HDL-CR-84-076-1

January 1984

MM&T-Ceramic Metal Substrates for Hybrid Electronics, Handbook

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Prepared by

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Defense Electronics Center
Baltimore, MD 21203

Under contract

DAAK21-80-G-0076

U.S. Army Electronics Research
and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HDL-CR-84-076-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* MM&T -- Ceramic Metal Substrates for Hybrid Electronics, Handbook		5. TYPE OF REPORT & PERIOD COVERED Contractor Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR*(s)* A.B. Timberlake and F.E. Merti HDL contact: Albert Lee		8. CONTRACT OR GRANT NUMBER*(s)* DAAK21-80-G-0076
9. PERFORMING ORGANIZATION NAME AND ADDRESS Westinghouse Electric Corporation Defense Electronics Center Baltimore, MD 21203		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PRON No. 810P1556M1A9
11. CONTROLLING OFFICE NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, MD 20783		12. REPORT DATE January 1984 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

HDL Project No.: 80308A/804082

Supplemental accounting classification: 0655151P4250 2570 S11173

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Insulated metal subtrates
Porcelain enameled steel (PES) substrate properties
Properties of thick-film conductors on PES substrates
Wire bondability
Solderability
Resistor properties
Resistor stability
Hybrid manufacturing technology

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The Handbook is a compilation of data and other relevant information obtained in the course of an 18-month program, details of which were presented in the final report published in August, 1983.

The various known constructions of insulated metal (IM) substrates are described. The properties of porcelain-enameled steel (PES) substrates relevant to high-volume manufacture of thick-film hybrid microelectronic assemblies are presented. (Continued on Supplementary Sheet)

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

ITEM 20. ABSTRACT (Continued)

Typical properties of thick film conductors and resistors fired on PES substrates are described. Comparisons with alumina substrate materials are made. Wire bondability, solder back leach resistance, dependence of resistor properties on resistor geometry, and resistor stability data are presented. Thick-film and hybrid assembly experience with PES substrates are discussed.

A bibliography citing numerous articles on PES, plasma-sprayed ceramic on metal, polymer thick film materials, and organic-metal laminates is included.

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FOREWORD

Widespread interest has been aroused in the hybrid microelectronic industry in recent years by the introduction of the insulated metal (IM) substrate as a replacement for alumina. The concept of using a substrate consisting of a metal plate covered by an insulating coating is attractive compared to printed circuit (PC) boards or alumina for a number of reasons. For a hybrid electronic or printed wiring assembly manufacturer to convert successfully to the use of IM substrates, two steps must be accomplished. First, the manufacturer must establish that it is advantageous to make the conversion and that the goals are attainable. Second, the processes, controls, and design guidelines for manufacturing the assemblies must be sufficiently developed and available to be used.

The U. S. Army required additional substrate strength in the thick-film hybrids used in ordance devices. IM substrates appeared to offer this property, but it had not been established that hybrids could be built which exhibited the other properties high-volume producibility, low cost, reliability, and functional versatility necessary for this application. The Army and Westinghouse DEC have therefore carried out a program to detail the methods and technology relevant to high-volume production of thick-film hybrids made with IM substrates. The individual elements of a hybrid electronic assembly with IM substrates were studied separately in detail, and the results brought together in a pilot production of a fuze amplifier currently used by the Army.

This handbook is one of the products of that program. It has been written to assist potential users of IM substrates, with emphasis on the technology for using thick-film circuitry on porcelain-enameled steel (PES). In preparing this handbook we have assumed that the reader is familiar with the thick-film process, materials, and equipment. Most of the information presented was obtained in carrying out the present contract. An extensive bibliography is also presented.

1. INTRODUCTION

1.1 Why Insulated Metal Substrates? For many years electronic devices have been assembled into functional hardware using one of three technologies for interconnection and support: discrete components mounted on a chassis and connected by wire printed-circuit (PC) boards with "dual-in-line" packaged active devices; and hybrids, with precious metal circuit patterns connecting bare chip components on alumina substrates. In discussing the motivations for new substrate technologies, we will consider only PC and hybrid technologies.

PC technology has had wide appeal and is the most used at the present time. PC boards consist of laminated layers of epoxy, fiberglass, and copper foil. Circuitry is formed in the copper foil by photolithography, etching, and plating. Boards 2 to 3 feet on a side with 10 or more layers of circuitry are commonplace. The technology lends itself to high-volume and automated assembly techniques. PC boards have characteristics which limit their use in many applications, however. The most prominent limitations are low thermal conductivity, relatively high thermal expansion coefficient, low flexural strength, inability to withstand sustained temperatures above 200°C, and inadequte circuit density for many very large-scale integration (VLSI) devices.

Hybrid circuits consist of conductor interconnect patterns formed on ceramic or glass substrates by screen printing (thick film) or evaporation, plating, and photo-etching (thin film). Active devices and integrated circuits in bare chip form are mounted directly on the substrate and electrically connected by fine wire. Hybrid technology offers maximum density, good heat dissipation, and high speed. However, circuits are limited in size to approximately 3 x 3 in. They tend to be more expensive than PC boards.

In the middle 1970's, an alternative technology which promised to combine the desirable features of both PC and thick-film technologies began to receive publicity [1, 2, 3]. The General Electric Company, Mattoon, Illinois, had for many years been supplying a camera flash connector to Polaroid Corporation. The connector, called a "flashbar," consisted of a simple conductor pattern connecting flash cubes to an edge connector. Overall size was about 2 x 6 in. The card was a porcelain enameled steel (PES) substrate

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1. Hilson, D.G., and Johnson, G.W., New Materials for Low Cost Thick-film Circuits, Solid-State Technology, Oct. 1977, p. 49.

2. Wicher, D.P. and Hatfield, W.B., Porcelain Steel Technology: A Bona Fide Alternative?, Proceedings ISHM Symposium, 1978, pp. 176-187.

3. McDermott, "Improved Materials Promise Low Cost, High Reliability Hybrid Circuitry", Electronic Design, 18, Sept. 1, 1978, p. 41-42.

with a screen-printed silver thick-film conductor fired at 600°C. A similar circuit board had been supplied to Sylvania Corporation by Erie Ceramic Arts, Erie, PA. These boards have been supplied by the millions and have proven to be rugged, reliable, and cheap.

The flashbar experience apparently stimulated research and development on the use of PES substrates at several companies. Alpha Metals created a division to manufacture and market PES substrates, and promoted their use vigorously. Erie Ceramic Arts and General Electric also marketed substrates for thick-film hybrid circuitry. Most of the major thick-film ink vendors began offering lines of inks formulated for the low firing temperatures required by PES substrates.

PES substrates were seen as a replacement for both PC boards and thick-film alumina substrates. Compared to PC boards, they offered the advantages of ruggedness, improved heat-dissipating capability, ability to withstand high ambient temperatures and other hostile environments, the precision of screened resistors, and higher circuit density. Compared to alumina they offered strength, ability to be made in sizes larger than 3 x 3 in., lower cost, and capability for plated through holes. In addition, there were potential features that had not been exploited - the concept of substrates with bends or curves in them, for example.

Since then, the PES industry has fluctuated as it has matured[4,5]. Alpha Metals has divested itself of its PES substrate operation. General Electric is not actively marketing substrates. Singer R&D, a very serious investigator in the early years, has not exhibited any PES activity for several years. On the positive side, Frenchtown American has acquired the PES interests of Plessey Frenchtown Porcelain and is marketing PES substrates. Scientists at RCA David Sarnoff Research Center developed a high-temperature porcelain and a line of compatible, copper-based inks which appear to have many desirable properties[6,7]. This system was developed to replace PC boards in television receivers, and was reported to be very successful technically. Northern Telecom, Honeywell, and A-C Spark Plug Division of General Motors are reportedly ready to start mass production of circuitry on PES substrates. Toshiba Corporation has reported the fabrication

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4. Schabacker, R.B., Porcelain Enameled Substrates for Hybrid Circuits and Printed Circuits. European Hybrid Microelectronics Conference, 1979.

5. Spector, M., Porcelain Coated Steel Substrates for High Density Component Interconnection, Insulation Circuits, 25, 1, Jan. 1979, pp. 15-17.

6. Onyshkevych, L.S., Porcelain Enameled Steel Substrates for Electronic Application Proc. 1980 PEI Forum.

7. RCA Review, 41, 2, June, 1981 (11 papers)

of thick film circuits on bent PES substrates, thus realizing one of the early potentials of PES[8].

In recent years, other configurations using the insulated metal (IM) concept have been proposed and developed. Styles predicated on the use of the thick-film technology have included steel coated with alumina by plasma spraying[9], anodized alumina with polymer thick film circuitry[10,11], and molybdenum coated with screen-printed thick-film dielectric.[12] Configurations predicated on PC technology include a process where by a metal plate is isolated by polyimide. Layers of circuitry insulated by layers of polyimide are built up successively in a fashion similar to PC technology.[13] In another technique, the circuitry is formed by threading fine wire around a polyimide coated-metal core. Multiple layers are formed by insulating each layer of wire with polyimide.[14]

The potential advantages offered by these substrates include the following:

(a) Strength,

(b) Large size,

(c) Good heat transfer,

(d) Adaptability to different requirements,

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8. Iwase, N.; Nojima, M.; and OAdaira, H., "Thick Film Circuit on Bent Porcelain-Steel Substrate", Proceedings Int. Symp on Hybrid Microelectronics, 1982, pp. 1-8.

9. Dittrich, T.J., Smyth, R.T., and Weir, J.D., Production of Electric Coatings by Thermal Spraying, Proceedings ISHM Symposium, 1977, pp. 274-276.

10. Miura, W., Fuura, Y., Kazami, A. and Yamagishl, M., Insulated Metal Substrates for Power Hybrid IC's, Proceedings ISHM Symposium, 1977, pp. 222-227.

11. Miura, W., Fuura, Y., and Kazami, A., High Power IC on Insulated Metal Substrate, Proceedings ISHM Symposium, 1969, pp. 379-397.

12. Agarwal, U.,K., Turski, Z., and Mendicino, P., Low-Cost Increased Packaging Density with Molybdenum Substrates, Proc. 1981 ISHM Symp., pp. 353-358.

13. Lebow, S., A Method of Manufacturing High Density Fine Line Printed Circuit Multilayer Substrates Which Can Be Thermally Conductive, NEPCON West, 1981.

14. Lassen, C.L., Use of Metal Core Substrates for Leadless Chip Carrier Interconnection, Electronic Packaging and Production, 21, 3, March 1981.

(e) Survivability in hostile environments,

(f) High circuit density and,

(g) Built-in ground plane.

It is evident that many of the substrates discussed could replace either PC boards or hybrids in selected applications. It will be the intent of this handbook to help the reader become more aware of applications where IM substrates have advantages, and to provide guidance in their use.

1.2 Why a Handbook? As discussed in the previous sections, by 1979 a considerable amount of interest had been generated in the electronics industry by the PES substrate. Many advantages had been identified, and at least two companies were using them in volume where low cost, reliable performance, and ruggedness were important. However, as often happens when a new technology is introduced, the early enthusiasms turned to disillusionment and skepticism. Companies attempting to replace alumina with porcelainized steel for use with existing circuit layouts would find that the gain from such a change was not worth the investment required. The unique advantages of PES or other IM substrates were not exploited. Technical problems, in many cases a result of inadequate understanding of the proper use of the substrate, were publicized and contributed to the disillusionment.

Harry Diamond Laboratories, a component of the U. S. Army Electronics Research and Development Command, needed a substrate having the strength of PES for use in ordnance fuzes. They also recognize that the use of IM substrates in hybrids would require the establishment of a manufacturing technology dedicated to that particular substrate.

1.3 The ERADCOM-HDL/Westinghouse Program. In August of 1980 the Westinghouse Systems Development Division, Baltimore, Maryland, was awarded a contract to conduct a Manufacturing Technology Program, "Ceramic Metal Substrates for Hybrid Electronics." The purpose of the program was to detail the methods and technology relevant to high-volume production of thick-film hybrid electronic assemblies made with IM substrates. A hybrid circuit made on a ceramic substrate for ordnance projectile fuzes was used to model the technology in a pilot production run.

The program was divided into functional tasks to explore various aspects of thick-film IM substrate production:

(1) The selection and thorough characterization of IM substrates.

(2) The delineation of properties of thick-film inks and the preparation of guidelines for thick-film designs and processes.

(3) The pilot production of a bare chip hybrid circuit now used in large quantities in ordnance fuzes, to verify the results of the first two phases.

The technology gained in this program was to be presented to the public in three media: a final report, an industry demonstration, and a handbook detailing guidelines for design, selection of materials, and fabrication processes for manufacture of thick-film hybrids on IM substrates. This document is that handbook.

The information presented in this handbook was obtained in the course of the program[15]. Measured data on commercially available substrates and thick film inks are presented. Since we studied only a fraction of the thick film inks available, data taken from manufacturer's specification sheets on as many inks as could be found are also given.

Although the MM&T program emphasized the particular processes and materials relevant to thick film on PES substrates, information was obtained on other core metals, coatings, and coating techniques. The feasibility of various coating/metal-core combinations is estimated, at least to the extent of telling whether or not a combination has been done.

It is intended that the handbook be useful to electronic assembly manufacturers presently building both alumina-based hybrids and PC assemblies. For the hybrid manufacturer, the important differences and similarities between alumina and PES substrate processing will be indicated. For the PC assembly manufacturer, the limits of what might be achieved will be highlighted. Finally, it is hoped that substrate and thick film manufacturers will recognize areas where materials need to be improved.

The main body of the handbook deals with the selection, specification, and use of commercially available substrates and thick-film inks. It is beyond the scope of this document to tell how to enamel a steel substrate or formulate a thick-film paste. However, where one is presented a choice (for example, between a substrate coated by dipping or by electrophoretic deposition), some discussion will be provided. Knowledge and familiarity with thick-film processing is assumed.

2. SUBSTRATES.

In this section, the options in core metals and coatings available to a potential user of IM substrates are discussed. The properties of metals and coatings which could be or have been used are tabulated. Information is presented on the feasibility of various combinations, and on substrate

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15. Westinghouse Electric Corp., DEC, A.B Timberlake and F.E. Merti, Authors, Final Report, Contract No. DAAK21-80-G-0076, Ceramic Metal Substrates for Hybrid Electronics, prepared for U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, Md., August, 1983.

structures successfully achieved. Since most of the development on IM substrates has been on PES, the major portion of the section will be devoted to the properties, characteristics, and use of PES substrates.

2.1 Materials Considerations. In selecting a substrate configuration for use in a thick film hybrid assembly, the manufacturer needs the following information:

(a) The environment the assembly will be exposed to,

(b) Thermal and mechanical properties of the assembly housing structure,

(c) Thermal and mechanical properties of components to be mounted on the substrate,

(d) Weight and size limitations,

(e) Circuit power dissipation and operating frequency,

(f) Cost limitations,

(g) Anticipated production volume.

Usually the mechanical and thermal ambients seen by the assembly in operation will dictate the choice of metal, while circuit considerations will dictate the choice of coating. Selection of materials may then become an iterative process determined by the compatibility of materials with each other, or by the availability of suitable thick film materials.

Table 1 lists many mechanical and thermal properties of numerous metals that might be considered as core materials. These metals were selected because they possess at least one outstanding property, or are known to be compatible with a coating process.

Table 2 consists of a matrix of coatings and cores, with a comment on available knowledge relevant to each combination.

It should be recognized that the properties of the coated substrate will be a combination of the properties of the coating and of the metal core. Frequently, a rule of additives can be used to predict a property of the coated substrate. For example, the thermal conductivity of a coated metal normal to the coated surface can be calculated from

$$\frac{1}{k_n} = \frac{1}{100} \sum^{i} \frac{a_i}{k_i} \qquad (1)$$

where:

k_n = effective thermal conductivity through the coated substrate,

TABLE 1. PROPERTIES OF SUBSTRATE CORE METALS

METAL/ALLOY	ASTM or INDUSTRY DES.	DENSITY, Gm/cm^3	MELTING POINT, °C	THERMAL EXP. COEF TEMP RANGE	THERMAL EXP. COEF TCE, °C	THERM. COND, W/M/°C	ELECT. RES. μOHM-CM	TENSILE STRENGTH, 10^3 PSI
ENAMELING STEEL	IF	7.8	14-1500	20-650	14.9	46.7	15-20	45
ALUMINUM	PURE	2.70	660	20-100	23.6	247	2.66	6.5
ALUMINUM	6061/T4	2.71	582-652	20-100	23.6	180	4.3	35.
COPPER	CDA102	8.93	1083	20-100	17.0	398	1.67	32-55
MOLYBDENUM	-	10.22	2615	20-1000	5.75	142	5.7	95
TITANIUM	98.9, 99.5	4.5	1667	20-400	10.2	15.6 - 19.9	48-60	38-100
STAINLESS STEEL	AISI 303	8.03	1400-1420	0-100	17.3	16.3	72	90-110
STAINLESS STEEL	AISI 430	7.75	1427-1510	0-100	10.4	26.1	60	80-90
ALLOY 42	-	-	-	25-300	4.88	13	70	82
KOVAR	-	-	1450	25-350	4.89	19	47	76-80
16 Cu - 68 INVAR 16 Cu	-	-	-	25-200	6.9	63 (1.)	-	-

1. Normal to surface.

TABLE 2 INSULATED METAL SUBSTRATE STRUCTURE

COATINGS / METAL	ELPOR-I ENAMEL	ELPOR-II ENAMEL	EK5/EK6 ENAMEL	AL_2O_3 POWDER B (105 SF)	AL_2O_3 POWDER C (Linde A)	MIXED CERAMIC POWER D (334F)	THICK FILM DIELECTRIC
ENAMELING STEEL	CA	CA	-	-	-	-	-
KOVAR	-	-	LP	-	-	-	-
ALLOY 42	-	-	LP	LP	LP	LP	1-
CU-INVAR-CU (16-68-16)	NO	CA	NP	NP	NP	NP	NI
STEEL-INVAR-STEEL	CA	CA	-	-	-	-	-
TITANIUM	-	-	-	-	-	LP	NI
COPPER	-	CA	-	-	-	-	-
ALUMINUM	-	CA	-	-	-	-	-
430 STAINLESS STEEL	-	-	-	NP	NP	NP	-
303 STAINLESS STEEL	CA	-	-	-	-	-	-
MOLYBDENUM	-	-	-	NP	NP	NP	LP

Code: CA, Comercially available
LP, Successful prototypes have been reported.
NP, Attempts have been reported unsuccessful
- , No information on this structure has been found in this program.

A Ferro Corporation
One Erieview Plaza
Cleveland, Ohio 44114

B Plasmadye Division of Geotel, Inc.
3839 South Main Street, P.O. Box 1559
Santa Ana, California 92702

C Metco Incorporated
1101 Prospect Avenue
Westbury, L.I., New York 11590

D Linde Division
Union Carbide Corporation
270 Park Avenue
New York City, New York 10017

a_i = percent of total thickness represented by ith layer, and

k_i = thermal conductivity of ith layer.

A more complex calculation is required when predicting the coefficient of thermal expansion. In this case, the relative elastic moduli of the core metal and coatings also have an effect. Then, the longitudinal coefficient α_L is given by

$$\alpha_L = \alpha_1 + \frac{(\alpha_2 - \alpha_1)\, a_2 E_2}{a_2 E_2 + a_1 E_1} \qquad (2)$$

where:

α_1, α_2 = coefficients of thermal expansion of layer 1 and layer 2,

E_1, E_2 = moduli of elasticity of two materials, and

a_1, a_2 = fractional thicknesses of the two layers.

2.2 Coating Techniques.

2.2.1 Plasma Spraying. Most of the coating materials cited in table 2 are applied by enameling or thermal spraying. Very little information is available on the suitability of flame or plasma-sprayed ceramic for use in thick-film substrates. In addition to a brief report by Metco, Inc.,(9) only the work done at Westinghouse at both the R&D Center and Defense Electronics Center on Air Force contract(16) has addressed this question.

Table 3 summarizes the results achieved by Westinghouse on small (1 x 2 in.) and large (4 x 4 in.) substrates made by plasma spraying. It was possible to achieve coatings which survived the coating processes. Surface finishes were approximately 140 micro-inches (u in.) for 105 SF, 150 u in. for Linde A, and 260 u in. for 334F. In comparison, a typical as-fired 96 percent alumina substrate has a 20 to 30 u in. surface finish. Although 1 x 2 in. substrates could be fired several times, only three 4 x 4 in. substrates could withstand one 850°C thick-film firing.

In view of the undeveloped state of this technology for providing thick-film substrates, it is recommended that the interested reader review the literature in the bibliography for more complete information. Commercial vendors of plasma-spray equipment and materials are also excellent sources of information.

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9. Dittrich, F. J., Smyth, R. J., and Weir, J. D., Production of Electric Coatings by Thermal Spraying, Procedures ISHM Symposium, 1977. pp. 274-276.

16. Westinghouse Electric Corp., DEC, M.R. Lucas, author, First Interim Report, Contract No. F33615-80-C-5046, prepared for AFWAL, Wright-Patterson AFB, OH. January, 1982.

TABLE 3. PROPERTIES OF PLASMA-SPRAYED CERAMIC ON METAL

Metal	Coating	Results of Coating	Effect of 850°C Thkr Film Profile
Alloy #2	105SF	Good	No Change
	334F	Good	Warping
	LINDE A	Good	No Change
430 Stainless Steel	105SF	Good	Oxidation, Chipping
	334F	Good	Warping
	LINDE A	Good	Oxidation, Chipping
Molybdenum	105SF	Good	Oxidation of Moly
	344F	Oxide Cones Through	-
	LINDE A	Good	Oxidation of Moly
Copper Clad INVAR	105SF	Good	Coating Pops Off
	334 F	Coating Spalls Off	-
	LINDE A	Good	Coating Pops Off
Titanium	105 SF	Not Done	-
	334 F	Good	No Change
	LINDE A	Not Done	-

2.2.2 Thick Film Polymers. If satisfactory substrate materials cannot be used because of the temperatures involved in thick-film firing, it may be possible to use polymer thick films. These are resins loaded with a functional powder, such as silver, which are applied to a substrate by conventional screen printing. The firing requirements, however, are significantly different from conventional film requirements, Polymer thick films are cured at temperatures ranging from 125°C to 600°C. Among the inks available are overglazes which can be screened on a metal substrate for insulation. Conductor, dielectric, and resistor layers can then be screened in the proper sequence, with the first overglaze layer insulating the circuit from the metal substrate.

Polymer thick films are not presented here in depth, since they were not considered on the present contract. However, several review papers are listed in the bibliography.

2.2.3 Porcelain Enameling. By far the largest amount of development in the IM substrate field has taken place with PES substrates. The history of this development has been traced briefly in section 1 and in the contract final report. For more detail, the reader is referred to papers by Hilson[1], Schabacker[4,5], and Lim.[17]

2.2.3.1 Core Metals. It is possible to apply adherent porcelain enamels to many metals for use in temperate environments. However, the choice of metals suitable for porcelainizing is more limited when the substrate must undergo multiple firings in a thick-film firing furnace at temperatures over 600°C. Table 4 lists metals in addition to "enameling steel" which can be successfully enameled for thick-film processing.

TABLE 4. METAL CORES FOR THICK FILM PORCELAIN ENAMELED SUBSTRATES

Metal	Enamel	Maximum Thick Film Temperature, °C	Source
Steel	EL-POR-1, EL-PORII-1	600-625	FERRO-ECA and (a) (b) Frenchtown American
Steel	RCA-Devitryifying	900-1000	REF (7)
Copper-Invar-Copper	EL-POII-2	625-650	FERRO-ECA and (a)(b) Frenchtown American
Alloy 42	EK5/EK6	850-925	
303 Stainless Steel		600	Frenchtown American (b)
Steel-Invar-Steel		600	Frenchtown American (b)

(a) FERRO-ECA Electronics Company
3130 West 22nd Street, P.O. Box 8305
Erie, PA 16505

(b) Frenchtown American Corp.
8th and Harrison Streets
Frenchtown, NJ 08825

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4. Schabacker, R.B., Porcelain Enameled Substrates for Hybrid Circuits and Printed Circuits. European Hybrid Microelectronics Conference, 1979.

5. Spector, M., Procelain Coated Steel Substrates for High Density Component Interconnection, Insulation Circuits, 25, 1 Jan. 1979, pp. 15-17

17. Lim, C., and Hughes, E.W., "Characterization of Procelain Enamel Substrates for Electronic Application", American Ceramic Society, Chicago, Il., April 29, 1980, RCA Review, 42, 2, June, 1981.

For further information on the feasibility for thick film of enameled metal substrates it is suggested the Erie Ceramic Arts or Ferro Corporation be contacted.

2.3 Porcelain Enameled Metal Substrates for Hybrid Manufacturing.

2.3.1 Substrate Characteristics. A thick-film hybrid substrate of any construction must meet certain conditions of flatness, smoothness, edge definition, and thickness. Otherwise, printing quality, registration of patterns from layer to layer, laser trimming, and various assembly operations will be adversely affected. Achieving these conditions is a different matter for a PES substrate than it is for an alumina substrate, since these conditions are determined by the forming and pre-treatment of the metal and by the coating process variables. In addition to these "typical" substrate concerns, a PES substrate has the potential for other kinds of unique defects. For example, porcelain pin holes, chips, high sodium content, and bubbles can occur if the coating process is not well controlled. Finally, there is concern over softening temperature of the porcelain, which is typically very close to the firing temperature of the thick films used.

In this section, the effect of these characteristics on the manufacture of thick-film hybrid microelectric assemblies is discussed. The magnitudes and variations in magnitudes found in the MM&T contract are summarized, and the "best case" specification a vendor can be expected to accept is presented.

Table 5 lists many tests that can be used to measure the properties of substrates for purposes of vendor qualification, lot qualification, or manufacturing process control. The ranges of values obtained in the MMT program on three lots of substrates each from GE and Erie Ceramic Arts are presented in table 6. More detailed data can be found in the program final report[15].

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15. Westinghouse Electric Corp. DEC, A.B. Timberlake and F.E. Merti, authors, Final Report, Contract No. DAAK21-80-G-0076, Ceramic Metal Substrates for Hybrid Electronics, prepared for U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD August, 1983.

TABLE 5. RECOMMENDED SUBSTRATE TESTING

Property tested	Method	Sample from first lot
Dimensions	Calipers	All
Surface finish	ANS1 B 46.1	All
Flatness/camber	Flat plate and dial gage	All
Edge meniscus	Profilometer	15/lot
Surface resistivity	ASTM D257	2/lot
Dielectric constant, dissipation factor, and dielectric strength	ASTM D150	2/lot
Coefficient of thermal expansion	ASTM E228 C372	2/lot
Thermal shock	MIL-STD-883B Method 1011.2, Cond B	2/lot
Thermal conductivity	ASTM C408	2/lot
Softening temperature	ASTM C372	1/lot
Alkali content	Chemical analysis	To be determined
Area scans for elements listed Na, Ca, Si, Al, Fe, Ni	Microprobe	2/lot

TABLE 6. SUMMARY OF SUBSTRATE TESTING

Property	Test method	Unit of measure	Range of values	Comment
Surface finish	Profilometer 0.030 cutoff, Arithmetic Average	micro-inches	5 - 10	all vendors
Edge meniscus height	Profilometer	milli-inches	1.0 - 2.2 1.7 - 1.8	GE
Edge meniscus width	Profilometer	milli-inches	77 - 97 90 - 98	GE ECA
Surface resistivity	50 Vdc	ohms	$1.2 - 2.8 \times 10^{11}$	-
Dielectric constant	1 kHz - 1 MHz	--	7.5 - 8.4	-
Dissipation factor	1 kHz - 1 MHz	--	0.003 - 0.004	-
Dielectric strength	--	V/cm	$3 - 4 \times 10^5$	-
Coefficient of thermal expansion	Quartz dilatometer	10^{-6}in/in°C	13.3 - 14.8 18.3 8.4	Averaged over 40-300°C temp. range Porcelain enameled stainless steel Porcelain enameled stainless steel-Invar-Steel laminate
Thermal conductivity	--	W/m/°C	4.8 - 5.2 2.9 - 3.0	ECA GE
Softening temperature	Quartz dilatometer	°C	565 - 600	
Sodium content	Chemical analysis	Wgt. percent	2.4 - 2.7 2.4 - 5.8 0.21 - 0.28	GE ECA Plessey
Potassium content	Chemical analysis	Wgt. percent	5.8 - 7.0 5.4 - 6.0 9.2 - 14.8	GE ECA Plessey

2.3.2 Discussion of Significant Properties.

2.3.2.1 Surface and Edge Effects. Porcelain enameled metal substrates will usually exhibit a cross-section with features as shown in figure 1. The characteristics include the buildup of coating at the edge, and around holes, known as meniscus, and a curvature or bow. The magnitudes of these effects are within the control of the substrate supplier, and can be reduced by proper design of stamping dies, etching before coating, and annealing to relieve strains.

Edge meniscus height and width can be measured using a surface profilometer, such as marketed by Gould, Clevite Division, or Tencor Instruments. Thickness, flatness, and bow can be measured using a flat plate and dial gage in conjunction with micrometer calipers.

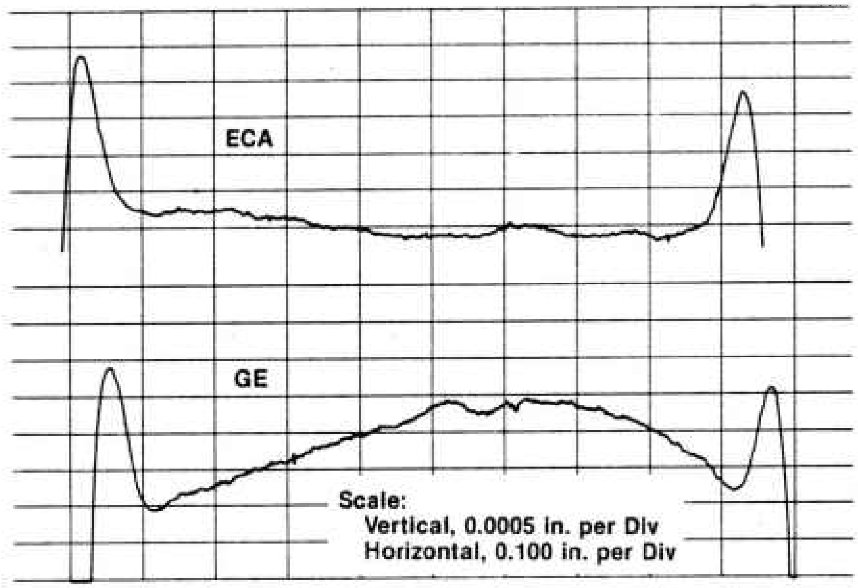

Figure 1. Typical profilometer traces of ECA (top) and GE (lower) substrates

2.3.2.2 Coefficient of Thermal Expansion. Coefficient of thermal expansion can be measured by cutting one inch square pieces from samples taken from the lot. The sample is placed in a controlled-temperature furnace. One end of the sample is fixed in place, and the other end contacts a quartz rod which in turn contacts a displacement. As the sample is heated to the desired temperatures, its change of length due to expansion is sensed by the transducer and recorded as a function of temperature.

The thermal expansion coefficient, α, is usually given as a linear approximation over a particular temperature range. (The incremental expansion coefficient at a single temperature may vary considerably from this value.) The linear approximation is calculated using equation 3,

$$\alpha = \frac{L_T - L_0}{L_0 (T - T_0)} \qquad (3)$$

where

L_T = length of the specimen at elevated temperature T, and

L_0 = length of the specimen at lower temperature T_0.

As might be expected, the metal core dominates the value.

It was found that lot-to-lot consistency of substrates from three vendors was within about five percent.

2.3.2.3 Softening Temperature. Enamel softening temperature establishes the maximum temperature at which thick-film inks used on the substrate may be fired. Thus, it has a profound effect on thick-film properties. This point is usually understood and compensated for by the user in setting up an operation. However, inconsist- encies occur in softening temperature. Since firing temperatures are always near the expected softening temperature of the enamel, a small decrease in this characteristic be detrimental to the quality of the fired film.

Enamel softening temperature can be measured in the quartz dilatometer apparatus used to measure thermal expansion coefficient. Substrates are cut into 1/4 x 1/4 in. pieces and stacked, approximately six high. The stack is then heated to approximately 800°C in air to fuse the pieces together. The thermal expansion measurement procedure is then carried out, with temperature increasing until the stack stops expanding and begins to decrease in length, as indicated on the chart recorder. The temperature at which zero slope occurs on the expansion curve is taken as the softening point.

It was found on substrates available in the mid-1981 period that softening temperatures on three lots each from three vendors, without exception, were lower than the typical recommended firing temperatures of most thick-film inks. For this reason, measurement of this quantity is considered necessary for lot qualification.

2.3.2.4 Thermal Conductivity. Thermal conductivity of a substrate is a key factor in determining the temperature rise of power-dissipating components such as diodes, transistors, and resistors. It may be calculated using equation (1), with k_1 (porcelain) being 0.014 W/cm/deg C.

It was shown[15] that the effective thermal conductivity of the PES sub- strate is determined by the porcelain, rather than by the metal. If power dissipation is a problem, PES substrates may provide advantages over PWB. However, it is essential that the porcelain be maintained as thin as circuit conditions permit. Direct contact between the metal core and the power-dissipating components is also important.

Thermal conductivity is typically measured by placing a specimen between two constant temperature baths, measuring the heat flow through the specimen and temperature gradient across it. Specimens must be flat for this method to be accurate. Otherwise, a low-conductivity air gap is placed in series with the specimen and causes an erroneously low reading.

2.3.2.5 Other Properties. Table 6 lists measured values of numerous electrical and chemical properties measured on three vendors substrates. Although these properties are important in many applications, they do not significantly affect the manufacturability of the substrates, and will not be discussed further here.

2.4 Summary.

The substrate evaluation provided data both about the various properties of PES substrates and about the uniformity of many of these properties from piece to piece and lot to lot.

Exceptions for thermal conductivity and porcelain softening temperatures, there were no unexpected results in the measured properties of substrates. Thermal conductivities were lower than had been calculated for these materials. Softening temperatures were also lower than expected. In several cases the softening temperature could have been as much as 75 degrees lower than the optimum firing temperatures of certain thick-film inks that were used. This situation could lead to distortion of thick-film patterns, although in later tests no such problem occurred.

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15. Westinghouse Electric Corp. DEC, A.B. Timberlake and F.E. Merti, authors, Final Report, Contract No. DAAK21-80-G-0076, Ceramic Metal Substrates for Hybrid Electronics, prepared for U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, Md August, 1983.

Dimensionally, the substrates were quite satisfactory. Edge menisci were almost always less than two mils high, and were consistent. Pinholes and bumps in the porcelain were virtually nonexistent. The treatment of the metal before enamelling is critical to the acceptability of the finished substrate, as a flat surface is required for processing thick films. Bowed and warped metal will yield bowed and warped substrates. Generally, the substrate suppliers are aware of the need for flatness, and are able to process the metal to obtain flat substrates.

3. THICK-FILM MATERIALS AND PROCESSES

3.1 Scope. This section describes the properties and processing of various thick-film paste types on PES substrates. The substrate material is limited to steel cores coated with ELPOR I enamel. Wherever possible, results are compared to similar materials used in typical thick-film applications on alumina. Discussion is designed to facilitate the transition of a typical alumina-based production line into a similar one based on PES.

3.2 Thick Film Pastes.

3.2.1 Availability. Table 7 lists the thick film vendors that produce and market pastes for PES substrates. Table 8 lists the ink types available with vendor-measured properties, where provided. Materials marked with an asterisk were further examined during the technology assessment portion of the program.

3.2.2 Observed Properties.

3.2.2.1 General. The physical properties of pastes for PES use were similar to pastes formulated for use on alumina. Rheologies, percent solids, and printing kinetics were virtually identical. Print-resolution capabilities were also very similar to traditional pastes.

3.2.2.2 Conductors. Principal differences in comparison to alumina-based materials are increased fired thickness (especially in Pd/Ag materials) and increased sheet resistivity. As both of these properties are strongly affected by degree of sintering, these effects are not surprising.

The most significant results obtained for conductor materials were in the areas of wire bondability and solderability. These results are discussed in detail in section 4.

3.2.2.3 Resistors. Because of the complex chemical reactions that occur during the development of conduction mechanisms during resistor firing, poor performance of resistor materials fired at PES-compatible temperatures would not be surprising. Measured results, however, give an encouraging picture of resistor performance. Table 9 and figures 2 to 7 give the variation of resistance with geometry and firing temperature and the trimmed and untrimmed stabilities for the pastes studied. The initial sheet resistivities, repeatabilities, and variations with both geometry and firing temperatures of the pastes studied are generally as good as those expected for conventional pastes fired at 850°C on Al_2O_3. While some concern must be noted relative

TABLE 7 PASTE VENDORS MARKETING PES MATERIALS

Vendor Address	Phone Number
Electro-Science Laboratories, Inc. (ESL) 2211 Sherman Avenue Pennsauken, New Jersey 08110	(609)663-7737
Electro Materials Corp of America (EMCA) 605 Center Avenue Mamaroneck, New York 10543	(914)698-8434
EMD Cermalloy, Inc. 320 Long Island Expressway South Melville, New York 11747	(526)694-7900
E. I. DuPont deNemours & Co Photo Products Department Electronic Materials Division Wilmington, Delaware 19898	(800)441-9475
Materials Science & Technology, Inc. (MS&T) 801 Newton Avenue and Division Street Camden, New Jersey 089103	(609)663-5976
Remex Corporation 155 Philmont Avenue Feasterville, Pennslyvania 19047	
Thick Film Systems (TFS) 324 Palm Avenue Santa Barbara, California 93101	(805)963-7757

TABLE 8. INKS FOR PES SUBSTRATES

Conductors:

Vendor	Form	Cat No.	Firing Temp Range °C	Solderability Pb/In	Solderability Pb/Sn	Wirebondability Alumina	Wirebondability Gold
ESL	Pt/Au	5835	625±25	Yes	Yes	-	
	Au	8835-1B	625±25	Yes	No	No	Yes
	Pb/Ag	9694A*	625±25	No	Yes	No	No
	Ag	9996A*	625±25	No	Yes	-	Yes
EMCA	Au	6145	600±50	-	No	Yes	Yes
	Pt/Ag	6144	600±50	-	Yes	Yes	Yes
	Pd/Ag	6143	600±50	-	Yes	Yes	No
	Pd/Ag	6142	600±50	-	Yes	Yes	Yes
	Ag	6141	600±50	-	Yes	Yes	Yes
EMD Cermalloy	Ag	C8800	620	-	Yes	-	-
	Pd/Ag	C4800	620	-	Yes	-	-
	Au	C5800	620	-	No	-	-
DuPont	Pd/Ag	7711*	650±5	-	Yes	-	-
	Pt/Ag	7712*	650±5	-	Yes	-	-
	Ag	7713*	650±5	-	Yes	-	-
MS&T	Pt-Ag	2126	600-625	-	Yes	-	-
	Pd-Ag	2146	-	-	Yes	-	-
TFS	Au	3045*	525-600	-	No	No	Yes
	Pt/Au	3106	600±50	No	Yes	No	Yes
	Ag	3347*	510±600	No	Yes	No	Yes
	Pd/Ag	3414	600±20	-	Yes	-	Yes
	Pd/Ag	3418*	600±20	-	Yes	-	Yes
	Pt/Pd/Ag	3535	600	-	Yes	-	Yes
	Cu	5514	600±10	-	Yes	-	Yes
	Ni	5517	600±10	-	Yes	-	-

TABLE 8. INKS FOR PES SUBSTRATES (Continued)

Resistors:

Vendor	Product No.	Resistivity Range (ohm/sq)	Firing Range (°C)	TCR (ppm)
ESL	3100 series*	10 to 1 M	625±25	200
EMCA	2000-1 series	10 to 1 M	650	200
EMD Cermalloy	PRS series	10 to 1 M	620±10	300
DuPont	7600 series*	15 to 1 M	620±5	250
MS&T	3500 Series	100 to 10 k	600-625	
TFS	600 Series*	100 to 1 M	600±25	250

DIELECTRICS:

Vendor	Product No.	Firing Range °C	Dielectric Constant
ESL	4030	590+10	10
EMCA	9042*	625	15
EMD Cermalloy	I9800	620	-
DuPont	7701*	650+5	10
MS&T	4070	580	-
	4072	600	-
	4075	625	-
Remex	7140	625-650	10-14
TFS	1120*	600±10	9-12

TABLE 9. RESISTOR MATERIALS - EFFECT OF FIRING TEMPERATURE

Paste type	Nominal firing temp (°C)	Change (%) $\frac{(R_T - 25°C) - (R_T + 25°C)}{R_{To}} \times 100$
DP 7611	650	8
7612	650	59
7613	650	0.9
7614	650	23.9
7615	650	62.7
7616	650	123
ESL 3111	625	-
3112	625	-18.5
3113	625	99.5
3114	625	121
3115	625	166
3116	625	199.5
TFS 600-101	600	129.9
102	600	-43.5
103	600	2.4
104	600	129
105	600	405

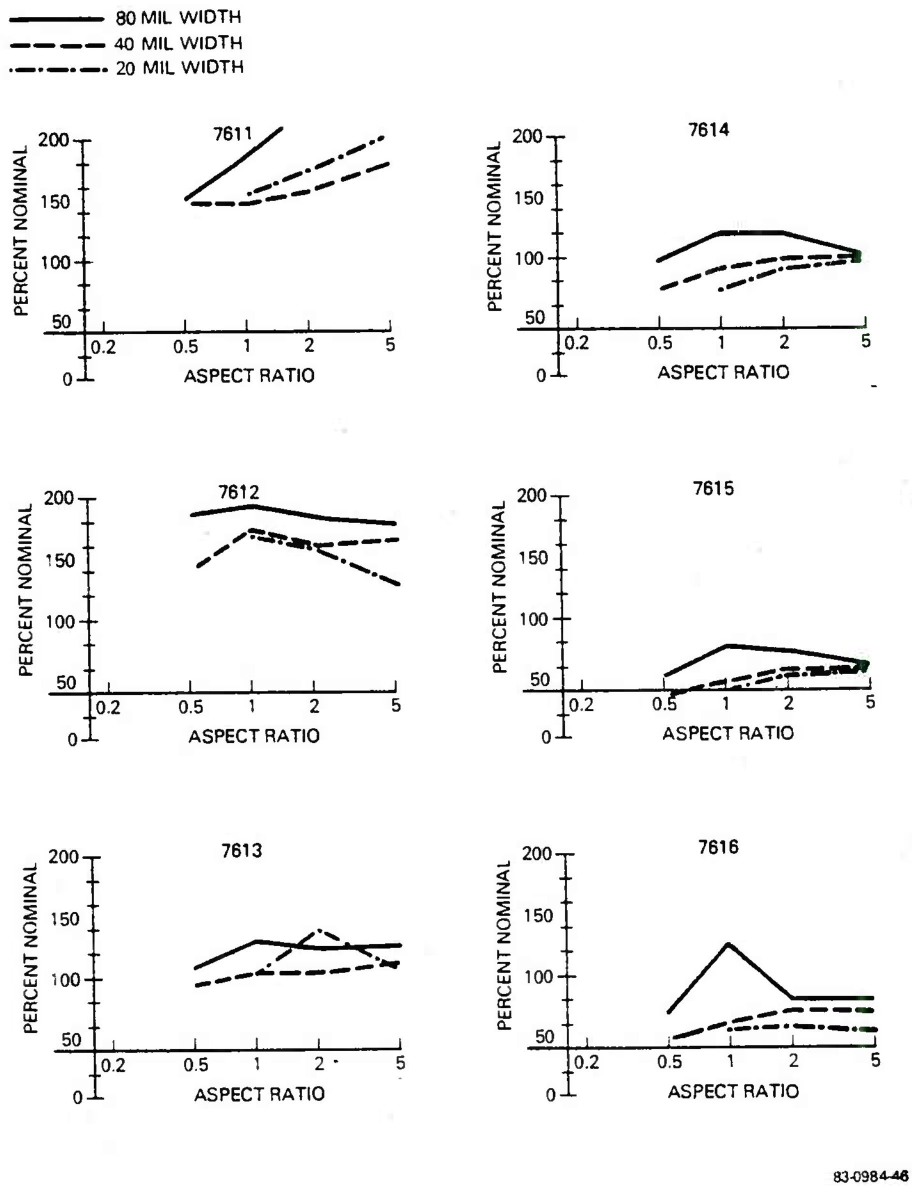

Figure 2. Variation of resistance with geometry for Dupont 7600 series resistor pastes.

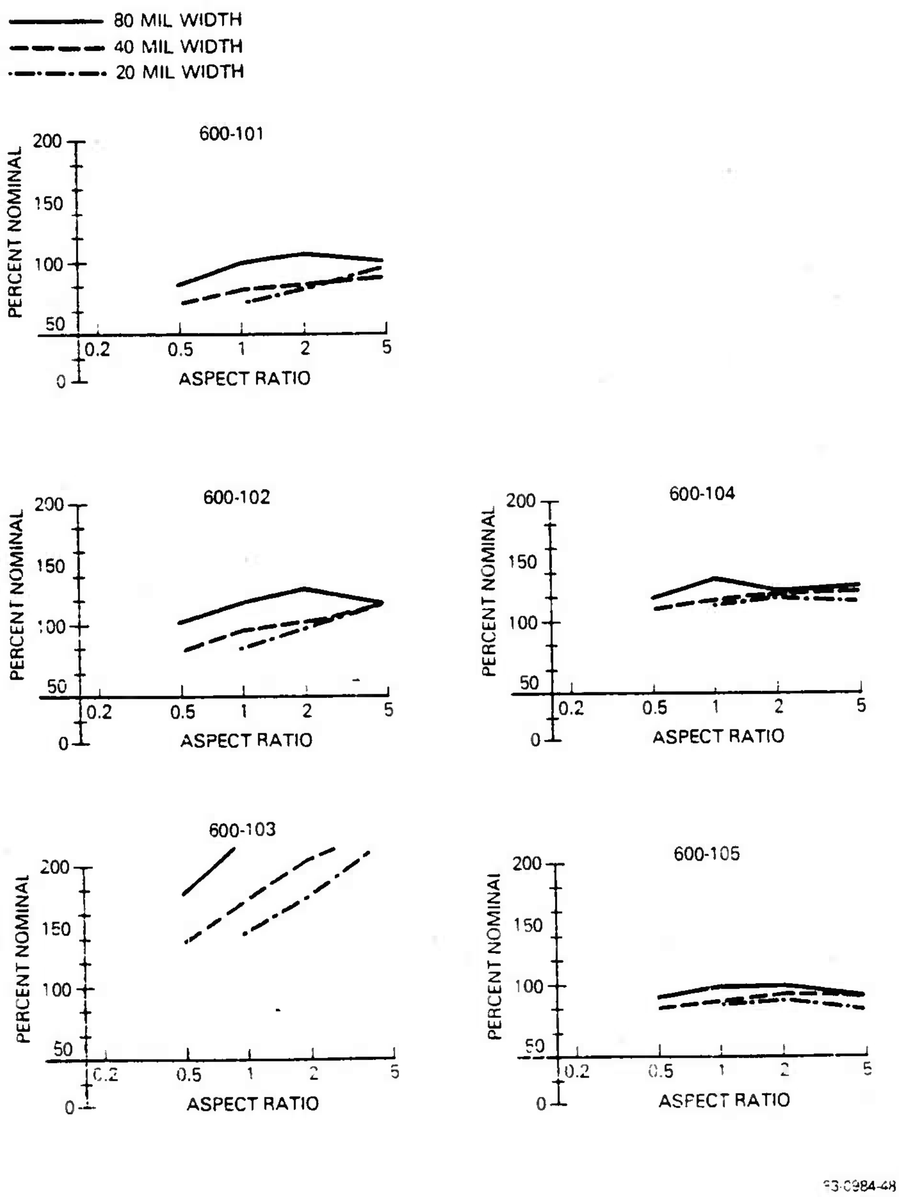

Figure 3. Variation of resistance with geometry for TPS 600 series resistor pastes

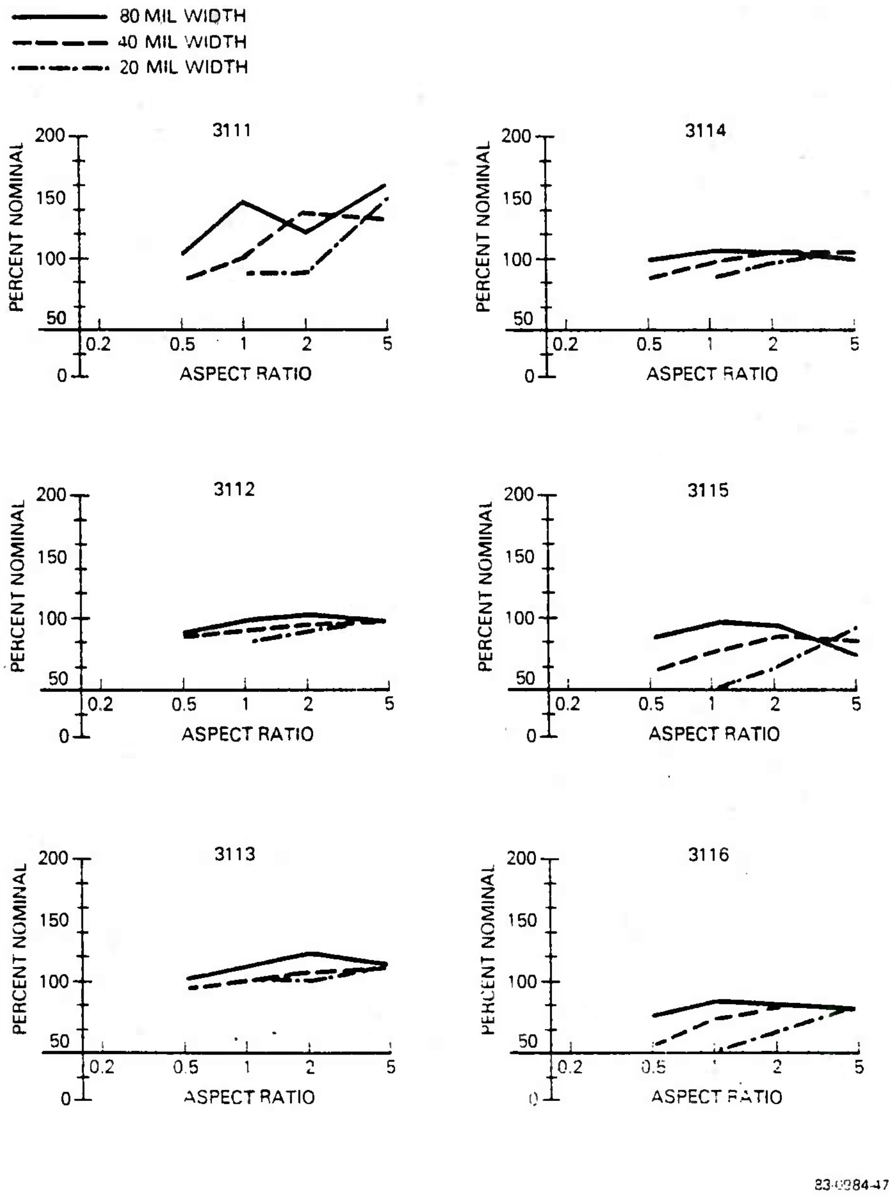

Figure 4. Variation of resistance with geometry ESL 3100 series resistor pastes

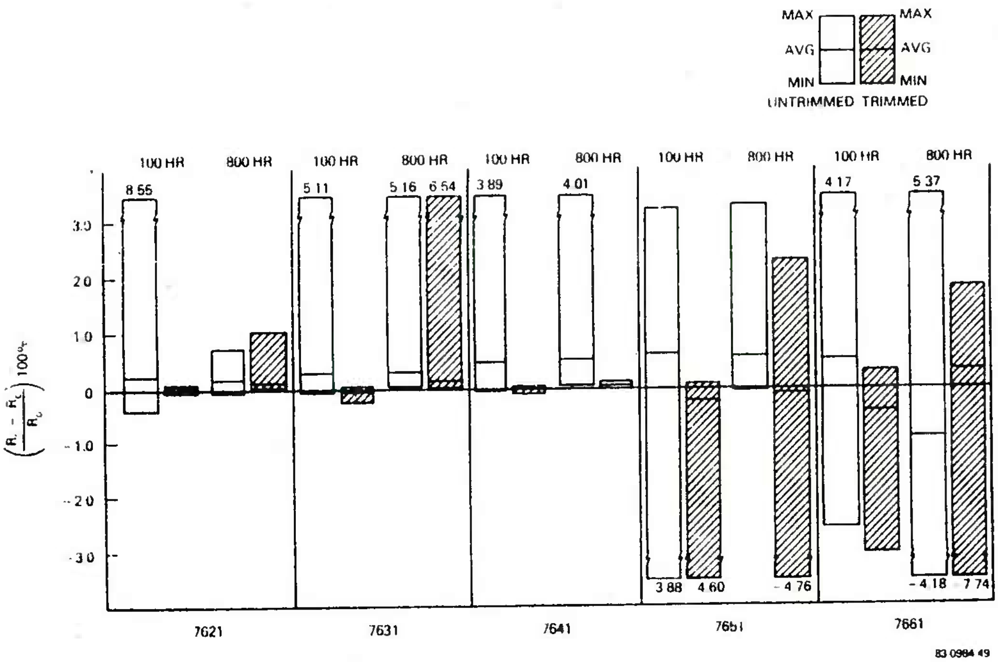

Figure 5. Long term stability, Dupont 7600 series.

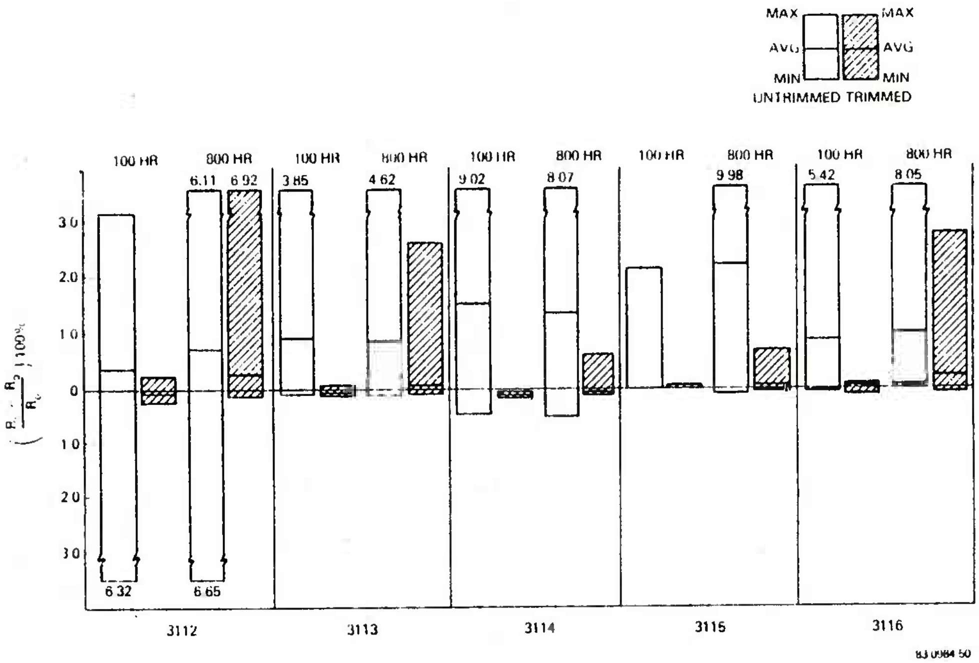

Figure 6. Long term stability, ESL 3100 series.

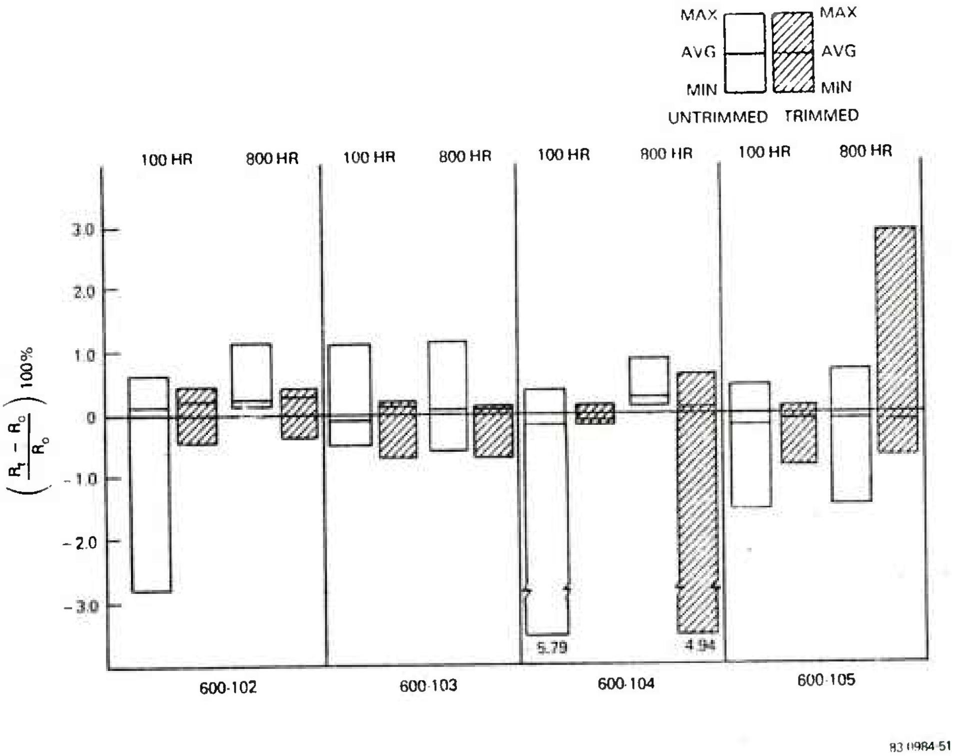

Figure 7. Long term stability, TFS 600 series.

to resistor stability, these materials would be suitable for use in a variety of circuit applications. The results of the stability testing, however, bear further discussion.

The likelihood of interaction with the substrate material is high for PES materials because the softening point of the substrate material was below the firing temperature of the resistor inks in most cases. These substrate/ resistor interfaces could be both brittle and highly stressed, causing the formation and growth of microcracks during laser trimming. These microcracks could lead to long-term resistor instability.

The results indicate that while average drift of each of the resistor materials was generally acceptable (less than 0.5 per cent after 800 hr), the distribution of individual drifts was unacceptably high. The range of drifts frequently exceeded 4 percent and sometimes exceeded 7 percent. Trimming appeared to enhance resistor stability, as untrimmed resistors tended to drift more than identically processed trimmed resistors. This behavior was also reported by Allington et al.[18] Some variation between vendors was observed, with ESL resistors drifting most, followed by DuPont, with TFS showing significantly less drift.

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18. Allington, T.R., and Cote, R.E., Characterization of Thick Film Composites on Porcelain Steel Substrates, Solid-State Technology, January 22, 1979, p. 81.

One possible mechanism for the observed reaction is the interaction between the porcelain substrate insulation and the resistor composite during firing mentioned earlier. This may give rise to the formation of a highly stressed interfacial layer during firing. The relief of these stresses would be poorly controlled and therefore unpredictable. Laser trimming may provide some stress relief and contribute to greater stability. This possibility is supported by the greater stability shown by the TFS pastes, which are fired at a lower temperature, at or below the softening point of the enamel. Obviously, more work is required to fully document and understand this behavior. However, based on these results, real concern exists as to the suitability of these materials for use where precise values are required.

3.2.2.4 Dielectrics. Thick film dielectric paste materials have extremely stringent use requirements, especially for multilayer applications. The printing, drying and firing operations must yield a coating that can reflow sufficiently to close any pinholes and voids left by the printing operation, yet does not fill vias required for interlayer connections, nor spread to cover nearby conductors such as wirebonding pads. Additionally, the resulting insulating layer must have acceptable dielectric properties. Because the rheological properties of dielectric functional materials are different from conductors or resistors, dielectric paste technology frequently matures at a lower rate.

Dielectric testing for this program was limited to examining the potential of existing materials as crossover patch dielectric in resistor-bearing substrates (such as the M734 amplifier). However, because the test patterns selected also provide for examination of properties such as via resolution, some inference of suitability for multilayer application can be made.

The dielectrics tested and test results are listed in table 10.

The results indicate that none of the materials evaluated was better than marginally acceptable. While the dielectric constants and dissipation factors were acceptable, the integrity of the insulating layer was difficult to maintain, given the low maximum firing temperatures. All the materials except the EMCA 9041-1 exhibited an unacceptable tendency to form pinhole-related shorts. In order to produce reliable crossovers routinely in volume production, +100% isolation is required at the testing level performed. While the EMCA 9041-1 produced acceptable isolation, the material tended to separate between the two dielectric layers during adhesion testing. In the case of the DuPont and ESL materials, shorting was so severe as to make dielectric property measurement impractical. No evidence of substrate/dielectric incompatibility was found, and when measurement was possible, electrical properties were comparable to thick-film dielectric materials used on alumina. It is likely that further processing work, particularly increasing the fired dielectric thickness and altering drying/firing schedules, would eliminate the above failure modes. However, this investigation indicates that processing windows are likely to be small and more material development is indicated.

TABLE 10. DIELECTRIC PASTE EVALUATED AND TESTED RESULTS

Material	Campatibility	Thickness (in.)	Adhesion	Isolation (% Passed) Capacitors	Isolation (% Passed) Lines	Vias open (%)	K	Tan (σ)	Resistivity (Ωcmx10^{12})
TFS 1120TCG	A	0.0015	A	96	85	98.8	7.8	0.001	2.45
DuPont 7701	A	0.0022	A	95.3	70	100	*	*	*
EMCA 9041-1	A	0.0017	U	100		99	8.3	.003	80
ESL M4030	A	0.0011	A	43.5		25	*	*	*

U Unacceptable
A Acceptable
* Testing halted

3.3 Processing--Comparison to Alumina. In each subsection below, the areas for concern and process modifications encountered during the transition of a production from alumina to PES technologies are detailed.

3.3.1 Substrate Condition/Preparation. Chipouts, pinholes, and cracks were not found to be a problem with PES substrates. Ordinary solvents, e.g., inhibited methyl chloroform, perchoroethane, alcohol fluorocarbons, and xylene were acceptable for cleaning and degreasing. Burrs on the substrate shear tabs had to be removed with a flat file. These burrs should be removed by the substrate vendor as part of specification/purchasing agreement.

3.3.2 Screen Printing. Good vacuum seal for substrate holddown is difficult to maintain because of substrate meniscus. Magnetic fixtures are easily designed and present no problem during use. Magnetic fixturing may be easier to maintain because no moving parts are involved. Fixturing must allow for tabs; again, no problems were encountered with redesigned tooling. No process changes are required for actual printing. No effects due to substrate camber were noted. Resolution of 0.010 in. lines on 0.020 in. centers was routinely obtainable to the substrate edge, with meniscus height specified as in section 2. Care should be taken to compensate for the increased thickness shown by some PES-compatible conductor pastes. This could cause spreading of subsequent prints because of poor screen/substrate gasketing. Some modification of printer setup parameters may be indicated.

3.3.3 Drying. Drying temperatures were similar to alumina-based processing. PES substrates have greater thermal mass and cool more slowly than alumina, making handling immediately after removal from the dryer difficult.

3.3.4 Firing. Reduction in firing temperature from the 800 to 1000°C range to the 500 to 700°C range requires furnace readjustment; however, profiles are well within the range of conventional thick-film furnaces and these profiles can be easily maintained. Sensitivity to firing temperature change is comparable to alumina-based materials. Lower firing temperatures cause deterioration of conductor paste properties as described earlier. The design, process, or both must be adjusted to maintain hybrid performance. These changes are aimed at improving wirebondability and possibly lowering track resistivity. These changes are described in detail in section 4. Firing of resistors requires compromise between desirablility of higher firing to meet vendor recommendations (as high as 650°C for DuPont) and the potential for poorly controlled resistor substrate interactions when the firing temperature is well above the enamel softening point (approximately 600°C for the enamels studied).

3.3.5 Laser Trimming. Because the resistor materials and the enamel coatings investigated here are similar in composition (oxide fillers in a glassy matrix) and color, there is relatively little difference in their material removal rates during laser trimming. In contrast, when resistors screened and fired on alumina are trimmed, significantly greater laser energy is required to penetrate the substrate than to vaporize the resistor. For this reason, care must be taken when trimming resistors on PES to remove the resistor without boiling away the enamel, exposing the metal core and giving rise to shorting between the metal core and the resistor. Since the range of acceptable trim parameters including focal distance, bite size, Q-rate, and power is quite small, substrate flatness and thickness range over a lot of substrates must be both specified and controlled in a production operation. Routine trimming was impossible on lots of substrates which exhibited excessive bowing. Substrates prepared by lapping the enamel flat before thick-film processing eliminated this problem, but the extra processing would significantly increase substrates costs and the thinner enamel coating would make the acceptable laser parameter ranges smaller.

Fortunately, samples fabricated using three different lots of ECA substrates were sufficiently flat that trimming could be done over the entire substrate without laser adjustment. However, the potential for problems related to flatness may limit the size of substrates that may be processed in volume with resistors undermining one of the real advantages offered by PES technology.

3.4 Summary-Thick Film. This section outlines the properties and processing characteristics of thick-film materials for use on PES substrates. The information herein will provide a starting point for those currently using conventional thick-film processing on alumina and considering PES substrates.

The thick-film materials (conductors, resistors, and dielectrics) are readily available from a variety of vendors. Material properties are generally within the range of acceptability for those designed for use on alumina with a few noteworthy exceptions. With the obvious exception of firing temperature, processing is nearly identical with conventional thick films. Cycle times, design rules, and yields would be about as expected for circuits on alumina in non-multilayer applications. Acceptable multilayers would be difficult to fabricate with acceptable yield. While material limitations restrict the range of useful circuit types, a wide range of circuits can be routinely fabricated using this technology.

The principal difficulties associated with the conductor materials concern wirebondability; unique, costly processing was required to produce a reliable wirebondable surface, with only limited success. Resistor materials showed a tendency to drift more than alumina-based materials. Dielectric pastes that gave consistently hermetic surfaces after two printings were not available. Careful incoming testing is required to ensure lot-to-lot reproducibility. By exercising care during circuit selection and when choosing processing options, one can find acceptable combinations which minimize the above material limitations.

Thick-film process, printing, drying, firing and trimming are very similar to those on alumina, but tighter processing tolerances, especially in the trim area, are required.

4. ASSEMBLY

A principal area of concern in the use of PES or IM substrates is their compatibility with assembly processes such as chip attachment, wire bonding, and soldering. In this section, we will discuss how these operations are performed and typical results that can be expected.

4.1 Epoxy Attachment of Active Chips. Experience in the MM&T program with epoxy attachment of silicon device chips on PES substrates has been identical to experience with chip attachment to alumina substrates. Chips were attached with the epoxies and cure cycles listed in table 11 without problem. In push-off tests, the force required to remove the chips ranged from 2 to 5 kg. In many cases the chip was destroyed before removal. Bond breaks were always in the epoxy, never in the porcelain. An environmental stress consisting of the operations in table 12 did not have a measurable effect on the quality of the bonds as determined visually and by push-off tests. It is concluded, therefore, that conventional epoxy chip mount processes that are satisfactory for use with alumina substrates will be satisfactory for use with PES.

TABLE 11. EPOXIES USED FOR CHIP MOUNTING

Material	Type	Curing Temperature °C	Curing time (minutes)
Ablebond 36-2	Conductive	125	60
Ablebond 41-5	Dielectric	125	60
Dupont 8762	Dielectric	160 200*	120 120
Dupont 5504	Conductive	160 200*	60 120

*Two-step curing process

TABLE 12. TEST PLAN DETAILS--PACKAGING EVALUATION

Test	Sample size	Test conditions
Push-off	4 substrates, 5 chips per substrate	
Thermal shock	4	15 cycles, 0 to 100°C
Temperature cycle	4	10 cycles, -55°C to +125°C
Bake	4	168 hours at 125°C
Constant acceleration	4	Centrifuge, 10,000 g, 1 min.
Push-off	As above	

4.1.2 Solder Mounting of Components. Solder mounting of components involves selection of materials and design of a process that takes into account the characteristics of solder on thick-film metalization. Principal concerns are;

(a) wetting of metalization by the solder,

(b) leaching, or dissolution, of the film by the solder,

(c) strength of the solder joint, and

(d) reliability of the solder joint.

When designing a process for use with IM substrates one must consider the following problems;

(e) Thick-film conductor material,

(f) Firing parameters,

(g) Surface preparation,

(h) Solder material,

(i) Solder application, and

(j) Solder reflow method.

The thick-film conductor used for solder pads may be selected for a variety of reasons, such as low cost, conductivity, adhesion, or compatibility with resistors. The most widely used conductors for PES substrates are believed to be silver, palladium silver, and platinum silver. The use of eight silver-bearing inks studied in the MM&T program(15) are summarized in the following sections.

4.1.2.1 Solder Wetting. The wetting of eight silver-bearing conductors fired at 600°C in Sn62 solder was found to be generally good. Table 13 shows that all conductors in the group achieved at least 85 percent initial wetting, and half of the group achieved 100 percent. In many cases, however, the solder wetting characteristics deteriorated as higher firing temperatures were used. It is hypothesized that the best solder wetting is obtained when the firing

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15. Westinghouse Electric Corp., DEC, A.B. Timberlake and F.E. Merti, authors, Final Report, Contract No. DAAK21-80-G-0076, Ceramic Metal Substrates for Hybrid Electronics, prepared for U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, Md, August, 1983.

TABLE 13. INITIAL TEST RESULTS, SOLDER WETTING AND LEACH RESISTANCE, Sn62 Pb36 Ag2 SOLDER, 220 $\pm$ 3°C

Material	Type	Fired Print thickness (10^{-3} in.)	Initial wetting (%)	Number of dips to reduced wetting		
				to 75%	to 50%	to 25%
DP 7711	PdAg	0.64	90	3	4	5
DP 7712	PtAg	0.60	95	18	27	30
DP 7713	Ag	0.27	85	1	2	12
ESL 9694	PdAg	0.80	100	22	26	30
ESL 9595A	PtAg	0.51	100	9	14	20
ESL 9996A	Ag	0.50	100	22	25	33
TFS 3418	PdAg	0.62	100	10	12	14
TFS 3347	Ag	0.34	90	3	11	14

temperature is below the porcelain softening temperature. In 96 Sn-4Ag solder wetting characteristics were somewhat degraded, as seen in table 14.

TABLE 14. INITIAL TEST RESULTS, SOLDER WETTING AND LEACH RESISTANCE, 96Sn 4Ag SOLDER, 250 $\pm$ 3°C

Material	Type	Fired Print thickness (10^{-3} in.)	Initial wetting (%)	Number of dips to reduced wetting		
				to 75%	to 50%	to 25%
DP 7711	PdAg	0.64	100	5	7	9
DP 7712	PtAg	0.60	95	7	8	9
DP 7713	Ag	0.27	100			1
ESL 9694	PdAg	0.80	100	6	7	9
ESL 9595A	PtAg	0.51	50		1	2
ESL 9996A	Ag	0.50	90			5
TFS 3418	PdAg	0.62	100			4
TFS 3347	Ag	0.34	50			3

4.1.2.2 Leach Resistance. The silver-bearing conductors evaluated in the program showed leaching characteristics similar to those of conventional thick films fired at high temperatures. Data are shown in Table 15. One significant difference was observed: the films were never completely leached away by the solder. Rather, a point would be reached when the pad was no longer wet by the solder. A metallic pad of significant thickness always remained. This effect could be advantageous if total de-wetting occurred, since the electrical continuity of the circuit would not be affected by the action of the solder. If it were necessary to use the "de-wet" substrate, conductive epoxy could be used for component mounting.

In leach resistance testing none of the three compositions tested was clearly superior. In addition, there was not a strong dependence on firing temperature, until good wetting was no longer obtained.

TABLE 15. SOLDER WETTING AND LEACH RESISTANCE OF SILVER-BEARING CONDUCTORS

		Solder wetting at various temperatures, (°C)									
Material	Composition	575		600		625		650		675	
DP 7713	Ag	-		G	1	P	1-2	P	6-8	N	
ESL 9996A	Ag	-		G-E	4-15	G	4-5	G	5-11	--	
TFS 3347	Ag	G	3	F-G	1-3	P	3	-	-	--	
EP 7711	PdAg	-		G	-	F	2-3	F	5-13	F	2-4
ESL 9694	PdAg	-		G-E	7-15	G-E	15+	G-E	15+	--	
TFS 3418	PdAg	F	7-8	G	9	G-E	10-12	-	-	--	
DP 7712	PtAg	-		G-E	5-15	G	4-5	F	7-13	N	
ESL 9595A	PtAg	-		G-E	5	G	4-15	P	9-10	--	

P - Poor
F - Fair
G - Good
E - Excellent

4.1.2.3 Adhesion. The strength of solder joints to silver-bearing conductors on PES measured in peel ranged from approximately 100 to 1000 PSI. Details of the tests and results are given in the MM&T final report.(15)

Strengths are affected by the type of conductor material used and by the substrate firing temperature. Certain characteristics seem to be shared by all pastes of a particular type, discussed in the following sections.

4.1.2.3.1 Platinum-Silver. Bond pull strengths averaged slightly higher on the two platinum-silver inks tested than on the other materials. A tendency toward lower strength as firing temperature increased was observed. The tendency may be more pronounced in low-platinum-content inks. Poor wetting at the higher temperatures may have contributed to lower observed strengths. The failure mode in solder pads on platinum silver usually involves porcelain removal. This type of failure indicates the maximum strength that can be achieved with PES substrates, in this case about 1000 PSI.

4.1.2.3.2 Palladium-Silver. Solder joints to palladium-silver pads show a tendency to increase in strength as firing temperature is increased, until the maximum temperature is exceeded. This is true in both high- and low-palladium-content inks. The predominant failure mode involves a separation within the pads. It is hypothesized that the higher firing temperatures increase the sintering of metal powders, thus increasing the interlayer strength. Therefore, the highest firing temperature possible with the particular substrate is recommended if palladium-silver inks are to be used for solder pads.

4.1.2.3.3 Silver. Silver is an inconsistent performer in solder pull strength testing. At best, the failures are in the porcelain, as with platinum silver. However, the data showed too much scatter to permit firm conclusions.

4.1.2.4 Conclusion: Solderability of PES Substrates. The solder wetting, leach resistance, and adhesion strength tests were intended to disclose common, generally applicable characteristics of solderable thick films on PES substrates. The tests performed required considerable subjective interpretation, and for this reason the results must be treated carefully. Similarly, the scatter in the data, particularly in the adhesion tests, makes the statistical significance of the tests marginal. However, by analyzing the trends which could be discerned and correlating them with other information and knowledge, it is possible to make hypotheses which may be useful.

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15. Westinghouse Electric Corp., DEC, A.B. Timberlake and F.E. Merti, authors, Final Report, Contract No. DAAK21-80-G-0076, Ceramic Metal Substrates for Hybrid Electronics, prepared for U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD August, 1983

1. Adhesion of film to porcelain. Such adhesion suggests strong interaction even at low temperatures.

2. Anomalous apparent leach resistance of pure silver compared to other materials. (Also noted by Linder of G.E.).[19] We equate leach resistance with dewetting. The PdAg and PtAg dewet rather than leach, because of selective dissolution of the silver. The remaining films are platinum-rich or palladium-rich, and are not easily wet with solder.

This condition suggests that the low firing temperature required by these substrates is insufficient to promote alloying of the metallic constituents.

3. Failure mode of solder joints on PdAg pads. Failures of these joints seemed to occur <u>within</u> the films. This phenomenon suggests primarily that very little sintering of the metal powders has taken place. Also, the firing temperatures of thick films for PES substrates are in the range where palladium oxide forms, but below the range where it decomposes. The palladium oxide may inhibit sintering of the powders. It was observed that PdAg films fired at 650°C failed by removal of porcelain, indicating that the cohesion of the film was increased. However, the 650°C firing temperature usually resulted in degraded solderability.

4.2 Chip-to-Substrate Fine-Wire Interconnection.

An essential technology for fabrication of bare-chip (integrated-circuit die) hybrid circuitry is attachment of fine (0.001 in.) wire to chips and substrates. Three basic techniques exist in the hybrid industry for doing this: thermocompression, in which a gold wire is bonded to a metallized semiconductor chip and substrate by simultaneous application of heat and pressure; ultrasonic bonding, in which ultrasonic energy and pressure are applied to the wire and surface to achieve a bond; and thermosonic bonding, in which heat, pressure, and ultrasonic energy are used. The completed bonding operation forms a metallurgical bond between the chip and the substrate.

For an automated assembly process, emphasis must be placed on thermosonic bonding of 1-mil gold wire, since this is the technology used in all commercially available automatic wire bonders.

In a wire-bonding operation many variables must be controlled for a successful outcome. Surface cleanliness, wire characteristics, capillary (bonding tips) shape and size, bonding pressure, substrate temperature, ultrasonic energy level and duration, and substrate clamping--all determine the quality and reliability of the bonds achieved. Even when surfaces known to be wire bondable (e.g., plated gold on alumina) are used, the conditions cited above must be properly handled. In attempting to wire bond to a new material on a new substrate it is necessary to find, if possible, the set of conditions which will result in satisfactory wire bonds for that material.

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19. Linder, P.A., Green, D., Porcelainized Steel Substrate Technology: State-of-the-Art. Considerations In Its Applications, Proceedings ISHM Symposium, 1980, pp. 89-98.

With PES substrates the problem is compounded by a substrate surface relatively unknown for hybrid assembly. In addition, the metal films formulated for porcelain fire at a much lower temperature than the films with which most hybrid experience has been gained.

Besides the MM&T program, only two other references providing detailed data on wire-bonding on commercial PES substrates have been found. Johnson et, al,[20] bonded 0.001 in. gold wire to silver-bearing and gold thick film conductors with excellent results. Lindner and Green[19] ultrasonically bonded 0.005 in. aluminum wire to silver and silver bearing conductors. The latter study is only partially relevant, since bonding parameters and pull-test results applicable to 0.005 in. aluminum wire will be completely different from those applicable to 0.001 in. gold wire.

In this document emphasis is placed on Westinghouse experience with thermosonic bonding of 0.001 in. gold wire. In addition, the results achieved by Johnson,[20] who used a different hardness wire and different bonding method, are summarized and discussed.

4.2.1 Test Conditions and Criteria. In developing a suitable wire-bonding process for a new conductor- substrate combination it is advisable to design a wire-bond test pattern that simulates actual conditions. The pattern should be such that all wire loops are uniform both in height and in ball-stitch separation. A pattern of rectangular pads 0.015 x 0.040 in. separated by 0.040 in. is used at Westinghouse.

In evaluating materials and processes, criteria should be established. The following were used by Westinghouse in the MMT program:

(a) Numbers of multiple hits required to achieve a bond. If more than one "hit" or attempt is required to bond the wire to the substrate, it is futile to consider automatic wire-bonding,

(b) Numbers of failures in destructive pull testing with less than 3 grams force. Bonds would fail a nondestructive pull test enough to indicate an unsatisfactory process,

(c) Numbers of ball and stitch lifts in destructive pull testing. In an established process where well-characterized materials are used, there should be no ball or stitch lifts, which are indicative of an unreliable bond. In evaluating new materials, bond lift counts serve as an index of bonder process development.

19. Linder, P.A., Green, D., Porcelainized Steel Substrate Technology: State-of-the-Art. Considerations In Its Applications, Proceedings ISHM Symposium, 1980, pp. 89-98.

20. Johnson, R.W., Wilson, L.K., and Kinser, D.L., Characteristics of Thermal Compression Wire Bonds to Thick Film Conductors on Procelain Substrates, Proceedings Electronic Components Conference, 1979, pp. 206-212.

(d) Relative percentages of wire breaks and stitch lifts. A high percentage of stitch lifts is undesirable and indicates a process which needs improvement.

It should be noted that the average breaking strength of the bond is of less importance than the failure mode. Wire breaks are the most desirable failure modes, regardless of the force required. Ball and stitch lifts should be considered unacceptable when 0.001 in. wire is used.

For each conductor being evaluated it is necessary to establish optimum wire-bonder operating conditions. Frequently, the conditions used for similar materials can be used to obtain bonds strong enough to test.

4.2.2 Bonding to Silver-Bearing Conductors.

4.2.2.1 Machine Setup. In the recent MM&T program, bonding gold wire to the silver-bearing PES thick-film materials proved to be very difficult. The major difficulty was formation of satisfactory stitch bonds. At low power/time settings, the wire would not stick to the metallization. At high power settings the wire would be severed or severely damaged by the bonder tip. The bonding "window" proved to be very narrow. This situation was reflected in pull-test results obtained on "successful" bonds, i.e., where the loop could be completed.

The results of all wire-bondability tests on seven of the eight silver-bearing conductor are presented in tables 17 through 23. Data for gold wire/thermosonic and aluminum wire/ultrasonic are shown. Three surface treatments described in table 16 were used. The data illustrate the following points:

(a) Pure silvers were most bondable.
(b) Palladium-silvers were least bondable.
(c) The predominant failure mode was stitch breakage.
(d) There was a wide spread in pull strengths.
(e) Formation and integrity of the ball bond was satisfactory.
(f) A large percentage of failures were under three grams.
(g) Burnishing with a fiber-glass brush was detrimental to wire bonding.
(h) Aluminum wire/ultrasonic bonding was less successful than gold wire/thermosonic bonding.

TABLE 16. SURFACE TREATMENT OF WIRE BOND TEST SAMPLES

Code	Description of treatment
A	Unburnished
B	Burnished, fiberglass brush
C	Plasma cleaned

TABLE 17. WIRE-BOND PULL-TEST RESULTS, DUPONT 7712 PtAg

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm) Mean	SD	Failure mode distribution (%) Wire	Stitch	Lifts	Under 3 gm
TS	10	A	4.7	2.5	10	90	0	30
TS	25	A	6.5	1.5	48	52	0	8
TS	25	A	6.5	2.2	16	84	0	12
TS	23	B	1.3	1.2	0	100	0	76
US/AL	24	A	5.2	4.1	0	75	25	40

[a] TS = thermosonic, gold wire.
US = ultrasonic, aluminum wire.
[b] See codes in table 16.
[c] SD = standard deviation.

TABLE 18. ESL 9595A PtAg Wire-Bond Pull-Test Results

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm) Mean	SD	Failure mode distribution (%) Wire	Stitch	Lifts	Under 3 gm
TS	26	A	6.2	2.2	23	77	0	12
TS	0	B					Could not attach bonds	
TS	25	A	6.9	2.3	24	76	0	12
TS	25	B	3.9	1.5	8	92	0	12 (fiber glass)
TS	25	A	5.2	2.0	0	100	0	16
US	12	E	8.5	2.8	0	100	0	0

[a] TS = Thermosonic, gold wire.
US = Ultrasonic, aluminum wire.
[b] See codes in Table 16.
[c] SD = Standard Deviation.

TABLE 19. WIRE-BOND PULL-TEST RESULTS, DEPONT 7713 Ag.

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm) Mean	SD	Failure mode distribution (%) Wire	Stitch	Lifts	Under 3 gm
TS	25	A	5.4	2.5	20	80	0	28
TS	25	A	3.6	2.1	0	100	0	36
TS	23	B	2.1	1.6	4	96	0	83
TS	10	C	8.1	1.3	80	10	10	0
TS	26	C	6.5	2.2	44	56	0	8
US	18	A	5.9	4.2	0	84	16	28

[a] TS = Thermosonic, gold wire
US = Ultrasonic, aluminum wire
[b] See codes in table 16
[c] SD = standard deviation

TABLE 20 ESL 9996 Ag. WIRE BOND PULL TEST RESULTS

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm) Mean	SD	Failure mode distribution (%) Wire	Stitch	Lifts	Under 3 gm
TS	10	C	6.4	2.6	40	60	0	10
TS	25	A	7.7	1.2	60	40	0	0
TS	23	C	7.1	1.6	39	61	0	0
TS	25	A	7.7	2.6	28	68	4	4
TS	25	B	4.1	3.1	0	100	0	48
US	16	A	6.0	3.9	0	81	19	25
TS	30	B	7.6	1.5	40	47	13	0
TS	25	A	5.3	2.2	4	96	0	4
TS	25	B	4.7	1.6	0	64	36	24

[a] TS = Thermosonic, gold wire
US = Ultrasonic, aluminum wire
[b] See codes in Table 16
[c] SD = Standard Deviation

TABLE 21. WIRE-BOND PULL-TEST RESULTS, TFS 3347 Ag

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm) Mean	SD	Failure mode distribution (%) Wire	Stitch	Lifts	Under 3 gm
TS	25	A	5.9	2.3	28	72	0	8
TS	25	A	5.2	2.1	8	92	0	16
TS	25	B	2.2	2.2	40	96	0	72
TS	25	C	7.6	1.5	56	44	0	0
US	37	A	9.7	4.4	0	97	3	8

[a] TS = thermosonic, gold wire.
US = ultrasonic, aluminum wire.
[b] See codes in table 16.
[c] SD = standard deviation

TABLE 22. WIRE-BOND PULL-TEST RESLTS ESL 9694 PdAg

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm) Mean	SD	Failure mode distribution (%) Wire	Stitch	Lifts	Under 3 gm
TS	26	A	6.6	1.7	31	69	0	0
US		A	Not bondable					
TS		A & B	Not bondable					

[a] TS = thermosonic, gold wire
US = ultrasonic, aluminum wire
[b] see codes in Table 16
[c] SD = standard deviation

TABLE 23. WIRE-BOND PULL-TEST RESULTS TFS 3418 PdAg

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm) Mean	SD	Failure mode distribution (%) Wire	Stitch	Lifts	Under 3 gm
TS	25	A	5.1	2.4	28	60	12	16
US	0	A,B	Not bondable					

[a] TS = thermosonic, gold wire
US = ultrasonic, aluminum wire
[b] See codes in table 16
[c] SD = standard deviation

Effort was also devoted to making thermocompression bonds using 1-mil gold wire. With a capillary temperature at 465°C and substrate temperature of 160°C, attempts on all materials were poor or completely unsuccessful. Raising the substrate temperature to 235°C made it possible to achieve bonds on the pure silvers, but the other materials were not bondable. This effort was not pursued.

4.2.2.2 Data of Johnson et al. The results described above were achieved using thermosonic bonding. Substrate temperature was 150°C, and the wire elongation was 3-5 percent. Johnson et al,[(20)] using thermocompression bonding with pulse-heated capillary, obtained very different results on similar materials.

The pull test data on bonds on all materials after fabrication, and after aging 1000 hours at 150°C, are shown in table 24. Data for conductors printed directly on porcelain, and over dielectric, are presented. The mean pull strengths for all conditions fell in a fairly narrow range from 5.51 to 6.22 g. More significantly, it was reported that 99 percent of the breaks were in the wire, and no breaks under three grams were reported.

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20 Johnson, R.W., Wilson, L.K., and Kinser, D.L., Characteristics of Thermal Compression Wire Bond to Thick Film Conductors on Porcelain Substrates, Proceedings Electronic Components Conference, 1979, pp. 206-212.

TABLE 24. WIRE-BOND DATA OF JOHNSON, WILSON, AND KINSER[20]

Material	Composition	Mean pull strength (grams)			
		On porcelain		On dielectric[b]	
		Initial	Aged[a]	Initial	Aged
TFS 3045	Au	5.79	6.04	6.18	6.22
TFS 3106	Pt-Au	5.66	5.80	5.89	5.94
TFS 3535	Pt-Pd-Ag	6.10	5.89	6.18	5.82
TFS 3408	Pd-Ag	5.80	5.59	5.71	5.51

a Aged 1000 hours at 150°C

b TFS 1129 dielectric.

Wire: 0.001 in. gold, 2-7 % elongation

Machine: Hughes Model 360 Pulsed-Tip Thermocompression

Bonding Temperatures: Tip, 550°C; Stage, 135°C

Thick Film Parameters: Fired at 600°C peak, 10 min. dwell on Alphamet substrates from Alpha Metals Corp.

20 Johnson, R.W., Wilson, L.K., and Kinser, D.L., Characteristics of Thermal Compression Wire Bond to Thick Film Conductors on Porcelain Substrates, Proceedings Electronic Components Conference, 1979, pp. 206-212.

These results indicate that the pulsed-tip thermocompression method should be considered. For automatic thermosonic bonding, pulsed capillary heaters are available, and their use seems indicated by Johnson's data.

4.2.3 Bonding to Gold Conductors. The major portion of the MM&T effort to establish satisfactory wire bonding to PES substrates was devoted to work with gold conductor inks. Most of this work was done with Thick Film Systems 3045. In addition, a few substrates with Cermalloy 4350 and Plessey C5800 golds (provided as fired by the vendor) were evaluated.

4.2.3.1 TFS 3045. Initial tests indicated that the TFS 3045 could be wire bonded with more success than had been achieved with the silvers. Table 25 and figures 8 and 9 present the results of tests made after the bonding parameters were optimized. It can be seen that, relative to the silvers, mean breaking strengths are higher, the data spread is less, there are fewer lifts and low-value breaks, and a higher percentage of breaks are in the wire, rather than the stitch. However, the results are still inferior to those achieved on conventional gold films on alumina. This problem is discussed in section 4.3.3.

Table 25 also presents results for thermocompression bond testing on TFS 3045. Substrate and capillary temperatures were 235°C and 465°C, respectively. In contrast to our experience with the silver-bearing thick-film inks, thermocompression bonding resulted in greatly improved wire bonds. For both burnished and unburnished films, the distributions were narrow, as can be seen in figure 10. Most significantly, all breaks were in the wire. Burnishing did not seem to affect the results, although it was felt that the burnished surface was preferable.

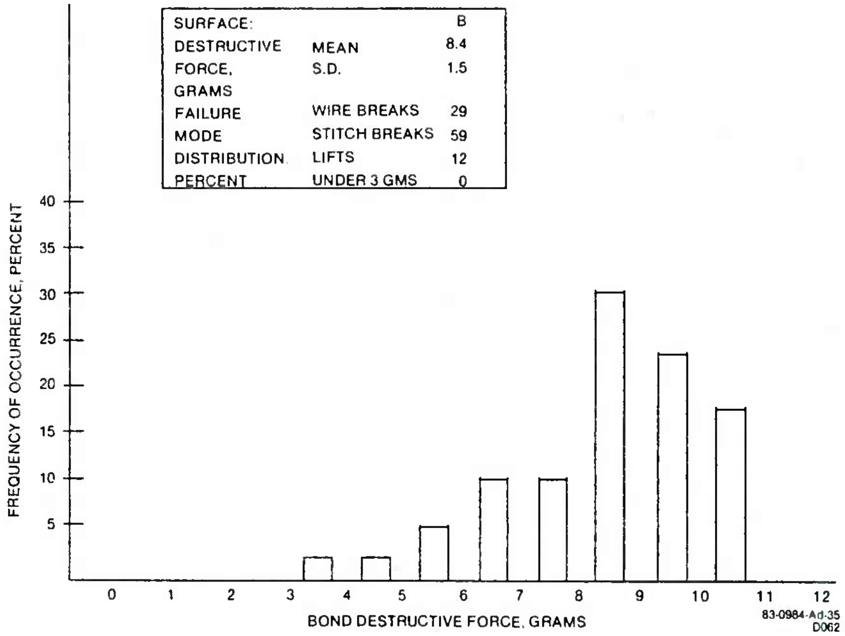

Figure 8. Distribution of pull test failures, thermosonic bonds, TFS 3045 Au, Burnished.

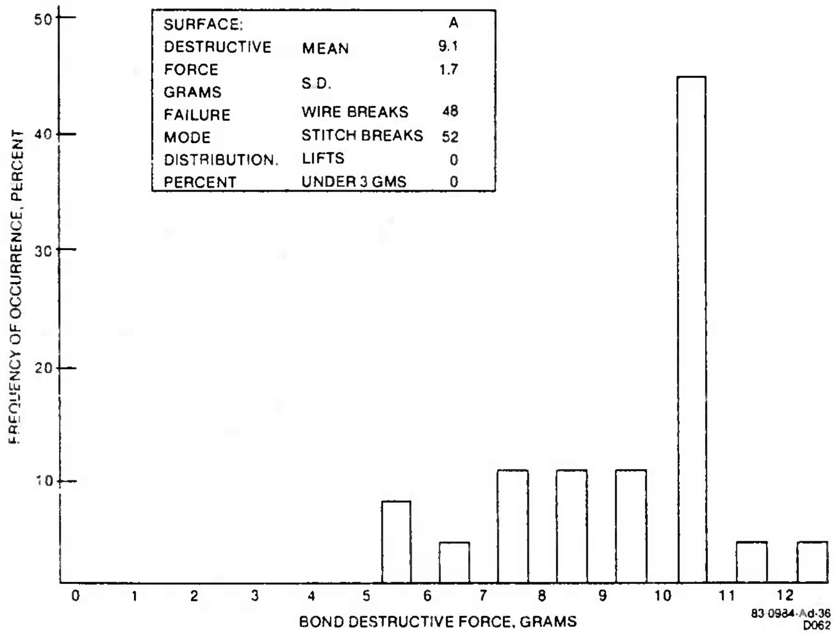

Figure 9. Distribution of pull test failures, thermosonic bonds, TFS 3045 Au, Unburnished.

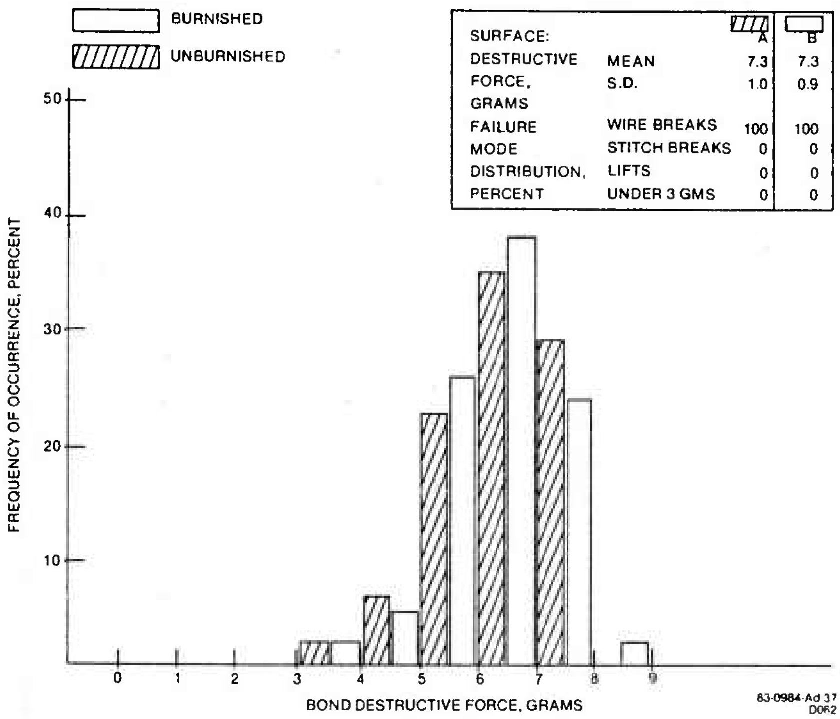

Figure 10. Distribution of bond strengths, thermocompression bonds to TFS 3045 Au.

4.3.2.2 <u>Cermalloy 4350 and Plessey C5800</u>

Sample substrates with patterns printed in Cermalloy 4350 gold and Plessey EMD C5800 were provided by the vendor. Both were on Alpha substrates, and were fired at 625°C. The pattern consisted of a meandering line approximately 20 mils wide, crossing back and forth across the substrate.

The results of thermosonic bond testing on one Plessey and two Cermalloy samples are shown in table 26. Distributions are shown in figures 11 and 12.

The results of testing the C5800 were especially impressive when compared to results on high-temperature films on alumina. Pull-strength distributions were tight, and no low-value failures occurred. The only negative feature was the difficulty in making satisfactory stitch bonds to the Cermalloy 4350. Large percentages of the breaks involved partial lifts at the stitch. It was felt that this problem could be reduced with more optimization.

TABLE 25. WIRE BOND PULL TESTS RESULTS. TFS 3045
GOLD OR PES SUBSTRATES.

Parameters	Results According To Bonding Method					
	TS	TS	TS	TS	TC	TC
Substrate temperature (°C)	150	150	150	150	235	235
Surface	B	A	B	B	B	A
Number bonds	105	25	77	50	59	66
Mean destructuve force (gm)	7.7	9.1	8.4	7.7	7.3	7.3
Standard deviation (gm)	1.7	1.7	1.5	2.1	0.8	1.0
Wire breaks (%)	0	48	29	46	100	100
Stitch breaks (%)	93	52	59	52	0	0
Ball or Stitch (%) lifts, (%)	7	0	12	2	0	0
Under 3 gm (%)	5	0	0	4	0	0

TABLE 26. WIRE BOND PULL TEST RESULTS FOR GOLD THICK FILM FIRED AT 625°C, THERMOSONIC-BOND, 1-MIL GOLD WIRE

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3gm
Cermalloy 4350	54	A	9.0	1.3	39	61[b]	0	0
Cermalloy 4350	65	B	8.1	1.4	25	75[b]	0	0
Plessey-EMD C5800	116	B	9.6	1.1	54	46	0	0

[a] See Table 16 for code.
[b] Partial breaks and partial lifts.

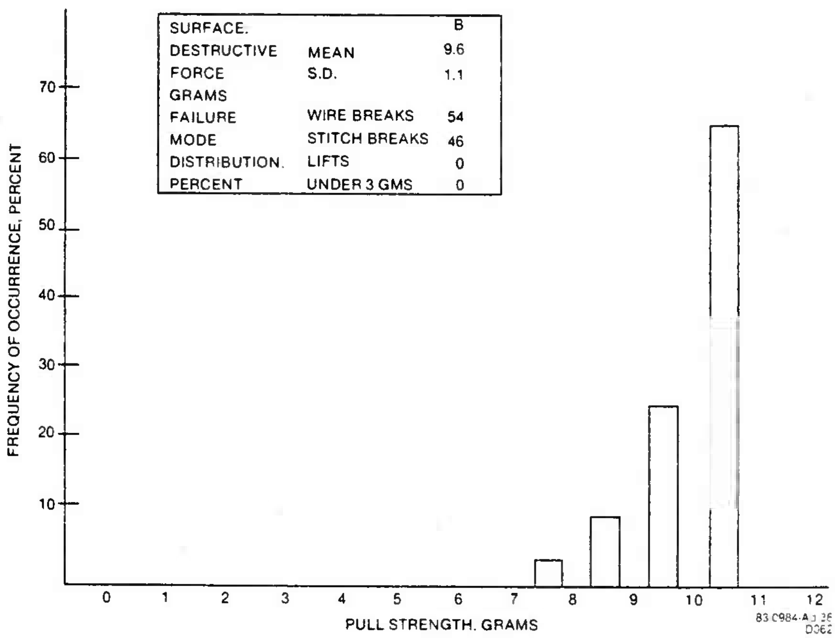

Figure 11. Distribution of pull test failures, thermosonic bonds, Cermalloy/EMD C5800 Au.

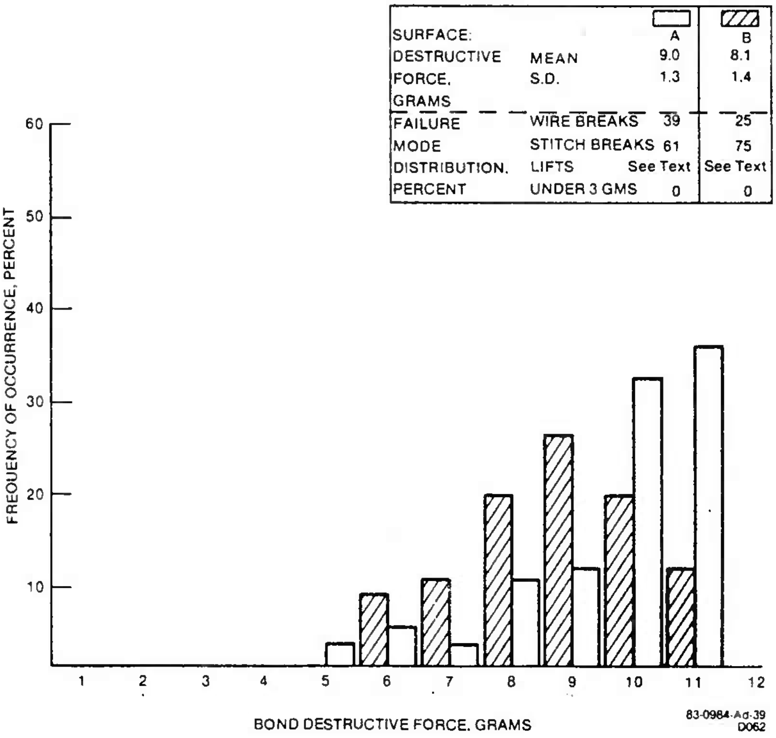

Figure 12. Distribution of pull test failures, thermosonic bonds, Germalloy 4350 Au.

4.3.3 Improved Wire Bonding.

4.3.3.1 Thick-Film Modification. In the MM&T final report[13] the causes of wire bonding problems with PES substrates were discussed in detail. It was shown that the high glass content and poor sintering of PES conductors were responsible for these problems, to a large extent.

Since the degree of metal particle sintering is a function of temperature, some benefit could be gained by increasing firing temperatures. The performance of Plessey and Cermalloy golds fired at 625°C tends to substantiate this speculation. However, it was seen in the solderability testing that 625°C was a practical limit on firing temperature of PES substrates then available. Recent substrate configuration have increased maximum firing temperatures to 675°C, which should be beneficial to wire bonding.

The second characteristic detrimental to wire bonding, high glass content, can also be addressed. It was found that overprinting wire bonding pads with an "unfluxed" gold significantly improved the wire bonding of both silver-bearing and gold thick film. The unfluxed gold, which contains only gold powder and an organic binder, provides a highly metallic surface for bonding. Table 27 shows wire bonding results for samples of previously fired silver-bearing conductors overprinted with Cermalloy 4300 UF, an unfluxed gold. Data for overprinted TFS 3045 gold, both fired and unfired, are shown in figure 13. Except for Dupont 7711 Pd-Ag, which the overprint did not

TABLE 27. WIRE BOND PULL TEST RESULTS, SILVER-BEARING CONDUCTORS OVERPRINTED WITH CERMALLOY 4300 UF.

Bottom conductor	Quantity	Destructive force (gm)		Failure mode distribution (%)			
		Mean	SD	Wire breaks	Stitch breaks	Lifts	Under 3 gm
DP 7712, fired	10	8.9	0.8	90	10	0	0
DP 7713, fired	10	9.3	0.6	100	0	0	0
ESL 9694, fired	10	9.5	0.6	100	0	0	0
TFS 3347, fired	10	9.2	0.7	100	0	0	0
TFS 3418, fired	10	9.3	0.9	100	0	0	0

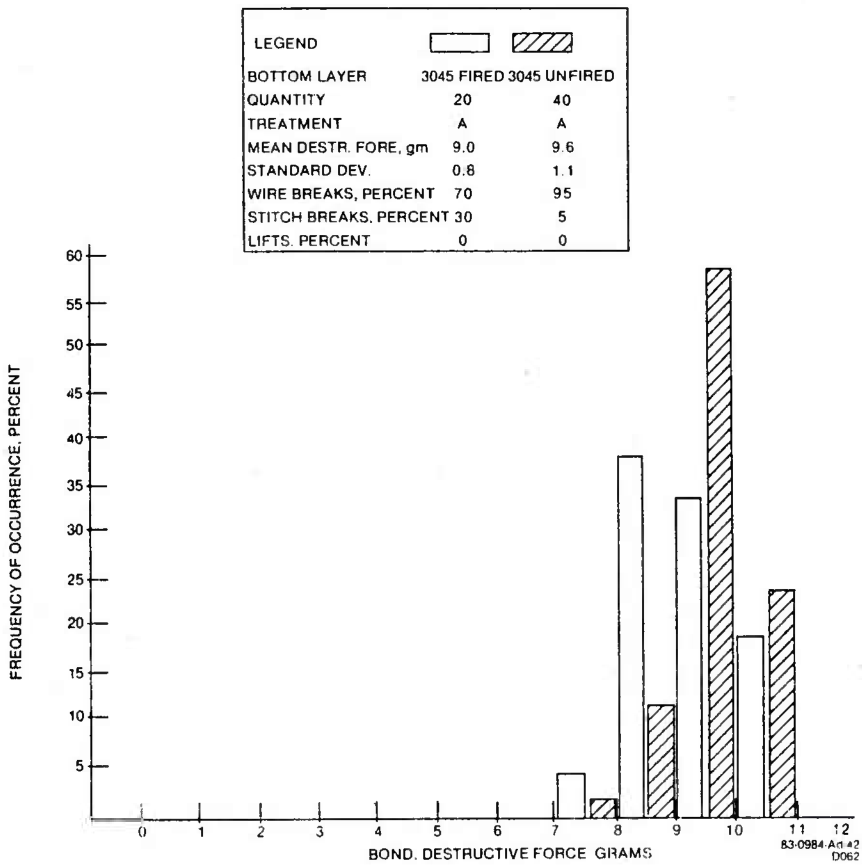

Figure 13 Wire-bond pull-test results, TFS 3045 overprinted with Cermalloy 4300 UF.

adhere to, overprinting brought about significant improvement in the wire bondability of all materials tested. It was felt that performance was the same regardless of whether the base conductor was fired or unfired. Overprinting the fired conductor saves one firing cycle. This saving must be balanced against the risk of damage in working with unfired conductor patterns.

4.3.3.2 Wire-Bonding Operation Modifications. In addition to the thick-film modifications discussed above, several changes in the wire-bonding processes and equipment from those used in the MM&T should improve the results. If gold conductors cannot be used because of cost, such changes would be a necessity.

If automatic, hence thermosonic, bonding is not a requirement, the excellent results obtained by Johnson should be studied. Pulse heated capillary thermocompression bonding appears to be a viable technique. Dealing with thermosonic bonding, it is felt that the results obtained in the MM&T program could have been improved upon by the following modifications:

(a) Lower elongation wire. A "harder" wire than the 3 to 5% elongation wire used might have reduced the damage to the wire in stitch bonding.

(b) Higher substrate temperature. This may be limited by the components in place during bonding.

(c) Capillary tip of larger radius. Again, less cutting of the wire would occur during stitch formation.

(d) Use of capillary heating. More heating of the bond area would be possible without damage to components on the substrate.

4.4 Summary-Wire Bonding

Although the silver-bearing thick-film conductors as a group did not prove to be satisfactorily wire bondable in the MM&T program, it is felt that the problems can be overcome without major difficulty. Indeed, the higher firing temperatures now possible with newer PES substrates may have resulted in much better wire bondability for the conductors used. Over-printing with an unfluxed conductor (it need not be gold) can also bring about significant improvement. Finally, optimization of the wire-bonding process, including materials and equipment, has the potential to bring about satisfactory wire bonding.

4.5 Assembly

As was the case in thick-film operations, PES substrates usually did not require substantial changes of procedure for successful assembly. An exception must be made, of course, in discussing wire bonding. Since the wire-bonding difficulty occurred at such a late date in the program, it was not possible to try several alternative approaches to making the bonds. These could have included use of a heated capillary, use of a harder (or softer) wire, different thick-film firing profile, and different conductor ink. Inasmuch as it had been possible to have a satisfactory wire-bonding process in the earlier phase of the program, it seems entirely probable that a satisfactory solution exists for the assembly operation.

5. SUMMARY

In the course of the technical phase of the MM&T program large amounts of data were acquired pertaining to the characteristics and use of PES substrates in thick-film hybrids. These data were presented and discussed in the program final report. In this document a condensation of these data in a form useful for guidance to those considering use of PES substrates has been attempted. The significant observations are discussed in the next few paragraphs.

5.1 Substrates. - A thick-film hybrid substrate, whatever its other properties, must meet minimum conditions of flatness and surface smoothness. Close tolerances must be met on length, width, and thickness. The insulating coating must be thick enough and pinhole free to isolate the metal core from the substrate. These are fundamental requirements. Our data indicate that vendors are able to supply substrates which meet these requirements, with two qualifications. First, substrate flatness should be very carefully specified. Second, for certain applications, it may be necessary to discuss with the vendor techniques for reducing the size of the edge meniscus. The coatings on all substrates used in the thick-film and product verification phases were uniformly excellent--free of pinholes, chipouts, blisters, and other defects.

5.2 Thick film. - After a film is printed, it must be fired in a temperature schedule that promotes various characteristics in the film. In this process, an interaction occurs between the film and the substrate, the extent of which must be controlled enough to permit beneficial effects, such as adhesion, but minimize deleterious effects, such as glassy, nonsolderable film surfaces. Substrates evaluated in this program softened at approximately 600°C, and interacted deleteriously with fired films above 625°C. Most thick-film inks formulated for PES substrates are said to achieve optimum properties in the 600 to 650°C range. Thus, there may be a very narrow temperature window in which satisfactory film properties can be obtained.

It should be noted that during processing of hundreds of substrates in the MM&T program no obviously deleterious interactions between the substrate and the thick film were seen at any firing temperature. That is, there were no blisters, "brown plague", "floating" patterns, or other undesirable conditions which are readily visible. However, films fired at 650° or 675°C had a very different appearance from those fired at lower temperatures and were generally not as solderable. In addition, the most stable resistors were those fired at 600°C. Conductor films fired at 575°C were exceptionally adherent and conductive, and could be used for many applications. However, their strength in solder peel was relatively low.

Newly developed in PES substrates which have become available since the program ended can be fired at higher temperatures. Improved thick-film characteristics should result.

5.3 Assembly. - In assembly, all operations except wire-bonding were similar in execution to the same operations on conventional substrates. Chip-mounting, epoxy bonding, solder application, solder reflow, and cleaning were all performed using standard procedures. In wire-bonding, a process always requiring the utmost care, a solution which worked for test pieces did not work for a production run. Although the reason for this particular failure is not known, it was shown that wire bonding to a film was improved by increasing the gold-to-glass ratio, and by increasing the film sintering. These changes would require development effort by both the substrate vendor and the thick-film ink vendor.

Porcelain-enameled steel substrates of consistently high quality are available on the open market. Manufacturing processes for thick film hybrids using the substrates have been developed. It appears that PES and IM substrates may be on the threshold of living up to the potential they showed a decade ago.

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