- An operating point was selected for the unglazed samples: a pulse rate of 5 KHz at 475 mW at .25 ips.
- The 25 mil wide resistors, both glazed and unglazed, trimmed at the operating point are less stable than the 50 mil wide resistors.
 - Stability for glazed 25 mil resistors ranged from -.05% to +.44% change in resistance after all tests.
 - Stability for unglazed 25 mil wide resistors ranged from -.23% to +3.14% change in resistance after all tests.
 - Stability for glazed 50 mil resistors ranged from -.05% to +.16% change in resistance after all tests.
 - Stability for unglazed 50 mil wide resistors ranged from -.09% to +1.01% change in resistance after all tests.
- Glaze significantly improves trimmed resistor stability.
- Laser trimming and glaze does not effect TCR.
- TCR is within the manufacturer's specification of ± 100 ppm/ $^{\circ}$ C.

Observations - 1939 Paste

From the data shown in Appendix D the following general observations can be made:

- The 825/30 and 850/30 firing profiles produced resistors with values mostly above the design value ranging from approximately -10% to +35% from nominal.
- The 875/30 and 850/60 firing profiles produced resistors with values above the design value ranging from approximately +10% to +65% from nominal.
- Resistor values increased as resistor size increased for each profile.
- The glaze overcoat does not effect post fired resistor values.
- An acceptable operating range was established for glazed and unglazed samples.
- Laser trimming does not appear to have a large impact on resistor stability.
- The stability of glazed samples trimmed within the envelope ranged from +.08% to +.2% change in resistance after all tests.

- The stability of unglazed samples trimmed within the envelope ranged from +.05% to +.11% change in resistance after all tests.
- An operating point was selected for the glazed samples: a pulse rate of 3 KHz, at 550 mW at .375 ips.
- An operating point was selected for the unglazed samples: a pulse rate of 5 KHz at 475 mW at .25 ips.
- The 25 mil resistors, both glazed and unglazed, trimmed at the operating point had similar stability.
 - Stability for glazed 25 mil resistors ranged from -.13% to +.29% change in resistance after all tests
 - Stability for unglazed 25 mil resistors ranged from -.06% to +.49% change in resistance after all tests
 - Stability for glazed 50 mil resistors ranged from -.15% to +.21% change in resistance after all tests
 - Stability for unglazed 50 mil resistors ranged from -.12% to +.35% change in resistance after all tests
- Glaze improves laser trimmed resistor stability.
- Laser trimming and glaze does not effect TCR.
- TCR is within the manufacturer's specification of ± 100 ppm/ $^{\circ}$ C.

Observation - 1949 Paste

From the data shown in Appendix E the following general observations can be made:

- The 825/30 firing profile produced values, for 25 mil and 50 mil wide resistors, that were less than the nominal design value.
 - The values ranged from approximately -28% to -3% from nominal.
- The 825/30 firing profile produced values, for 100 mil wide resistors, that ranged from approximately -15% to +25% from nominal.
- The 850/30 firing profile produced resistor values that ranged from approximately -14% to +20% from nominal.
- The 875/30 firing profile produced values that ranged from 5% to 85% from nominal.
- The 850/60 firing profile produced results similar to the 850/30 profile with resistor values that ranged from approximately -8% to +30%.
- Resistor values increased as resistor size increased for each profile.
- The glaze overcoat does not effect post fired resistor values.
- An acceptable operating range was established for unglazed samples.
- An acceptable operating range was defined for the glazed samples, however the envelopes are smaller and area of overlap is much less.

- Laser trimming resistors, glazed or unglazed, reduces their stability.
- The stability of glazed samples trimmed within the envelope ranged from +.06% to +.31% change in resistance after all tests.
- The stability of unglazed samples trimmed within the envelope ranged from -.03% to +.27% change in resistance after all tests.
- An operating point was selected for the glazed samples: a pulse rate of 4 KHz at 625 mW at .4 ips.
- An operating point was selected for the unglazed samples: a pulse rate of 4 KHz at 450 mW at .4 ips.
- The 25 mil wide resistors, both glazed and unglazed, trimmed at the operating point are less stable than the 50 mil wide resistors.
 - Stability for glazed 25 mil wide resistors ranged from -.07% to +.74% change in resistance after all tests.
 - Stability for unglazed 25 mil wide resistors ranged from -.1% to +1.28% change in resistance after all tests.
 - Stability for glazed 50 mil wide resistors ranged from -.07% to +.25% change in resistance after all tests.
 - Stability for unglazed 50 mil wide resistors ranged from -.33% to +1.08% change in resistance after all tests.
- Glaze makes a significant improvement in trimmed resistor stability.
- Trimming unglazed resistors effects TCR
 - There is an approximate 30 ppm/°C difference between trimmed and untrimmed.
- There is no difference in TCR between trimmed and untrimmed on glaze samples.
- TCR is within the manufacturer's specification of ± 100 ppm/°C.

Observations - 1959 Paste

From the data shown in Appendix F the following general observations can be made:

- The 825/30 firing profile produced resistors with values ranging from above to below the nominal design value.
 - The values ranged from approximately -40% to +70% from nominal.
- The 850/30 firing profile produced resistors with values less than the design nominal ranging from approximately -40% to -5% from nominal.
- The 875/30 firing profile produced resistors with values similar to the 825/30 profile. They ranged from -25% to +45% from nominal
- The 850/60 firing profile produced resistors with values similar to the 825/30 profile ranging from approximately -35% to +55% from nominal.

- Resistor values increased as resistor size increased for each profile.
- The glaze overcoat does not effect post fired resistor values.
- An acceptable operating range was established for glazed and unglazed samples.
- Laser trimming resistors, glazed or unglazed, reduces their stability.
- The stability of resistors with glaze overcoat is significantly better than those that are unglazed.
 - The stability of glazed samples trimmed within the envelope ranged from +.04% to +.29% change in resistance after all tests.
 - The stability of unglazed samples trimmed within the envelope ranged from -.36% to +1.87% change in resistance after all tests.
- An operating point was selected for the glazed samples: a pulse rate of 3 KHz at 550 mW at .375 ips.
- An operating point was selected for the unglazed samples: a pulse rate of 4 KHz at 450 mW at .4 ips.
- The stability of untrimmed resistors for this paste decade is less than for the other paste decades.
 - The stability for glazed 100 mil wide resistors ranged from -.24% to +.27% change in resistance after all tests.
 - The stability for unglazed 100 mil wide resistors ranged from -.17% to +.3% change in resistance after all test.
- The 25 mil wide resistors, both glazed and unglazed, trimmed at the operating point are less stable than the 50 mil wide resistors.
 - Stability for glazed 25 mil resistors ranged from -.19% to +.67% change in resistance after all tests.
 - Stability for unglazed 25 mil wide resistors ranged from +.28% to 11.84% change in resistance after all tests.
 - Stability for glazed 50 mil wide resistors ranged from -.12% to +.54% change in resistance after all tests.
 - Stability for unglazed 50 mil wide resistors ranged from -.12% to 5.97% change in resistance after all tests.
- Glaze makes a significant improvement in trimmed resistor stability.
- Trimming unglazed resistors effects TCR
 - There is an approximate 100 ppm/°C difference between trimmed and untrimmed.
- There is no difference in TCR between trimmed and untrimmed on glaze samples.
- TCR is within the manufacturer's specification of ± 100 ppm/°C on trimmed glaze samples.

- TCR on trimmed unglazed samples does not meet manufacturer's specifications of ± 100 ppm/ $^{\circ}$ C at -55° C.

ACCOMPLISHMENTS

Data gathered and analyzed during this evaluation have established the following:

- Characterization of the laser trim process using Du Pont 1911, 1921, 1931, 1939, 1949, and 1959 resistor pastes on 2 layers of Du Pont 5704 dielectric printed on 96% alumina ceramic substrate.
- Characterization of the operating performance of these laser trimmed resistors.

Analysis of the data has allowed the following recommendations to be made:

- 1911 paste should not be used because of paste cracking after firing leading to poor resistor stability.
- The minimum resistor dimension should be 0.050 inches.
- Resistors should be glaze over-coated to maximize stability and minimize changes in TCR due to laser trimming.
- TCR, for trimmed/glazed samples, was determined to be within the manufacturer's specification of $\pm 100 \text{ ppm/}^\circ\text{C}$.
- Preliminary estimates, for glazed samples, indicate that resistor tolerances as tight as $\pm 1\%$ are possible with 100% yield for resistors made with 1921 through 1959 pastes. Since this is preliminary, it is recommended initially that tolerances should not be tighter than $\pm 2\%$.

FUTURE WORK

An additional characterization was conducted, in parallel with this effort, on Du Pont 2000 series resistors for use on low temperature cofired ceramic. Resistor performance on this substrate was very good. This resistor series will be evaluated on 2 layers on Du Pont 5704 dielectric on 96% alumina substrate to determine its potential. Dependent on the results of this evaluation, further evaluations of resistor performance on additional layers of dielectric will be conducted. This will determine the effects of dielectric thickness on resistor performance.

APPENDIX A

Test Results For The 1911 Paste

Pre Trim Distribution

825° C/30 Minute Profile

Figure 2

850° C/30 Minute Profile

Figure 3

875° C/30 Minute Profile

Figure 4

850° C/60 Minute Profile

Figure 5

Operating Envelope

No Glaze on Resistors

Figure 6

Glaze Over-coated Resistors

Figure 7

APPENDIX B

Test Results For The 1921 Paste

Pre Trim Distribution

825° C/30 Minute Profile

Figure 8

850° C/30 Minute Profile

Figure 9

875° C/30 Minute Profile

Figure 10

850° C/60 Minute Profile

Figure 11

Operating Envelope

No Glaze on Resistors

Figure 12

Glaze Over-coated Resistors

Figure 13

Stability For Resistors Trimmed Within The Operating Envelope - Unglazed

50 MIL WIDE RESISTOR (TRIMMED)

Figure 14

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 15

Stability For Resistors Trimmed Within The Operating Envelope - Glazed

50 MIL WIDE RESISTOR (TRIMMED)

Figure 16

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 17

Stability For Resistors Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR (TRIMMED)

Figure 18

50 MIL WIDE RESISTOR (TRIMMED)

Figure 19

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 20

Stability For Resistors Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR (TRIMMED)

Figure 21

50 MIL WIDE RESISTOR (TRIMMED)

Figure 22

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 23

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR

Figure 24

50 MIL WIDE RESISTOR

Figure 25

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR

Figure 26

50 MIL WIDE RESISTOR

Figure 27

APPENDIX C

Test Results For The 1931 Paste

Pre Trim Distribution

825° C/30 Minute Profile

Figure 28

850° C/30 Minute Profile

Figure 29

875° C/30 Minute Profile

Figure 30

850° C/60 Minute Profile

Figure 31

Operating Envelope

No Glaze on Resistors

Figure 32

Glaze Over-coated Resistors

Figure 33

Stability For Resistors Trimmed Within The Operating Envelope - Unglazed

50 MIL WIDE RESISTOR (TRIMMED)

Figure 34

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 35

Stability For Resistors Trimmed Within The Operating Envelope - Glazed

50 MIL WIDE RESISTOR (TRIMMED)

Figure 36

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 37

Stability For Resistors Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR (TRIMMED)

Figure 38

50 MIL WIDE RESISTOR (TRIMMED)

Figure 39

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 40

Stability For Resistors Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR (TRIMMED)

Figure 41

50 MIL WIDE RESISTOR (TRIMMED)

Figure 42

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 43

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR

Figure 44

50 MIL WIDE RESISTOR

Figure 45

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR

Figure 46

50 MIL WIDE RESISTOR

Figure 47

APPENDIX D

Test Results For The 1939 Paste

Pre Trim Distribution

825° C/30 Minute Profile

Figure 48

850° C/30 Minute Profile

Figure 49

875° C/30 Minute Profile

Figure 50

850° C/60 Minute Profile

Figure 51

Operating Envelope

No Glaze on Resistor

Figure 52

Glaze Over-coated Resistors

Figure 53

Stability For Resistors Trimmed Within The Operating Envelope - Unglazed

Figure 54

Figure 55

Stability For Resistors Trimmed Within The Operating Envelope - Glazed

Figure 56

Figure 57

Stability For Resistors Trimmed At The Operating Point - Unglazed

Figure 58

Figure 59

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 60

Stability For Resistors Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR (TRIMMED)

Figure 61

50 MIL WIDE RESISTOR (TRIMMED)

Figure 62

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 63

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR

Figure 64

50 MIL WIDE RESISTOR

Figure 65

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR

Figure 66

50 MIL WIDE RESISTOR

Figure 67

APPENDIX E

Test Results For The 1949 Paste

Pre Trim Distribution

825° C/30 Minute Profile

Figure 68

850° C/30 Minute Profile

Figure 69

875 ° C/30 Minute Profile

Figure 70

850° C/60 Minute Profile

Figure 71

Operating Envelope

No Glaze on Resistors

Figure 72

Glaze Over-coated Resistors

Figure 73

Stability For Resistors Trimmed Within The Operating Envelope - Unglazed

50 MIL WIDE RESISTOR (TRIMMED)

Figure 74

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 75

Stability For Resistors Trimmed Within The Operating Envelope - Glazed

Figure 76

Figure 77

Stability For Resistors Trimmed At The Operating Point - Unglazed

Figure 78

Figure 79

Figure 80

Stability For Resistors Trimmed At The Operating Point - Glazed

Figure 81

50 MIL WIDE RESISTOR

Figure 82

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 83

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR

Figure 84

50 MIL WIDE RESISTOR

Figure 85

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR

Figure 86

50 MIL WIDE RESISTOR

Figure 87

APPENDIX F

Test Results For The 1959 Paste

Pre Trim Distribution

825° C/30 Minute Profile

Figure 88

850° C/30 Minute Profile

Figure 89

875° C/30 Minute Profile

Figure 90

850° C/60 Minute Profile

Figure 91

Operating Envelope

No Glaze on Resistors

Figure 92

Glaze Over-coated Resistors

Figure 93

Stability For Resistors Trimmed Within The Operating Envelope - Unglazed

Figure 94

Figure 95

Stability For Resistors Trimmed Within The Operating Envelope - Glazed

50 MIL WIDE RESISTOR (TRIMMED)

Figure 96

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 97

Stability For Resistors Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR (TRIMMED)

Figure 98

50 MIL WIDE RESISTOR (TRIMMED)

Figure 99

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 100

Stability For Resistors Trimmed At The Operating Point - Glazed

25 MIL WIDE RESISTOR (TRIMMED)

Figure 101

50 MIL WIDE RESISTOR (TRIMMED)

Figure 102

100 MIL WIDE RESISTOR (UNTRIMMED)

Figure 103

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR

Figure 104

50 MIL WIDE RESISTOR

Figure 105

Analysis Of Resistor Tolerance and Yield Based on Samples Trimmed At The Operating Point - Unglazed

25 MIL WIDE RESISTOR

Figure 106

50 MIL WIDE RESISTOR

Figure 107

APPENDIX G

Miscellaneous Data

TCR For 1900 Series Paste- No Glaze

TCR - NO GLAZE											
HOT	PASTE	R @ 25 TIME 1	R @25 TIME 2	R @25 TIME 3**	R @ 125 TIME 1	R @125 TIME 2	R @125 TIME 3**	TCR @ 125	TCR @ 125	TCR @125	AVERAGE
trimmed	1921	185.859000	185.859000	185.859000	186.720000	186.719000	186.724000	46.325	46.272	46.541	46.379
untrimmed	1921	149.382000	149.382000	149.382000	150.073000	150.068000	150.074000	46.257	45.923	46.324	46.168
trimmed	1931	2.048030	2.048030	2.048030	2.066700	2.066670	2.066700	91.161	91.014	91.161	91.112
untrimmed	1931	1.982100	1.982100	1.982100	1.999630	1.999540	1.999620	88.442	87.987	88.391	88.273
trimmed	1939	32.676000	32.676000	32.676000	32.784000	32.785000	32.785000	33.052	33.358	33.358	33.256
untrimmed	1939	25.521900	25.521900	25.521900	25.639200	25.638800	25.638800	45.961	45.804	45.804	45.856
trimmed	1949	267.693000	267.693000	267.693000	267.977000	268.003000	268.005000	10.609	11.580	11.655	11.282
untrimmed	1949	210.281000	210.281000	210.281000	211.212000	211.216000	211.218000	44.274	44.464	44.559	44.433
trimmed	1959	2.088020	2.088020	2.088020	2.070770	2.071030	2.071200	-82.614	-81.369	-80.555	-81.513
untrimmed	1959	1.617900	1.617900	1.617900	1.622920	1.622970	1.622970	31.028	31.337	31.337	31.234
COLD		R @25 TIME 1**	R @25 TIME 2**	R @25 TIME 3**	R @ -55 TIME 1**	R @-55 TIME 2**	R @-55 TIME 3**	TCR @ -55	TCR @-55	TCR @-55	
trimmed	1921	185.859000	185.859000	185.859000	185.994000	186.001000	185.989000	-9.079	-9.550	-8.743	-9.124
untrimmed	1921	149.382000	149.382000	149.382000	149.561000	149.558000	149.547000	-14.978	-14.727	-13.807	-14.504
trimmed	1931	2.048030	2.048030	2.048030	2.044150	2.044160	2.044260	23.681	23.620	23.010	23.437
untrimmed	1931	1.982100	1.982100	1.982100	1.981640	1.981760	1.981730	2.901	2.144	2.333	2.460
trimmed	1939	32.676000	32.676000	32.676000	32.819000	32.820000	32.821000	-54.704	-55.086	-55.469	-55.086
untrimmed	1939	25.521900	25.521900	25.521900	25.605900	25.607000	25.609200	-41.141	-41.680	-42.757	-41.859
trimmed	1949	267.693000	267.693000	267.693000	269.355000	269.353000	269.415000	-77.608	-77.514	-80.409	-78.510
untrimmed	1949	210.281000	210.281000	210.281000	211.127000	211.106000	211.125000	-50.290	-49.042	-50.171	-49.834
trimmed	1959	2.088020	2.088020	2.088020	2.115990	2.116490	2.117230	-167.443	-170.437	-174.867	-170.916
untrimmed	1959	1.617900	1.617900	1.617900	1.629170	1.629250	1.629250	-87.073	-87.691	-87.691	-87.485
	HP3478A - 4 wire										

Table 1

TCR For 1900 Series Paste - Glaze

TCR - GLAZE											
HOT	PASTE	R @ 25 TIME 1	R @25 TIME 2	R @25 TIME 3**	R @ 125 TIME 1	R @125 TIME 2	R @125 TIME 3**	TCR @ 125	TCR @ 125	TCR @125	AVERAGE
trimmed	1921	189.000	189.000	189.000	189.965	189.954	189.947	51.058	50.476	50.106	50.547
untrimmed	1921	148.721	148.721	148.721	149.480	149.475	149.472	51.035	50.699	50.497	50.744
trimmed	1931	1.933	1.933	1.933	1.952	1.952	1.952	98.648	97.665	97.458	97.924
untrimmed	1931	1.695	1.695	1.695	1.711	1.711	1.711	96.696	95.870	95.634	96.067
trimmed	1939	32.279	32.279	32.279	32.430	32.428	32.427	46.780	46.160	45.850	46.263
untrimmed	1939	25.758	25.758	25.758	25.897	25.895	25.894	53.926	53.343	53.111	53.460
trimmed	1949	250.784	250.784	250.784	251.900	251.894	251.888	44.500	44.261	44.022	44.261
untrimmed	1949	191.250	191.250	191.250	192.139	192.133	192.130	46.484	46.170	46.013	46.222
trimmed	1959	1.968	1.968	1.968	1.974	1.974	1.974	30.594	30.238	30.086	30.306
untrimmed	1959	1.629	1.629	1.629	1.634	1.634	1.634	31.311	31.925	31.311	31.516
COLD		R @25 TIME 1**	R @25 TIME 2**	R @25 TIME 3**	R @ -55 TIME 1**	R @-55 TIME 2**	R @-55 TIME 3**	TCR @ -55	TCR @-55	TCR @-55	
trimmed	1921	189.000	189.000	189.000	189.166	189.159	189.160	-10.979	-10.516	-10.582	-10.692
untrimmed	1921	148.721	148.721	148.721	148.836	148.837	148.846	-9.666	-9.750	-10.506	-9.974
trimmed	1931	1.933	1.933	1.933	1.929	1.929	1.929	29.162	28.839	28.968	28.990
untrimmed	1931	1.695	1.695	1.695	1.693	1.693	1.693	11.504	11.947	12.021	11.824
trimmed	1939	32.279	32.279	32.279	32.384	32.386	32.383	-40.661	-41.436	-40.274	-40.790
untrimmed	1939	25.758	25.758	25.758	25.832	25.835	25.833	-36.106	-37.465	-36.688	-36.753
trimmed	1949	250.784	250.784	250.784	251.759	251.726	251.746	-48.598	-46.953	-47.950	-47.833
untrimmed	1949	191.250	191.250	191.250	191.959	191.972	191.973	-46.340	-47.190	-47.255	-46.928
trimmed	1959	1.968	1.968	1.968	1.981	1.981	1.981	-86.395	-85.315	-83.918	-85.209
untrimmed	1959	1.629	1.629	1.629	1.640	1.640	1.640	-84.418	-85.109	-84.495	-84.674
HP3478A - 4 wire											

Table 2

REFERENCE

¹Schmidt, Helen E., and Allington, Trevor R. "Laser Trimming Resistors Over Dielectric." Hybrid Circuit Technology, October, 1985, pp. 35-43.

M97053647

Report Number (14) KCP--613-5890

Publ. Date (11) 199706

Sponsor Code (18) DOE/DP, XF

UC Category (19) UC-704, DOE/ER

DOE