AD-A054 271 RAYTHEON CO WALTHAM MASS RESEARCH DIV F/G 9/5
MANUFACTURING METHODS AND TECHNOLOGY MEASURE FOR ARC-PLASMA-SPR--ETC(U)
DEC 77 J J GREEN, H J VANHOOK, R J MAHER DAAB07-75-C-0043

UNCLASSIFIED S-2287 NL

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Manufacturing Methods and Technology Measure for Arc-Plasma-Sprayed Phase-Shifter Elements

Final Engineering Report

27 June 1975 to 15 November 1977

Contract No. DAAB07-75-C-0043

Placed by

US Army Electronics Command
Production Division
Production Integration Branch
Fort Monmouth, NJ 07703

Raytheon Company
Research Division
Waltham, MA 02154

Distribution Statement

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Manufacturing Methods and Technology Measure for Arc-Plasma-Sprayed Phase-Shifter Elements.	5. TYPE OF REPORT & PERIOD COVERED Final Technical Rep[redacted]t. 27 Jun[redacted]75 - 15 Nov[redacted]77
	6. PERFORMING ORG. REPORT NUMBER S-2287
7. AUTHOR(s) J.J. Green, H.J. Van Hook, R.J. Maher [redacted] D. Masse	8. CONTRACT OR GRANT NUMBER(s) DAAB07-75-C-0043
9. PERFORMING ORGANIZATION NAME AND ADDRESS Raytheon Research Division, 28 Seyon Street, Waltham, MA 02154	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2759441
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Electronics Command, Production Div., Production Integration Branch, Fort Monmouth, NJ 07703	12. REPORT DATE Dec[redacted]77
	13. NUMBER OF PAGES 198
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

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

Arc plasma spraying
Ferrites
Dielectrics
Phase-shifters
Microwave phase shifter materials
Lithium ferrites

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

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Abstract Cont'd.

deviation of 20°. Insertion loss was < 1 dB for 24 of the 50 samples and < 2 dB for 35. The insertion phase of the phase shifters showed a standard deviation of 40°, about double the variation found in identical c-band phase shifters made by conventional techniques. These fluctuations in insertion phase are attributable to density variations in the ferrite coating the order of ± 3 percent. The coercive force on plasma-sprayed material was $2 < H_c < 3.5$ Oe, somewhat larger than the same material when conventionally fired (H_c = 1 Oe), and attributable to the higher porosity of this material.

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Manufacturing Methods and Technology Measure for Arc-Plasma-Sprayed Phase-Shifter Elements

Final Engineering Report

27 June 1975 to 15 November 1977

<u>Object of Study</u>

The objective of this manufacturing and methods technology measure is to establish the technology and capability to fabricate phase-shifter elements by the arc-plasma spraying techniques.

Contract No. DAAB07-75-C-0043

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H. J. Van Hook
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D. Massé

<u>Distribution Statement</u>

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ABSTRACT

The arc-plasma-spray (APS) process has been used to fabricate dielectric-loaded phase shifters of a c-band geometry. The ferrite material is a Li-Ti-Mn ferrite with magnetization ($4\pi M_s$) of 1200 G and a dielectric constant (K') of 18.7. The dielectric is Li-Ti-Mn-Al ferrite with $4\pi M_s = 0$ and K' = 20. An oven arrangement and sample transfer scheme have been developed which allows a production rate of 5 sprayed boules per hour. A production run of 200 samples was made at this rate. For 50 phase shifters measured at 5.45 GHz the differential phase shift was 393° with a standard deviation of 20°. Insertion loss was < 1 dB for 24 of the 50 samples and < 2 dB for 35. The insertion phase of the phase shifters showed a standard deviation of 40°, about double the variation found in conventional c-band phase shifters. These fluctuations in insertion phase are attributable to density variations in the ferrite coating the order of $\pm$ 3 percent. The coercive force on plasma-sprayed material was $2 < H_c < 3.5$ Oe, somewhat larger than the same material when conventionally fired ($H_c = 1$ Oe), and attributable to the higher porosity of this material.

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PURPOSE

The phased-array radar antenna is now well established as a means of achieving agile search and multi-target tracking in the current and projected military environment. Each new system with its phased-array antenna has many thousands of radiating elements. Since each element contains a ferrite phase shifter, it is appropriate to develop manufacturing methods and processes that will minimize the cost of each phase shifter.

The purpose of this program is to develop a manufacturing capability for producing a c-band phase-shifter element by arc-plasma spraying of a lithium-titanium ferrite onto a dielectric substrate. In this process, a high temperature diffusion bond between the toroidal envelope and dielectric core permanently mates the ceramic parts, thus eliminating the need for any joining material. The switching wires are threaded through interior slots after final machining and can be replaced or renewed at any time. The primary objective is to produce the phase control element as a finished composition with acceptable microwave properties and a reasonably high yield. To achieve sound composites, one of the properties needing constant monitoring is the match in thermal expansion coefficient between the ferrite coating and the dielectric.

A second important area for control and reproducibility is the thermal environment during spraying. Thermal conditions are influenced mainly by arc current, the arc gas and powder gas velocities, and the substrate-to-gun separation distance. The density and uniformity of the ferrite deposit depend on the reproducibility of these parameters and on the spray dried particle size and size distribution of the ferrite material.

Finally, to achieve a low unit cost, it is necessary to improve yield and reduce machining costs by working with local machine shops to improve overall efficiency.

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GLOSSARY

Annealing - A heating schedule similar to firing but performed on a dense material to relieve strain, improve homogeneity or recrystallize a microcrystalline material.

Arc Plasma Spraying - High-temperature deposition technique in which molten or partially molten material is sprayed onto a heated substrate.

Coercive Force - The horizontal displacement of the magnetization vs applied field curve the hysteresis loop at zero induced field. A measure of the energy required to move magnetic domains through a solid material.

Core Material - The dielectric material which fills the hollow space within the ferrite toroid.

Dielectric - Oxide compounds which exibit polarization in electric fields.

Dilatometer - A device for measuring thermal expansion.

Elastic Modulus - The ratio of stress-to-strain (in pounds/in.^{2} or Newtons/in.^{2}) in isotropic materials which gives an indication of the stiffness or resistance to deformation. Also referred to as Young's modulus. Typically 10 to 50 $\times 10^6$ psi for oxides.

Ferrite - Oxide compounds of iron and other elements that exhibit a spontaneous magnetic moment due to magnetic spin dipole alignment within the structure.

Hysteresis Loop Properties - The display of magnetization vs applied field for a toroidal or long rod-shaped sample of a ferromagnetic material. The display, generally obtained or low frequencies ($\leq$ 102 Hz) is useful in predictions of the magnetization properties and phase shift behavior at microwave frequencies ($\approx 10^{10}$ Hz).

Firing - Any high-temperature process performed on a material, but usually referring to a heating schedule which transforms a powder aggregate into a dense ceramic.

Isostatic Pressure - A powder compaction technique in which a sealed deformable container (e.g., a rubber bag with powder inside) is subject to a uniform compacting pressure from all sides.

Latched State - State of remnant magnetization after application of an applied field sufficient to magnetize in one or two opposite (180°) directions.

Lithium Ferrite - A class of ferrite materials with the general formula $Li_{.5+x/2-y2}Ti_xZn_{y2}Fe_{2.5-3x/2-y}O_4$ characterized by a saturation magnetization of $0 < 4\pi M_s < 3600$, a dielectric constant $18 < K < 20$, and frequently used in microwave devices.

Magnetic Compensation - A condition obtained in a specific ferrite composition and/or at specific temperatures where the magnetic moment is zero. At this point the opposed magnetic sublattices within the single phase composition exactly compensate.

Magnetometer - A device for measuring magnetic moment.

Microwave - That part of the electromagnetic spectrum between 100 MHz and 100 GHz.

Phase Shifter - A microwave device which serves as the active element in phased-array radar systems where the state of magnetic polarization is used to control the phase length of the electromagnetic energy. Also called phase control element.

Remanent Magnetization ($4\pi M_r$) - The value of induced field remaining in a material with toroidal geometry at zero applied field following the application of an applied field sufficient to uniformly magnetize a material.

Saturated Magnetization ($4\pi M_s$) - The saturation magnetization (c.g.s.) is the magnetic moment gauss/cm^3 of a material in an external DC field of sufficient magnitude to align the magnetic moment in the material parallel with it.

Saw Kerf - That portion of a solid removed by the cutting blade. The kerf width is usually about 5 percent wider than the width of the blade.

Scanning Electron Microscopy (SEM) - An instrument using electron excitation and emission to produce images at high magnification with good depth of field.

Spinel Ferrites - A class of iron oxide compositions having face-centered cubic crystal structures similar to the mineral spinel ($MgAl_2O_4$) and a magnetic moment which depends on composition.

Spray-Dried Powder - A form of powder aggregation where spherical particles of ~ 10 to 100 μm are produced which are themselves aggregates of much smaller (< 1 μm) particles. The advantage of this process is that the aggregates have better flow properties than untreated powder. The process is accomplished in a spray drier, a large funnel-shaped cavity into which a liquid suspension is sprayed and dried.

Stoichiometric - The idealized atomic proportions of elements in a chemical composition, such as the 1:2 in Mg:Al ratio in $MgAl_2O_4$. Departures from the exact integral proportions may have important effects on properties.

Stress-to-Failure - A statistical or average stress level of a solid where failure by brittle fracture propagation takes place, also called the modulus of rupture. Depends on surface conditions as well as intrinsic strength.

Thermal Expansion Coefficient - A parameter denoting the change in dimension ($\Delta\ell/\ell_o$) per unit temperature between ambient conditions and some elevated temperature. Since the actual expansion is not perfectly linear, one must specify the thermal interval of interest; i.e., $\alpha_{20}^{1000°} = 15$ ppm $°C^{-1}$ denotes expansion between 20°C and 1000°C has our average slope $\Delta\ell/\ell_o\,\Delta T$ of $+15 \times 10^{-6}$ in./in./°C.

Toroid - A ring-shaped or hollow rectangular tube specimen used in magnetic measurements, particularly the hysteresis properties.

X-Ray Analysis - Analysis of crystal structure (X-ray diffraction), elemental composition (X-ray fluorescent analysis) to control processing or elucidate property variations using short wavelength radiation.

1.0 INTRODUCTION

1.1 History of C-Band Phase-Shifter Elements

Ferrite components were used in radars long before phased-array antennas. The idea of obtaining differential phase shift by placing small slabs of ferrite material at the planes of circular polarization in a waveguide originated in the 1950's. Differential phase-shift circulators made with permanent biasing magnets located outside the waveguide have been used for more than 20 years. However, these devices have never required particularly tight materials property tolerances, nor have they been significant contributors to overall system cost.

In the early 1960's the differential phase-shift circulator geometry was modified to make a latching-type variable phase shifter. The permanent biasing magnets were removed and the flux path was closed inside the waveguide by using a toroidal cross-section. The inclusion of many thousands of these devices in a phased-array antenna has posed a severe challenge to the ferrite materials properties, and has heightened the impact of the phase shifter on systems cost.

Unfortunately, at C-band and below, a large volume of ferrite material is required for a single phase shifter. In addition to the large volume, this material cost has been aggravated by the need to use the expensive rare-earth garnet materials to achieve low insertion loss and acceptable temperature performance in devices operating below 6 GHz. In the mid-1960's Temme, Ince, and Stern (1967) [1] pointed out that a high-dielectric constant nonmagnetic material, inserted into the magnetic toroid, would significantly reduce the required dimensions of both the ferrite and waveguide. This reduction of the ferrite volume made it possible to consider the expensive garnet materials for use in low-frequency (< 6 GHz) phased arrays.

Present c-band phased-array antennas tend to use a garnet toroid with a dielectric insert for the phase-shifter element (Fig. 1). The rectangular toroid is 5.145 in. long, 0.250 in. high, 0.220 in. wide, with 0.050 in. walls. The dielectric insert is barium tetratitanate (also called K-38 because its dielectric constant is 38). The toroid is formed around a steel pin, then fired to a dense ceramic. The dielectric is formed and fired as 1.5 kg bars. Each bar yields about 40 inserts machined to the final dimensions. Since the toroid is an as-fired piece with a center hole which cannot be guaranteed to be absolutely straight or uniform in cross-section, the insert is undersized (0.109 in. by 0.139 in. cross-section) and is coated with a resin material just before it is inserted into the (0.120 in. by 0.150 in.) toroid opening. Grooves are machined on each side of the insert to allow for the three copper wires used to switch magnetic polarization. In assembly, the wires are fitted into the slots, the mating surfaces and wire slots are coated with resin, the two parts are forced together, and the composite of toroid insert wire and resin is put through a complex thermal cycle to cure the resin.

1.2 Difficulties with the Current Approach

While many tens of thousands of phase shifters have been fabricated for various phased array antennas, the manufacturing process could be improved both to reduce cost and to enhance antenna performance. The present process has several disadvantages. First, it is expensive to assemble the tight-fitting component parts. Second, the resin material does not have completely reproducible curing characteristics, and requires that the curing cycle be varied from run to run. Third, the switching wires are bonded permanently by the resin. If a wire should break during manufacture or in later use, the entire unit must be scrapped.

These three problems add to device cost. However, there is also evidence that the resin can seriously affect phase-shifter performance, causing a variation in insertion phase from one unit to the next. This variation could could cause the radar beam to broaden and the sidelobes

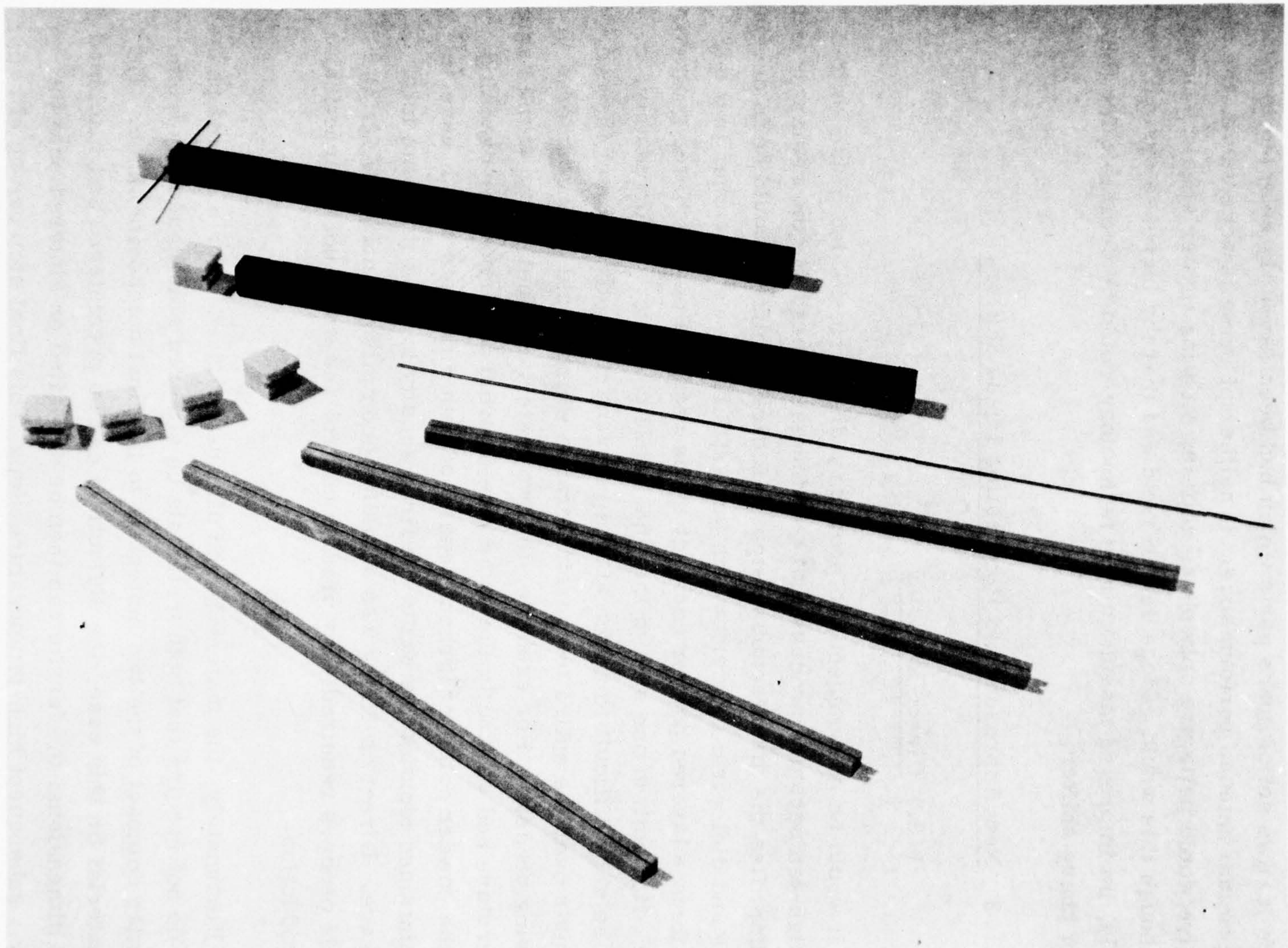


Figure 1 K-38 Dielectric Rods, K-16 Dielectric Spacers, and Ferrite Toroid Manufactured at Raytheon

to increase. To prevent degradation of the radar beam, each antenna might require its own set of spare parts which had been carefully selected to maintain optimum antenna performance. If neither of these is acceptable, the alternative would be to use only phase shifters meeting tighter specifications, even though this would reduce device yield and thereby increase system cost. Clearly, an improved manufacturing technology would be desirable for this type of phase shifter.

1.3 New Approaches to Fabricating Phase Shifters

1.3.1 Direct co-firing

It would be advantageous to produce a dielectric-loaded phase shifter by a high-temperature process that eliminates the need for the resin material and simplifies the manufacturing steps. A direct solution would be to develop ferrite and dielectric powders which are sufficiently well matched that one could form a layered powder compact in the required phase-shifter geometry, then co-fire both in one step to the final dense ceramic. Unfortunately, it would be very difficult to match all the relevant characteristics of the two materials over the entire temperature range which would be encountered in the firing process. For example, the two materials must sinter at the same temperature and at exactly the same rate to avoid distortions or cracking. Also the powder compact (green) density of both materials would have to be maintained identical as would the fired density to yield the same total shrinkage. Direct co-firing was actually accomplished in 1974 (Fig. 2), but this process required very precise control and would not be practical for production.

Fortunately, the materials and dimensions needed for a c-band phase shifter do not require that both materials be sintered simultaneously from the powder compact of the two materials to the final composite shape. The core material (in this case, the dielectric) can be presintered and machined to final dimensions; the ferrite can then be deposited or sintered onto the core by a subsequent high-temperature step. This final step can be either arc-plasma spraying or firing-in-place.

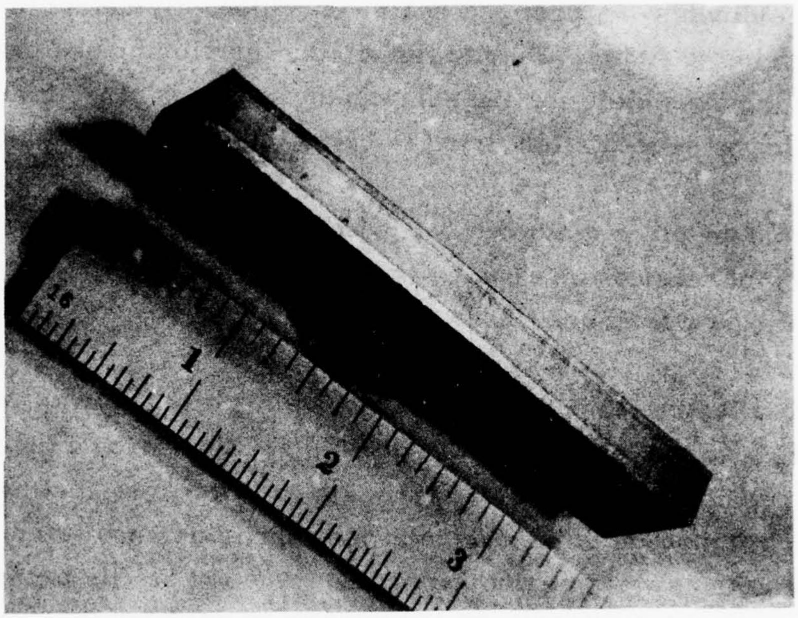


Figure 2 Photograph of Layered Composite with Outer Ferrite Layers (1250) and Dielectric Core.

1.3.2 Co-manufacturing by firing-in-place

At the start of the arc-plasma-spraying outlined in this report, the firing-in-place technique was under development at Raytheon for only a few months. As it has since evolved, the process is very similar to arc-plasma spraying in that both methods make use of similar dielectrics and are fired on at similar temperatures. In firing-in-place a conventionally processed ferrite powder is isostatically pressed into a toroid, just as is done for current phase shifter elements. A prefired and premachined dielectric is inserted immediately prior to firing. During firing, the ferrite shrinks onto the dielectric, leaving open slots for the subsequent insertion of switching wire. Some machining is needed after firing to bring the element to final dimensions.

The firing-in-place method has not yet reached the stage where the reproducibility of tens of units can be tested, but results on individual samples have shown some promise.

A critical factor in developing the firing-in-place, as well as the co-firing method, was the fabrication of spinel-type dielectrics with a range in dielectric constant(k') and thermal expansion coefficient ($\bar{\alpha}$) for the matching of $\bar{\alpha}$ and the optimization of k' relative to the ferrite composition. While the spinel dielectrics were developed before the start of this program for experiments in direct co-firing, they were also needed for the APS program outlined in this report.

1.3.3 Arc-plasma spraying

The arc-plasma-spray (APS) process was first applied to the production of microwave phase shifters by R. Babbitt[2]. It was already a well-established process for refinishing critical metal parts with wear-resistant, temperature-insensitive coatings. This process can be used to spray low-melting-point (aluminum) or refractory (tungsten) metals or metal oxides because of the wide latitude in latent heat transfer from the very hot plasma to the particulate feed material.

Babbitt et al.[2,3] were the first to apply the APS technique to electronic materials. In the process developed by Babbitt, ferrite powder is partially melted by an intense plasma heat source and deposited at high temperatures (1300° C) in dense, microcrystalline form onto a dielectric substrate whose thermal expansion matches that of the ferrite. The phase-shifter boules are sprayed in a single axial pass with rapid (100 rpm) rotation in a 750° C oven. They are later heated to 1015° C to optimize the dielectric and magnetic properties. A machining step then removes the excess ferrite, and a final anneal (to remove the machining stress) completes the manufacturing process.

Before this program began the ferrite powder used in the initial experiments at ECOM and Raytheon was a lithium-titanium-manganese ferrite developed for conventional ferrite processing. This powder has been generally satisfactory for APS, although certain additives to the powder (i.e., binder content, Bi_2O_3 additive, etc) may not be optimal for the latter. The development of these compositions both at Raytheon and elsewhere has been directed toward a replacement for the more expensive garnet materials.

In developing the ferrite material, our goal was to produce a material with a high dielectric constant, magnetic properties which are stable with temperature and insensitive to stress, as well as lower materials cost. The Li-Ti ferrite does meet all of these requirements in conventionally fired form. Babbitt was able to show that these same compositions, when plasma sprayed and annealed under appropriate conditions, would also yield microwave properties that compare favorably with existing garnet materials. Having succeeded in reproducing Babbitt's results[4] in our laboratories, we concluded that there was no intrinsic materials limitation to replacing the current garnet with a plasma-sprayed Li-Ti ferrite. Of course, properties required some improvement and yield and production rates were unknown, but in general the prospects were favorable.

Our experience with the plasma spray equipment was limited to about six months' work using a furnace geometry that was clearly inappropriate for production. However, one could see at this point that the dielectric-loaded phase shifter geometry was well suited to the APS process. The cross-sectional area of the dielectric (0.120 by 0.150 in.) is small enough to be heated rapidly without thermal shock and large enough to support the extra weight of the plasma-sprayed ferrite coating. Dielectric loading had also reduced the necessary toroid wall thickness (0.050 in. required) to the extent that an adequate ferrite coating along the five-inch long dielectric could probably be deposited in 10 to 15 minutes of spraying time. Assuming that the transfer time between sprayings could be shortened to half this spraying time, the desired production rate of 40 per day could be achieved with one station and one operator.

This report will describe in detail the program to develop manufacturing methods for the production of such phase shifters.

2.0 PROCESS, EQUIPMENT, AND TOOLING OF ARC-PLASMA-SPRAYED PHASE SHIFTERS

2.1 Ferrite Powder Development

The characterization of ferrite powders used in the APS process has become one of the most important controls in the MMT program. With the benefit of hindsight, it is clear that the choice of a composition that would give the required magnetic properties was sound, but the ferrite particle size measurements and process controls were not comprehensive enough to completely characterize subtle changes in the powder that led to important differences in APS behavior and to differences in coating density. Nevertheless, we did make serious efforts to standardize processing and to characterize the ferrite powder as completely as possible.

2.1.1 Magnetic properties

The choice of ferrite composition is an essential first step to meeting the phase-shifter performance characteristics set by the garnet material presently used in c-band phase shifters. The saturation magnetization ($4\pi M_s$) is a primary factor since this affects the phase-shifter parameter of phase shift and magnetic loss. Room temperature data on $4\pi M_s$ versus Mn and Li + Ti content are shown in Fig. 3. The inset above the main figure shows the effect of Mn addition to pure Li-ferrite (x = 0). The main figure shows the influence of Mn substitution combined with Li-Ti. Mn addition raises $4\pi M_s$ in all compositions. This indicates either a preference of Mn^{+3} for the A sites or a Mn substitution on B sites which displaces some Li from B to A, thus increasing $4\pi M_s$.

Zinc substitution in Li-ferrite and Li-Ti-ferrite raises $4\pi M_s$ for $0 \leq Zn \leq 0.35$. At higher concentrations $4\pi M_s$ decreases due to a weakening of intersublattice exchange, aided by the very rapid decrease in T_c with Zn content. The Li and Ti substitutions also lower T_c, although not as rapidly as Zn addition. Table 1 shows data for Li-Ti and Li-Ti-Zn ferrites on the temperature coefficient of the magnetization $\Delta M_s / M_s \Delta T$ between

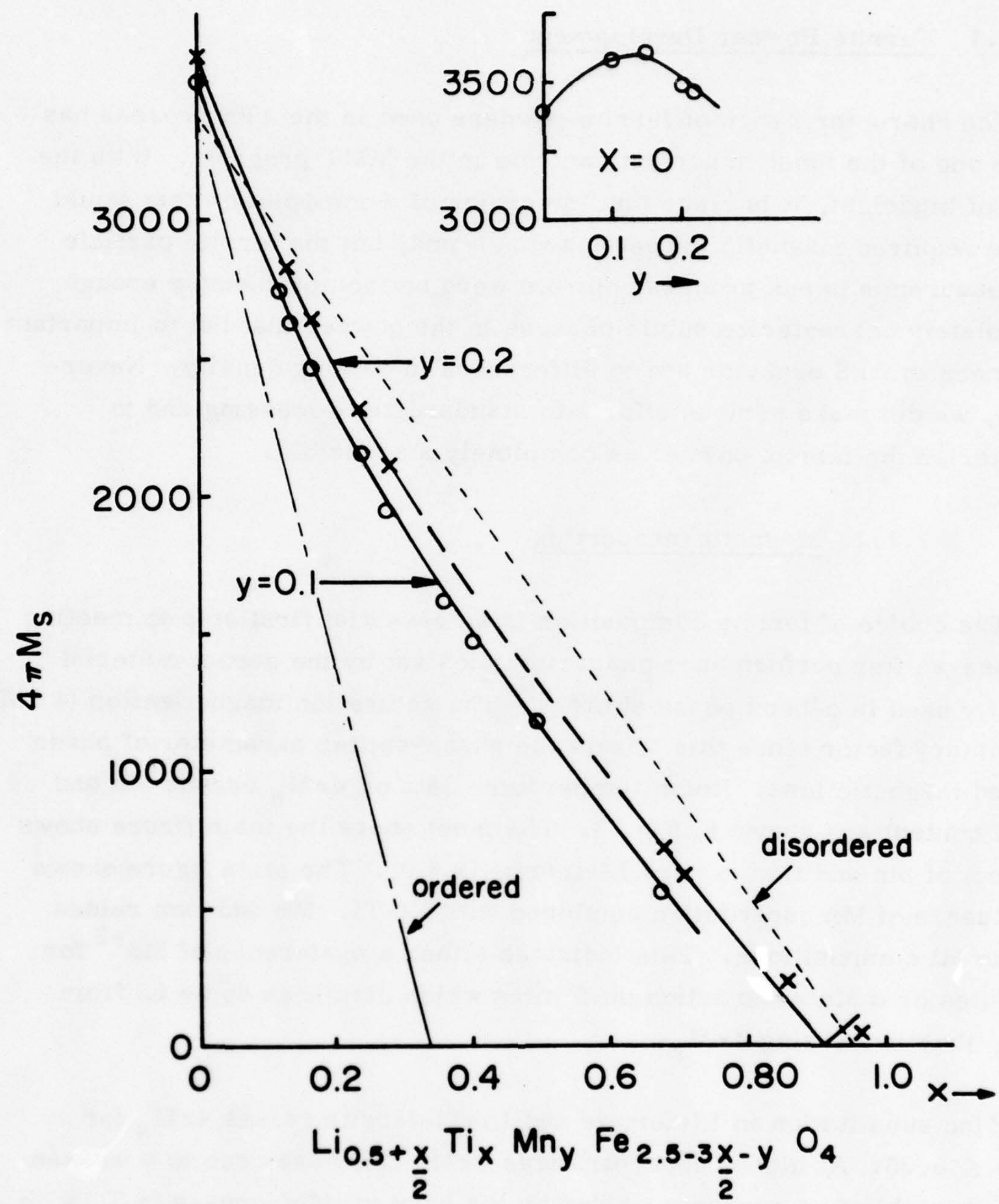


Figure 3 Magnetization versus Composition at 20° C for $Li_{0.5 + \frac{x}{2}} Mn_y Ti_x Fe_{2.5 - \frac{3x}{2} - y} O_4$.

20° C and 120° C relative to the 20° C value and estimates of T_c. In this example these materials contain a constant Mn level of 0.10 per formula unit to control dielectric loss.

The magnetization curves are shown for the first three compositions in Table 1 in Fig. 4. The slope of the curves near 20° C changes only slightly with composition. Thus the percentage increase in coefficient depends on the decrease in $4\pi M_s$ due to the reduction in T_c. In the last example (a zinc-containing 1250-gauss material), combined substitutions of Zn and Li-Ti have reduced T_c and raised the temperature coefficient substantially.

TABLE 1

CURIE TEMPERATURE OF SEVERAL Li-Ti FERRITES

Saturation Magnetization	Zn Content	Mn Content	Ti Content	T_c (°C est.)	Temp. Coeff. %/°C
3600 G	0	0.10	0	625	0.09
2250 G	0	0.10	0.26	525	0.13
1250 G	0	0.10	0.50	390	0.18
1250 G	0.10	0.10	0.54	310	0.27

The results shown in Table 1 indicate that Zn substitution should be kept to a minimum because of its very strong effect on T_c and thereby on the temperature coefficient of M_s. The reason for the rapid loss of temperature stability is that Zn substitution requires additional Li and Ti substitution to bring $4\pi M_s$ back to a given value. The effect of the two substitutions is additive in terms of the depressive effect on T_c. For these reasons we decided not to introduce Zn.

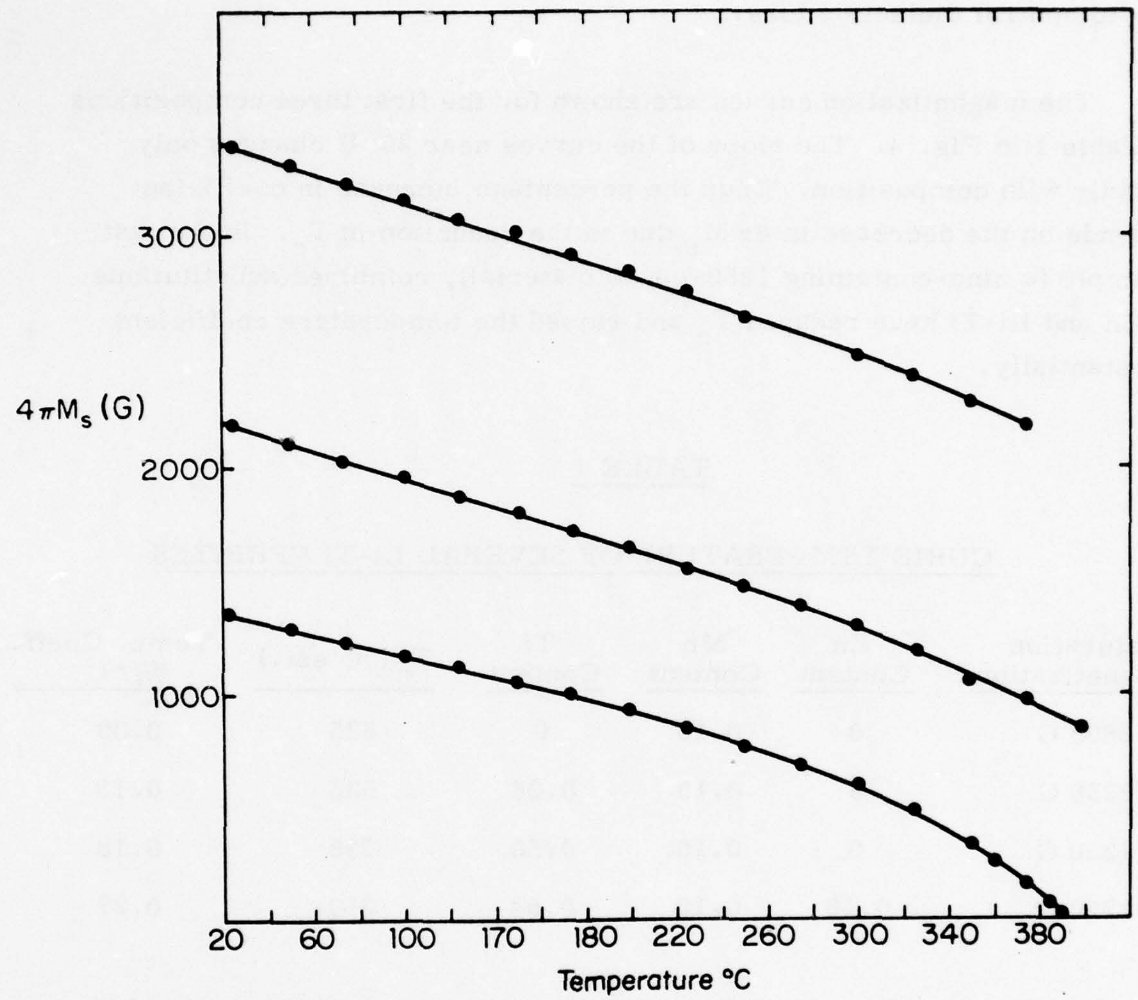


Figure 4 Magnetization versus Temperature for Several Li-Ti Ferrites.

2.1.2 Remanent magnetization

The remanent magnetization (B_r or $4\pi M_r$) of the 1250-gauss Li-Ti-ferrite is the order of 850 to 900 gauss in dense material. The theories (Grieffer[5]) relating B_r to ferrite composition stress the importance of the dominance of the magneto-crystalline anisotropy (K_1) over stress-induced anisotropy ($\sigma \cdot \lambda_i$) in achieving the highest B_r possible. The Wijn (1954) model theorizes that a maximum B_r occurs when domains within the individual grains relax to the nearest [111] easy axis direction for $K_1 < 0$, a situation possible when K_1 dominates. To minimize the demagnetization energy, Goodenough[6] has proposed the creation of small reversal domains at grain boundaries and near second phases or pores, especially when a local stress is present. The magnitude of B_r depends on the number and size of these reversal domains because their collective volume determines how far B_r will be reduced from the theoretical value of $B_r = 0.87\ M_s$ for cubic anisotropy. For lithium ferrite the dominance of crystalline over strain-induced anisotropy permits relatively large ratios of B_r/M_s, typically 0.70 to 0.75.

The theories relating B_r to ceramic microstructure stress the avoidance of secondary phases and porosity to obtain a maximum B_r. Second phase and porosity reduce B_r in two ways: first, by reducing the volume of magnetic material, and second, by providing discontinuities and regions of local strain which favor the creation of the reverse domains.

Since the latching phase shifter calls for $H_c < 1$ Oe, it is essential to maintain hysteresis loop squareness and thereby high B_r. The first priority should be the development of process controls which will yield a dense, uniform-grain-size ferrite after plasma spraying and annealing.

2.1.3 Coercive force

Coercivity is probably the most microstructure-sensitive of the magnetic properties of importance to phase-shifter performance. It is influenced both by porosity second-phase content and by polycrystalline grain size. If porosity and second-phase content are kept below 1 percent to satisfy the requirement for high B_r, then coercive force is determined primarily by grain size and anisotropy (i.e., composition).

In addition to the grain size dependence of H_c, many workers [5] have reported that Zn rapidly lowers H_c in Li-ferrite compositions. A semi-empirical relationship between H_c and material properties reported by Grieffer correlates with these observations:

$$H_c = \frac{\sigma_w}{M_s L} ,$$

where M_s is the magnetic moment, L is an average grain size, and σ_w, the wall energy, is given by

$$\sigma_w = 4 \left[A (K_1 + \lambda_i \sigma) \right]^{1/2} .$$

In the second equation, A is the exchange parameter (roughly proportional to T_c), K_1 is the anisotropy constant, λ_i is the isotropic magnetostriction, and σ is the internal stress at the domain wall.

There are two ways in which substitution of zinc reduces H_c. First, Zn enhances grain growth in annealing, which produces a larger polycrystalline grain size. Second, the reduction in T_c reduces both the exchange parameter A and the magnetocrystalline anisotropy constant K_1, again decreasing H_c. Unfortunately, zinc substitution also leads to a large temperature sensitivity of M_s and B_r and to a rounding of the hysteresis-loop shoulder because squareness depends on a large K_1. The deterioration in hysteresis loop squareness is particularly bad for the low H_c latching-type phase shifters because it makes it more difficult to reproduce B_r.

Other substitutions such as Co and Mn can also change wall energy through alteration in anisotropy (K_1) and magnetostrictive (λ_i) parameters. One might expect Mn to affect H_c through the magnetostrictive term ($\lambda_i \sigma$)

in the wall energy equation. Our previous studies of Li-ferrite compositions with identical microstructures and different Mn concentrations ($0.01 \leq y \leq 0.01$) have shown, however, that Mn content has no appreciable effect on hysteresis loop squareness or coercive force. Therefore, the Mn concentration can be determined entirely by other considerations such as dielectric loss. This behavior contrasts with that of cobalt and zinc, where substitutions change several properties, and a tradeoff must be made.

2.1.4 Particle size

The experimental results of APS runs made with R. Babbitt at ECOM at the beginning of the program (to be described in Section 2.4.1) gave strong indication that spray-dried Li-Ti ferrite powders from Raytheon Special Microwave Device Operations were equivalent to other commercial sources. We chose to use the SMDO ferrite powder, since it gave us direct access to processing history, as well as the opportunity to ask for processing changes if necessary. The first delivery of material, a 34 Kg batch, was made in September 1975. To produce a free-flowing aggregate for the APS gun, the ferrite powder was spray-dried after the final milling step. This treatment is the same as that used to prepare powder for automatic die pressing, where a free-flowing material is essential. In spray-dried form, the particles are aggregates of the much finer ($< 1\,\mu m$) ferrite powder. A scanning electron micrograph of a spray-dried particle $\sim 30\,\mu m$ in diameter is shown in Fig. 5. The larger particles are generally hollow, as evidenced in this case by the hole at right center in the spherical agglomerate. The small particles are held together by a small amount (> 2 percent by weight) of organic binder.

Particle size control is very important for uniformity in APS melting, since residence times in the plasma flame are the order of microseconds. We requested that the supplier keep the larger spray-dried powder fraction taken from the main chamber separate from the fines fraction which is collected from the effluent in a cyclone separator. Figure 6 shows the results of this first crude separation of the powder into a coarser "chambers

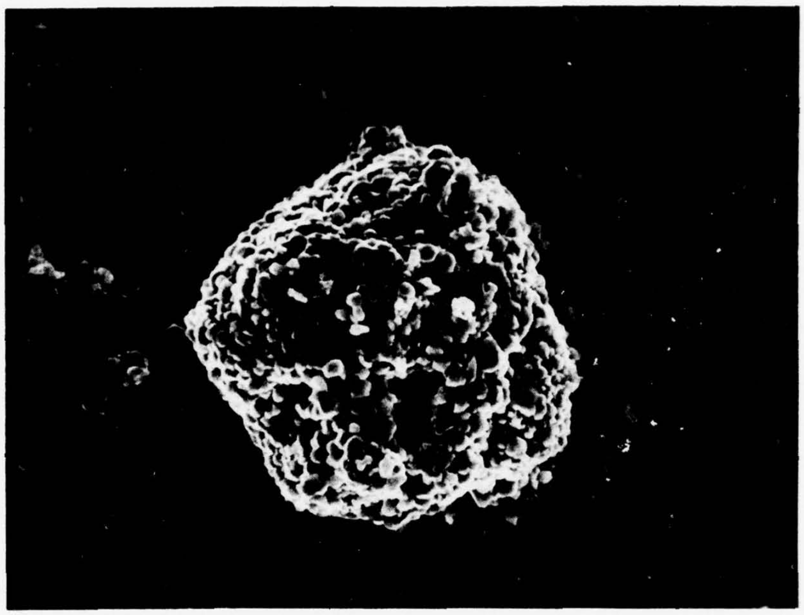
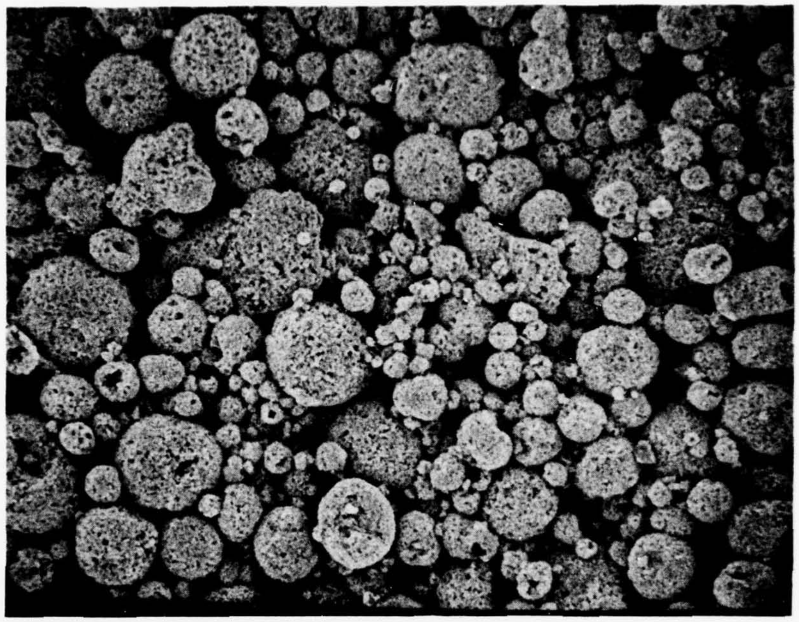


Figure 5 SEM Photograph of Spray-Dried Ferrite Powder at 2000×.

(a)



(b)

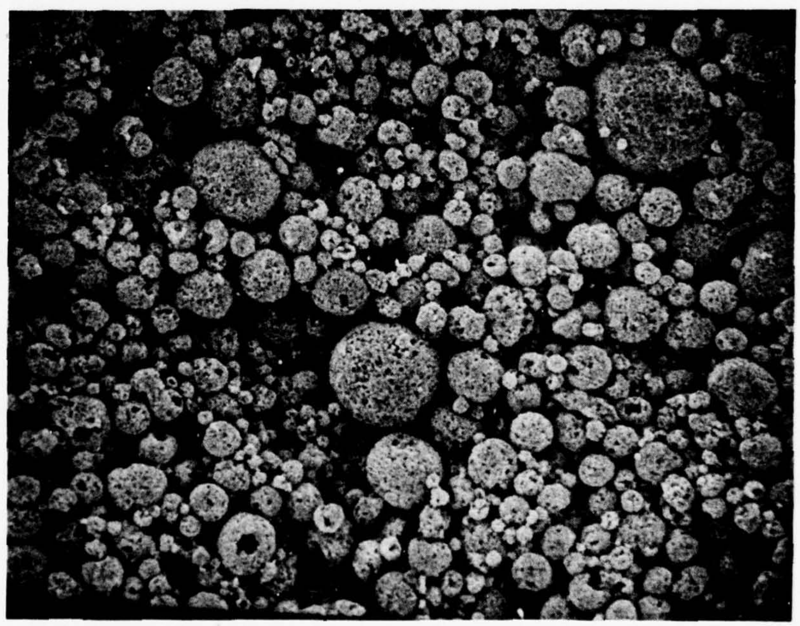


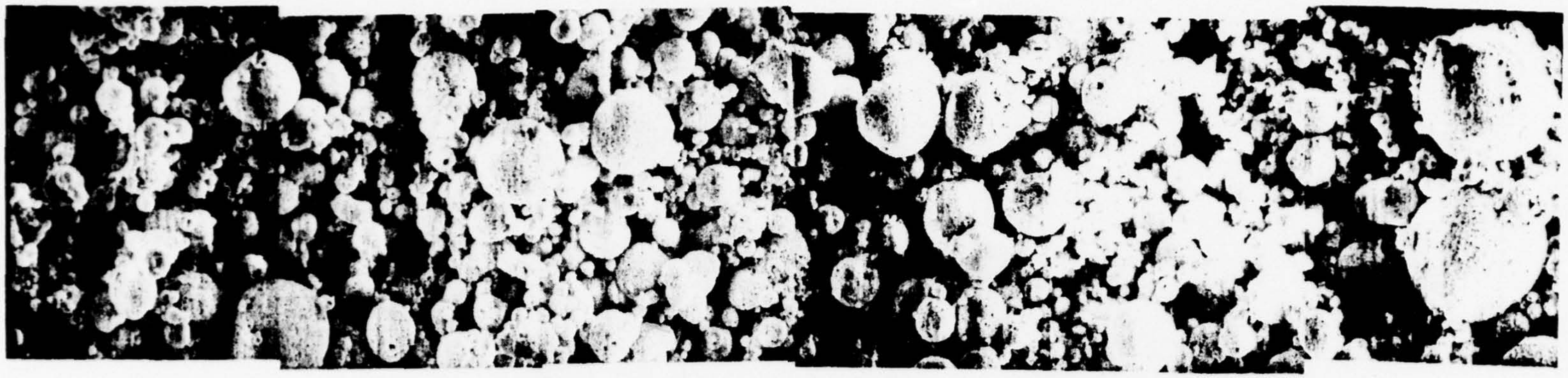
Figure 6 SEM Photographs of Spray-Dried Ferrite Powder (LMTF 53(G2)) at 400×.
(a) "Chambers fraction"; (b) "Fines fraction".

fraction" (Fig. 6a) and a "fines fraction" (Fig. 6b). The SEM operator was asked to take the photographs at random locations in the two powders. As can be seen, there is a considerable size range within each lot but, nonetheless, some size fractionation between "chambers" and "fines".

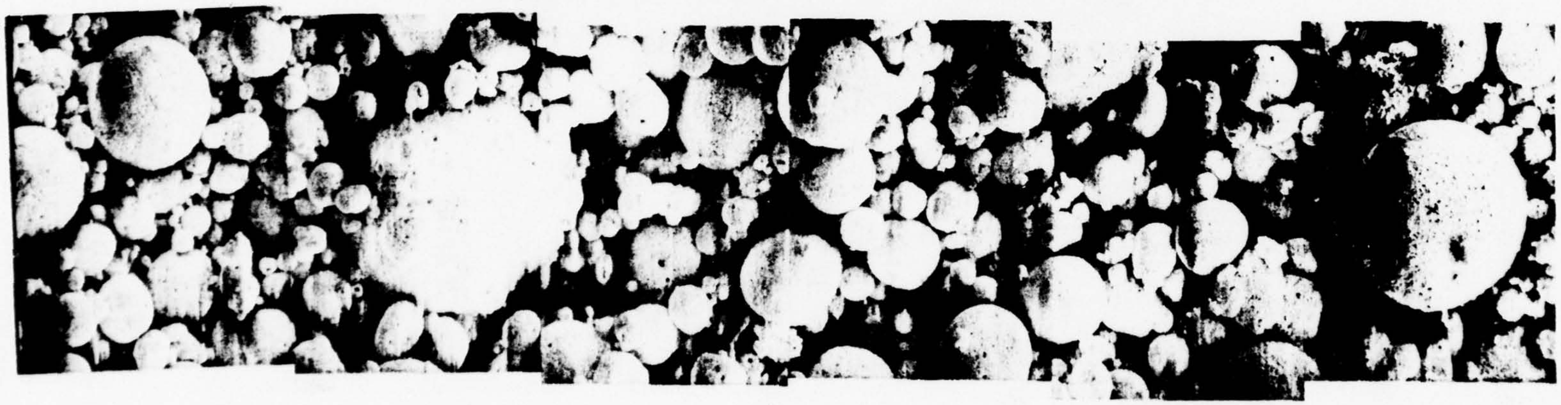
Sampling techniques for particle size analysis in powders cover a wide range in sophistication of instrumentation and size of the sample being analyzed. Unfortunately, there seems to be an inverse relation between these two factors. Methods such as the Coulter counter are very convenient and quantitative, but sample only a very small amount of material. Other methods, such as sedimentation and air permeation, sample a larger and possibly more representative portion, but measurements are more indirect and one must rely on assumptions about particle geometry and degree of dispersion that are not always justified. Screening can be used, but this method is rather impractical since spray particles are very fragile and easily broken, unless great care is exercised. Size analysis by counting individual particles is the most reliable method. It can, however, be very tedious to accumulate enough counts for a reliable sampling. Fortunately, the use of a semiautomatic counting device, coupled with the easily resolved size and shape of spray-dried powders, can speed the process considerably.

We have used a Zeiss particle size counting device (described in Appendix I) to generate histograms of the spray-dried particle size of the different ferrite batches. The ferrite powder discussed in conjunction with the particle size counter in Appendix I and shown in Fig. 6 is characterized as LMTF53(G2). This powder in general had poorer flow charcteristics than later materials, as for example, the LMTF50(G3) powders shown in Fig. 7 and in the histogram Fig. 8. Note that when all the particles in a photograph are counted, the average size is much smaller than one might estimate visually.

Some of the ferrite powders used in the later APS runs in this program had very good flow characteristics and produced sound phase shifters.



Fines



Chambers

Figure 7 Photographs of Spray-Dried LMTF50(G3) Powder (400×).

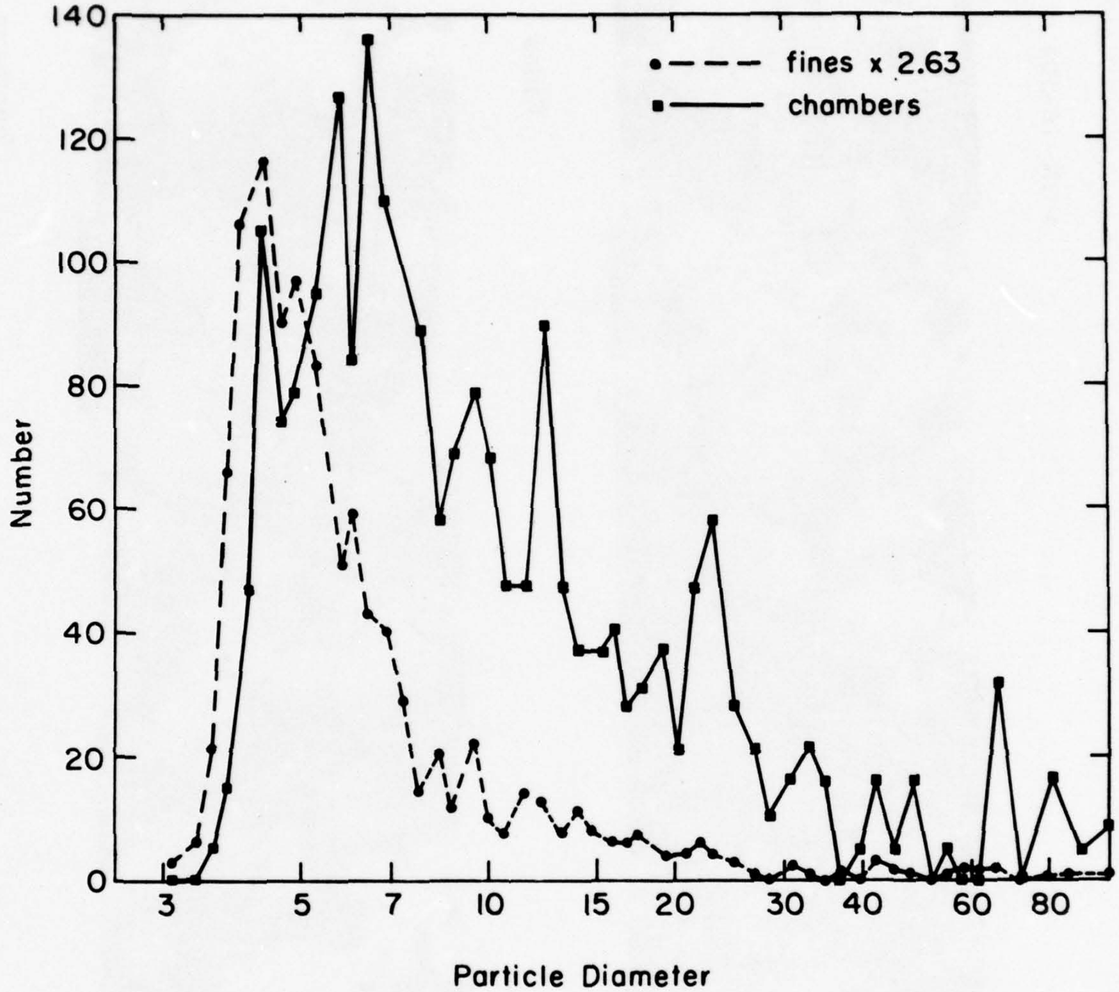


Figure 8 Histogram of Particle Size from Fig. 7. Vertical Scale on Chambers × 2.63.

Two examples were the LMTF475(G5) and LMTF475(G7) powders, both of which had been formulated with less Ti (x = .475) to increase $4\pi M_s$ and compensate for the lower density of APS ferrite (~92 percent of d_x) as compared with conventional firings (~99 percent of d_x) of the same powder.

Figure 9 shows one SEM photograph of spray-dried G5 powder from the chambers fraction and one from the fines fraction collected in the cyclone separator at the exit end of dryer. Figure 10 shows similar SEM photographs of the G7 ferrite powder. The photographs are a collection of six sequential individual photos of a representative region of powder samples taken originally at 400× magnification. Size reduction for publication in this report has reduced the magnification to 175× .

The spray-dried particles in a photograph were counted at the original magnification. To determine the number of counts needed to generate a histogram representative of the sample, we divided the photograph in half and generated separate histograms of the two parts, approximately 800 counts in each. If a doubling of the number of counts does not change the histogram shape, the smaller number is adequate. What is an adequate count is, of course, a subjective evaluation, and we have had to adopt arbitrary criteria to set limits. We have decided that a change in mean particle size of > 20 percent, or radical differences in the shapes of the two distribution curves, would indicate insufficient data for a histogram representative of the powder.

Figure 11 shows two curves for the G7 fines powder fraction – one curve indicating the count in the lower half of Fig. 10; the other, the top half of Fig. 10. Every resolvable particle was counted, totally 1672 different particles of different diameters. The two curves differ in mean value by approximately 15 percent and the particles have similar sizes, indicating that this count is adequate by our standards.

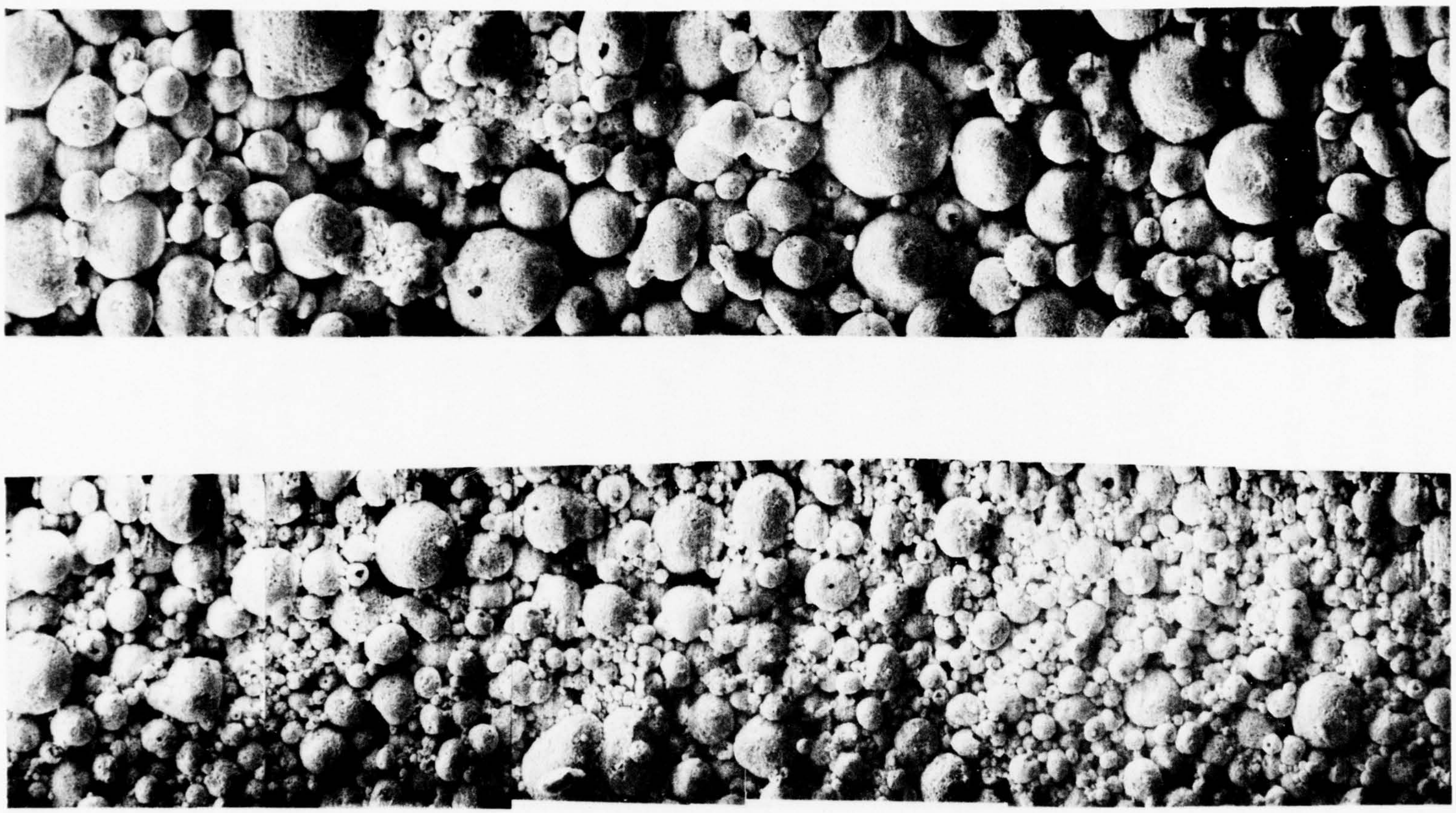


Figure 9 SFM Photographs at 400× of Spray-Dried Ferrites LMTF475(G-5). Top: Chambers fraction; Bottom: Fines fraction.

Figure 10 SEM Photographs at 400 × of Spray-Dried Ferrites LMTF475(G-7).
Top: Chambers fraction; Bottom: Fines fraction.

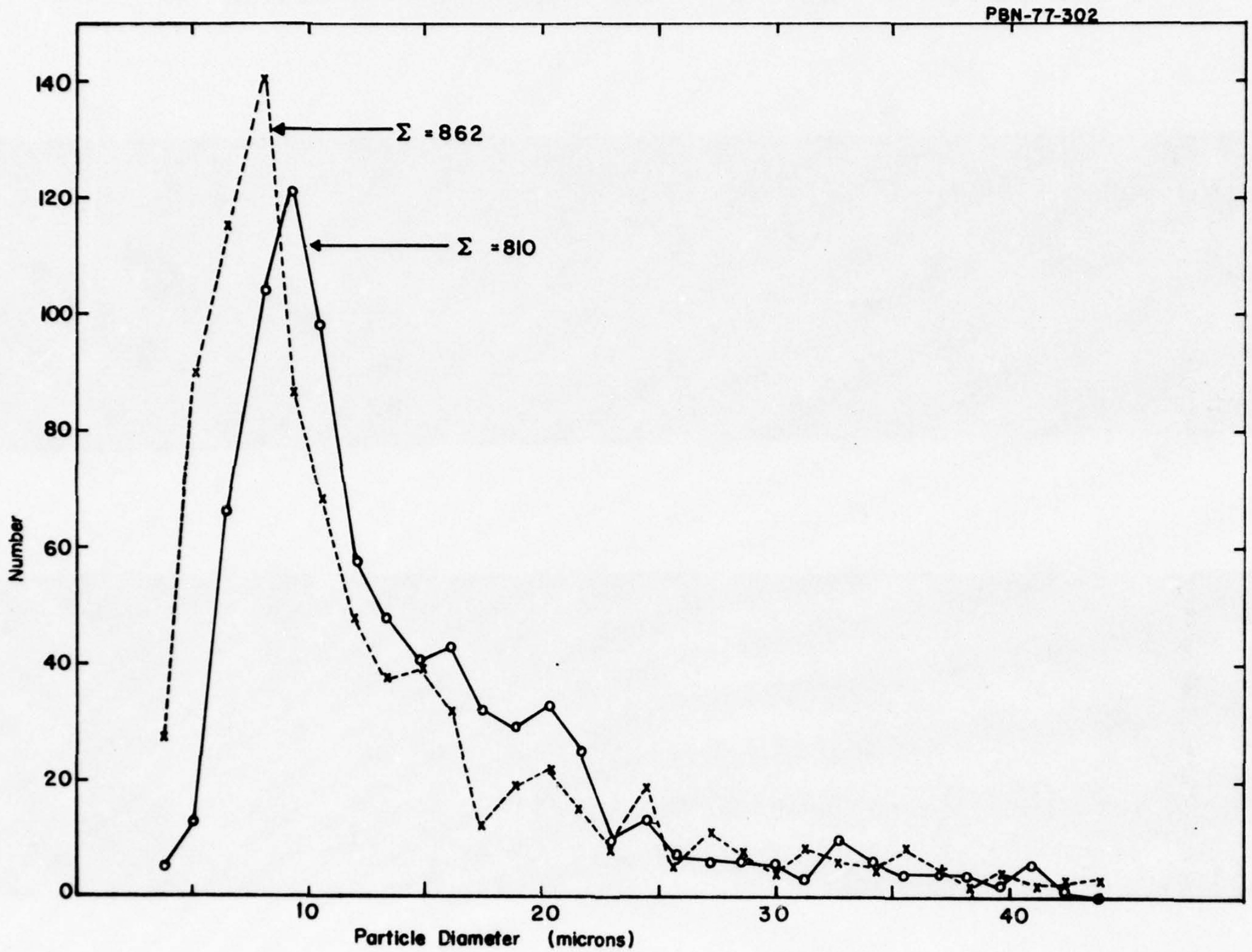


Figure 11 Histogram of G7 Fines Powder Fraction Counted on the Lower and Upper Halves of the Photo in Fig. 10.

Figure 12 is a particle size histogram which compares 1454 counts of the LMTF475(G5) fines fraction powder in Fig. 9 with 1672 counts of the LMTF475(G7) fines fraction powder in Fig. 10. The G7 powder appears to have a slightly larger particle size at the peak area below 10 microns and a larger proportion of the larger particles as well. The histograms have not been corrected for the 13 percent difference in total counts between powders, which would alter the appearance of the curves to some degree.

We also studied the chambers fraction of the G5 and G7 powders. The number of particle counts is significantly less for these powders, and the counting statististics less reliable. The six photographs making up the G5 chambers view in Fig. 9 had 325 particles, whereas the total number for the G7 chambers in Fig. 10 was 261 particles. The corresponding numbers for the fines fraction in these two photographs are 1454 and 1672, respectively.

Histograms of the particle size distribution for the smaller size range of the G5 (0) and G7 (x) chambers fractions are shown in Fig. 13. A comparison of the two curves does not suggest differences in size distribution that seem apparent when comparing photographs; that is, the G7 powder seems to have more uniform and larger particles than the G5 powder.

The differences in flow characteristics and in APS deposition efficiency of these "good" powders compared with very poor materials such as LMTF475(G-8) used in the final production run might be influenced more by moisture content or state of agglomeration rather than by particle size or distribution. We have found that optimum flow and deposition characteristics result from powders that are dried near 100° C and then screened. Higher drying temperatures produce poorer flowing powders, perhaps because they drive off the binder that holds together the spray-dried agglomerates. Certainly any break up in the spray-dried particles would interfere with flow.

It is difficult to pinpoint why the screening is beneficial, because screen sizes are generally much larger than all but a few large spray-dried

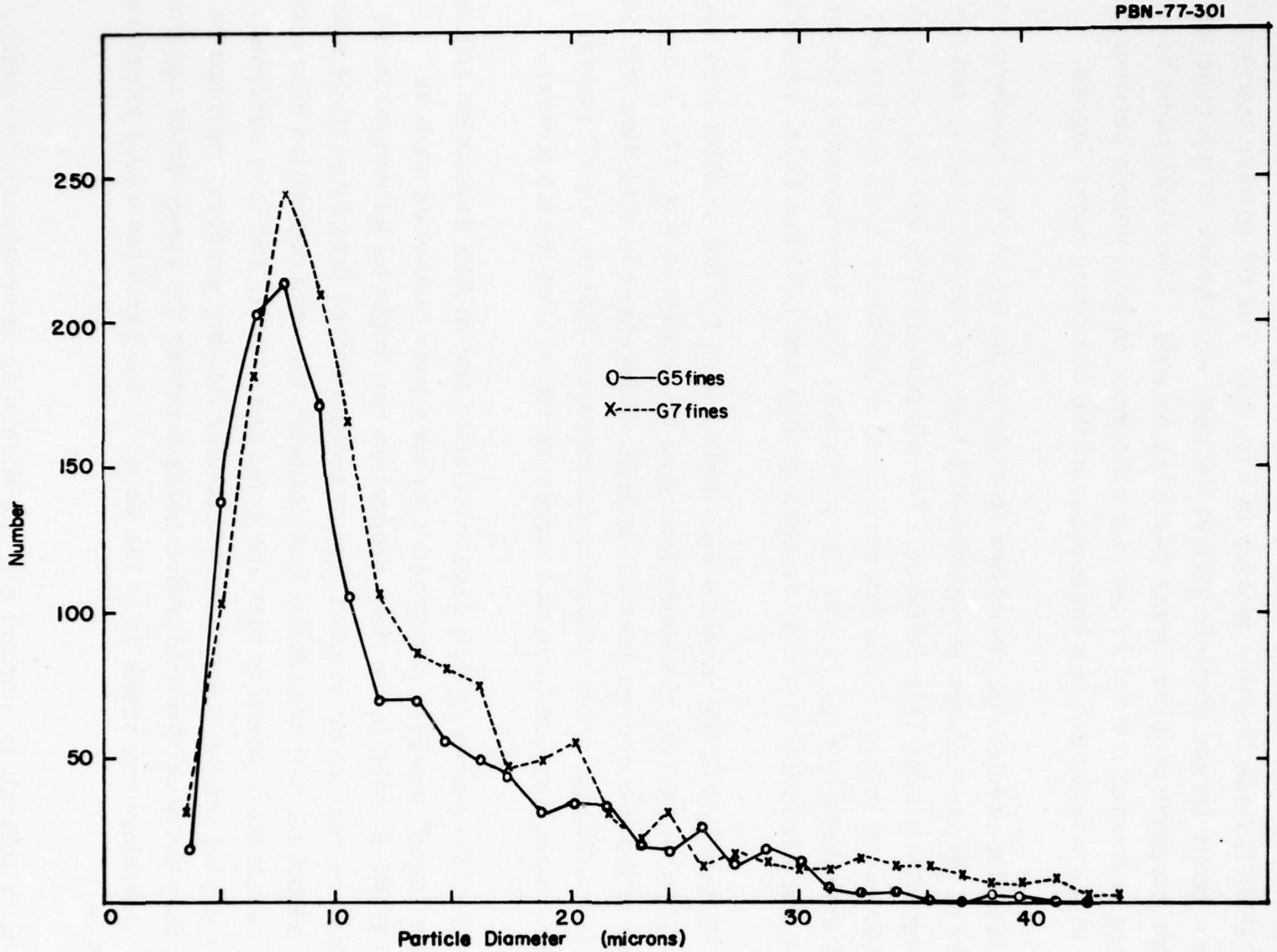


Figure 12 Particle-Size Histogram Graphing the LMTF 475(G5) Fines Fraction Powder from Fig. 9 and the LMTF 475(G7) Fines Fraction Powder from Fig. 10.

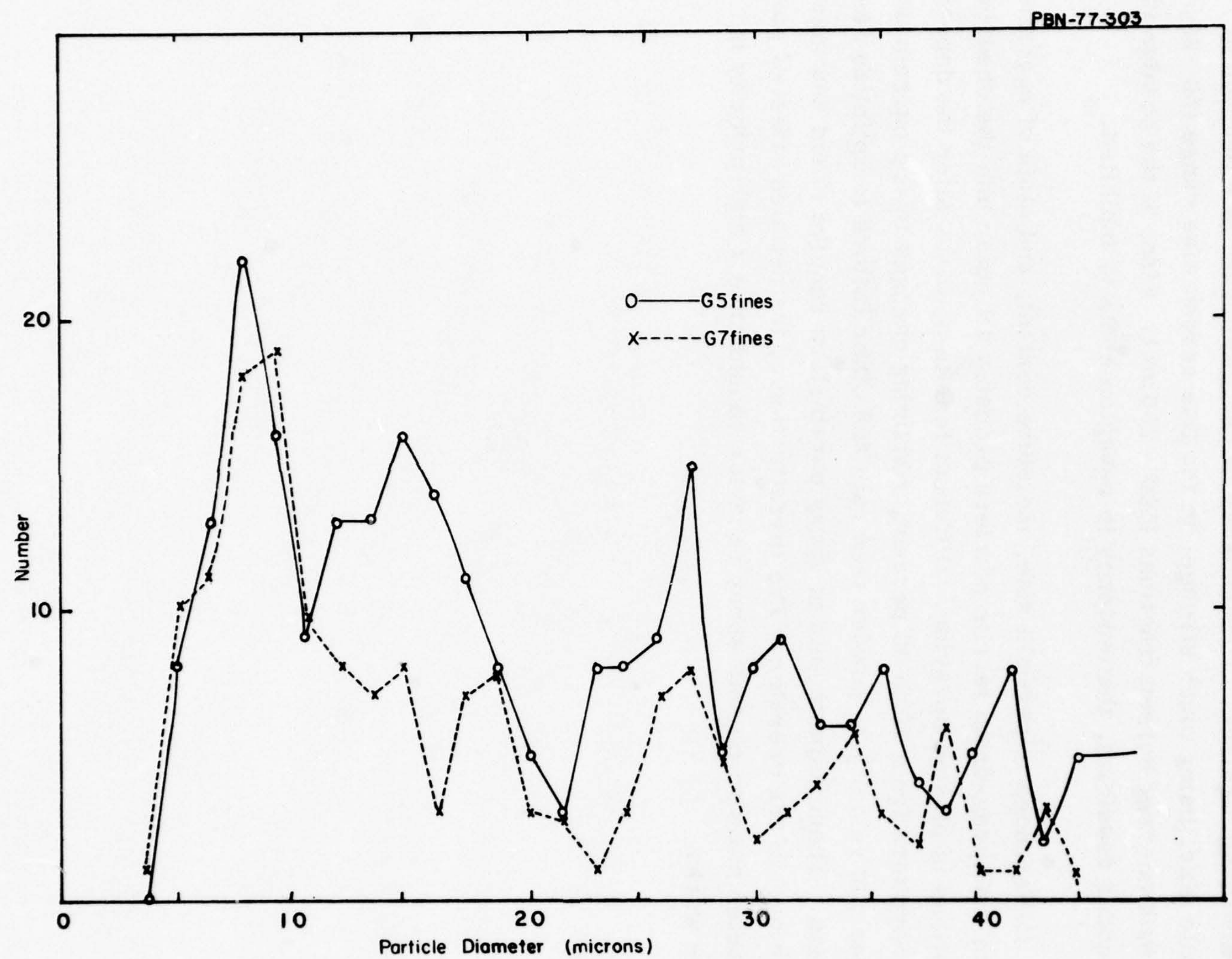


Figure 13 Histogram Graphing Particle-Size Distribution of the Smaller-Size Range of G5 and G7 Chambers Fractions.

particles. We speculate that the major effect of the screen is not to separate the small particles from the large, but to break up groups of smaller particles that hang together. The tendency to reagglomerate is a function of particle size, being much stronger in the fine screen size range (50 -80 μm) than with coarser screen fractions (100 - 200 μm). Also, if the powder is kept under dessicant, the tendency to reagglomerate is inhibited.

Differences in particle size, moisture content, and state of agglomeration in the spray-dried ferrite powders probably all enter into the observed variations in plasma spraying. Different ferrite powders alter the deposit rate anywhere from 20 to 50 percent, requiring changes in arc current and powder gas velocity – powder feed rate and other factors to optimize deposition. These adjustments in spray parameters require talent and ingenuity on the part of the operator. The investigation of the detailed effect of particle characteristics on plasma spray behavior should have a high priority in future work.

2.2 Development of Dielectric Material

The dielectric compositions developed for arc-plasma spraying (APS) are spinel solid solutions with the same crystal structure as the magnetic ferrite. Substitutions of Li and Ti in the spinel can reduce $4\pi M_s$ to zero and increase the dielectric constant slightly. While a major concern with these materials is that we maintain magnetic compensation, i.e., that $4\pi M_s \approx 0$, the prime need for successful APS production is that the thermal expansion of the dielectric match the ferrite exactly. The LMTF 190 material, with a nominal composition of $Li_{.97}Mn_{.1}Ti_{.95}Fe_{.98}O_4$, has proved to be a good thermal-expansion match to the 1200 G ferrite. However, this material has a non-zero magnetization: room-temperature values of $4\pi M_s = 90$ have been obtained. To reduce this residual moment to zero, a series of dielectrics was developed with higher Ti content, to reduce $4\pi M_s$, coupled with Al_2O_3 substitutions to bring the thermal expansion coefficient into line with the plasma-sprayed ferrite.

2.2.1 Thermal expansion data

Matching the expansion coefficient of the dielectric is probably the key to successful arc-plasma spraying of ferrite phase-shifter elements. Since the spinel ferrites have both large elastic modulus and small stress-to-failure, mismatch-induced strains must be kept very small over the entire temperature range to avoid fracture.

The expansion coefficient was measured on all of the compositions listed in Table 2. Cylindrical samples between 1.3 in. and 2 in. long were placed in the quartz dilatometer. Programmed heating and cooling rates of 2° C / min were used and the atmosphere was stagnant air. The data are printed out on a computer-controlled x-y plotter as expansion coefficient (α) versus measurement temperature minus ambient (T-A).

Figures 14 and 15 show thermal expansion $\Delta \ell / \ell_o$ (cross symbols) and α (x symbols) versus (T-A) for two samples which had the same dielectric composition but different amounts of Bi_2O_3. (Sample 200 (1) in Fig. 14 had 0.5 wt. percent Bi_2O_3, while Sample 200 (2) in Fig. 15 had 0.1 wt. percent Bi_2O_3). Because of the difference in bismuth additives, the two samples required different firing temperatures, and we wanted to determine whether the additive or the change in firing temperature would affect the expansion coefficient. A point-by-point comparison in $\bar{\alpha}$ reveals differences as large as 0.5 ppm for these two compositions. The differences, however, probably reflect inaccuracy in the measurement rather than intrinsic differences in expansion behavior because identical compositions to be described later show differences in $\bar{\alpha}$.

A series of dielectric compositions were also examined, in which increasing amount of Al were substituted for Fe in an attempt to determine the effect on expansion coefficient. Figure 16 shows $\bar{\alpha}$ vs. (T-A) for a dielectric with 0.07 atom substitution of Al for Fe. In this material $\bar{\alpha}$, at T-A = 100° C, is slightly higher than in the unsubstituted material (Figs. 14 and 15). Figures 17 and 18 represent samples from two different batches which have exactly the same composition, both in terms of major components and Bi_2O_3 content. (The Al substitution, w, is 0.15 in these samples). Differences in data points are again the order of 0.5 ppm, which could be caused either by instrumental error or by differences in sample density.

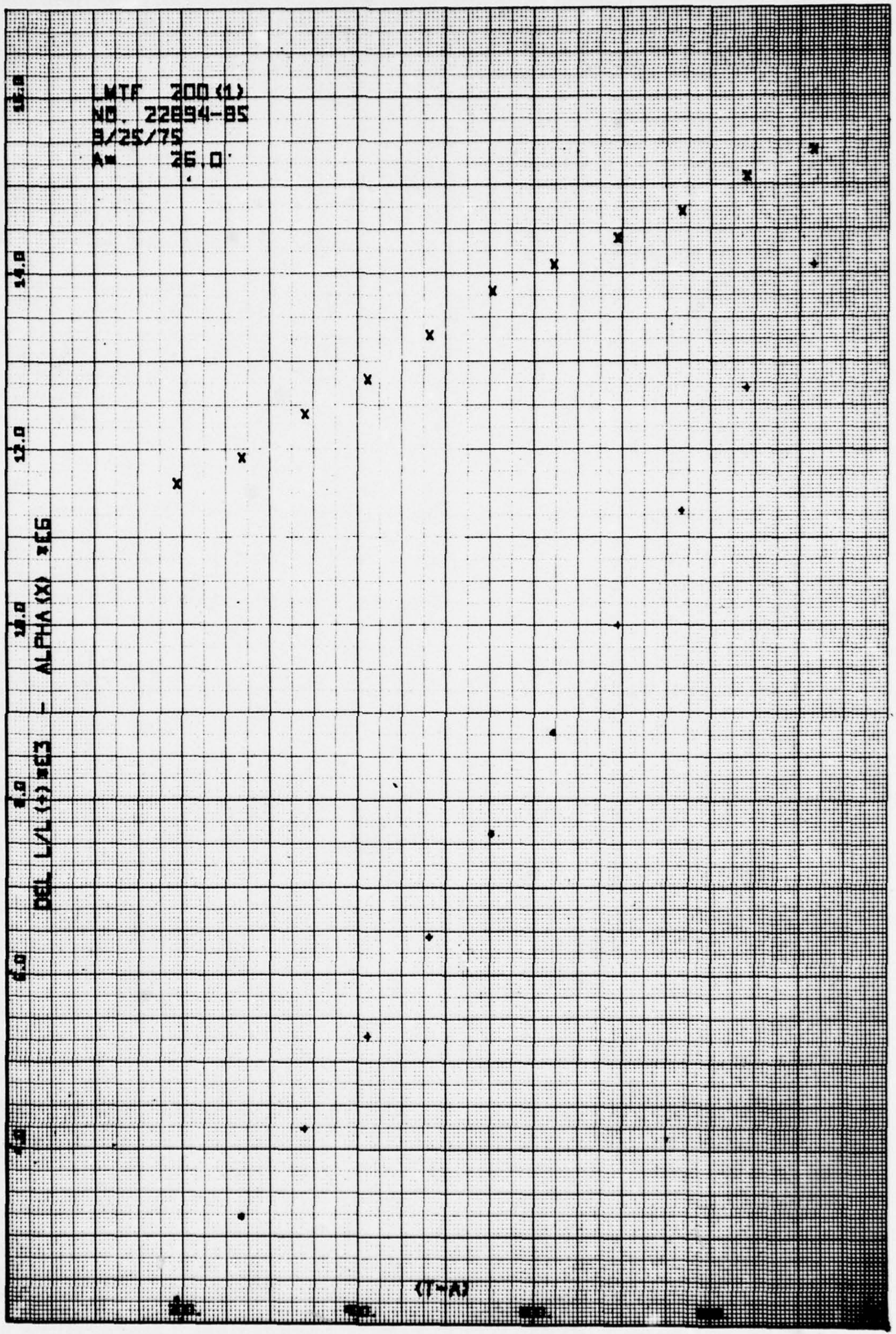


Figure 14 Thermal Expansion (α) vs. Measurement Temperature Minus Ambient (T-A) for Sample LMTF 200(1) with 0.5 wt. Percent Bi_2O_3.

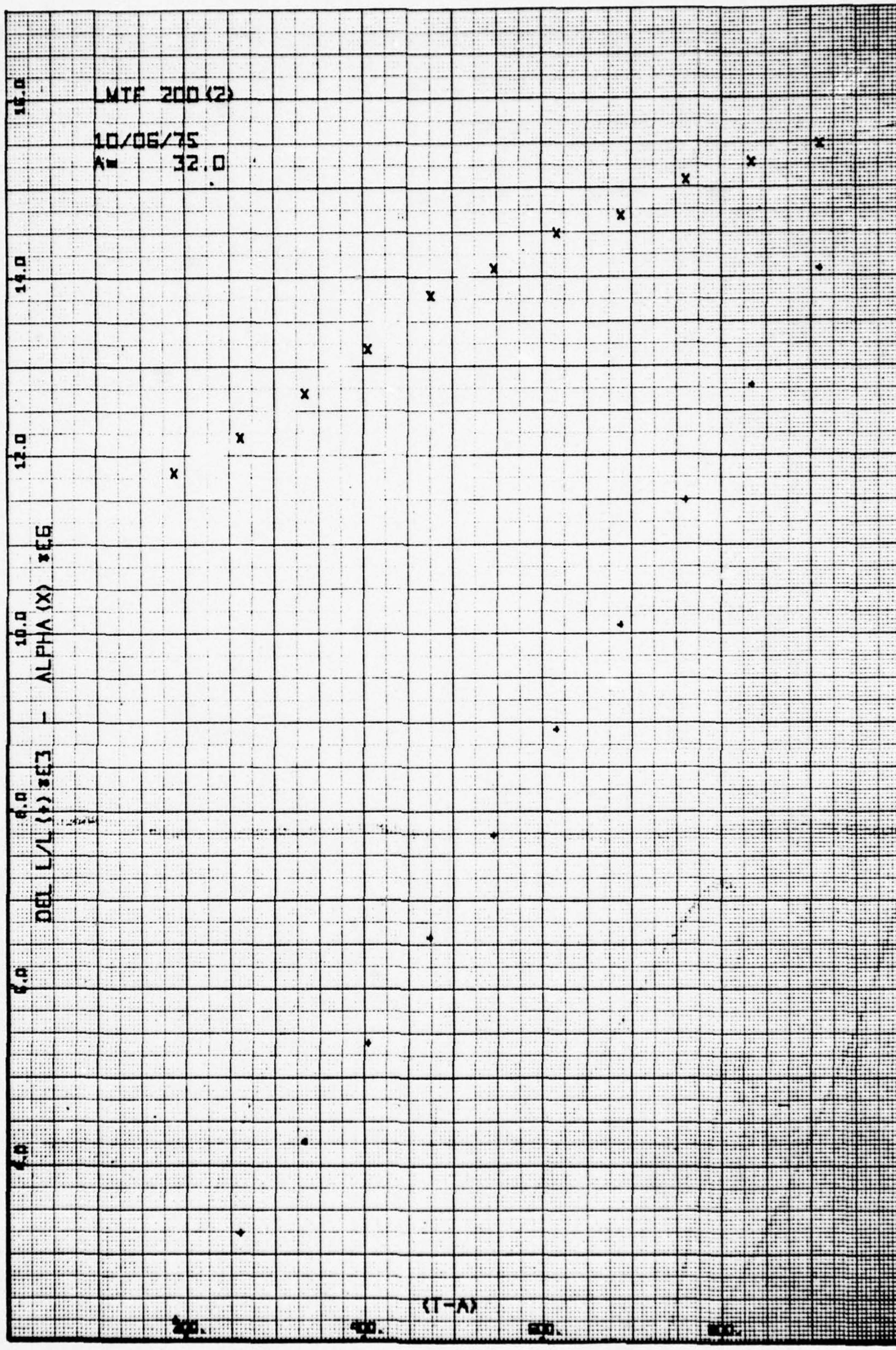


Figure 15 Thermal Expansion (α) vs. Measurement Temperature Minus Ambient (T-A) for Sample LMTF 200(2) with 0.1 wt. Percent Bi_2O_3.

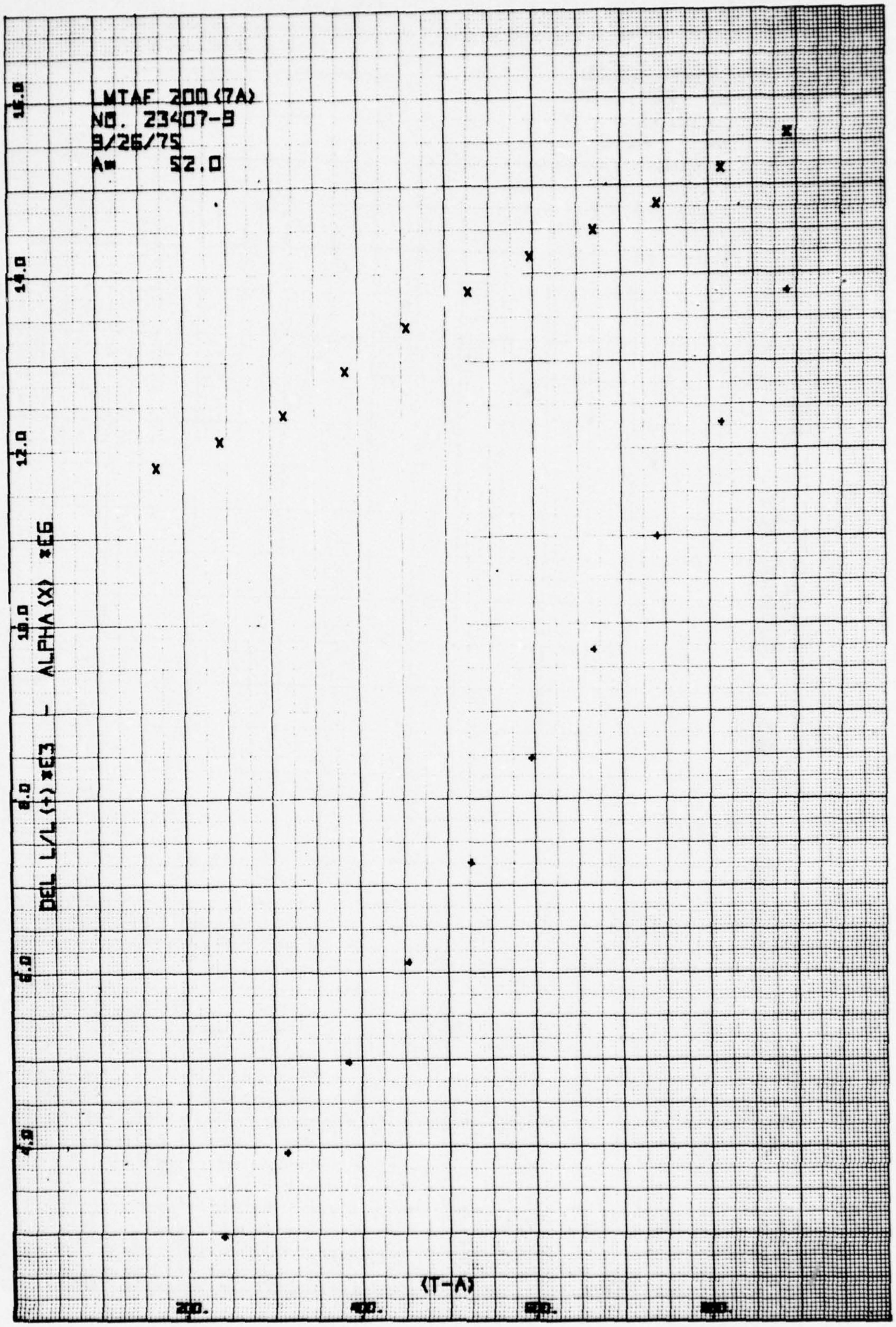


Figure 16 Thermal Expansion (α) vs. Measurement Temperature Minus Ambient (T-A) for Sample LMTF200(7A) with 0.07 Atom Substitution of Al for Fe.

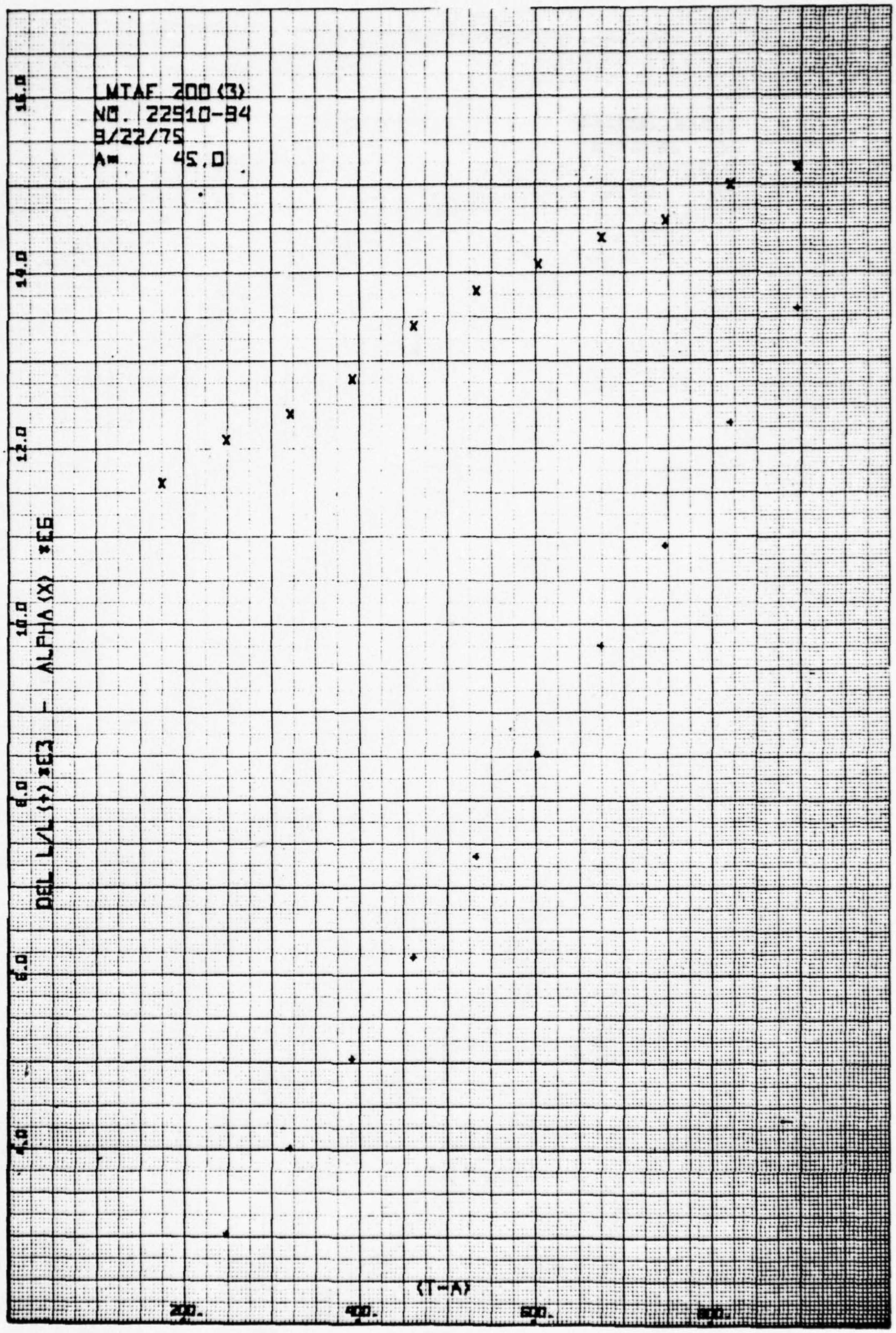


Figure 17 Thermal Expansion (α) vs. Measurement Temperature Minus Ambient (T-A) for Sample LMTF 200(3) with 0.15 Atom Substitution of Al for Fe.

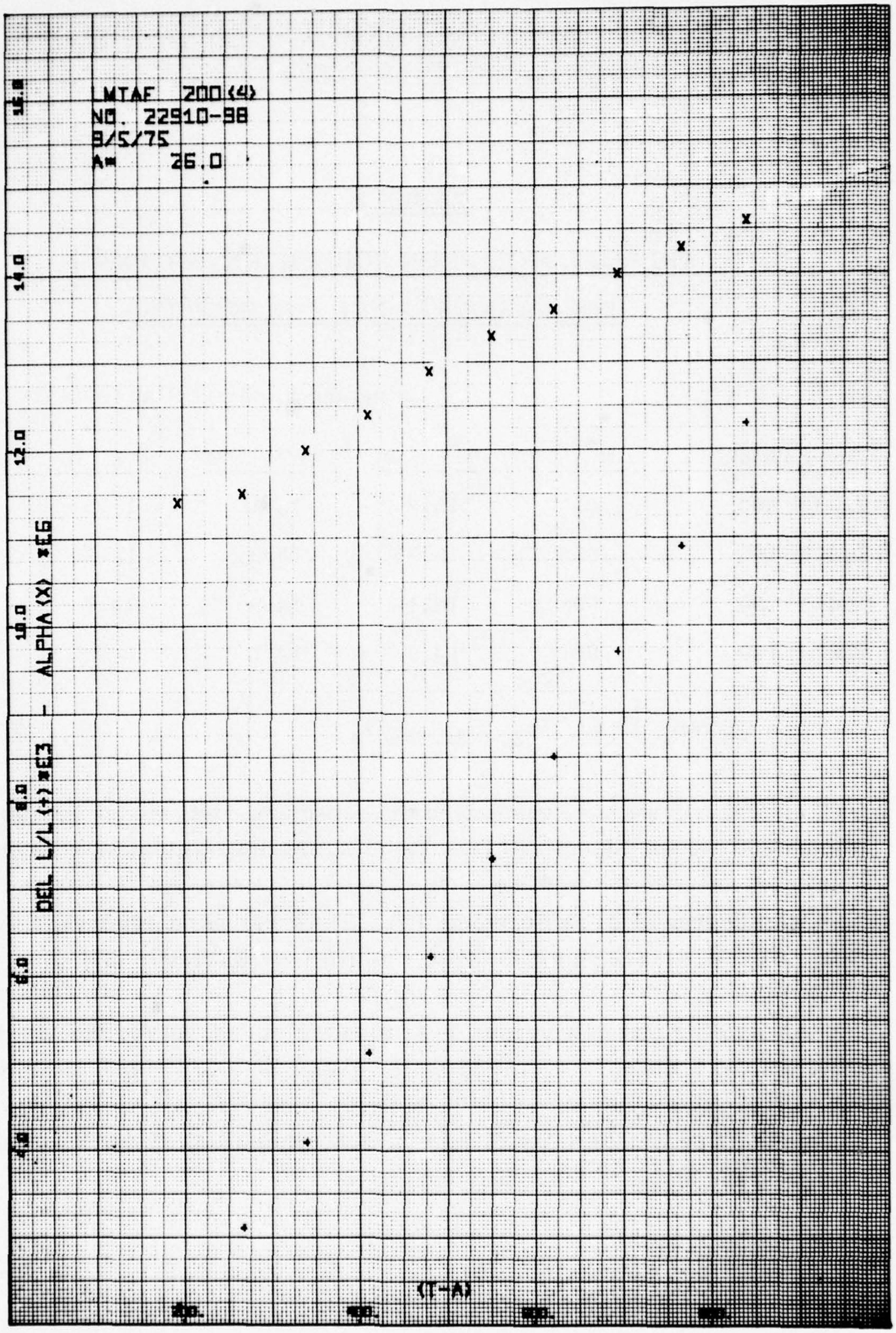


Figure 18 Thermal Expansion (α) vs. Measurement Temperature Minus Ambient (T-A) for Sample LMTF 200(4) with 0.15 Atom Substitution of Al for Fe.

TABLE 2

THERMAL EXPANSION COEFFICIENT AT 1000° C FOR VARIOUS SPINEL DIELECTRICS

α values in ppm/°C at 1000° C

Designation	x^*	$w^* = 0$	w = .10	w = .15
LMTF 200	1.00	15.8	15.1	15.0
LMTF 195	.975	15.25	15.0	14.85
LMTF 190	.95	15.1	14.9	14.7
LMTF 180	.90	14.9	14.7	

* $Li_{.5+x/2}Mn_{.1}Ti_xAl_wFe_{2.4-3x/2-w}O_4$

In Fig. 19 we have assembled the expansion coefficient $\bar{\alpha}$ versus (T-A) for the 200 series dielectrics (see Table 2 for composition) as a function of aluminum substitution for iron. One observes a decrease in $\bar{\alpha}$ at any temperature with degree of Al replacement (w). The $\bar{\alpha}$ values at 1000° C (T-A = 980) range from $\bar{\alpha}$ = 15.8 ppm/°C for w = 0 to $\bar{\alpha}$ = 14.6 for w = .25.

A similar plot of $\bar{\alpha}$ versus T-A is shown in Fig. 20 for the 190 dielectrics with w = 0 and w = .15. Smaller values of $\bar{\alpha}$ are found, as one would expect from the reduction in Li-Ti content. However, we do observe some change in slope for the $\bar{\alpha}$ vs. T plot, which, of course, indicates some change in the shape of the expansion curve.

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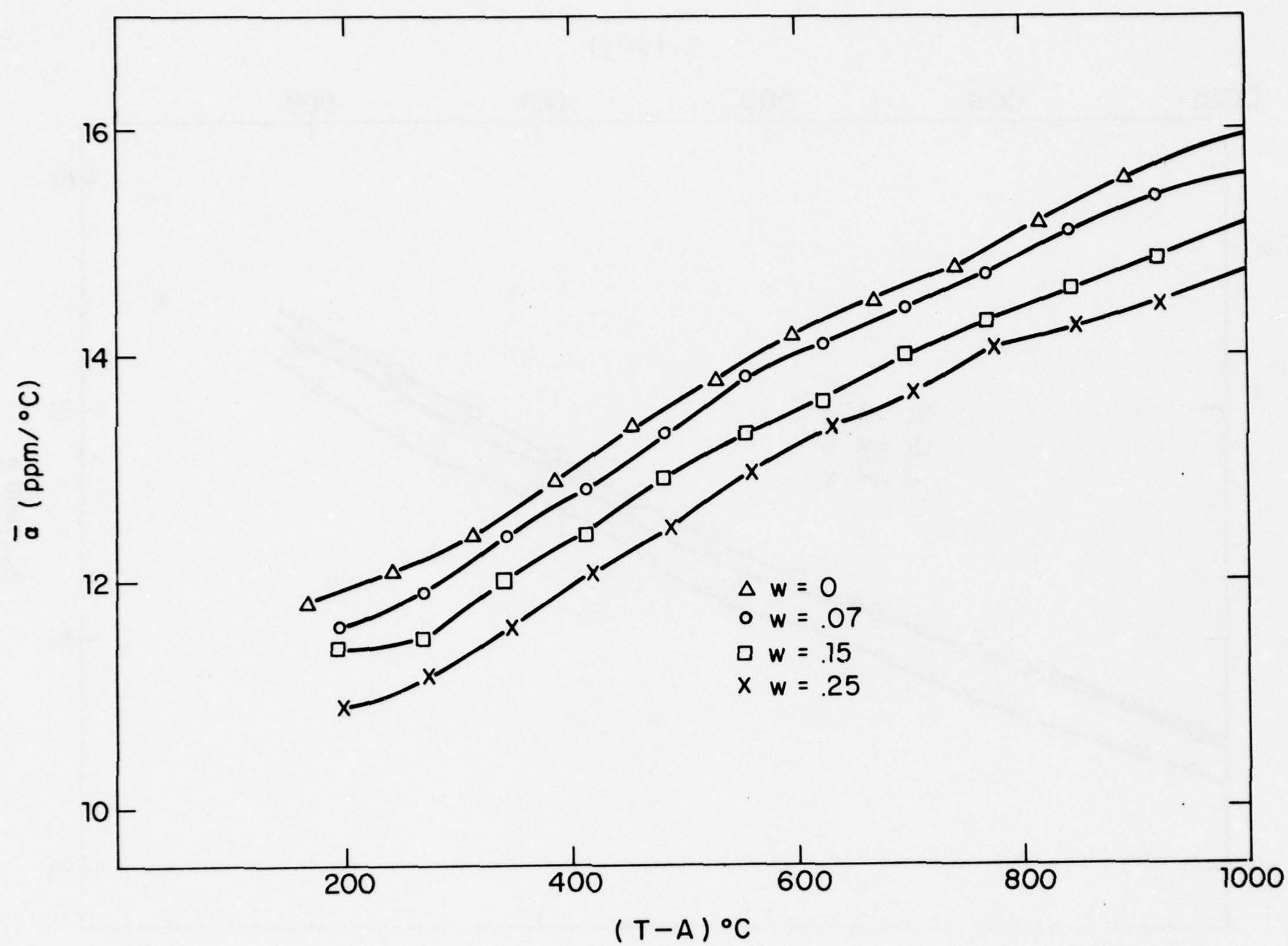

Figure 19 Thermal Expansion vs Temperature for the 200 Series Dielectrics.

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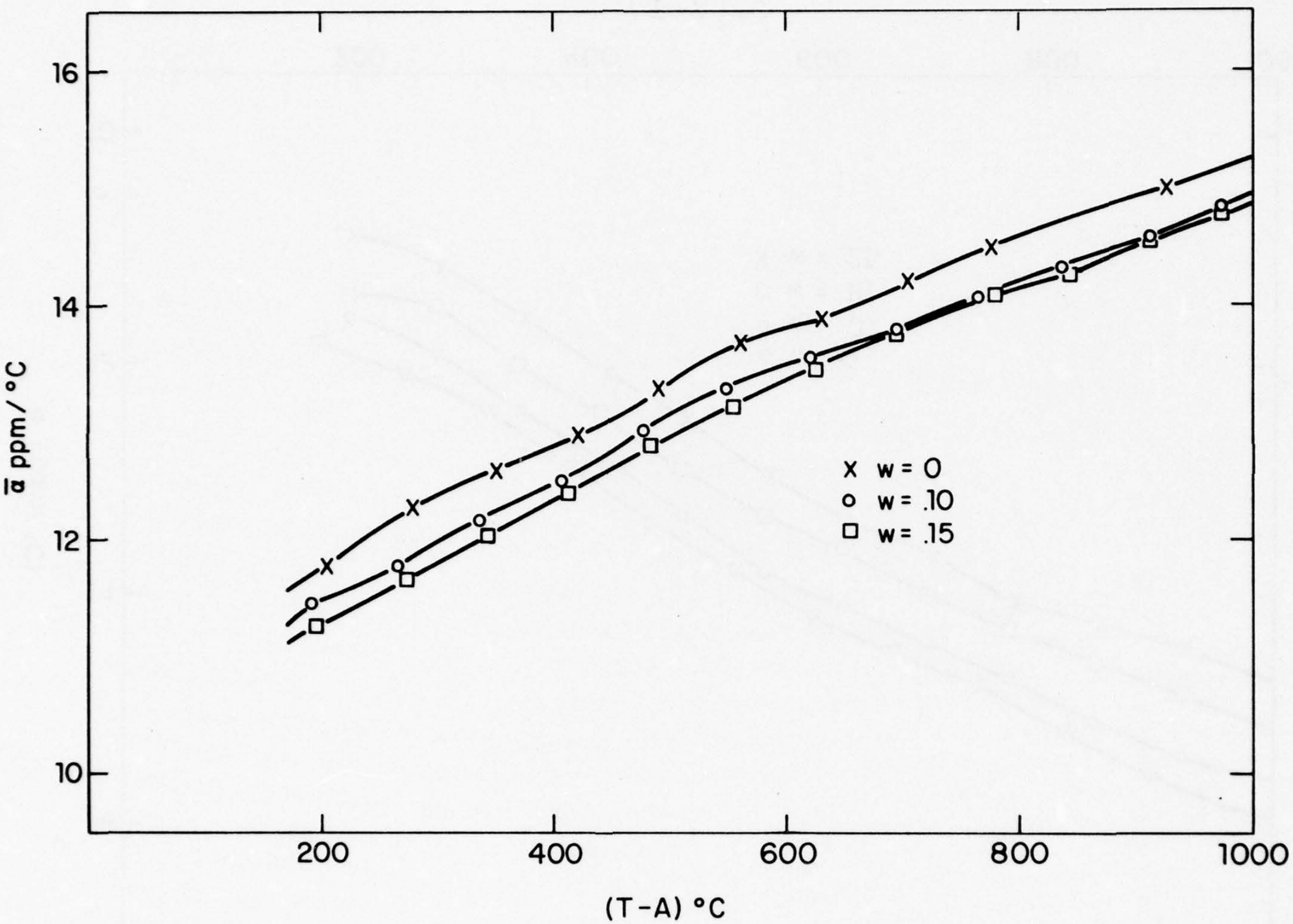

Figure 20 Thermal Expansion vs Temperature for the 190 Series of Dielectrics.

Figure 21 shows three dielectric compositions with the same Al content, w = .15, but with Li-Ti content varying from x = .95 to x = .975 to x = 1.00. It seems that, at higher Al content, expansion shows little variation with Li-Ti concentration. The data for x = .95 and x = .975, in fact, are reversed from the expected sequence, but the variation is within experimental error. The same set of curves for w = 0 would show a stronger dependence on Li-Ti content, i.e., more separation between $\bar{\alpha}$ values. Evidently, Al substitution reduces the effect of content on $\bar{\alpha}$ and also acts to decrease the $\bar{\alpha}$ versus T variation.

2.2.2 Dielectric constant

The dielectric constant (k') is another important parameter in the control of phase-shifter reproducibility. The measurements of k' yield the composition dependence shown in Fig. 22 for the series $Li_{.5+\frac{x}{2}}Mn_{.1}Ti_xAl_wFe_{2.4-\frac{3x}{2}-w}O_4$. Dielectrics which match the expansion characteristics of the 1200 gauss APS ferrite have values $18.5 \leq k' \leq 20.5$. Loss tangent in this series is readily maintained at $\tan\delta < 5 < 10^{-4}$.

2.2.3 Magnetization

In the design of the dielectric-loaded phase shifter, the core material is intended to be nonmagnetic. The Li-Ti-ferrite compositions developed for this program are spinel solid solutions and may have a finite magnetic moment arising from two causes: 1) an imperfect compensation of the magnetization in the material due to composition or firing conditions, 2) a local change in $4\pi M_s$ at the ferrite-dielectric interface due to interdiffusion during spraying or subsequent annealing steps. Since both ferrite and dielectric are members of the same solid solution series, interdiffusion, if it occurs to any appreciable extent, would produce a graded interface of changing $4\pi M_s$ between ~ 0 and 1200 gauss. Evidence to date indicates only minor interdiffusion with annealing. Our main concern at this point is to maintain zero magnetization in the various spinel dielectrics.

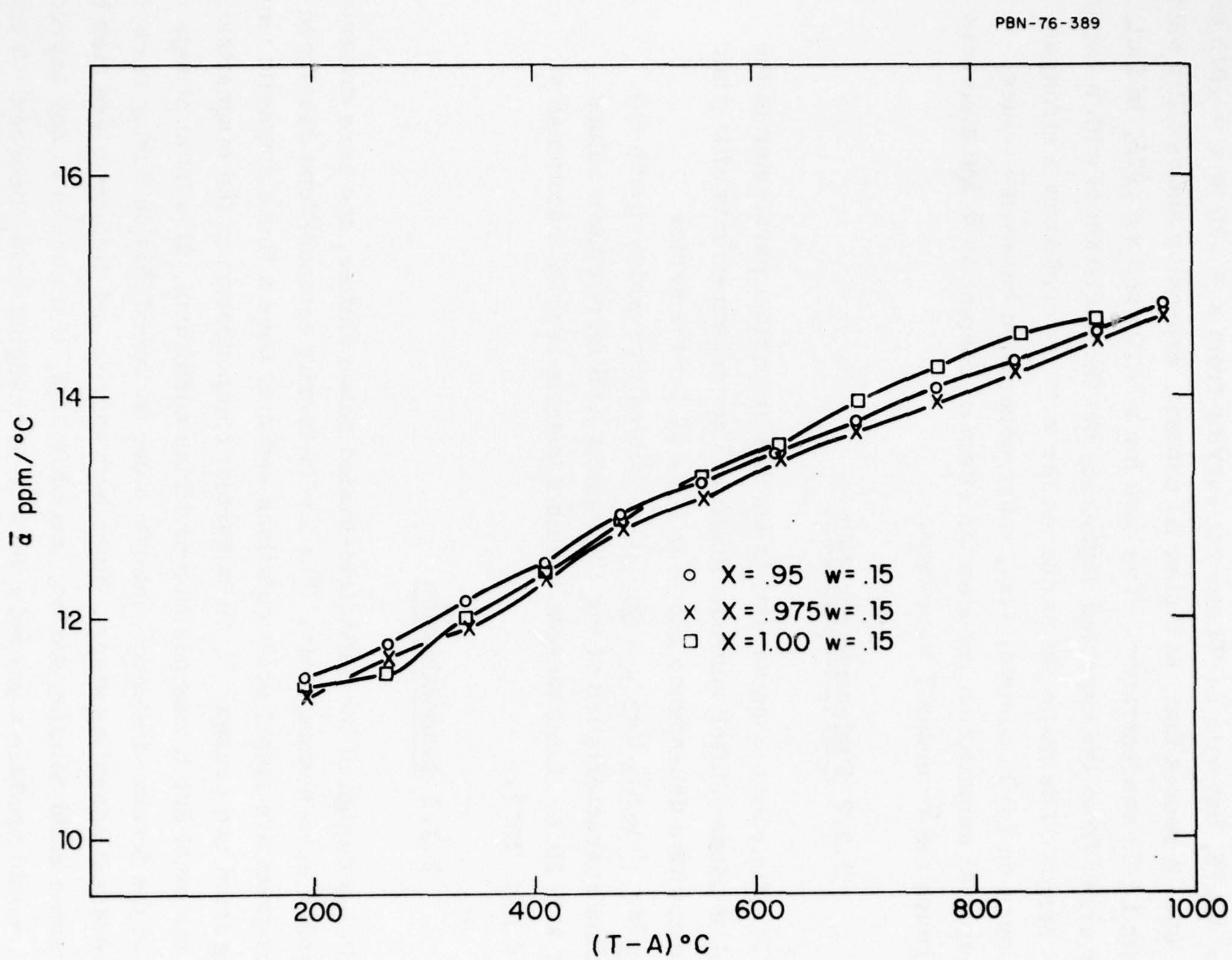

Figure 21 Thermal Expansion vs Temperature for Dielectrics with w = 0.15 and Variable Li-Ti Content.

PBN-75-232

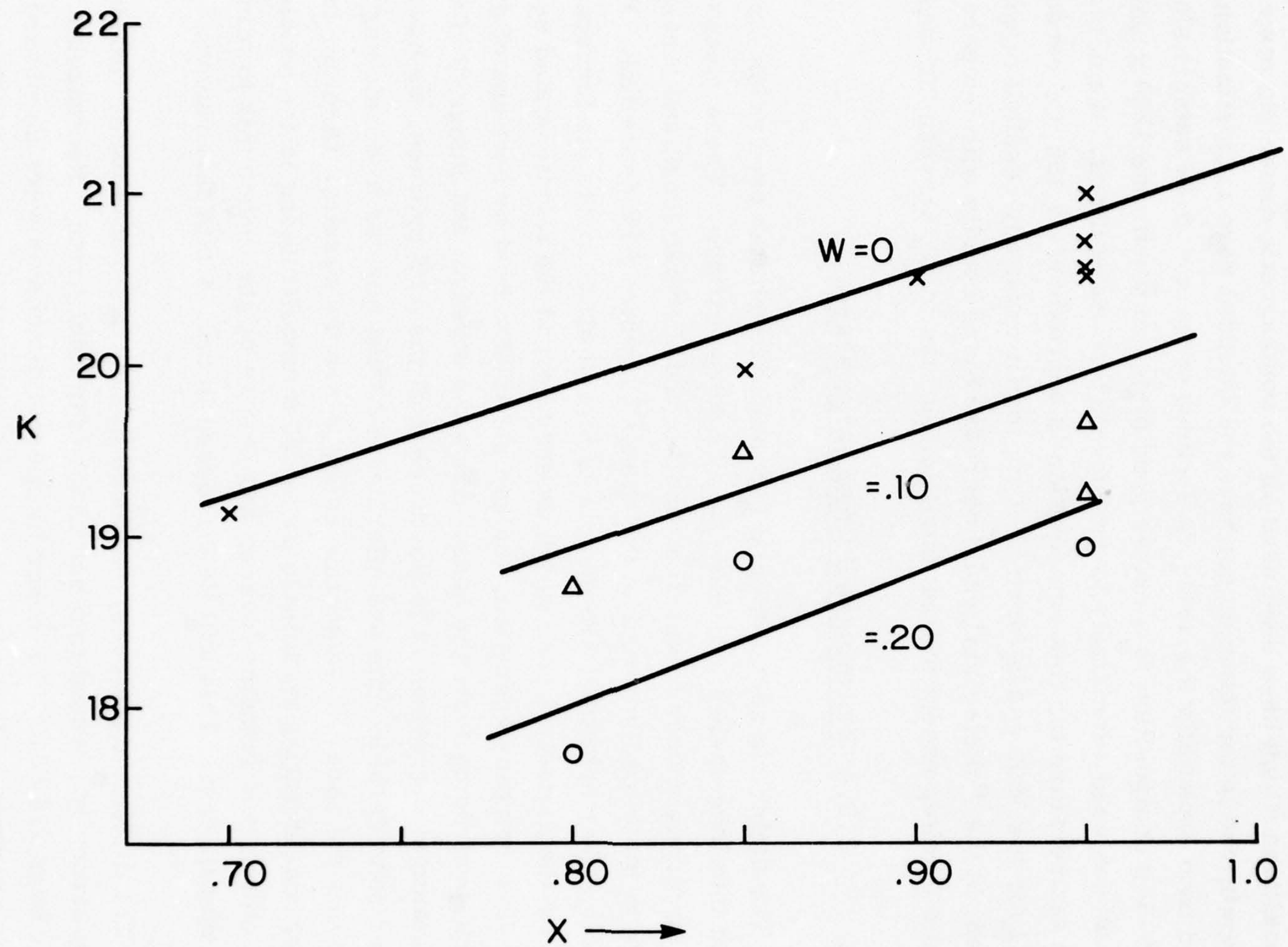

Figure 22 Dielectric Constant at 10 GHz vs Dielectric Composition in the Series $Li_{.5+\frac{x}{2}}Mn_{.1}Ti_xAl_wFe_{2.4-\frac{3x}{2}-w}O_4$.

Figure 23 shows magnetization versus temperature for two compositions (x = 0.70 and x = 0.85) which are beyond the compensated region and three compositions which have been used as the nonmagnetic dielectric material. As shown, the latter three do not have the intended zero magnetization. One should note especially the $4\pi M_s$ vs T curve of the x = 0.95 sample since this LMTF-190 composition is a rather good match in $\bar{\alpha}$ with the 1200 gauss ferrite and has been used extensively to produce APS phase shifters. We note the Curie temperature for this composition is approximately 160° C, versus 390° C for the 1200 gauss ferrite. This implies that any residual magnetic moment in the "dielectric" would decrease more rapidly with temperature than the ferrite, except for the small initial rise in M_s between 20° and 40° C

2.2.4 Forming and firing large shapes

The dielectric core material for the phase-shifter production must be ground into long shapes with very small cross-sections. These pieces must be strong enough to survive handling and thermal shock and straight enough to mate together well in the assembly before APS deposition. For example, after spraying, the sample is moved about inside the furnace by grasping the dielectric core which extends beyond the ferrite coated section. In the final grinding operation, the sample is also held by sections of dielectric protruding from the ends. Since the strength and integrity of this core material are essential to the success of the APS process, we have devoted considerable time and effort in this first quarter to developing and improving the core. This section summarizes the results. (Another important consideration relating to dielectrics manufacturing is the problem of the cutting and grinding losses, and how we might reduce this to minimize overall cost. This will be discussed in Sec. 4.0 of this report.)

The dielectric powders, produced by conventional ceramic processing are isostatically pressed into bar shapes for final firing. Rectangular shaped rubber bags 1.5 × 3 × 16 inches in internal dimension were purchased * for this program. The bags are enclosed in metal forms during the powder filling and isostatic pressing steps to avoid any slight warpage which could

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* Trexlar Rubber Co., Ravenna, Ohio

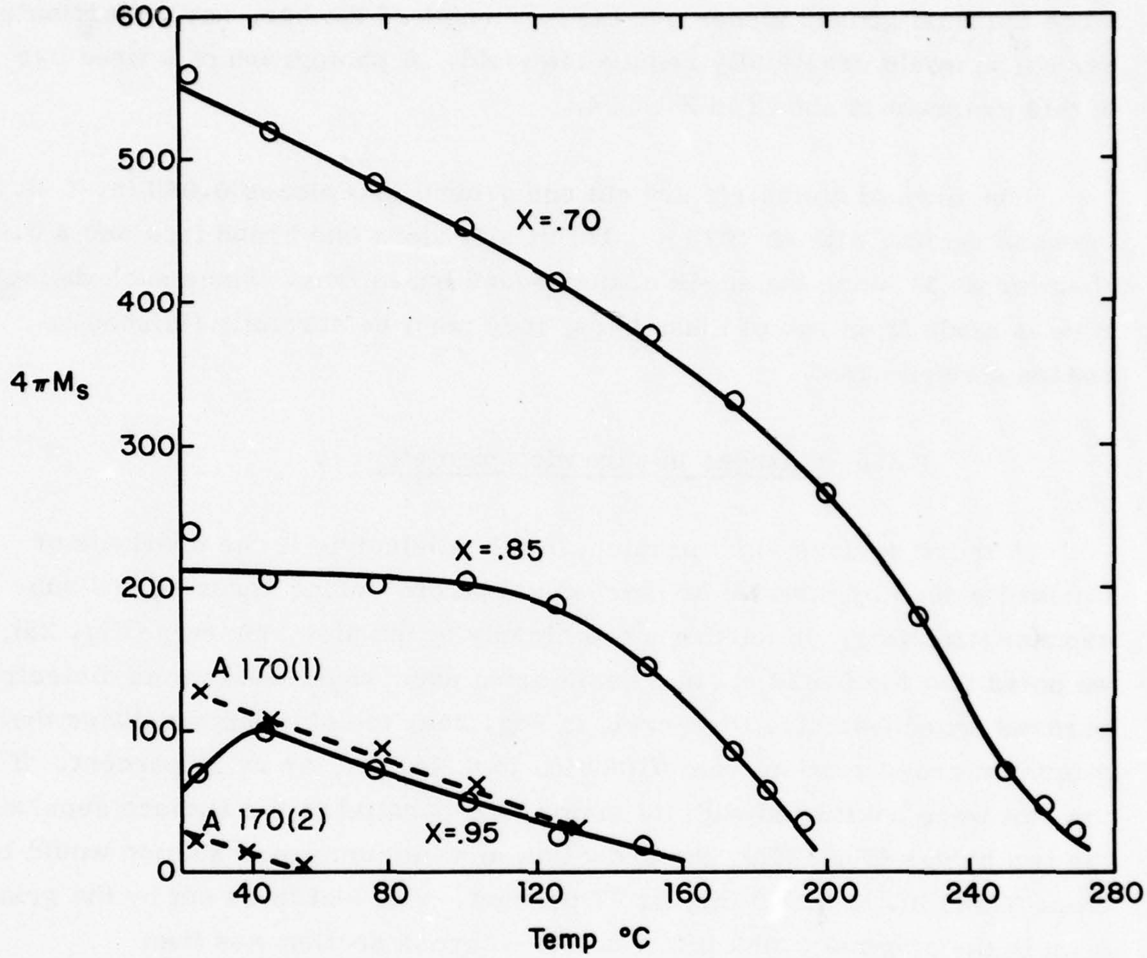

Figure 23 Magnetization versus Temperature for Several Li-Ti-Ferrite Compositions.

be made worse during firing. Special techniques are needed to load in the powder uniformly, as this can also lead to warpage despite the metal form. Since the final ground pieces are the full length of the bar, any distortion in bar shape would drastically reduce the yield. A photograph of a fired bar in this program is shown in Fig. 24.

The bars of dielectric are cut and ground into pieces 0.060 in. × 0.150 in. in cross section with an .020 × .020 in. slot along one broad face and a 0.005 in. chamfer at 45° along the edges of the second broad face. Since each dielectric core is made from two of these bars, they must be carefully finished to assure straightness.

2.2.5 Changes in wire slot geometry

A more serious yield problem for the dielectric is the breakage of finished pieces by thermal or mechanical stress during spraying and subsequent annealing. In looking more closely at the slot geometry (Fig. 25), we noted that the 0.020 in. slot depth deing used would weaken the dielectric, perhaps unnecessarily. Referring to Fig. 25a, the slot depth reduces the minimum cross section from 0.060 in. to 0.040 in., or by 33 percent. If the slot were positioned with its major axis parallel to the surface separating the two holves (Fig. 25b), the reduction in minimum cross section would be from 0.060 in. to 0.050 in., or 17 percent. The slot to be cut by the grinding shop in the original 0.060 in. × 0.150 in. cross section was then 0.010 in. × 0.040 in. along the center line of one broad face. This change poses no particular problem or cost increase in machining.

Another advantage of the change from horizontal to vertical long axis for the 0.020 in. × 0.040 in. slot is that exact registration of the two halves is not as critical. With the former (Fig. 25a) a misalignment of a few mils would make it difficult to insert three wires for the polarization switching. A similar misalignment with the second geometry would be far less serious in threading wires down the slot.

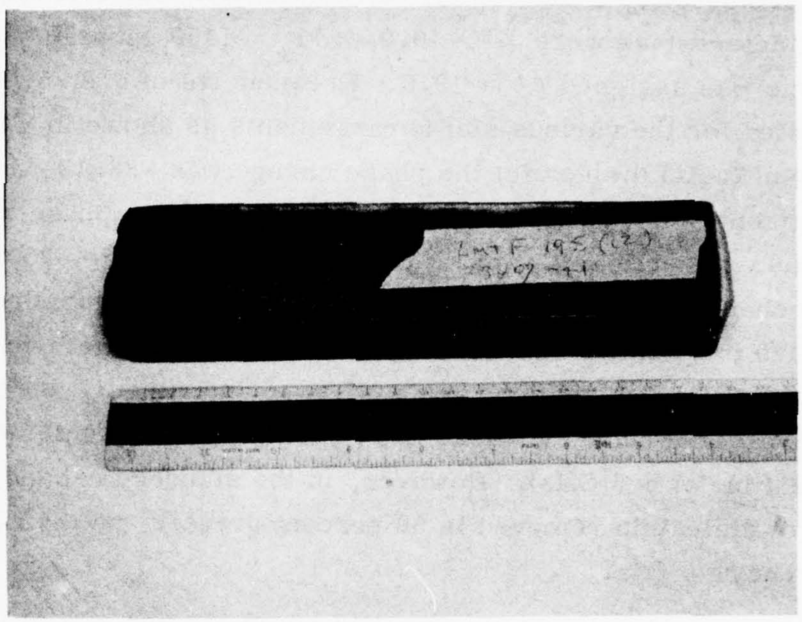

Figure 24 Bar of Li-Ti-Ferrite Dielectric Before Machining.

Since microwave interaction in the loaded phase shifter is fairly complex, it was not obvious a priori whether the change in slot geometry would enhance or degrade the dielectric interaction. A computer program was available which calculates the insertion phase change per inch ($\Delta\Phi$/ in) for this c-band geometry as a function of slot dimensions and location. The ferrite parameters used were $\epsilon' = 19.0$ $4\pi M_s = 1150$ gauss $B_r = 800$ gauss. The dielectric was assigned $\epsilon' = 19.0$. Frequencies of 5.2, 5.5, and 5.7 GHz were calculated for the various slot arrangements as shown in Table 3. With no slot present (solid dielectric) the phase change was -88.18°/ in. at 5.5 GHz. With the horizontal slot at center (Fig. 25a) the insertion phase was smaller (-77.29°/ in.). A vertical slot of the same dimensions (Fig. 25b) produced more phase change (-81.50°/ in.). The present slot configuration has outside slots of $(0.020 \text{ in.})^2$ and 0.020×0.040 so that with Li-Ti ferrite dielectric (discounting the fact that silicone resin $\epsilon' = 16$ and wire fill the slots) there is an effective phase change smaller than given by either center slot orientation (-69.89°/ in. at 5.5 GHz). However, in the standard c-band geometry the volume of dielectric removed is 50 percent greater, so the comparison may not be entirely fair.

The conclusion to be drawn from this study is that there is no penalty, but rather, an advantage in effective dielectric constant using the slot with its major axis vertical. This is important because the effective dielectric constant of the Li-Ti ferrite composite is less than the K-38-garnet composite by about 15 percent($\epsilon'_{eff} = 23$ versus $\epsilon_{eff} = 20$) and further reduction due to changes in slot geometry would make one-for-one replacement more difficult. Although this change does not affect magnetic phase shift or microwave insertion loss (and we have used both geometries in this contract), it seems clear that the new geometry (Fig. 25b) has definite advantages for phase shifters produced by APS deposition.

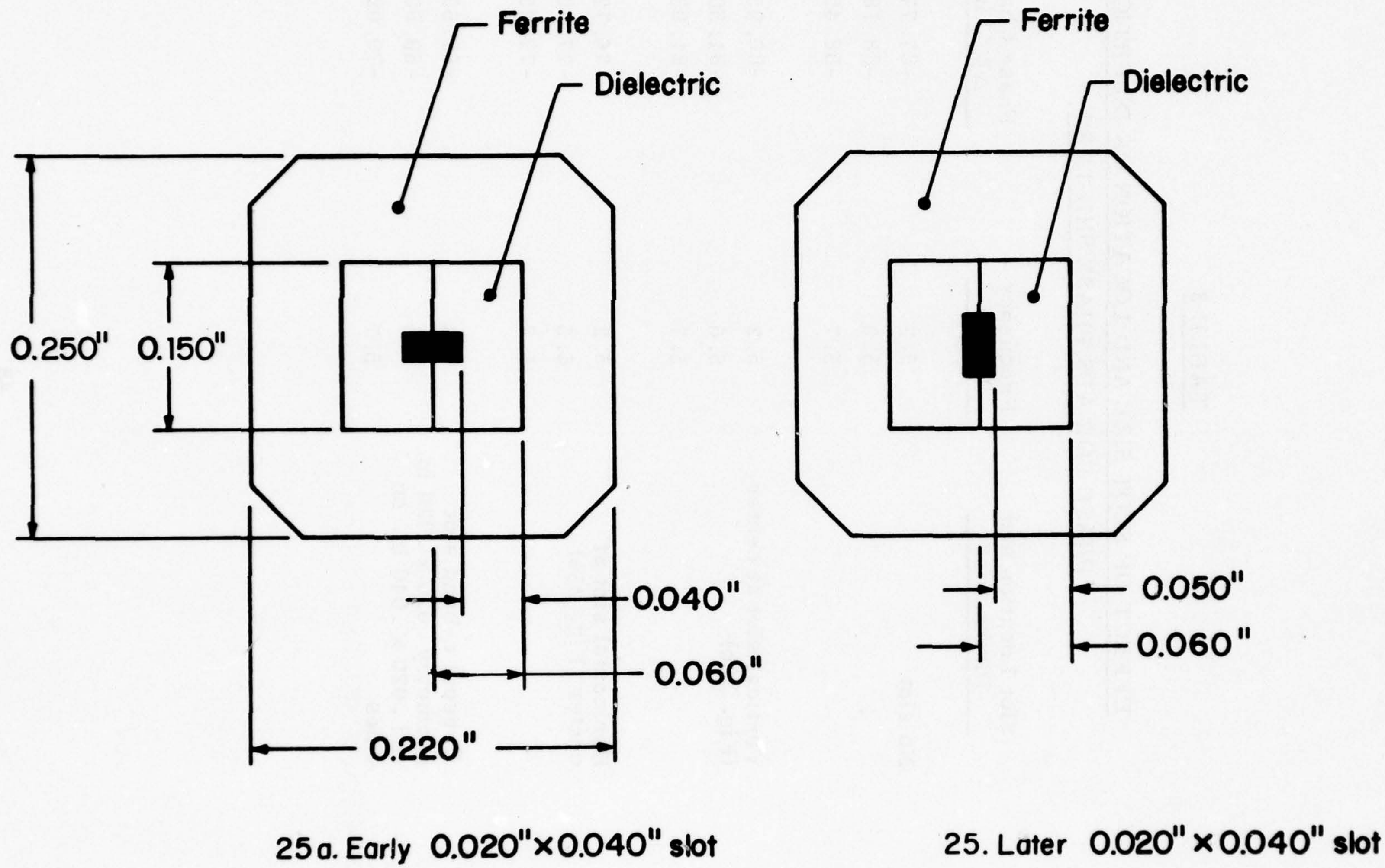

Figure 25 Location of Center Hole in Two-Piece Dielectric.

TABLE 3

EFFECT OF SLOT SIZE AND LOCATION ON INSERTION PHASE FOR APS PHASE SHIFTERS

Slot Location and Dimensions	Frequency (GHz)	Phase Change $\Delta\Phi$°/ in
No slot	5.2	-87.77
	5.5	-88.18
	5.7	-88.49
Vertical slot at center (Fig. 25b)	5.2	-80.95
	5.5	-81.50
	5.7	-81.93
Horizontal slot at center (Fig. 25a)	5.2	-76.72
	5.5	-77.29
	5.7	-77.25
Present c-band slot geometry .020 × .020 in. and .020 × .040 in. on sides	5.2	-69.69
	5.5	-69.90
	5.7	-70.09

2.3 Design and Construction of Raytheon APS Equipment

2.3.1 Initial design

Design and construction of the plasma-spray equipment was begun soon after the start of the program and was completed before the end of the first quarter. The experimental furnace used in exploratory work was unsuitable for production, both because of inadequate control of furnace temperature and because no more than one sample could be sprayed during a single work day. Furthermore, the original spray station used an inadequate hand crank to provide vertical translation along the rod, which was replaced by a hydraulic assembly in the new design.

The initial configuration is shown in Fig. 26. It shows the overall plan of providing two furnaces so the dielectric rod can be preheated in the upper furnace, maintained at a uniform and constant temperature during spray-coating, and returned to the upper furnace for storage after spraying. The rod would be rotated while moving slowly in a vertical direction during spraying.

The original furnace configuration is shown in Fig. 27. The upper furnace could be physically removed, so that annealing could be performed in a separate location. The upper furnace held both uncoated and ferrite-coated dielectric rods during the spraying operation. Before the start of the spraying workday, the upper furnace was loaded with a batch of dielectric rods and preheated to approximately 800° C. One rod was then placed into a chucking fixture, held from below, and lowered quickly to a position where plasma spraying could begin. Rotation and raising of the rod then proceeded at rates dictated by the plasma-spraying operation. Typical rates used in the ECOM experiments were 0.25 in. to 0.75 in. per minute.

Although the equipment did function well enough to allow the testing out of the double oven idea and the transfer between sprayed and unsprayed samples, there was a need for better temperature control and a better

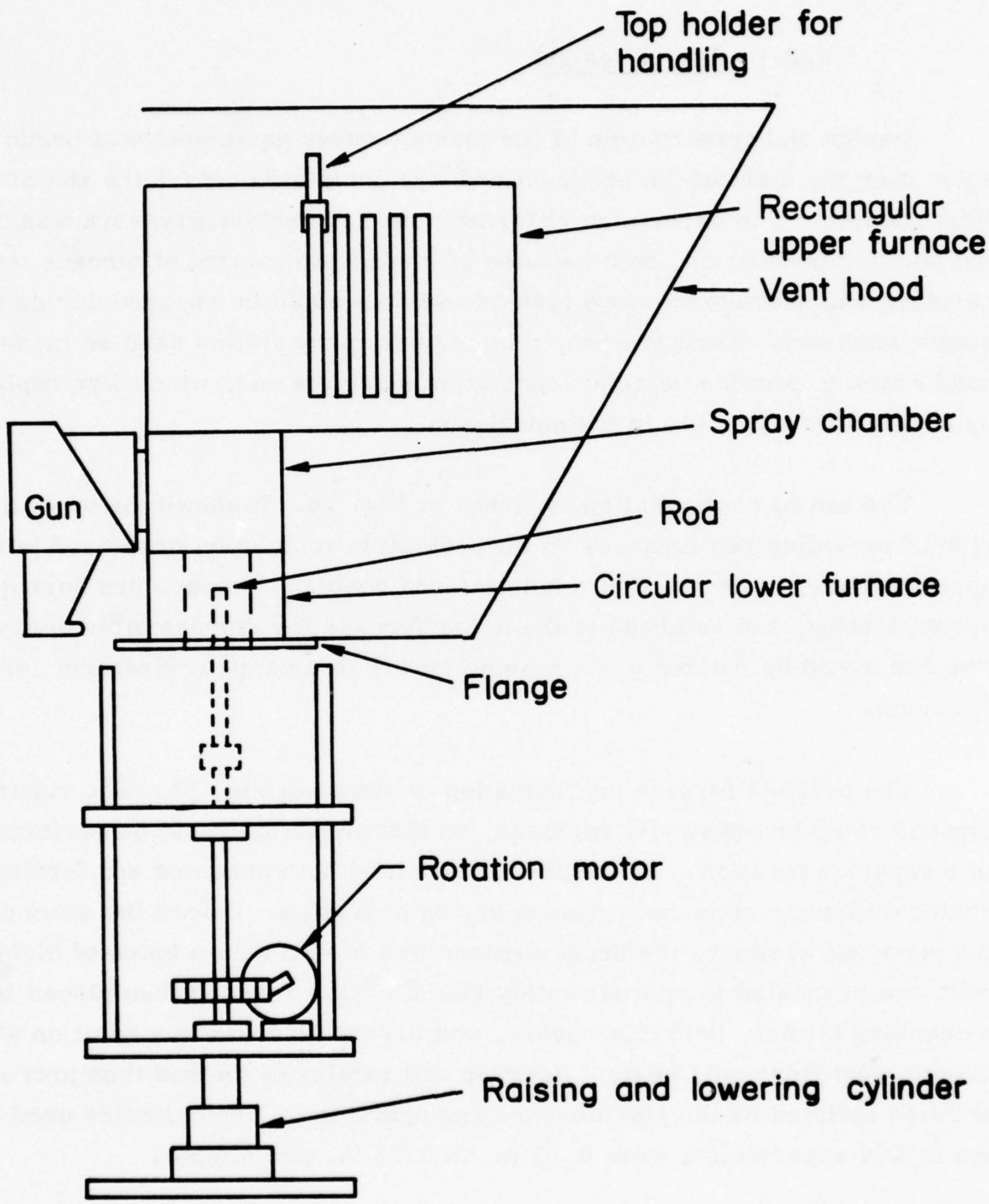

Figure 26 Arc-Plasma-Spray Furnace as Initially Planned.

PBN-75-755

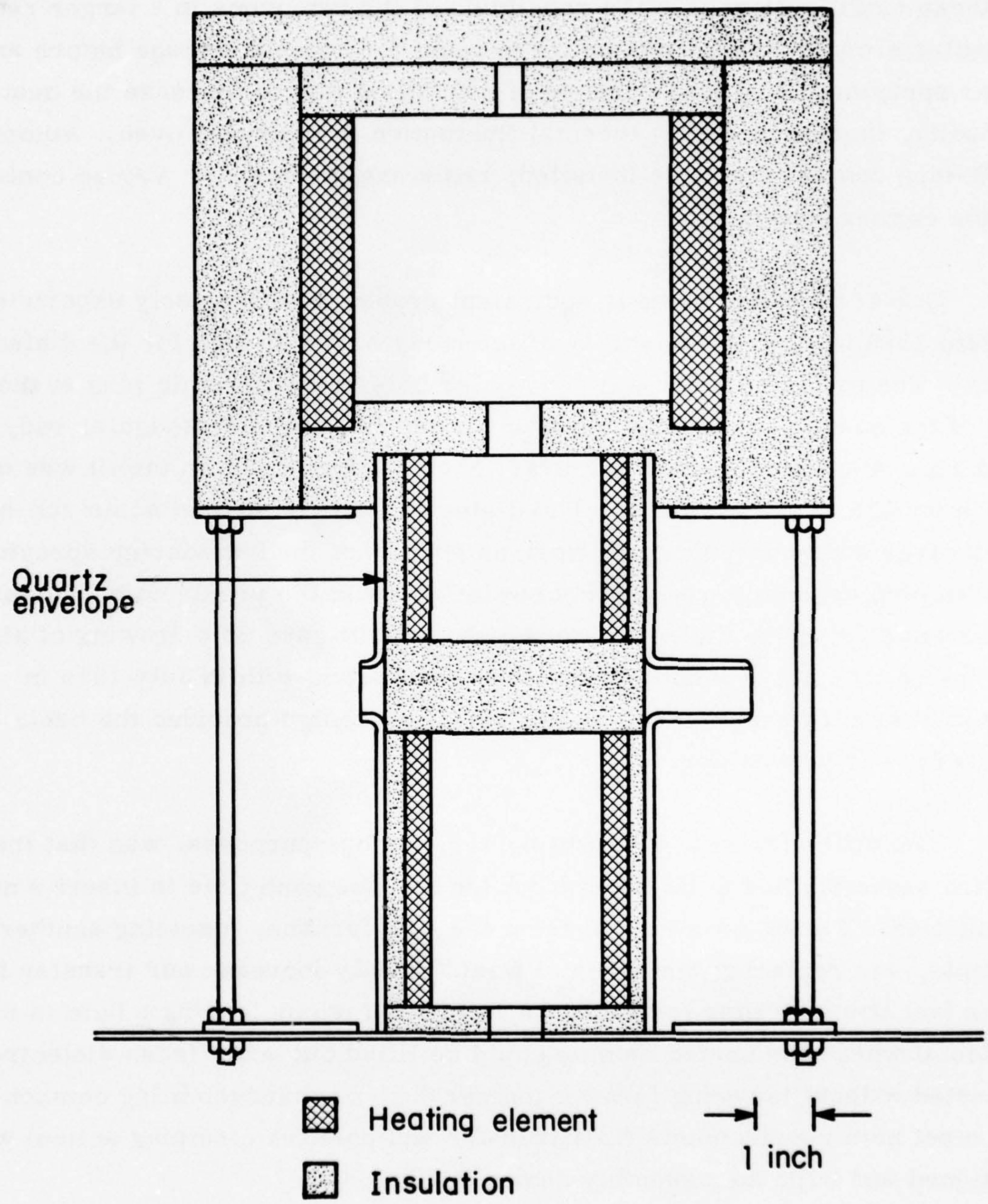

Figure 27 Furnace Arrangement for Arc-Plasma-Spray Unit.

arrangement for holding and rotating the dielectric rod during spraying. A number of equipment changes were made toward the end of 1975 following the visit in November of the contract technical adviser, R. Babbitt. One of these modifications was the rebuilding of the two ovens in a larger rectangular cross-section, making more room for sample storage before and after spraying. A second purpose of rebuilding was to increase the heat capacity, thereby reducing thermal fluctuation in the spray oven. Automatic SCR-type controllers were installed, replacing the manual Variac control of the earlier design.

One of the more serious equipment problems in the early experiments in late 1976 was the unreliability of the early holder design for the dielectric rods. The original holder was a circular hole in the ceramic plug at the top of the sample pedestal which was a close fit for the rectangular rod, making contact the the four corners. At ~ 100 rpm rotation the fit was not close enough to avoid wobble. The dielectric always showed some run-out at the free end and would often work up and out of the hole during spraying A clamping assembly was clearly needed to avoid the problems of holding and transferring the dielectric rods. R. Babbitt gave us a drawing of his clamping assembly, which we had seen and worked with in July 1975 in our preliminary experiments at ECOM. This design provided the basic ideas for our new holder.

The difficulty with Babbitt's holder, for our purposes, was that the entire assembly had to be taken from the furnace each time to insert a new dielectric. Taking the pedestal from the APS furnace, inserting another sample, and replacing the pedestal would greatly increase our transfer time. This fast transfer time had been the rationale for our leaving a hole in the pedestal where the coated sample could be lifted out and a fresh dielectric inserted without lowering furnace temperature or disassembling components. To meet both requirements (fast transfer and positive clamping action) we designed and built the assembly shown in Fig. 28.

The photograph shows two views of the jaw assembly mounted in the rotating pedestal tube. The jaws which grip the dielectric are forced apart

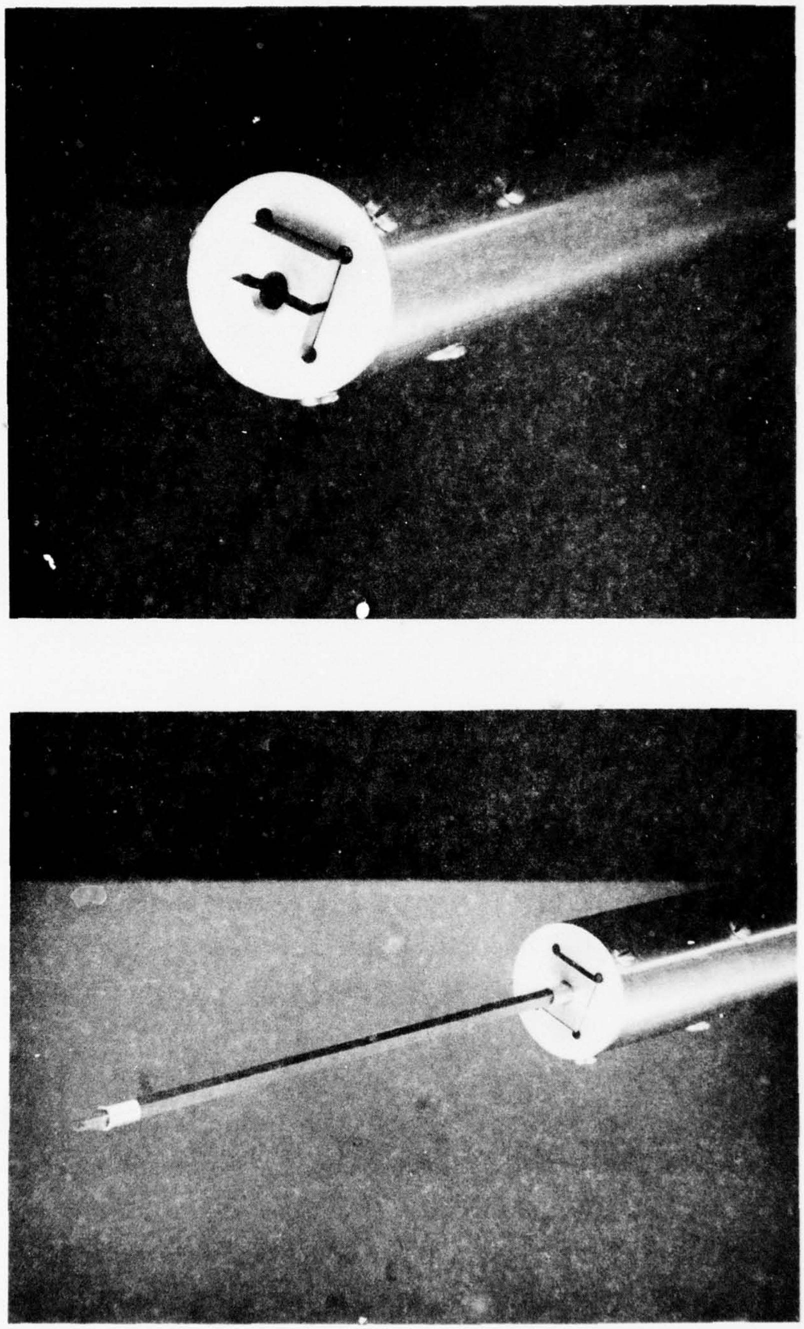

Figure 28 Pedestal Clamp Assembly and Pedestal with Dielectric Rod in Place for APS Deposition.

when moved upward through the square hole in the pedestal cap by pins which ride in the elongate slots. The pins are anchored to the circular cap with a small plate. Below the clamp assembly the connecting rod is hollow. This allows any ceramic pieces to fall through and out of this region. As shown in Fig. 28, the dielectric has metal collars at top and bottom to hold the two halves in position. The jaw clamp shut by a downward spring pull on the connecting rod, as in Babbitt's original design.

2.3.2 Vertical translation equipment

The vertical pedestal motion during APS despoition is controlled by a hydraulic system, which is continuously adjusted in rate to allow precise adjustment in deposit thickness. A schematic diagram of the equipment is shown in Fig. 29. The system allows rapid changes in speed in either direction and at any point in travel. Pressurized air is introduced at the upper left in the diagram and enters a Schraeder three-position, four-way hand valve. The three positions are up, neutral, and down for motion in these same directions. The neutral position stops the motion by venting the air last applied. The direction control valve provides pressurized air in one of the air/oil reservoirs to flow through Scovil valve A or B and then to one side of the hydraulic piston. The flow forces oil out of the opposed piston chamber. This outflow is controlled by one of the two flow valves on the return side of the line. The oil bleeds through the flow valve and into the reservoir, displacing the air at the top, which vents out through the direction control valve.

Table 4 summarizes the different travel modes and control functions for this equipment. For upward piston travel, the control valve air flow is from position 1 to 4, which pushes oil from the lower air oil reservoir through the Scovil B valve (plain arrow indicates unimpeded flow in that direction; crossed arrow indicates valve adjustable flow) and into the lower piston chamber. A controlled rate of rise for the pedestal is achieved by adjusting the slow (Hoke A) or fast (Scovil A) hydraulic valve (see Table 4) which bleeds oil into the upper reservoir and forces air to vent out from

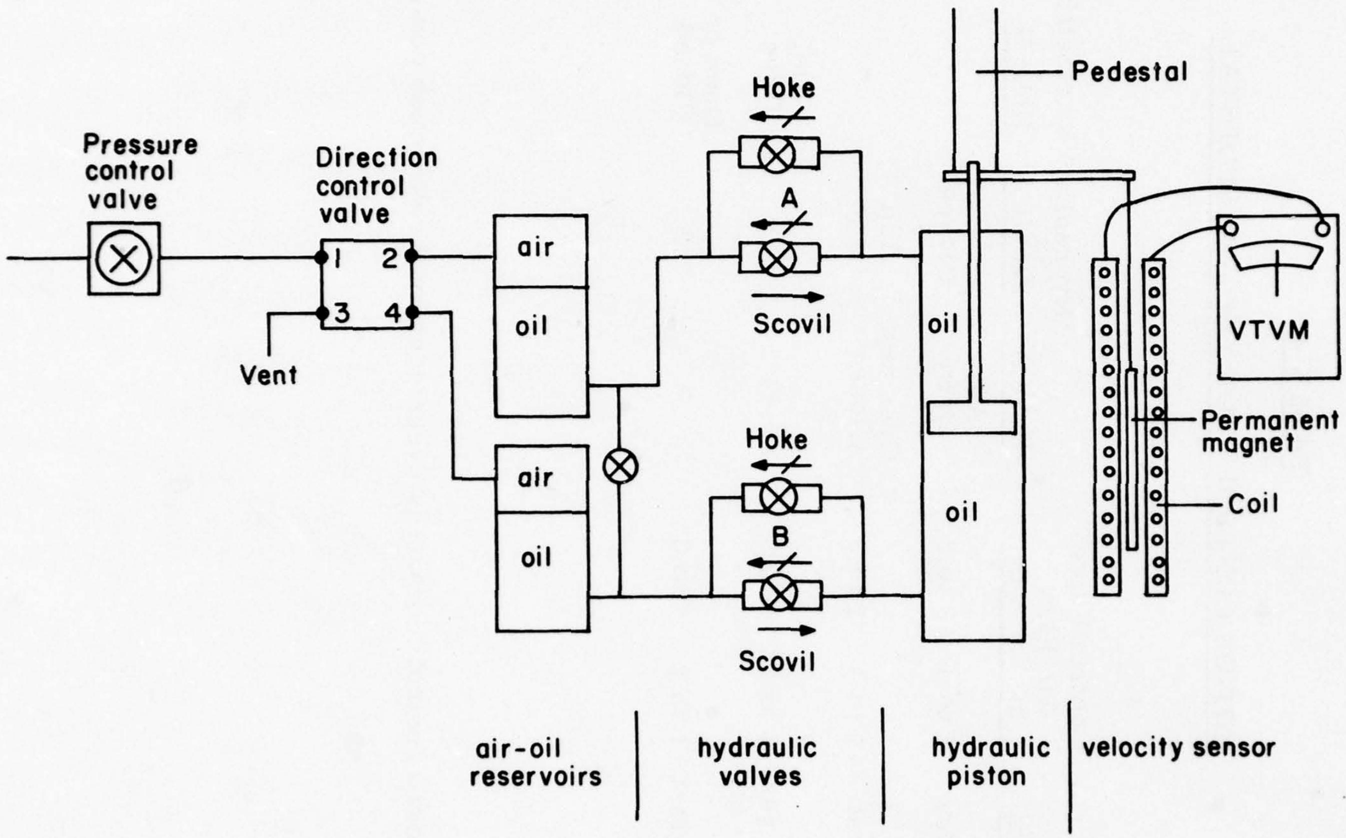

Figure 29 Schematic Diagram of Vertical Translation Equipment.

TABLE 4

MOTION CONTROLS FOR THE APS PEDESTAL

Mode	Motion	Control Valve Air Flow In	Control Valve Air Flow Out	Hydraulic Valve Settings Hoke A	Scovil A	Hoke B	Scovil B
1	up slow	1 to 4	2 to 3	Adj. Open	Closed	*	*
2	up fast	1 to 4	2 to 3	Open or Closed	Adj. Open	*	*
3	down slow	1 to 2	4 to 3	*	*	Adj. Open	Closed
4	down fast	1 to 2	4 to 3	*	*	Open or Closed	Adj. Open

* Open or closed control function is overridden by the direction control valve.

position 2 to 3 in the direction control valve. Controlled (fast or slow) down-motion can be achieved by changing the air valve position and using the B valves for rate control.

2.3.3 Vertical motion sensor

The monitoring of vertical motion of the pedestal is important for uniform and reproducible coating by the APS process. Since the vertical motion is controlled hydraulically, there is no positive dependence of velocity on dc motor setting and screw pitch as one normally finds with motor control. The hydraulic system, on the other hand, gives a greater flexibility in changing rate or position rapidly. However, one cannot be certain that the hydraulic valves can be reset to reproduce exactly a given velocity. What was needed was a method for sensing the instantaneous pedestal velocity which can be used for final adjustment of the hydraulic control valves. The velocity transducer shown schematically in Fig. 30 has served this purpose very well, giving precise indication between 0.1 in./min. and 100 in./min., which is well in excess of the range of interest.

The sensor works on the simple principle that a permanent magnet of high induction moving axially within a closed coil induces a dc voltage which is proportional to the product of the number of turns of wire per unit length and the number of lines of force generated by the permanent magnet. In effect, the device is simply an electric generator where many turns of wire yield a measurable voltage, even at speeds as low as 0.1 in./min. For velocities the order of one in./min. used in plasma spraying, the output of the velocity transducer is approximately 0.4 millivolt, a voltage easily detected by a standard laboratory voltmeter.

The last of the major changes in equipment design on this contract took place at the end of 1976, between the completion of the confirmatory sample run and the production run. We found that the APS samples were not meeting magnetic property specifications because of distortions in shape which were evidently occurring during the spray operation. The bowing of samples was rather small, i.e., less than 0.30 in. in the six-inch length, but this amount was enough to cause significant changes in ferrite wall thickness and in magnetic properties, particularly a reduction in phase shift. It was decided that one contributing factor might be nonconcentricity or wobble in the pedestal assembly relative to the plasma gun.

We theorized that radial nonuniformities in the deposit pattern would produce differential temperatures and differential strains, which could produce the warping observed. This situation could be brought under control by a more exactly aligned system.

The translation equipment was therefore redesigned and rebuilt to improve its reliability for the APS process. A photograph of the redesigned pedestal tube assembly is shown in Fig. 30. The tube and rotational drive motor move up and down on the rectangular block (b), which is guided by linear bearings within the block and the two vertical guide rods (g). The end of the pedestal tube (p) is made to rotate on axis by screw adjustments on two metal disks at the base of the tube having a 0.5 in. steel ball captured in retaining slots between the disks. This pedestal assembly, which has leveling screws at the base, sits on a steel plate, which is attached to metal rods suspended from another plate. This second steel plate underlies the plasma-spray furnace and the upper holding oven. Such an elaborate arrangement of metal support plates and interconnected equipment (shown schematically in Fig. 31) was designed so that the pedestal assembly and spray and holding ovens are interconnected and cannot move independently.

At this point there was still the possibility that the stubstrate would wobble at the free end. To avoid this problem, an upper idler bearing (see dashed lines) was built which could be used to capture the free end of the substrate. In this scheme a graphite part would replace the upper metal clip and provide a conical tip for rotation within the bearing tube.

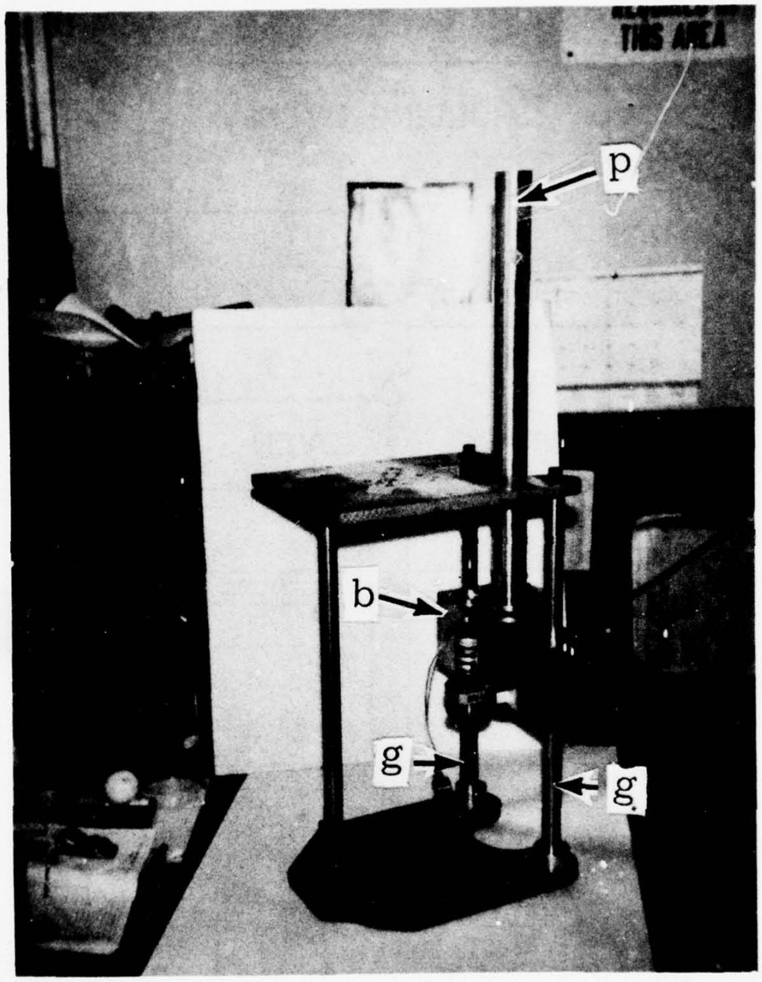

Figure 30 Pedestal Tube Assembly for Arc-Plasma Spraying.

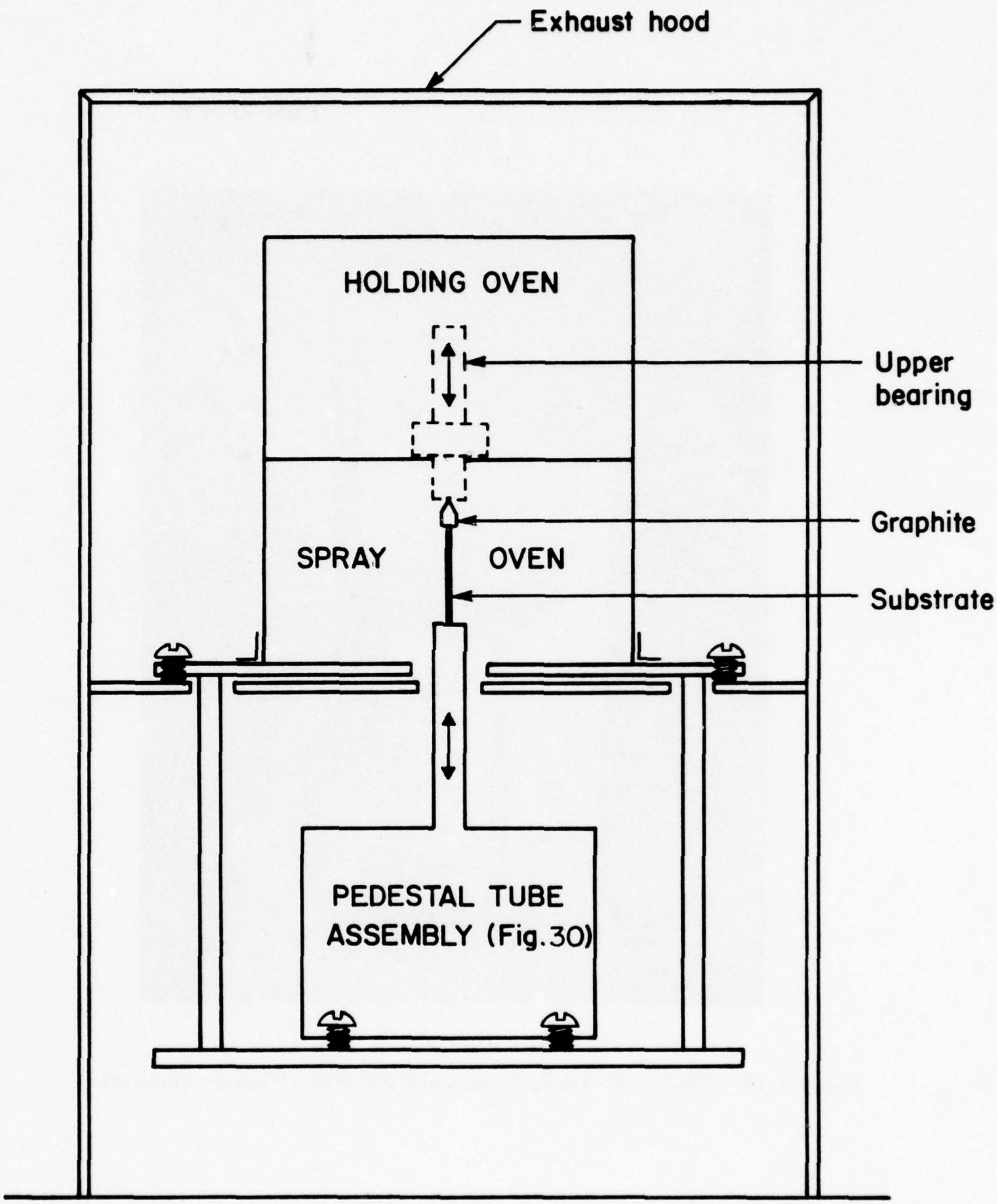

Figure 31 Diagram of Metal Supporting Plates and Interconnected Equipment.

Fortunately, it was not necessary to use the upper bearing to avoid substrate wobble. The improved pedestal assembly (Fig. 30) was, in fact, sufficient. The objection to the use of the bearing is that it would have to be removed after each run for sample transfer into the holding oven. The bearing would be hot (600° C) and difficult to maneuver.

2.4 Experimental APS Runs

2.4.1 Initial experiments at USAECOM Labs

In July 1975, just after the start of the contract, a four-day visit was arranged at USAECOM Laboratories to conduct APS runs using Army equipment with the guidance of R. W. Babbitt. Machined substrates and the Li-ferrite spray-dried ferrite powder to be used in these experiments were produced at Raytheon before the trip. Our purpose was to learn as much as possible about APS procedures at ECOM and to test out our starting materials with their equipment.

A summary sheet of the experimental conditions used are shown in Table 5. In these experiments a mixture of argon and helium (~10:1 ratio, see col. 4) was used whereas in subsequent work only argon was used. The oxygen carrier gas flow rates in these experiments were also higher than flow rates used in subsequent work.

Some limited studies of hysteresis properties and microwave evaluation were made on two of the samples from this preliminary run. The results are summarized in Table 6. Sample R13, which was 2.5 in. after machining (originally full-length samples were made) gave 57.6° phase shift ($\Delta\phi$) per inch with one turn 15 amp drive. This corresponds to 296° for a full-size toroid. Insertion loss would be > 2 dB if this sample were full size.

The second sample, No. R7, had somewhat better properties ($\Delta\phi$) = 74.4°/in. and insertion loss (I.L.) of 0.16dB/in.) giving $\Delta\phi$ > 340° and I.L. < 1 dB if the toroid were full size.

2.4.2 Early APS experiments at Raytheon

Following the initial experiments at Fort Monmouth, we began APS runs at Raytheon using equipment modified in light of the experience at USAECOM Laboratories. During the period of November 1975 through

TABLE 5

APS EXPERIMENTAL RUNS MADE AT ECOM LABORATORIES

Date	Run	Ferrite Powder	Dielectric Substrate	Arc Gas (cu. ft./hr.)	Arc Current (amps)	Oxygen Carrier Gas (cu. ft. /hr.)	Powder Feed (cu. ft. /hr.)	Spray Distance (in.)	Oven Temp (^{o}C)	Spray Time (min.)	Anneal (^{o}C)
7/28/75	1	LMTF 53	LMTF 190 (3, 4)	Ar/He 65/07	320	75	65	2	620-680	13	1160
	2		LMTAF 200 (3)	Ar/He 70/07	350	80	75	2	650-750	11	-
	3		LMTAF 180 (3)	Ar/He 70/07	350	80	75	2	750-800	11	-
	4		LMTF 200 (1)	Ar/He 80/07	350	80	75	2	750-800	8 1/2	-
	5		LMTF 190 (3, 4)	Ar/He 80/20	320	100	100	2	750-780	8 1/2	-
	6		LMTAF 200 (3)	Ar/He 75/07	350	80	75	2	700-760	9	1020
7/29/75	7		LMTF 190 (3, 4)	Ar/He 75/07	350	60	55	2	740	16 1/2	-
	8		LMTF 190 (3, 4)	Ar/He 75/07	350	80	80	1 3/4	700-760	10	-
	9		LMTAF 180 (3)	Ar/He 75/07	350	80	80	1 3/4	700-720	Run	Aborted
	10		LMTAF 180 (3)	Ar/He 75/07	350	85	78	1 3/4	720	9 1/2	-
	11		LMTF 200 (1)	Ar/He 75/07	350	85	75	2	720	10 1/2	-
	12		LMTAF 200 (3)	Ar/He 75/07	350	85	78	2	710	11 1/2	-
	13	Ampex 1202	LMTF 190 (3, 4)	Ar/He 78/07	320	80	70	2	700	12	1000
7/30/75	14	Ampex 1202	LMTAF 180 (3)	Ar/He 78/07	320	80	70	2	710-675	12	-
	15	LMTF 53	LMTAF 180 (3)	Ar/He 78/07	320	80	70	2	700-725	12	-

TABLE 6

DATA ON ENGINEERING TEST SAMPLES

Test Location	Sample No.	Length (in.)	Drive Turns	Drive Current	H_c (Oe)	$4\pi M_r$ (gauss)	(5.5GHz) $\Delta\phi$ (deg.)	In. Loss (dB)	Ret. Loss (dB)
Annealed 1000°C, 1 hour in air									
Raytheon	R13	~2.7	2	12	2.9	790	(Annealed following APS at 1000°C)		
ECOM	R13	2.50	1	6	1.96	380	58.5		
ECOM	R13	2.50	1	8	2.24	497	99		
ECOM	R13	2.50	2	5	2.51	600			
ECOM	R13	2.50	1	10			117		
ECOM	R13	2.50	1	15			144	.75	15
ECOM	R13	2.50	1	20			149		
Raytheon	R13	2.50	1	6	1.94	206			
Raytheon	R13	2.50	1	8	2.68	446			
Raytheon	R13	2.50	1	15	2.99	614			
Raytheon	R13	2.50	2	6	2.88	639			
Raytheon	R13	2.50	2	8	3.05	712			
Raytheon	R13	2.50	2	15	3.09	749			
Annealed 1044°C, 1 hour in air									
Raytheon	R13	2.50	2	15	2.53	820			
Raytheon	R13	2.50	1	15			186	.4dB	19
Raytheon	R7	2.36	2	15	7.62	574	(APS sprayed, no anneal)		
Annealed 1044°C, 1 hour in air									
Raytheon	R7	2.36	2	15	2.95	649			
Raytheon	R7	2.36	1	15			140	1.0	15

Test performed at ambient temperature (21° C) in air on arc-plasma-sprayed samples of Li-Mn-Ti ferrite deposited on dielectric type LMTF-190(34) shaped into c-band geometry as described in text.

June 1976 seven sets of engineering samples were tested and reported on. Appendix III is the APS log of all the samples sprayed at Raytheon during this contract. Samples for the engineering tests represent those taken from the first 100 sprayed samples. Progress during this time was slow. Delays were primarily due to equipment problems associated with the changes from experimental apparatus to equipment compatible with the manufacturing rate required by the program. We found that steps leading from the design of apparatus capable of spraying a few samples per day to several per hour are not simple steps. We did encounter serious problems with sample cracking in the third and fourth engineering sample deliveries. In retrospect, the cracking problem was more likely attributable to the ferrite powder than to spray conditions.

Microwave properties on the toroidal engineering samples (sixth and seventh series) generally gave low insertion loss (~1 dB) but the saturation phase shift was typically 280° to 300°, about 15 percent below the contract requirement.

2.4.3 *Confirmatory sample production*

The contract schedule had called for the delivery of 20 confirmatory samples (full-size phase shifters) and a report at the end of October 1976. During the summer a large number of samples were sprayed in preparation for this testing. As the test results accumulated on these full-size phase-shifter samples, it became evident that the samples would not pass the confirmatory test because of a low B_r and therefore a phase shift below the required 340°. The B_r values were not only low, but showed considerable variation from one sample to the next, with no apparent relation to dielectric composition or spray conditions. We decided to section two of the full-size phase shifters which had low B_r. The samples were APS 170 with B_r = 508 gauss and APS 174 with B_r = 565 gauss. They had been sprayed during a session when other samples having good hysteresis loop and microwave properties were produced.

Each of the samples showed reasonably uniform ferrite walls at the exposed ends (see end 1 and end 2 in Figs. 32 and 33). The 5.145-in. samples were cut into three equal segments, which exposed two surfaces at the one-third distance (see 1/3, Fig. 32) and two surfaces at two-thirds the original length. For sample APS 170 the two dielectric halves showed 0.005-in. displacement at the on-third position and a severe nonuniformity in wall thickness. At the two-thirds position the wall was still nonuniform, the thin side remaining the same. The entire center segment evidently has one narrow and one thick wall, a condition which would be expected to produce a very low B_r. The final segment of APS, between the two-thirds location and end 2, has a nonuniform wall. The dielectric halves were still displaced 0.005 in. but were reasonably uniform at the ends. A similar dissection of sample APS 174 (Fig. 33) showed similar wall nonuniformities, although not as extreme as APS 170.

If we examine the machining process, it will be evident why the ferrite walls appear uniform at the ends and can still be a very nonuniform in the center. The machinist keys the grinding away of excess ferrite to the extreme ends of the sample where the bare dielectric rod extends beyond the ferrite coating. At the ends of the rod, then, assuming the machinist does his job, the ferrite coating around the dielectric is a uniform 0.050 in. These are the regions we see in cross section when the phaser is cut to its final length. Only destructive sectioning of the element would reveal the wall uniformities in the center regions prior to the development of X-ray transmission techniques.

It was evident from these findings that we could not meet the target date for the sample delivery. We asked for and received permission to delay the delivery of the confirmatory samples until January 1977. The last of the APS samples used in the confirmatory run were sprayed in early December. By this time we had obtained a new powder, LMTF475(G5), (see Table 7) with a higher $4\pi M_s$ which, with allowance for a lower APS density, gave $4\pi M_s = 1200$ gauss and a more favorable B_r and phase shift.

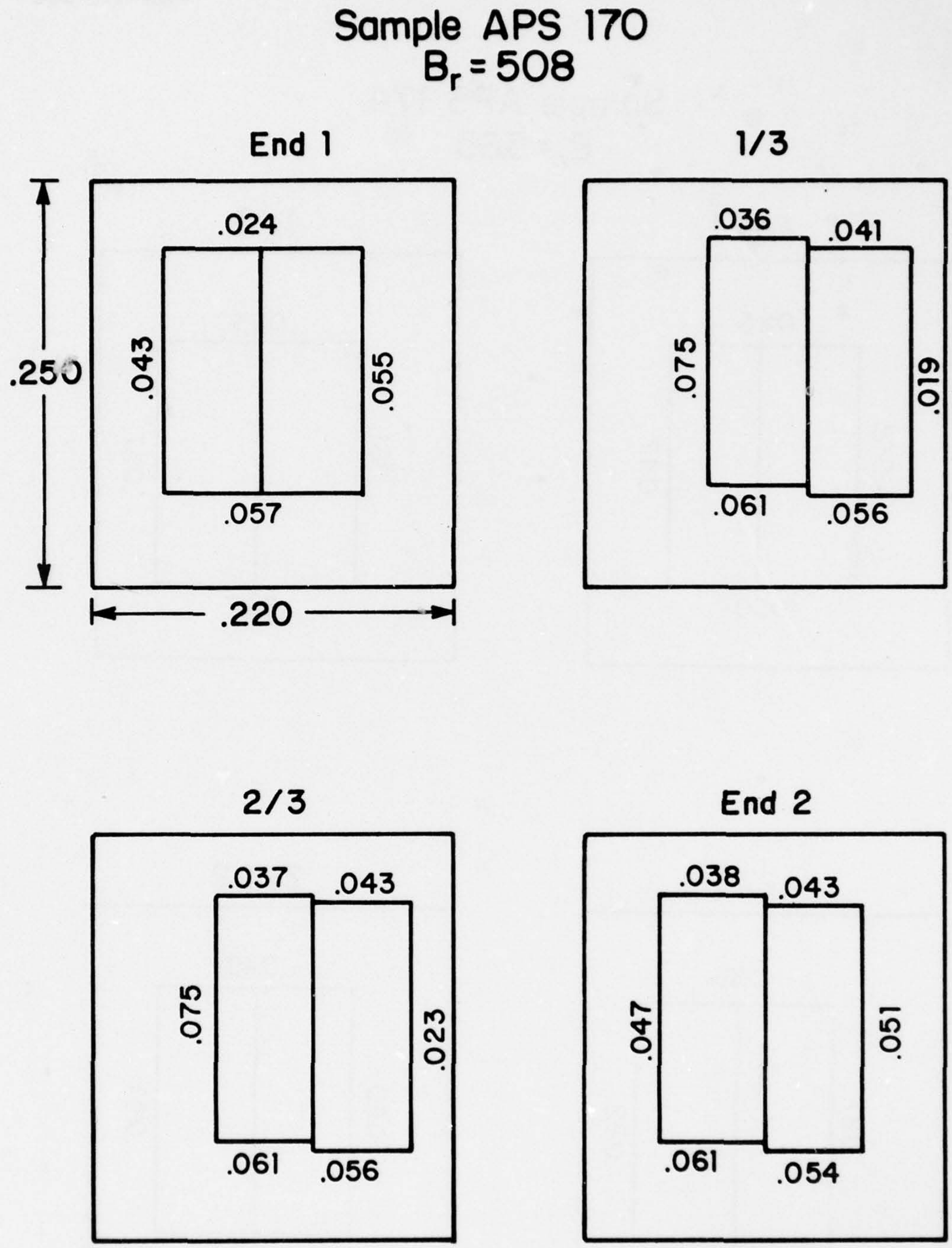

Figure 32 Cross Sections of Plasma Sprayed and Machined Phase Shifters. Wall thickness in inches as indicated

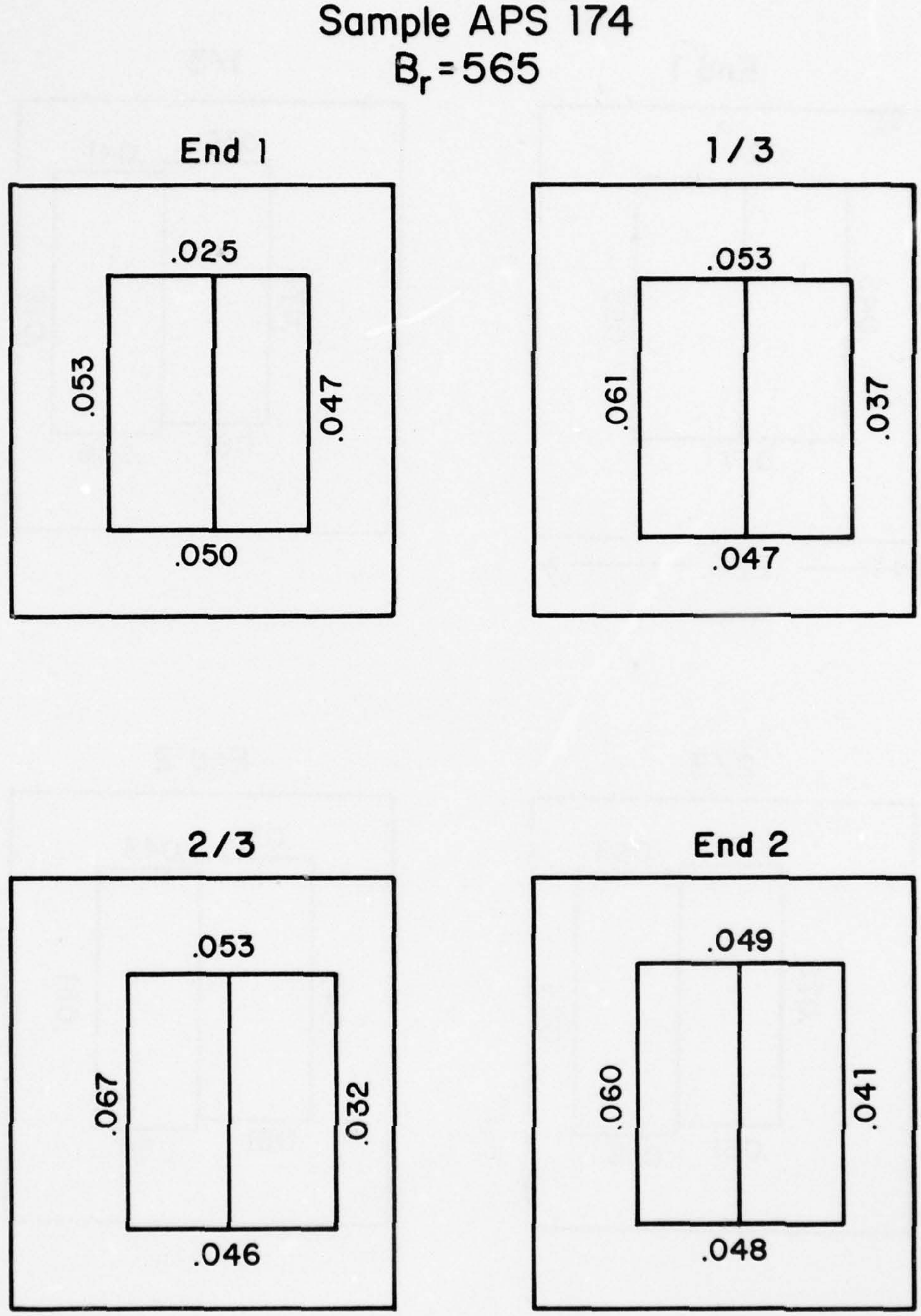

Figure 33 Cross Sections of Plasma Sprayed and Machined Phase Shifters. Wall thickness in inches as indicated

TABLE 7

CONFIRMATORY SAMPLE TEST RESULTS
(MIL-STD 831, Para. 5.6.10.1.4)

			Loop Properties								RF Properties at 5.45 GHz								
			25°C		- 30°C		+ 85°C				25°C			- 30°C			+ 85°C		
APS No.	W.G. Phase Shift	Temp. Meas.	H_c (Oe)	B_r (g)	H_c (Oe)	B_r (g)	H_c (Oe)	B_r (g)	$\frac{\Delta B_r}{B_r}$ (%)	Length (in.)	$\Delta\phi_{(o)}$	$I\phi_{(o)}$	I.L. dB	$\Delta\phi_{(o)}$	$I\phi_{(o)}$	I.L. dB	$\Delta\phi_{(o)}$	$I\phi_{(o)}$	I.L. dB
161		x	3.13	649	3.87	675	2.60	591	± 6.6	5.145									
162		x	3.02	636	3.60	665	2.55	576	± 7.2	5.145									
163	x		2.84	636						5.145	346	3732	1.0						
176	x		3.12	686						5.114	355	3711	1.4						
225	x		2.32	715						5.115	366	3646	0.7						
234	x		2.75	725						5.145	400	3715	1.88						
238			2.45	680						5.145									
241	x		2.68	733						5.145	371	3760	1.1	477	3687	1.4	315	3829	1.2
244		x	2.70	754	3.30	805	2.22	665	± 9.5	5.145									
264		x	2.84	767	3.33	808	2.28	682	± 8.1	5.145									
270		x	2.43	734	2.80	779	2.05	660	± 8.3	5.145									
274	x	x	2.84	733	3.52	777	2.47	666	± 7.7	5.145	383	3636	0.60	454	3430	1.0	318	3755	.3
277	x	x	1.85	753	2.15	808	1.64	660	± 10.1	5.145	380	3668	1.38						
279	x	x	2.85	770	3.35	796	2.43	711	± 5.6	5.145	416	3720	1.20						
281	x	x	2.53	789	3.43	830	2.12	730	± 6.4	5.145	410	3658	0.58						
282	x	x	1.46	869	1.80	929	1.22	804	± 7.2	5.145	423	3671	0.60						
286			2.39	771						5.145									
289			2.67	792						5.145									
291			2.91	739						5.145									
293			2.99	748						5.145									

Some of the samples sprayed with this new powder were reported on in the confirmatory sample report.

Tables 7 and 8 summarize the test results on the confirmatory samples. The number on the last of the samples, APS 293, indicates that almost 200 boules had been sprayed during the summer and fall of 1976 to produce the necessary 20 samples. In addition to the machining and testing on about half of these samples, a nondestructive technique (X-ray fluoroscopy) was developed to assess sample straightness after firing (see Appendix II) and to devise techniques to avoid this problem.

Table 8 shows H_c and B_r measured at 25° C on all 20 full-size phase shifters. Typical values of H_c are 2.5 - 3 Oe with B_r ranging from 650 to 870 gauss. The change in B_r between -30° and +85° C varied between ±6.5 and ± 10.1 percent about a mean value. We speculate that residual strains are a contributing factor to the variations in B_r. These same compositions fired conventionally show[7] a temperature variation of ± 9.2 percent over the same interval. The smaller percentage change in B_r for samples such as APS 279 indicates that the postulated stress effects are reducing temperature dependencies without sacrificing B_r or phase shift.

The microwave phase shift on ten of the confirmatory samples is shown in column 12 in Table 7. All of the samples exceed the required 340°. Insertion loss at 25° C is < 1 dB on about one-half of these samples. Insertion phase shows a rather disappointing variation from 3640 to 3760, a spread in phase which is typical of the present garnet-K-38 device. The mean square deviation in the series is 41°.

Table 8 shows the temperature variation in H_c and B_r from -30° to +85° C.

ECOM laboratories remeasured the ten confirmatory samples mounted in waveguides which were sent with the test results (Table 7). A comparison of the measurement of saturation phase shift ($\Delta\phi°$) and insertion loss (I.L.)

TABLE 8

HYSTERESIS LOOP PROPERTIES vs TEMPERATURE

(MIL-STD 831, Para. 5.6.10.1.4)

Toroid No.	H_c (Oe)						B_r (gauss)						$\frac{\Delta B_r}{B_r}$ (%)
	-30°C	-10°C	0°C	25°C	50°C	85°C	-30°C	-10°C	0°C	25°C	50°C	85°C	
161	3.87	3.52	3.52	3.13	2.84	2.60	675	660	659	649	630	591	± 6.6
162	3.60	3.52	3.32	3.02	2.75	2.55	665	655	651	636	611	576	± 7.2
244	3.30	3.01	2.84	2.70	2.47	2.22	805	787	781	754	722	665	± 9.5
264	3.33	3.24	2.99	2.84	2.54	2.28	808	793	787	767	736	682	± 8.1
270	2.80	2.66	2.55	2.43	2.21	2.05	779	763	754	734	710	660	± 8.3
274	3.52	3.36	3.15	2.84	2.73	2.47	777	763	754	733	705	666	± 7.7
277	2.15	2.13	2.06	1.85	1.79	1.64	808	792	781	753	719	660	±10.1
279	3.35	3.19	3,00	2.85	2.84	2.43	796	787	787	770	749	711	± 5.6
281	3.43	2.84	2.80	2.53	2.31	2.12	830	815	812	789	769	730	± 6.4
282	1.80	1.74	1.66	1.46	1.35	1.22	929	909	900	869	845	804	± 7.2

at 5.5 GHz and 25°C made at Raytheon and at the ECOM Laboratories is shown in Table 9. The differences between the Raytheon and ECOM results were negligible.

TABLE 9

Comparison of Microwave Data on Confirmatory Samples

	$\Delta\phi$ Raytheon Results		ECOM Results	
Sample No.	$\Delta\phi$ (deg.)	I.L. (dB)	$\Delta\phi$ (deg.)	I.L. (dB)
163	346	1.0	340	0.9
176	355	1.4	360	1.3
225	366	0.7	370	1.0
234	400	1.88	390	2.0*
241	371	1.1	400	1.2
274	383	0.60	400	0.9
277	380	1.38	400	0.9
279	416	1.20	420	1.5
281	410	0.58	425	0.7
282	423	0.60	425	0.6

* Reduced to 1.3 dB after additional one-hour anneal at 970°C.

2.4.4 Pilot production of 200 APS samples

After delivery of the 20 confirmatory samples in January, we began construction of the support elements for the ovens and spray equipment, as described in Section 2.3. The objective was to minimize the chance for sample wobble, which we believed responsible for the problems of sample bowing that caused the slip in delivery schedule. In addition to these changes, a further alteration was made in the holder geometry. The jaws (Fig. 28) which clamped the bare dielectric rod during spraying were replaced with a large tapered hole ~0.7 in. in diameter which would accept a graphite plug rather than the bare dielectric. The dielectric was forced into a hole machined in the center of the graphite plug. This change helped to reduce wobble substantially and also made it easier to transfer and store sprayed samples.

After making these changes in the equipment, a series of tests were run to prove out the new equipment. Approximately 50 samples were sprayed (APS 294 through APS 340) to test out the production process. A supply of spray-dried ferrite powder with the nominal composition $Li_{.735}Mn_{.10}Ti_{.475}Fe_{1.69}O_4$ was ordered from Raytheon SMDO, and several bars of dielectric with composition $Li_{1.0}Mn_{.10}Ti_{1.0}Al_{.07}Fe_{.83}O_4$ were fired and sent for machining. The wire slot on these pieces was machined with the long (0.040 in.) dimension parallel to the join between halves (Fig. 25b).

Permission to proceed with the pilot production run was received informally (by telephone) on April 4 and officially on May 7. The samples were to be sprayed at a rate of five per hour and, after annealing and machining to the final phase-shifter dimensions, to pass certain microwave tests. The production run was divided into five batches of 40 units. Of the 40 phase shifters, a government representative (DECASPRO) selected 20 which would be subject to hysteresis loop and microwave testing under government supervision.

2.4.4.1 First production batch

Table 10 shows the APS phase-shifter units, the X indicating random selections of the 20 whose hysteresis loops were tested. From these 20 samples, 10 were selected for microwave testing (Table 11), and from these 10 two were selected for microwave testing versus temperature (Table 12).

In general, the results on phase-shifter properties were good. Phase shift at 5.45 GHz was between 390° and 420°, which was well above the >340° requirement. Insertion loss was > 1 dB for about half of the samples tested. Insertion phase, however, was disappointing in terms of contract goals (s.d. = ± 15°) showing variations from the mean of ± 113 to -131. For a total insertion length of 3700° this amounts to ± 3.5 percent variation of phase.

TABLE 10

APS PHASE SHIFTER ELEMENTS SELECTION

BATCH NO. 1

Units Received	Selections 20	10	2	Units Received	Selections 20	10	2
303				353	X	X	
308	X			354	X	X	
317				358	X	X	
318				360			
320				363			
321	X			364			
325	X	X	X	367	X		
327				373	X	X	
328				374			
330				375	X		
331	X	X		378	X		
332	X			379	X		
335				380			
337	X			382			
338				383	X	X	
343				384			
345	X			385			
346	X	X	X	386	X	X	
348				387			
349	X			388	X	X	
351							

TABLE 11

APS PHASE SHIFTERS BATCH NO. 1

MICROWAVE MEASUREMENTS - ROOM TEMPERATURE

	$\Delta\phi$ (°)			I. L. (dB)			ϕ_{IN} (°)		
Serial No.	5.2	5.45	5.7	5.2	5.45	5.7	5.2	5.45	5.7
325	418	418	416	0.86	0.78	1.48	-125	-128	-135
331	411	409	408	1.24	1.16	1.64	- 97	- 98	-106
346	412	410	409	1.86	1.78	2.71	-131	-131	-137
353	400	397	397	0.42	0.67	0.64	REF	REF	REF
354	389	390	388	1.02	1.06	1.42	+ 1	+ 6	+ 7
358	409	408	408	0.50	0.35	0.60	- 43	- 44	- 53
373	408	407	407	0.84	0.76	1.60	+120	+113	+ 99
383	408	408	407	0.68	0.52	1.36	-113	-116	-124
386	404	403	401	1.00	0.93	1.98	- 95	- 96	-103
388	422	421	420	0.70	0.64	1.52	-119	-118	-126

TABLE 12

APS PHASE SHIFTER ELEMENTS BATCH NO. 1

TEMPERATURE MEASUREMENTS

Serial No. APS-325

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (Db)	4.18	0.86	1.80	1.56	0.78	1.64	1.36	1.48	2.06
$\Delta\phi$ (°)	513	418	335	535	418	337	550	416	340
ϕ_{IN} (°)	+124	REF	- 58	+102	REF	- 56	+ 97	REF	- 54

Serial No. APS-346

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	1.85	1.86	3.0	1.24	1.78	2.88	1.12	2.71	3.44
$\Delta\phi$ (°)	556	412	333	567	410	335	576	409	337
ϕ_{IN} (°)	+105	REF	-45	+ 91	REF	- 42	+ 83	REF	- 41

2.4.4.2 Second production batch

Table 13 indicates the 20 selected units and the 10 samples selected from this for microwave testing. The plasma log table (Appendix III) describes the spray conditions used for the 52 units (APS 439-388 inclusive) which were sprayed for batch No. 2.

Microwave data Table 14 shows phase shift is again high 372° - 414° and insertion loss meets the goal of <1 dB for half the samples. The very high loss for APS 424 is probably due to incomplete oxidation during the 1015° C two hour anneal. Insertion loss shows somewhat less of a spread (±80°) than that observed for batch No. 1. The temperature variation (Table 15) is typically + 150° at -30° C and -30° at + 85° C relative to the room temperature value.

Of the total 52 samples sprayed, twelve were lost in processing and testing. Five of these were broken during machining, two broke or chipped during annealing and the remaining five were rejected for cracks or bowing as revealed by X-ray fluoroscopy testing. The latter five were not machined.

2.4.4.3 Third production batch

The third batch APS 439 through 500 comprised 62 sprayed samples. The selection of 20 test samples was made on June 8 (Table 16) and from these 10 were given the required microwave testing (Table 17). We note that the phase shift is lower than the average from previous batches, most likely due to problems incracking of the ferrite coating. Insertion loss was again > 1 dB for half of the samples tested but losses were considerably higher in the cases remaining. Insertion phase variations shows fluctuations of ± 108 to -114 relative to a mean value.

The temperature variation of insertion phase (Table 18) in APS 442 (+229° to -117°) is very large relative to APS 476 (+88 to -42°) between -30° and ±85° C. These two samples were sprayed with the same ferrite

TABLE 13

APS PHASE SHIFTER ELEMENTS SELECTION

BATCH NO. 2

Units Received	Selections 20	10	2	Units Received	Selections 20	10	2
344				413			
347	X			415	X		
390	X	X		417	X		
391				422			
392				423	X		
393				424	X	X	
394	X	X		426	X		
395				427			
396				428	X	X	
397	X	X		429			
398				430	X		
399	X	X		431	X	X	
400				432			
401				433	X		
405				434			
406				435	X		
407				436			
408	X	X		437	X		
411	X	X	X	438			
412	X	X	X	439	X		

TABLE 14

APS PHASE SHIFTERS BATCH NO. 2

MICROWAVE MEASUREMENTS - ROOM TEMPERATURE

	$\Delta\phi$ (°)			I. L. (dB)			ϕ_{IN} (°)		
Serial No.	5.2	5.45	5.7	5.2	5.45	5.7	5.2	5.45	5.7
390	405	404	403	1.72	1.68	1.94	- 1	+ 3	+ 2
394	374	372	369	0.76	0.96	0.84	+80	+82	+86
397	397	396	395	0.66	0.72	0.58	+46	+49	+53
399	400	396	395	0.56	0.45	0.46	+46	+49	+50
408	398	397	396	0.40	0.68	1.40	-19	-17	-19
411	415	414	414	0.40	0.68	1.16	REF	REF	REF
412	411	410	410	0.76	1.14	1.56	-20	-20	-20
424	402	399	399	---	7.0 dB	---	-83	-81	-80
428	380	379	377	0.96	1.00	1.14	+19	+22	+21
431	390	389	386	1.40	1.54	2.08	- 6	- 3	- 2

TABLE 15

APS PHASE SHIFTER ELEMENTS BATCH NO. 2

TEMPERATURE MEASUREMENTS

Serial No. APS 411

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	2.0	0.40	0.60	0.66	0.68	0.76	1.36	1.16	1.00
$\Delta\phi$ (°)	554	415	334	535	414	337	523	414	337
ϕ IN (°)	+154	REF	-63	+124	REF	-57	+104	REF	-50

Serial No. APS 412

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	5.12	0.76	0.64	1.16	1.14	0.82	1.04	1.56	1.20
$\Delta\phi$ (°)	538	411	330	525	410	333	512	410	334
ϕ IN (°)	+167	REF	-50	+134	REF	-47	+114	REF	-42

TABLE 16

APS PHASE SHIFTER ELEMENTS SELECTION

BATCH NO. 3

Units Received	Selections 20	10	2	Units Received	Selections 20	10	2
440				463	X		
442	X	X	X	464			
444	X	X		466	X		
445				467			
446				468			
447	X	X		469	X		
449				471			
450				472	X		
451	X	X		475			
452	X	X		476	X	X	X
453	X			478			
454				479			
455				480	X		
456	X			481			
457	X			482	X	X	
458				484			
459	X			485	X	X	
460	X			486			
461				487			
462	X	X		488	X	X	

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MANUFACTURING METHODS AND TECHNOLOGY MEASURE FOR ARC-PLASMA-SPR--ETC(U)

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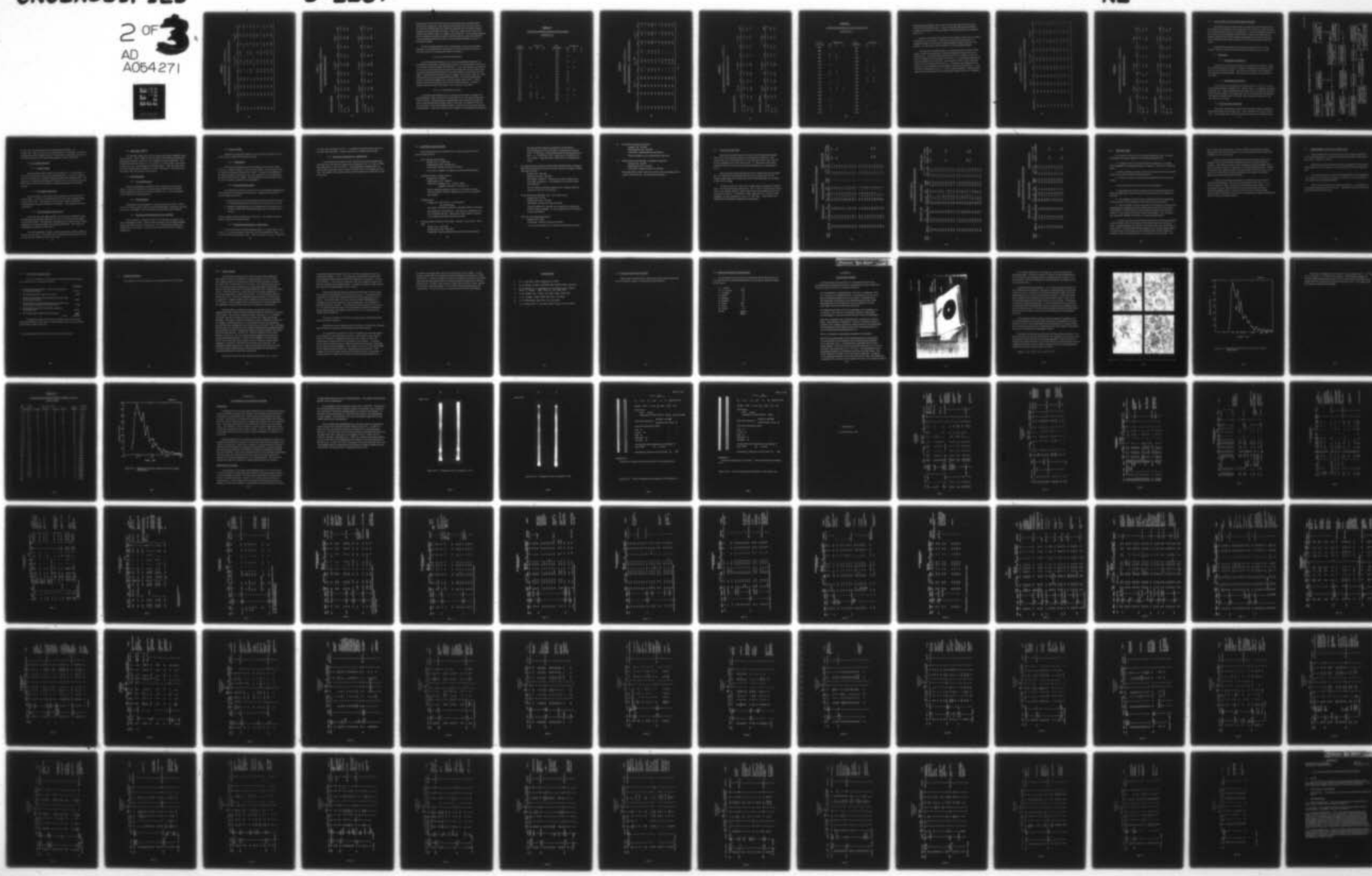

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TABLE 17

APS PHASE SHIFTERS BATCH NO. 3

MICROWAVE MEASUREMENTS - ROOM TEMPERATURE

	$\Delta\phi$ (°)			I. L. (dB)			ϕ_{IN} (°)		
Serial No.	5.2	5.45	5.7	5.2	5.45	5.7	5.2	5.45	5.7
442	394	393	392	1.84	1.98	2.54	-86	-85	-85
444	385	384	382	---	> 6.5	---	-111	-114	-109
447	376	375	374	4.0	3.84	4.44	-86	-87	-88
451	393	392	391	3.06	2.94	3.28	-66	-65	-60
452	376	375	374	---	> 7.0	---	-106	-106	-102
462	364	362	360	0.66	0.40	1.52	+74	+78	+90
476	393	392	391	0.64	0.72	0.64	- 2	- 3	+ 4
482	340	340	339	0.32	0.58	1.04	+104	+108	+120
485	385	384	383	0.46	0.56	0.32	+14	+15	+21
488	386	386	384	0.64	0.64	0.52	REF	REF	REF

TABLE 18

APS PHASE SHIFTER ELEMENTS BATCH NO. 3

TEMPERATURE MEASUREMENTS

Serial No. APS 442

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	6.04	1.84	2.44	2.22	1.98	2.42	2.24	2.54	2.52
$\Delta\phi$ (°)	519	394	325	503	393	326	492	392	329
ϕ_{IN} (°)	313	REF	-130	229	REF	-117	179	REF	-108

Serial No. APS 476

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	3.16	0.64	0.96	1.10	0.72	1.16	1.0	0.64	1.72
$\Delta\phi$ (°)	504	393	328	491	392	329	482	391	331
ϕ_{IN} (°)	112	REF	-47	88	REF	-42	75	REF	-38

powder batch (LMTF 475(G7)) onto the same substrate composition under very similar conditions. The weight of the finished units was very similar, 18.18 gm for APS 442 and 18.00 APS 476 indicating that the ferrite coating density must be essentially the same. The $4\pi M_r$ values of 755 G and 756G respectively further attest to a uniform ferrite density. This strongly suggests that the observed variation in insertion phase is due to causes not related to material properties but to air gaps at the waveguide interface or other instrumental causes.

Of the 22 sprayed samples lost in processing, 3 were too short after spraying, 4 were rejected for warping and 15 were rejected for excessive cracks in the ferrite coating again before machining.

2.4.4.4 Fourth production batch

In the fourth batch (Tables 19, 20, and 21) considerable difficulty was encountered with sample cracking much of which can be attributed to the use of a new batch of ferrite powder LMTF475(G8). In all, 145 samples were sprayed of which about half were rejected right after spraying and about one half of the remainder failed during machining or showed excessive cracks after the final anneal. Of the twenty samples chosen on August 9 for testing, 6 had $B_r < 600$ G indicates they would have insufficient phase shift. Of the ten samples subjected to microwave testing on No. 564 had a phase shift of 322°. The insertion loss was very high on all but two of the test samples. Insertion phase variation was also very large, ± 167° relative to the mean.

2.4.4.5 Fifth production batch

In the fifth batch (Tables 22, 23, and 24) we were able to change from the G8 powder at about the half way point (APS711) to a new spray dried batch LMTF 475(G9). This powder gave considerably better results and produced most of the finished phase shifters APS711-765 which are listed in Table 22. To be specific, of the 122 samples sprayed, 43 were made with LMTF 475(G8) ferrite powder. Only one of these 43 (No. APS700), was processed through final

TABLE 19

APS PHASE SHIFTER ELEMENTS SELECTION

BATCH NO. 4

Units Received	Selections 20	10	2	Units Received	Selections 20	10	2
404				604	X	X	X
491				605			
492				609	X		
497				611			
498				615	X	X	
505	X			617			
506				618	X	X	
507				619			
508				622	X		
509				625	X		
510	X	X		627	X		
511				633	X		
512				634	X		
517	X			635			
541	X	X		636	X		
562				637	X	X	
564	X	X		638			
567	X	X		640	X	X	
593	X	X	X	643			
594				644	X		

TABLE 20

APS PHASE SHIFTERS - BATCH No. 4

MICROWAVE MEASUREMENTS - ROOM TEMPERATURE

Serial No.	$\Delta\phi$ (°)			I.L. (dB)			ϕ_{in} (°)		
	5.2	5.45	5.7	5.2	5.45	5.7	5.2	5.45	5.7
510	360	360	362	0.60	0.88	1.64	+162	+165	+176
541	391	389	387	-----	8 dB	-----	- 62	- 62	- 60
564	332	332	330	0.52	0.60	1.32	-160	-153	-146
567	366	362	360	3.88	3.72	3.92	REF	REF	REF
593	398	395	394	4.20	4.10	4.05	- 60	- 60	- 58
604	404	402	400	1.80	1.72	1.36	- 10	- 9	- 8
615	380	378	376	-----	10 dB	-----	-105	-106	-107
618	402	400	400	-----	8 dB	-----	-105	-106	-107
637	394	391	388	-----	20 dB	-----	+144	+138	+132
640	388	382	380	-----	20 dB	-----	-166	-167	-170

TABLE 21

APS PHASE SHIFTER ELEMENTS - BATCH NO. 4

TEMPERATURE MEASUREMENTS

Serial No. APS 593

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	3.60	4.20	> 6.5	3.56	4.10	6.3	3.60	4.05	> 6.5
$\Delta\phi$ (°)	546	393	329	562	395	331	574	394	333
ϕ_{in} (°)	+117	REF	-47	+100	REF	-47	+92	REF	-47

Serial No. APS 604

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	> 6.0	1.80	1.40	3.54	1.72	0.86	2.72	1.36	.70
$\Delta\phi$ (°)	560	404	339	574	402	340	584	400	340
ϕ_{in} (°)	-58	REF	-136	-143	REF	-115	+117	REF	-105

TABLE 22

APS PHASE SHIFTER ELEMENTS SELECTION

BATCH NO. 5

Units Received	Selections 20	10	2	Units Received	Selections 20	10	2
680	X			734	X		
689				736			
690	X	X		737			
693	X	X		738			
698				739	X		
700	X			742			
710				743	X	X	
711	X	X		744	X	X	
712	X			746			
713				747	X	X	
714	X	X		750	X	X	
715				754			
717	X	X	X	755			
718				757			
720				758	X		
728	X			760			
729				761			
731	X			762	X		
732	X			764			
733				765	X	X	X

machining and annealing. All of the other test samples were made with LMTF 475 (G9) ferrite powder. From the 38 final APS samples (APS 728 through 765 inclusive), 24 were brought to final dimensions and included in batch No. 5.

Clearly, the mechanical strength of the samples made with G-9 powder is superior to G-8 material. Physically there is less cracking in G-9 sprayed samples, and the ferrite coating density is higher and also more uniform, as reflected in sample weight of machined phase shifters.

The microwave measurements on 10 samples shown in Table 23 also indicate better reproducibility in phase shift insertion phase state and insertion loss. The average phase shift in batch No. 5 is 409.9°, which is about 30° higher than the average in batch No. 4. The standard deviation (S) in phase shift for the 10 batch No. 5 elements was 6.89°, which contrasts with S = 21.96° obtained for batch No. 4. Insertion loss measured on the batch No. 5 test samples is also decidedly improved over batch No. 4. Six out of the 10 samples have I.L. > 1 dB at center frequency. Insertion phase spread is less than half of the corresponding range in batch No. 4 samples.

TABLE 23

APS PHASE SHIFTERS BATCH No. 5

MICROWAVE MEASUREMENTS - ROOM TEMPERATURE

	$\Delta\phi$ (°)			I. L. (dB)			ϕ_{in} (°)		
Serial No.	5.2	5.45	5.7	5.2	5.45	5.7	5.2	5.45	5.7
690	407	404	405	1.10	0.90	1.53	- 19	- 19	- 19
693	409	410	404	1.02	0.70	1.39	+ 32	+ 23	+ 27
711	404	403	403	0.42	0.40	0.96	- 40	- 44	- 47
714	396	396	396	0.90	0.72	0.62	+ 74	+ 74	+ 75
717	416	416	416	0.65	0.51	1.10	REF	REF	REF
743	415	414	413	2.50	2.30	2.80	- 66	- 66	- 66
744	413	414	410	5.42	5.38	5.60	- 50	- 50	- 52
747	417	417	417	1.01	0.90	1.37	+ 9	+ 5	+ 3
750	414	414	410	1.40	1.18	1.82	- 32	- 31	- 30
765	416	416	416	1.60	1.50	1.82	- 25	- 23	- 21

TABLE 24

APS PHASE SHIFTER ELEMENTS - BATCH No. 5

TEMPERATURE MEASUREMENTS

Serial No. APS 717

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	2.4	.60	.50	.98	.78	.78	1.02	.38	1.04
$\Delta\phi$ (°)	562	424	386	545	417	384	529	417	382
ϕ_{in} (°)	-40	REF	-128	-128	REF	-114	-178	REF	-100

Serial No. APS 765

	5.2 GHz			5.45 GHz			5.7 GHz		
	-30°	25°	+85°	-30°	25°	+85°	-30°	25°	+85°
I.L. (dB)	3.4	2.10	2.53	2.50	1.70	2.02	2.18	1.80	2.40
$\Delta\phi$ (°)	541	420	374	526	420	372	512	412	374
ϕ_{in} (°)	-61	REF	-134	-144	REF	-124	-204	REF	-120

3.0 FLOW CHART OF MANUFACTURING PROCESS

The APS process for phase shifter manufacture has undergone numerous changes in the lifetime of this program but has evolved to a set procedure for the confirmatory and pilot production runs. The only changes between these two events concerned equipment modification to improve the alignment and sample clamping action with a graphite plug rather than the bare dielectric, and a rebuilding of the support structure to avoid sample wobble from these causes.

A general flow diagram of the process is given in Fig. 34. The diagram includes testing at the 50 percent level required by the contract.

3.1 Dielectrics

3.1.1 Production of dielectrics

Dielectrics are currently produced in the Research Division in 4 kgm lots by ball milling and calcining. Powder is isostatically pressed in 1 kgm bars and fired in electric kilns. Five kilns are available, each capable of firing two bars simultaneously. One man can process the 8 kgm needed in one month.

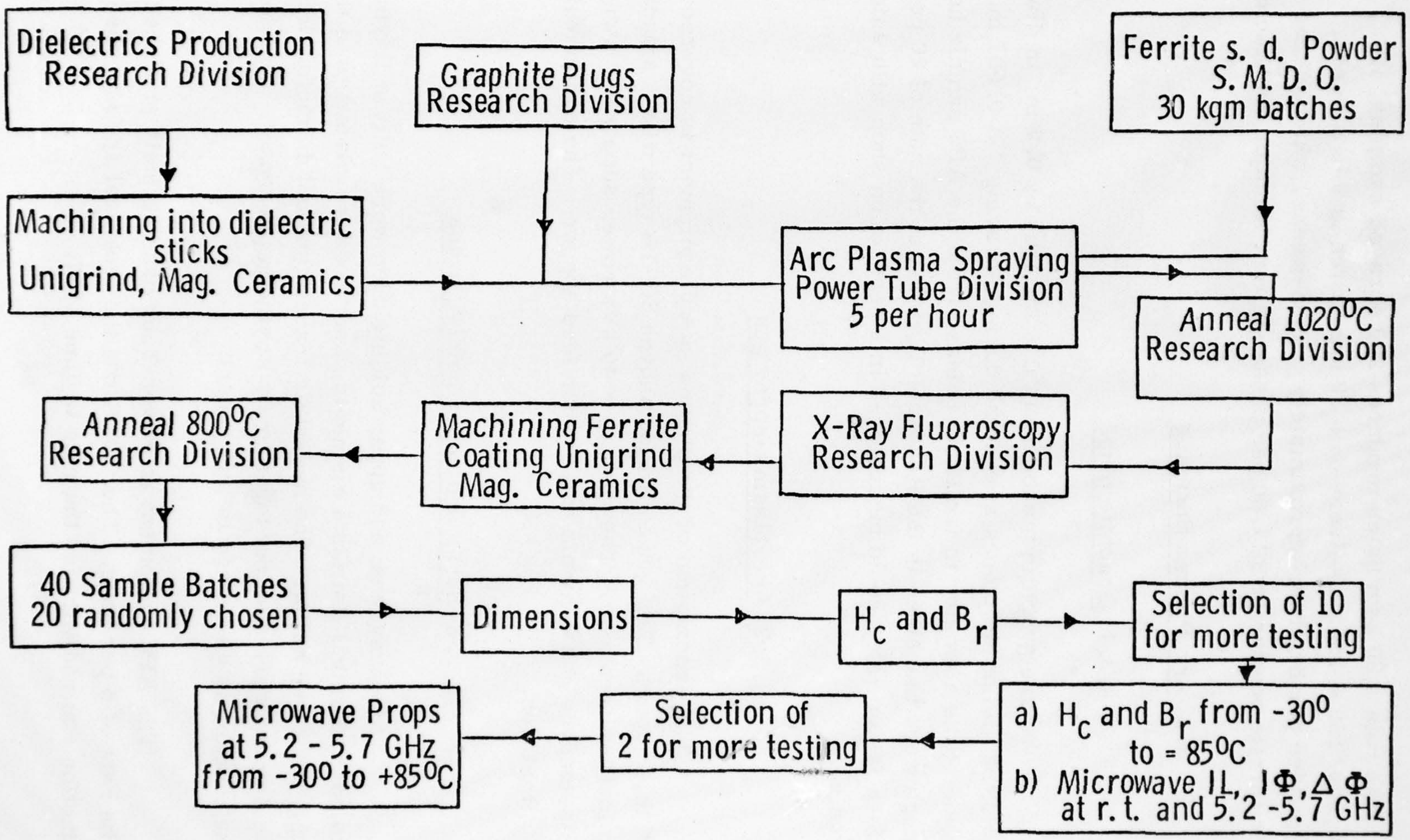
3.1.2 Machining of dielectrics

The fired bars are machined into sticks $0.060 \times 0.150 \times 7$ in. by one of two grinding shops: Unigrind, Inc., Dracut, Mass., or Magnetic Ceramics, Fairfield, N.J. Yield is typically 40 pieces per bar or 20 units for spraying. Three man-days effort are required per bar; ten are needed for 200 samples. The cost per dielectric pair is $ 10.00. With a one-piece dielectric, this cost could be cut in half.

3.2 Ferrite Powder Production

The spray-dried powder is produced in 30 kgm batches by Raytheon Special Microwave Devices Operation. Seven batches were used on the contract. We typically spray 150 gm of powder to produce each sprayed boule.

FLOW DIAGRAM FOR APS PILOT PRODUCTION



At this rate a 30 kgm batch produces 200 sprayed samples, i.e., 30,000/150 = 200. Delivery on a 30 kgm batch is 6 to 8 weeks. The hours expended per batch is approximately 3 man-weeks, which places the cost of the ferrite powder at $ 17.00 per phase shifter, a major cost factor.

3.3 Arc Plasma Spraying

3.3.1 Graphite plugs

We use graphite pieces about 0.8 in. long by 0.7 in. in diameter to hold the dielectric pieces at one end during spraying. A 0.007 in. taper is made of the diameter to facilitate release from the APS sample holder. The plugs were machined in the Research Division at the rate of 20 per man-day. Much faster rates could be achieved in a production shop with automatic tooling.

3.3.2 Arc-plasma-spray gun

The description of the plasma spray equipment is covered in Sec. 2 of this report. The gun is a Plasmadyne SG-1B type with a standard high-velocity attachment. The gun has a 40 kVa power supply and standard Plasmadyne gas controls and powder feed hopper. The equipment is owned by Raytheon.

3.3.3 Spray and upper holding ovens

The spray oven and upper holding oven were built at Raytheon using standard Kanthal flat plate elements, four 4 × 8 in. elements in the upper unit and three below. The hydraulic translation and dc motor driver rotation equipment were also put together by Raytheon personnel. The design and functioning is described in this report.

The APS equipment at Power Tube has routinely produced samples at the rate of 5 per hour. The COTR and the technical advisor observed a production run and verified the rate in June 1977.

3.4 Annealing at 1020°C

The sprayed coating must be heat-treated to bring the magnetic properties into line. This is done in electric kilns at the Research Division with programmed heating, soak time, and cooling to optimize properties. The standard anneal was a 100°C/m rise to 1015°C, a 4-hour soak, and cooling at 100°C/m, all in an atmosphere of flowing oxygen. With five kilns available, 200 boules could be annealed over one 3-day period. With production size kilns, that rate could be much greater.

3.5 Final Machining

3.5.1 X-ray fluoroscopy

Before committing the samples to final machining, we tested for flaws in coating or distortions in sample shape at the Research Division. Twenty samples per man-day was the production rate. X-ray testing may not be required in actual production.

3.5.2 Final grinding

Machining of coated samples to final dimensions of 0.220 × 0.250 × 5.145 in. ± 0.001 is done at one or more grinding shops. Output per man-day per shop is 15 samples. Final machining cost was $20.00 per element.

3.5.3 Removing machining stresses by annealing

The samples are annealed at 800°C at the Research Division to remove machining stresses. With five kilns available, 200 machined samples could be annealed over one 3-day period. The standardized schedule was 100°C/hour rise to 800°C, a two-hour soak, and a 100°C/hour cooling in stagnant air.

3.6 Sample Testing

Machined and annealed samples were produced in batches of 40, of which 20 were randomly selected for testing.

3.6.1 Dimensions

The external dimensions on the 20 samples were 0.220 × 0.250 × 5.145 in. to within ± 0.001 in. after the final anneal. Forty samples could be tested for dimension tolerance in 4 hours. We found that weighing the machined elements at this point was a very convenient way of monitoring the density of the ferrite coating. Density influences insertion phase of the device and should be monitored on all samples.

3.6.2 Hysteresis loop testing

At 15 amp-turns drive the coercive force and remanent magnetization were measured on the automatic loop tracer. Samples were required to meet the following criteria:

a) Coercive force at room temperature will be such that 90 percent of differential phase shift is obtained at 15 amps drive current.

b) Remanent magnetization at room temperature will be such as to produce at least 340° differential phase shift at 15 amps drive current.

Twenty samples could be measured per man-day. Ten samples from the 20 were selected for further testing.

3.6.3 Hysteresis properties vs. temperature

Coercive force and remanent magnetization were tested from -30°C to +85°C. B_r was well under ± 10 percent over the temperature range, i.e., ± 10 percent from the average value. Typical values for B_r were + 4 percent at - 30°C and -8 percent at +85°C. A standard toroid was used in each run to verify reproducibility. Sample output was 10 samples per man-day.

3.6.4 Microwave properties vs. temperature

Two samples were selected from each batch for tests of phase shift, insertion loss, and insertion phase versus frequency (5.2, 5.4, and 5.7 GHz) and temperature (-30°C to +85°C). The temperature measurements are rather time-consuming and the output is therefore low: one sample per man-day. This degree of microwave testing versus temperature would not be used in practice.

4.0 EQUIPMENT AND TOOLING

The following list gives pertinent data on each item used in the arc-plasma-spray process.

1. Five Lindberg electric kilns

   Design Cost: $1,500 each

   Replacement Cost: $2,000 each

   Ownership: Raytheon Research Division

   Each oven is capable of firing two 1 kg bars simultaneously.

2. Grinding machines (outside vendor)

   Design Cost: unknown

   Replacement Cost: unknown

   Ownership: Unigrind, Inc., Dracut, Mass.
   Magnetic Ceramics, Fairfield, NJ.

   Yield is typically 40 pieces per bar, or 20 units per spray. Three man-days' effort is required per bar; ten is needed for 200 samples.

3. Graphite plugs

   Design Cost: $2.00 each: $.50 material,
   $1.50 machining

   Ownership: Presently machined at Raytheon Research Division

   Each plug holds one dielectric. The plugs are machined at the rate of 20 per man-day. Much faster rates could be achieved in a production shop with automatic tooling.

4. Ferrite powder production (ball mills, calciners, spray drier, tunnel kiln)

   Design Cost: $250,000

   Replacement Cost: $500,000

   Ownership: Raytheon Special Microwave Devices Operation

The spray-dried powder is produced in 30 kg batches. We typically spray 150 g of powder to produce each sprayed boule. At this rate, a 30 kg batch produces 200 sprayed samples, i.e., 30,000/150 = 200. Delivery on a 30 kg batch is 6 to 8 weeks. Approximately 3 man-weeks are expended per batch.

5. Arc-plasma-spray equipment (Plasmadyne SG-1B gun with a Standard high-velocity attachment, spray oven plus controls, and upper holding oven plus controls)

   Design Cost: $20,000

   Replacement Cost: $25,000

   Ownership: Raytheon. The spray and upper holding ovens were built at Raytheon. The equipment is located at Power Tube Division.

   The arc-plasma-spraying equipment has routinely produced samples at the rate of 5 per hour.

6. X-ray fluoroscope (Radifluor 360, Torr X-Ray Corp.)

   Design Cost: $2,000

   Replacement Cost: $3,000

   Ownership: Raytheon Research Division

   Twenty samples per man-day were tested before being committed to final machining. X-ray testing may not be required in actual production.

7. Tools for determining dimensions:

   Design Cost: $100

   Ownership: Raytheon Research Division

   In 4 hours 40 samples can be tested for dimension tolerance.

8. Automatic hysteresis loop tracer

Design Cost: $5,000

Replacement Cost: $10,000

Ownership: Raytheon Research Division

Twenty samples can be measured per man-day.

9. Temperature measurements on magnetic properties

Design Cost: $1,000

Replacement Cost: $2,000

Ownership: Raytheon Research Division

The temperature measurements are rather time consuming and the output is therefore low: one sample per man-day.

5.0 DATA AND ANALYSIS

Hysteresis loop and microwave data on the 50 production samples that had the most thorough testing are summarized in Table 25. The coercive force at room temperature varies between 2 and 3.5 Oe, with no obvious dependence on ferrite density (col. 7). Phase shift also shows variation relative to B_r and ferrite density probably due to instrumental error.

Insertion phase shows fluctuations that are larger than we had hoped for. We expect that these fluctuations are due to variations in ferrite density, separations in the dielectric halves during spraying, and cracking in the ferrite coating.

Column 8 shows the range in B_r brought about by changes in temperature. The total percentage change from -30° to +85°C is the order of 12 percent, much smaller than the range in phase shift with temperature shown in the last two columns. In addition to $4\pi M_r$, phase shift is, of course, also dependent on other properties, such as k' and $4\pi M_s$. These factors can influence the temperature dependence considerably.

TABLE 25

DATA AND ANALYSIS OF APS PRODUCTION RUN

Batch No.	APS No.	Hysteresis Data: H_c (15 amp-turn drive)	Hysteresis Data: B_r (15 amp-turn drive)	Microwave Analysis: $\Delta\phi°$ (5.45 GHz, 25°C)	Microwave Analysis: I. L. (5.45 GHz, 25°C)	Microwave Analysis: ϕ_{in} (5.45 GHz, 25°C)	Weight (g)	Temperature Data: ΔB_r (%) -30°	Temperature Data: ΔB_r (%) + 85°	Temperature Data: $\Delta\phi°$ at 5.45 GHz (-30°C)	Temperature Data: $\Delta\phi°$ at 5.45 GHz (+ 85°C)
1	325	3.21	765	418	0.78	-128	---	1.6	-7.7	535	337
	331	3.07	760	409	1.16	- 98	---	-1.2	-7.0		
	346	3.22	768	410	1.78	-131	---	4.6	-7.9	567	335
	353	2.44	776	397	0.67	ref.	---	3.1	-9.7		
	354	3.33	753	390	1.06	+ 6	---	3.9	-7.0		
	358	2.42	787	408	0.35	- 44	---	3.8	-11.2		
	373	3.07	719	407	0.76	+113	---	3.1	-9.3		
	383	2.82	782	408	0.76	-116	---	4.1	-9.2		
	386	3.38	717	403	0.93	- 96	---	2.3	-7.8		
	388	3.31	782	421	0.64	-118	---	2.1	-8.3		
2	390	3.04	771	402	1.70	+ 3	---	2.1	-5.4		
	394	2.28	790	347	0.90	+ 82	---	3.5	-7.4		
	397	2.13	782	393	0.75	+ 49	---	3.3	-8.9		
	399	2.05	788	395	0.50	+ 49	---	3.2	-8.4		
	408	2.45	787	396	0.71	- 17	---	3.2	-8.3		
	411	2.45	820	411	0.60	ref.	---	3.1	-8.7	535	337
	412	2.41	807	408	1.10	- 20	---	4.6	-8.9	525	333
	424	3.22	730	398	7.0	- 81	---	1.5	-5.6		
	428	2.78	714	380	1.0	+ 22	---	1.1	-9.2		
	431	2.76	750	387	1.5	- 3	---	0.4	-9.8		

TABLE 25 (Cont'd.)

DATA AND ANALYSIS OF APS PRODUCTION RUN

Batch No.	APS No.	Hysteresis Data: H_c (15 amp-turn drive)	Hysteresis Data: B_r (15 amp-turn drive)	Microwave Analysis: $\Delta\phi°$ (5.45 GHz, 25°C)	Microwave Analysis: I. L. (5.45 GHz, 25°C)	Microwave Analysis: ϕ_{in} (5.45 GHz, 25°C)	Weight (g)	Temperature Data: ΔB_r (%) -30°	Temperature Data: ΔB_r (%) + 85°	Temperature Data: $\Delta\dot{\phi}$ at 5.45 GHz (-30°C)	Temperature Data: $\Delta\dot{\phi}$ at 5.45 GHz (+ 85°C)
3	442	2.64	755	393	1.98	- 85	18.18	4.9	-8.3	503	326
	444	3.10	725	381	6.5	-114	18.43	1.9	-7.6		
	447	2.99	719	373	3.8	- 87	18.36	3.0	-8.7		
	451	2.96	767	396	2.92	- 65	18.34	4.3	-9.0		
	452	3.05	716	376	7.0	-106	18.31	5.5	-8.8		
	462	2.67	697	363	0.40	+ 78	17.46	2.5	-5.3		
	476	2.70	756	393	0.72	- 3	18.00	4.2	-6.8	491	329
	482	2.69	689	345	0.58	+108	17.14	3.2	-6.4		
	485	2.66	769	384	0.56	+ 15	17.89	3.6	-7.4		
	488	2.61	774	388	0.64	ref.	17.96	2.8	-9.9		
4	510	2.17	707	360	0.88	+165	17.51	5.9	-8.3		
	541	2.91	715	389	8.0	- 62	18.58	3.8	-5.3		
	564	2.44	642	332	0.60	-153	17.18	3.7	-6.9		
	567	2.77	664	362	3.72	ref.	18.30	4.5	-7.7		
	593	2.91	700	395	4.10	- 60	18.34	3.6	-5.1	562	331
	604	2.81	677	402	1.72	- 9	18.69	2.7	-8.6	574	340
	615	2.86	597	378	10.0	-106	18.75	1.0	-4.9		
	618	2.83	640	400	8.0	-106	18.97	2.0	-6.4		
	637	2.79	603	391	20.0	+138	19.01	1.7	-4.0		
	640	2.82	613	382	20.0	-167	18.98	0.8	-3.6		

TABLE 25 (Cont'd.)

DATA AND ANALYSIS OF APS PRODUCTION RUN

Batch No.	APS No.	Hysteresis Data: H_c (15 amp-turn drive)	Hysteresis Data: B_r (15 amp-turn drive)	Microwave Analysis: $\Delta\phi°$ (5.45 GHz, 25°C)	Microwave Analysis: I. L. (5.45 GHz, 25°C)	Microwave Analysis: ϕ_{in} (5.45 GHz, 25°C)	Weight (g)	Temperature Data: ΔB_r (%) -30°	Temperature Data: ΔB_r (%) + 85°	Temperature Data: $\Delta\dot{\phi}$ at 5.45 GHz (-30°C)	Temperature Data: $\Delta\dot{\phi}$ at 5.45 GHz (+ 85°C)
5	690	3.09	731	404	0.90	-19	18.51	5.3	-8.9		
	693	2.70	782	410	0.70	+28	18.35	4.5	-9.9		
	711	2.69	742	403	0.40	-44	18.56	8.5	-11.5		
	714	3.18	748	396	0.72	+74	18.35	3.6	-5.5		
	717	2.62	804	416	0.51	ref.	18.36	9.8	-10.6	545	384
	743	3.30	713	414	2.30	-66	18.62	3.7	-8.3		
	744	3.30	703	414	5.38	-50	18.78	1.6	-4.9		
	747	3.41	737	417	0.90	+ 5	18.59	3.9	-11.7		
	750	3.25	732	414	1.18	-31	18.58	2.3	-6.3		
	765	3.46	727	416	1.50	-23	18.75	0.8	-6.9	526	372

6.0 SPECIFICATION

As a result of the first article and pilot production runs, we would recommend three basic changes in the manufacturing process:

1) A change from the two-piece dielectric substrates to a single piece contingent on developing techniques to apply or introduce the switching wires,

2) Better methods of quality control on the spray-dried ferrite powder to give more uniform deposition characteristics,

3) Develop methods of collecting and reusing the ferrite overspray powder.

A one-piece dielectric would solve several problems:

1) Machining time would be effectively cut in half and yield per bar would be significantly increased (about 30 percent) because of reduction in kerf loss.

2) The tendency for any bowing or distortion would be significantly reduced because of the doubling in cross section of solid material.

3) The possibility of partial separation of the dielectric halves during spraying and the changes in insertion phase which result therefrom would be eliminated. We have noted a typical dielectric separation of 0.003 to 0.008 in. in the central two-thirds of most APS samples. The variation in this separation certainly contributes to insertion phase spread.

A second area where improvement would produce important dividends is better quality control on the spray-dried ferrite particle size and size range. During spraying, the particles are heated from room temperature to about 1500°C in milliseconds through coupling to the very hot plasma gases. The penetration of the powder into the plasma stream and the rapidity of melting or partial melting depends very critically on particle mass. The more uniform the particle size, the more efficient this process becomes; large particles do not melt enough to stick and small particles overheat and volatiles (Li, Zn, O) are lost.

We have found through weighing experiments that the density of the deposited ferrite varies between samples sprayed with different ferrite powders. The density variation causes changes in thermal expansion match and may produce excessive cracking as in the LMTF475(G8) powder. Almost 75 percent of the samples sprayed with this powder yielded excessive cracking, yet we could detect no property differences to explain the problem. Better characterization tools are needed.

A third area needing improvement is reduction of ferrite powder losses during spraying. Losses are presently about 90 percent, i.e., of the 150 g sprayed, only 15 g remain in the machined phase shifter. Improvements in spray nozzle shape may increase the deposit efficiency. Another possibility would be recovery and reuse of over-spray powder. Reuse would be dependent on the degree of compositional change (volatilization) that has occurred during spraying.

7.0 REQUIREMENT FOR PILOT PRODUCTION

The processing and spray drying of the ferrite powder require the use of a 50 kg ball mill, a conventional calcining oven (850°C) and a spray drier with a capacity of 5 kg/hr.

Dielectrics production requires the same equipment at about 40 percent thruput level and, in addition, a periodic kiln for firing the dielectric bars.

The processing of the ferrites and the dielectrics for the production run made use at 5 percent of capacity of a 10,000 sq. ft. plant employing four skilled and two unskilled workers.

The arc plasma facility was contained in 600 sq. ft., making use of two skilled persons about one-third time. Annealing was done in one of two experimental size electric kilns.

8.0 COST FOR THE PILOT RUN

The cost breakdown for the various process materials and steps in the production run is summarized below.

		Unit Cost
1.	Spray dried ferrite powder, $50.00 per pound and 0.33 pound per boule	$17.00
2.	Processing cost for dielectric per pair	4.00*
3.	Dielectric machining costs at $245 per bar and yield of 25 dielectric pairs	10.00
4.	Plasma spray cost assuming setup and downtime and yield reduce production to three per hour	5.00*
5.	Machining of annealed phase shifter assuming 80 percent yield	25.00
6.	Two anneals plus inspection for dimension	2.00*
	Total	$63.00

The hysteresis loop and microwave testing, apart from the temperature dependence tests, would add about 100 percent to the cost of each phase shifter tested in this way.

* Cost is approximate and does not include overhead charges.

9.0 PROGRAM REVIEW

This subject is covered separately as an addendum to the final report.

10.0 CONCLUSIONS

The APS process has proved an effective and viable technique in fabrication of dielectric-loaded ferrite phase shifters of the Li-Ti type. The magnetic properties of plasma-sprayed materials generally compare favorably with conventionally fired ceramics. For example, all but one of the 50 microwave tested samples gave a differential phase shift greater than the 340° specifications, the average being 393° with a standard deviation of 20°. Insertion loss was < 1 dB on 25 of the 50 samples subjected to microwave testing and < 2 dB for 35 of the 50. In those instances where insertion loss was > 2 dB where additional testing was done, the loss could be reduced by a longer anneal in which oxidation would reduce the residual Fe^{+2} present. On the negative side the repeatability of insertion phase and the magnitude of coercive force (H_c) are not as good as conventional.

Insertion phase variation was about 2.5 times the goal of ± 16° standard deviation, being actually somewhat larger than production by conventional means. The sources of insertion phase variation are 1) A variable void space between the dielectric halves produced by separation during spraying. This source could be eliminated by using a single-piece dielectric. 2) Changes in insertion phase due to variations in ferrite coating density, particularly when changing from one ferrite batch to the next. The correlation between observed variation in ferrite density (deduced from weighing machined phase shifters) and the corresponding changes in insertion phase, are shown for production batch No. 3 in Fig. 35. Since the dielectric has a known density of 3.98 g/cc, one can calculate ferrite density directly from the weight and dimensional data. A phase shifter weighing 19.15 gm would have a ferrite with 100 percent density (4.35 kc) whereas a phase shifter weighing 17.4 gm has a calculated ferrite density of 87 percent. The weighing of finished phasers is a rapid and convenient check on ferrite density and therefore insertion phase variation and should be included on a material specification in any future production.

The coercive force on APS samples is typically $2 < H_c < 3.5$ Oe, consistently higher than these same Li-Ti ferrite compositions when conventionally fired ($H_c \sim 1$ Oe). The larger H_c is primarily due to porosity in the plasma sprayed materials which is typically 5 to 10 percent. H_c can be reduced to $\approx$ 1 Oe with Zn substitution, but at the expense of some temperature stability of the magnetization. A larger H_c implies a larger switching energy for the phase shifter driver circuit.

Apart from insertion phase variation and the larger coercive force, the most serious drawback of the APS process is cost. The process is not competitive at $63.00 per finished phaser with the present garnet K-38 device. On the other hand, the costs could be reduced substantially by changing to a one-piece dielectric and by finding lower cost suppliers of spray-dried ferrite powders. The intrinsic materials cost of Li-Ti-ferrite is ~ $3.00 per pound and large-scale manufacturers should eventually be able to approach this cost within a factor of two, a 10 × reduction from small-scale manufacture.

The reuse of some or all of the overspray powder should lower this major cost item even more.

Machining costs are high because of the ferrite removal after spraying and will always create some disadvantage for the APS process.

It is important to mention the indirect benefits that have been gained by working with a new fabrication process. A good deal has been learned about the feasibility of applying the APS process to other ceramic and metallurgical coating projects of importance to the military. At present, four of these materials projects within the Research Division are competing for the use of the APS equipment. One project is to coat X-ray target anodes with a tungsten-rhenium alloy onto a high-temperature substrate. Cost savings over present vapor deposition processing could be considerable. A second project is to fabricate refractory oxide IR transmitting domes by arc plasma spraying rather than by hot pressing or fusion casting. A third program would make use of plasma spraying to deposit electrodes for a TEA laser device. A fourth candidate is a project studying the activation of catalyst materials through melting oxide in different gaseous atmospheres at extreme temperatures. Finally, high-frequency phase shifter devices, which, because of the small coating thicknesses, may be fabricated advantageously by the APS process. We will continue to actively pursue these new technologies.

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11.0 PUBLICATIONS AND REPORTS

There were no publications or reports during the period associated with the research, study, or development under contract.

12.0 IDENTIFICATION OF TECHNICIANS

The following are the names of the personnel that worked on the contract and the total manhours performed by each during the interval covered by this report.

J. J. Green	45
H. J. Van Hook	1503
L. Lesensky	63
D. Massé	75
J. Saunders	149
O. Guentert	27
R. Maher	2782
H. Miller	595
W. Griffin	73
Others	3578.5
	8890.5

APPENDIX I

Particle Size Analysis

The Zeiss particle size analyzer is a semiautomatic device for measuring and recording particle size on photographic prints or negatives. The device shown in Fig. AI-1 operates as follows:

> An iris diaphragm, illuminated from one side, is imaged by a lens on to the plane of a plexiglass plate. An enlargement of the micrograph (transparent paper) is put on this plate. By adjusting the iris diaphragm the diameter of the sharply defined circular light spot appearing on the enlargement can be changed and its area made equal to that of the individual particles.
>
> The different diameters of the iris diaphragm are correlated, via a collector, with a number of telephone counters, each counter corresponding to a certain aperture interval of the iris diaphragm.
>
> When the measuring mark is equalized with a particle in the photograph, the footswitch is depressed. Thus the correlated counter is actuated, and a puncher marks the counted particle on the photograph. The photograph is then shifted until the next unmarked particle is above the stationary measuring mark, etc.
>
> About 15 minutes are required for analyzing 100 particles.
>
> Since the eye participates in the measuring process, the diameter of the particles to be measured in the photograph should possibly not be less than 1 mm. The instrument is provided with two measuring ranges. The first permits measuring particles of 1.0 - 9.2 mm diameter, the second such of 1.2 - 27.7 mm. The enlargement of the photograph should be in accordance with these limiting values. The particle sizes are divided into 48 continuous categories. In addition to the indicidual counters, which can be set back to zero, the instrument is equipped with a counter which registers the total of all counted particles.

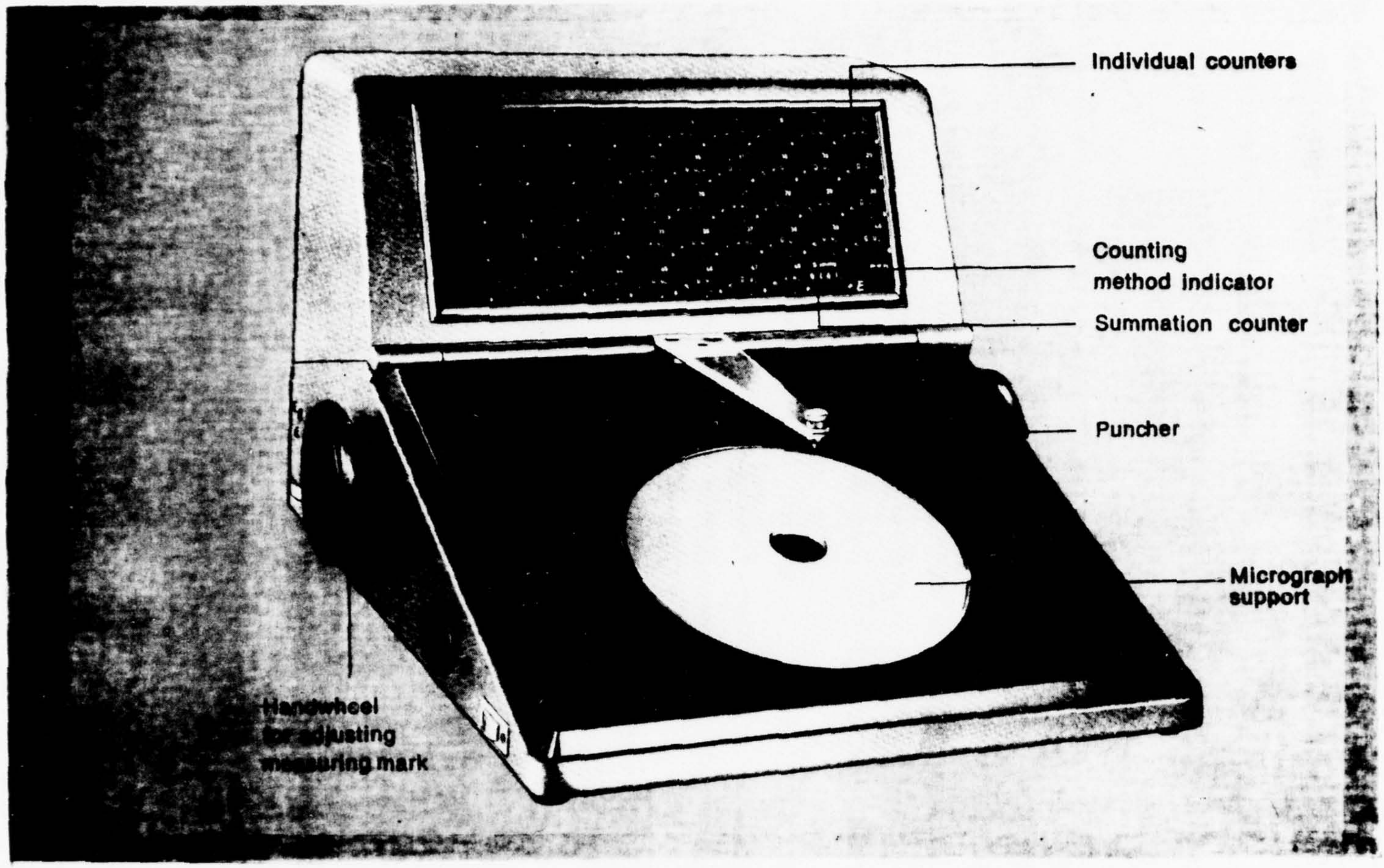


Figure AI-1 The Zeiss Particle Size Analyzer.

The counting registers are arranged on a scale of exponentially increasing width. The scale is termed "relative" by the manufacturer in that the width of each counting interval is proportional to its size. The scale distorts the true distribution somewhat but gives more detail on the small particle end.

Counting data for photographs 1, 2, 3, and 4 are given in Table AI-1 for 24 particle size categories, showing an average diameter and the size interval for each. The sum of all particles within each range in the four photographs in Fig. AI-2 is given in the next column. These values were used to generate the histogram of particle diameter shown in Fig. AI-3. The average diameter for the 600 particles is 5.5 microns. The distribution shows a pronounced skewness. In the counting process we measured all resolvable particle aggregates whether or not there was apparent attachment to other particles. The distribution therefore indicates particle diameters which may be smaller than the actual distribution of free-standing particles.

The skewness towards larger particles in powder G2 suggests that it may be advantageous to remove larger particles by screening or air classification to give a more homogeneous size distribution for arc plasma spraying. In any event we now have a fingerprint of the size range for this powder which can be compared with subsequent batches.

One further exercise was performed with the particle count data. The small particles may be large in number and yet represent only a small weight fraction (or volume fraction) of the powder aggregate. Since we know the particles are hollow and have a wall thickness of 2.5 microns and can estimate a density of 2.5 gm/cc for the walls, one can calculate an average particle weight for each size category using the formula

$$wt(gm) = \frac{\pi}{6}\, 2.5\, (d^3 - (d - 2.5)^3) \times 10^{-12}$$

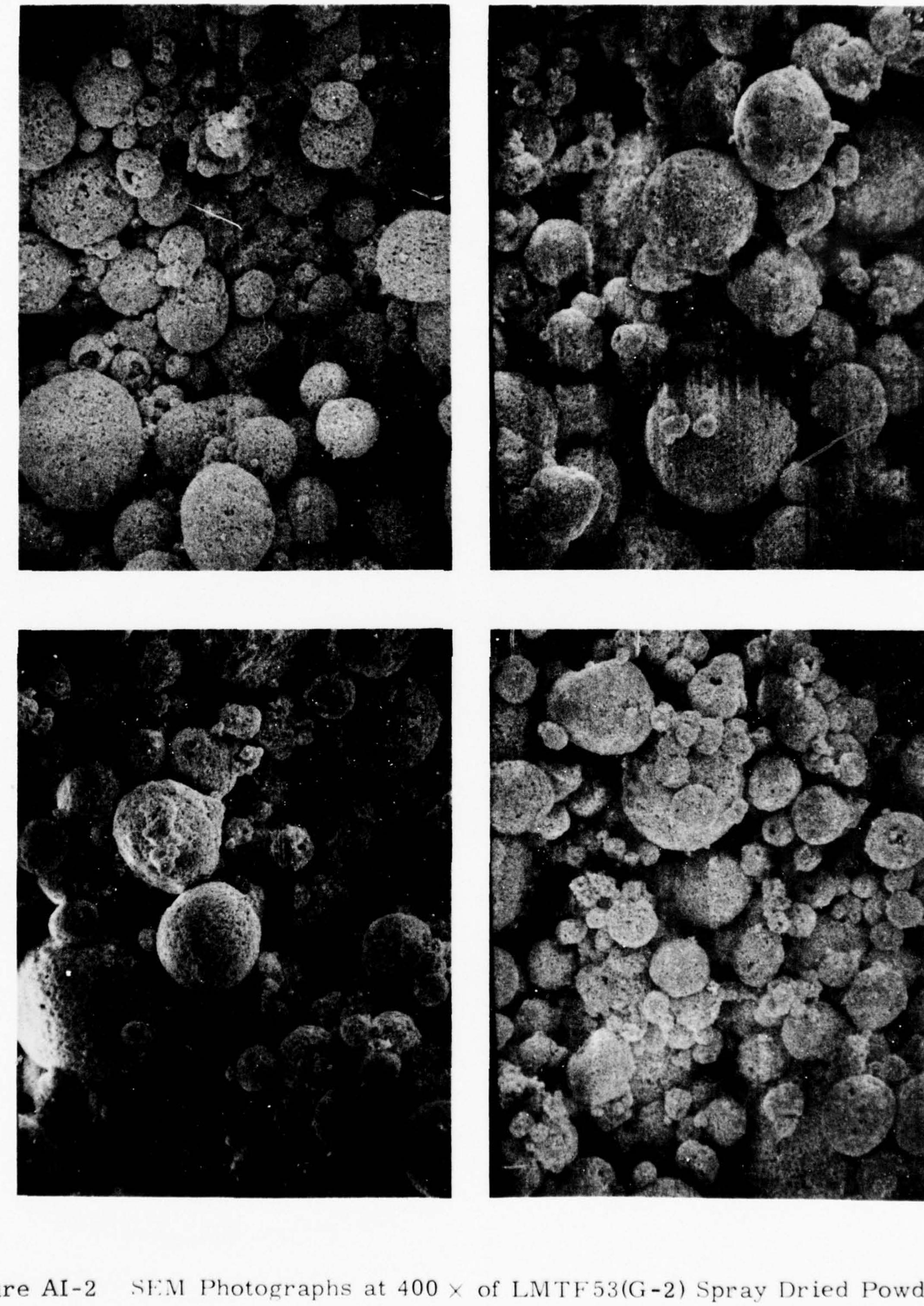


Figure AI-2 SEM Photographs at 400 × of LMTF53(G-2) Spray Dried Powder.

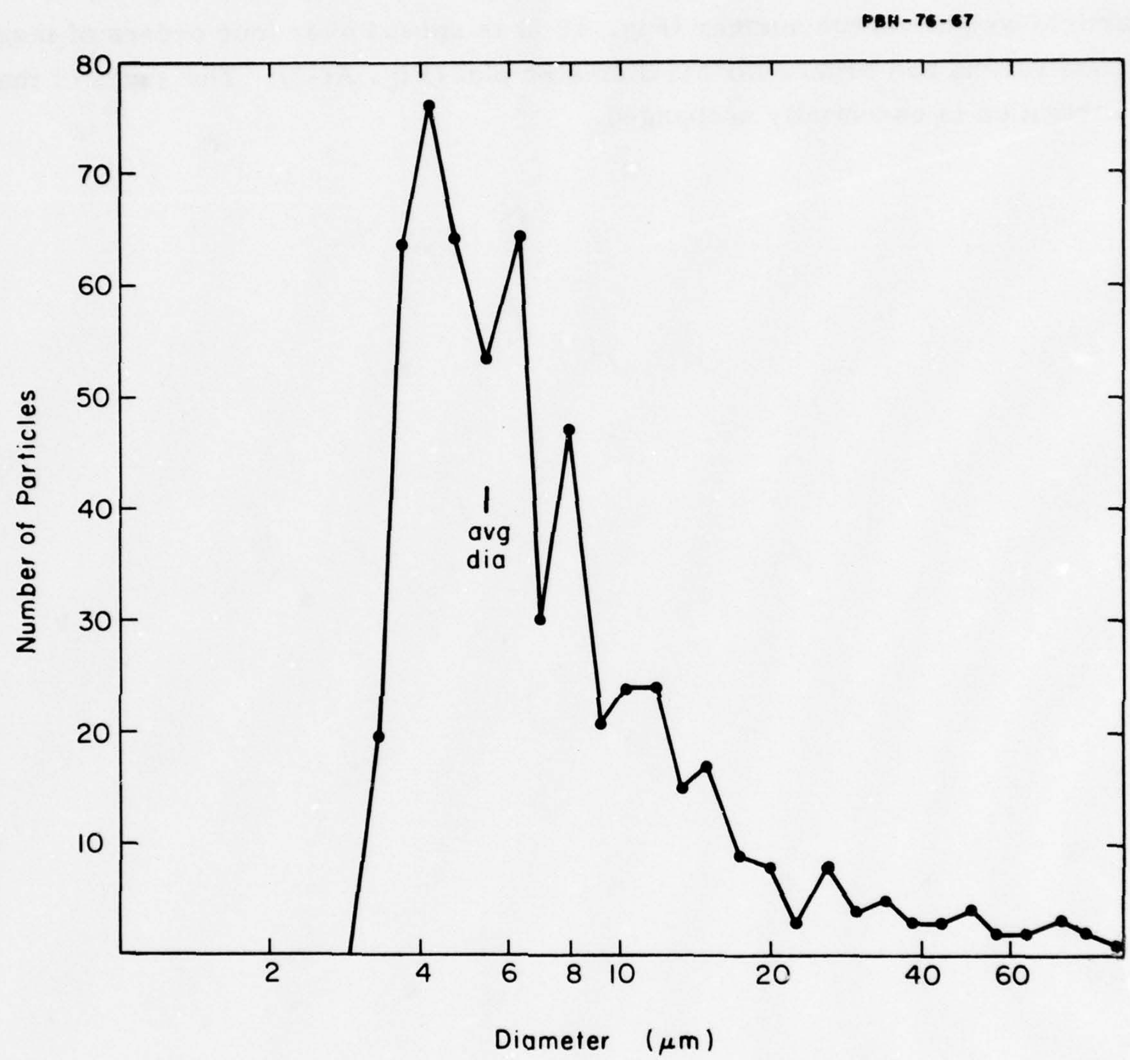


Figure AI-3 Histogram of Particle Size for Ferrite Powder LMTF53(G2).

The particle weights shown in Table AI-1 range between 46.37×10^{-12} gm for the smallest to $\sim 10^{-7}$ gm for the largest. The resulting histogram of particle weight versus number (Fig. AI-4) is spread over four orders of magnitude versus two orders for the diameter plot (Fig. AI-3). The shape of the distribution is essentially unchanged.

TABLE AI-1

PARTICLE SIZE DISTRIBUTION IN FERRITE POWDER

LMTF 53 (G2)

Avg. Size	Size Interval (Microns	Particle Counts Photo 1	Photo 2	Photo 3	Photo 4	Total Counts	Avg. wt. $\times 10^{12}$
3.3	0.5	5	14	0	0	19	46.4
3.7	0.5	28	24	13	0	65	64.0
4.2	0.5	29	17	17	14	77	90.6
4.8	0.6	15	13	13	25	66	128.8
5.5	0.7	8	17	18	10	56	182.4
6.3	0.8	18	10	14	11	66	255.5
7.0	0.9	4	4	15	7	30	329.7
8.0	1.0	12	10	14	11	47	452.4
9.1	1.2	4	3	7	7	21	610.1
10.5	1.5	7	5	4	8	24	845
12.0	1.6	7	5	5	7	24	1140
13.6	1.6	5	3	7	0	15	1503
15.0	2.0	2	4	6	5	17	1861
17.6	2.5	3	0	3	3	9	2629
20	2.6	2	4	0	2	8	3457
22.7	3.0	1	1	1	0	3	4522
26	3.5	2	2	4	0	8	6019
29.5	3.9	1	2	0	1	4	7840
34	4.2	2	1	2	0	5	10535
38	5.0	1	2	0	0	3	13264
44	6.0	2	1	0	0	3	17950
50	6.5	0	2	1	1	4	23337
57	7.5	0	0	1	1	2	30519
65	9.0	0	1	0	1	2	39904
75	10.0	2	0	1	0	3	53403
85	12.5	0	2	0	0	2	68865
100	--	1				1	95741

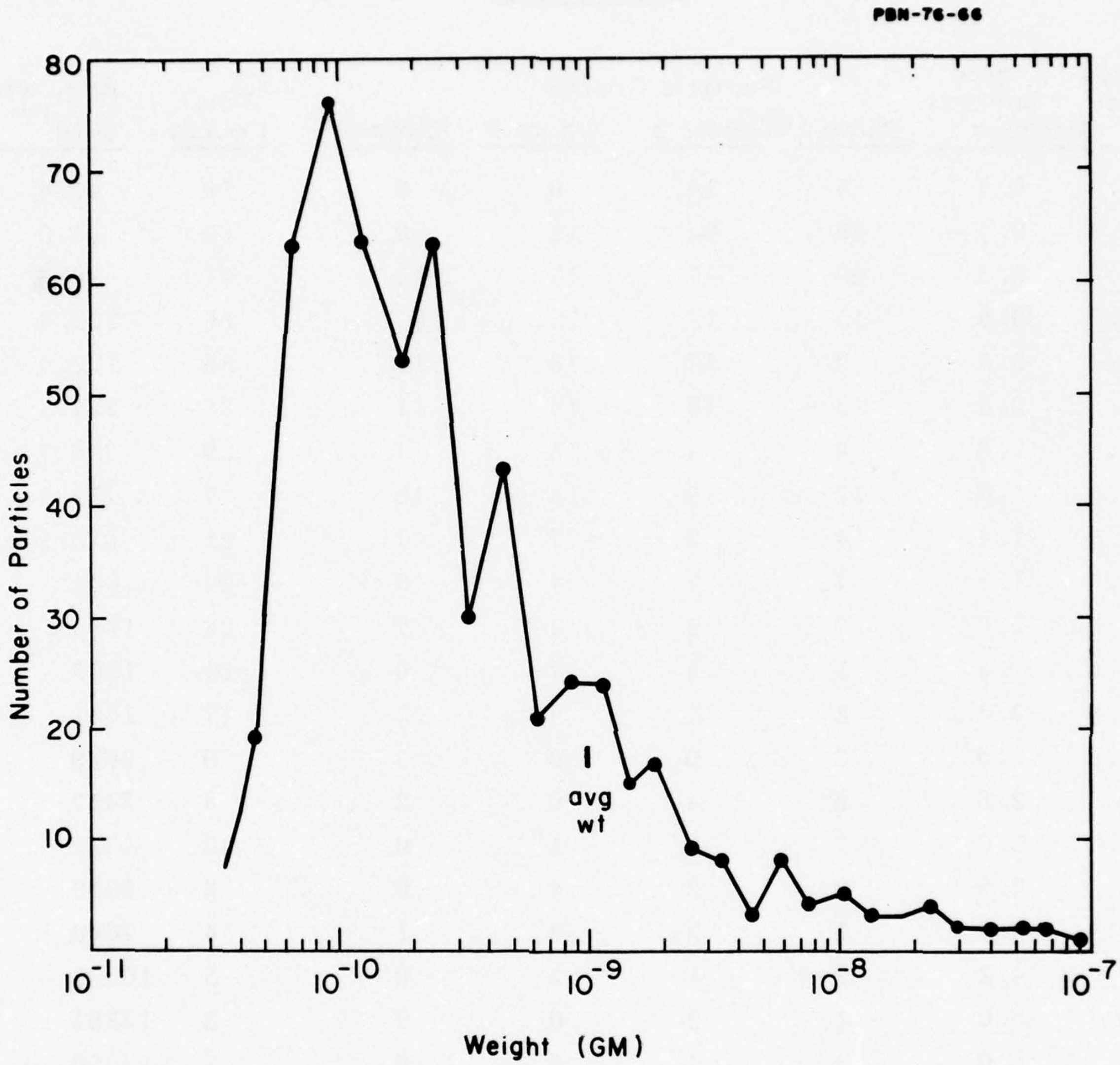


Figure AI-4 Histogram of Particle Weight for Ferrite Powder LMTF53(G2).

APPENDIX II

X-Radiography of Phase Shifter Elements

Introduction

The dissection of machined phase shifters from the confirmatory sample run had indicated a problem with warping, which resulted in uneven ferrite walls and low B_r and phase shift. With the exterior dimensions machined straight, any bowing or warping during spraying would produce walls thicker then the 0.50 in. dimension in some regions and a thinner wall on the opposite side. Very slight departures from straightness would have serious effects on B_r. For example, a bow of 0.020 in. in the five-inch length would mean a thinning of one ferrite wall to 0.050 - 0.020 = 0.030 in. and, since the thin wall is flux limiting, B_r in this region would be reduced by 0.020/0.050, or 40 percent.

Although dissection of machined samples gives unequivocal evidence of warping, the procedure is destructive and is done after final machining, which itself is a costly step. There was, therefore, a strong incentive to develop a nondestructive process for evaluating wall uniformity in machined samples, and even greater incentive for finding wall thickness nonuniformities before the final machining. Some early experiments with X-ray and light transmission down the center slot showed promise but could not be made quantitative. Studies of X-ray fluoroscopy showed much better potential. We eventually adopted and used this technique for inspecting production run samples.

Experimental Technique

A conventional X-ray fluoroscope (Radifluor 360, Torr X-ray Corp.) was used to take the transmission photographs of the phase-shifter elements in two orthogonal directions. Samples were placed directly on Kodak-type M film and irradiated at 80 kV 3mA for 3 to 4 minutes with lead screen intensification. This produced full-size negatives with shades of gray, depending on transmitted intensity. Photographs of APS 251 and 258 are prints of these negatives taken on two as-sprayed boules. The lighter areas indicate greater X-ray transmission.

The orthogonal views are shown in Figs. AII-1 and AII-2. H indicates that the join between the two dielectric halves is horizontal, and V indicates the verticality of this surface (perpendicular to the plane of the paper). In the latter, the join shows up as a thin white line where X-ray transmission is less impeded. The dielectric core with its machined center slot is also readily seen in these photographs.

X-ray transmission photographs have also been taken of machined elements as part of the analysis of phase shifters with low B_r. In APS 143 (Fig. AII-3) we see that the dielectric is straight but B_r is nevertheless quite low. The reason for the low B_r in this case is machining error shown in the right-hand view, where one wall averages 0.039 in. rather than the 0.050 in. required. Assuming a B_r = 800G for a perfectly machined sample, we see in this case that machining error accounts for all of the observed reduction in B_r. In Fig. AII-4 the X-ray shows a thin wall (left-hand view), this time brought about by a separation of the dielectric along the length which increased the core cross-section, reducing one ferrite wall.

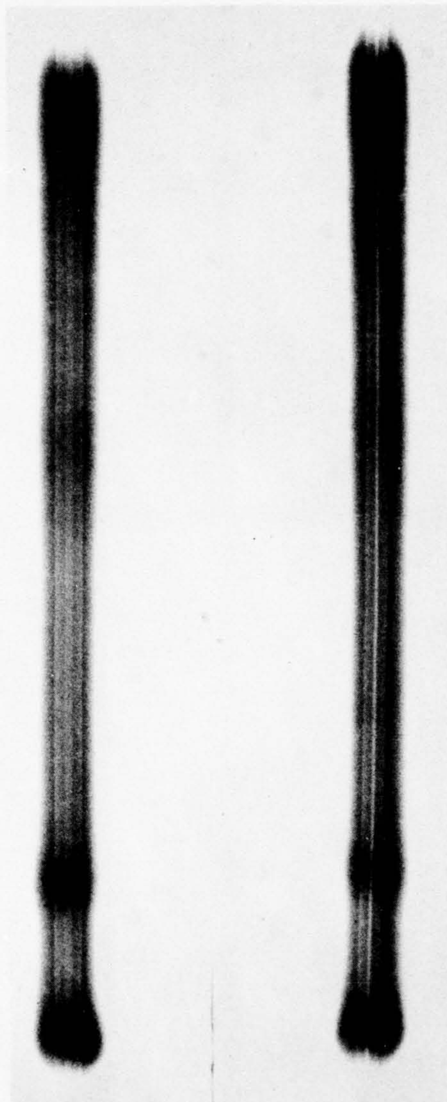


Figure AII-1 Orthogonal Views of Sample No. 257.

PBN-77-62

H V

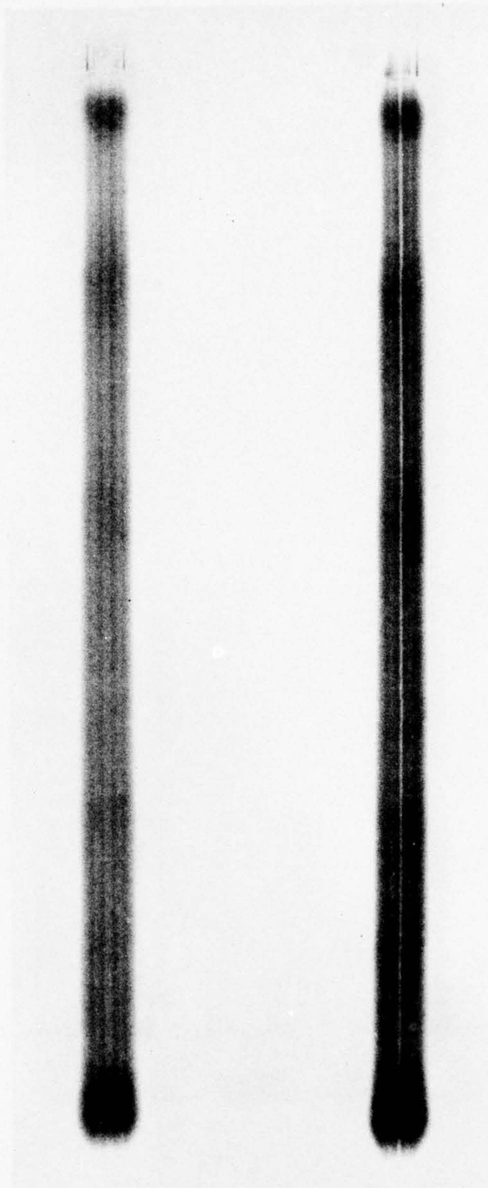
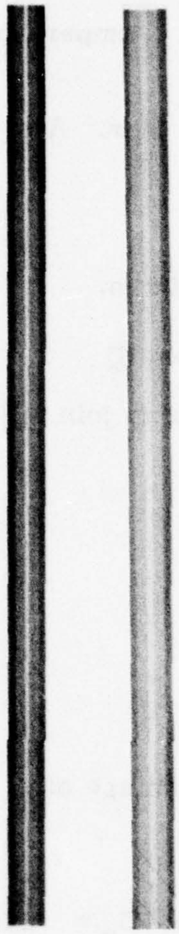


Figure AII-2 Orthogonal Views of Sample No. 258.

A. P. S. 143



H_c = 2.74 B_r = 626   at   30   ampere turns.

Anneal: 1010° 1.5 hrs. O_2; 800° 2 hrs. Air

Distortions:

Bow: .004 in.

Separation of insert halves: .006 in. for 2/3 length

Wide-slot dimension: Parallel to join ☒ Perpendicular to join ☐

Thin-wall dimensions (mils):

End: 37
Center: 36
End: 45
Minimum: 36
Average: 39

Average thin-wall dimension as percentage of ideal .050": 79 percent.

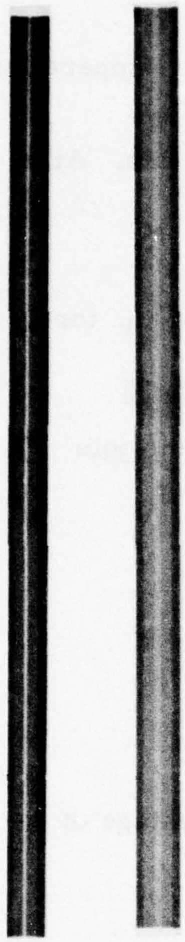
Estimated B_r based on cross-section: B_r = 629

COMMENTS:

Thin wall in strong direction due primarily to machining error.

Figure AII-3 X-Ray Transmission Photograph of APS Sample 143.

A. P. S. 146



H_c = 2.73 B_r = 587   at   30   ampere turns.

Anneal: 1010° 1.5 hrs. O_2; 1000° 1 hr. Air

Distortions:

Bow: .005 in.

Separation of insert halves: .006 in.

Wide-slot dimension: Parallel to join ☒ Perpendicular to join ☐

Thin-wall dimensions (mils):

End: 45
Center: 35
End: 40
Minimum: 35
Average: 40

Average thin-wall dimension as percentage of ideal .050": 80 percent.

Estimated B_r based on cross-section: B_r = 640

COMMENTS:

Separation along most of the length. Thin wall primarily machining error.

Figure AII-4 X-Ray Transmission Photograph of APS Sample 146.

APPENDIX III

Arc Plasma Spray Log

ARC PLASMA LOG
High Velocity Nozzle
B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Arc	Gas Flow-CFH	Powder	Hopper Speed %	Spray Distance in	* Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
11/7/75	4	LMTF53 G-2	LMTF190(35)	400	Ar 60	He 7.5	O_2 12.5	70	2 1/2	100	0.5	750	850	1020^0(11)-2hrs. -O_2	Loading at end of run
	5		LMTF190(35)	430	55	10	15	55	4	70	0.4			1030^0 - 10 min	Lava plug used
														1020^0(11)-1hr. -O_2	Increased D_S-spray distance to prevent shock
	6		LMTF190935)	430	65	6	15	75	2 1/2		0.5			1020^0(11)-1hr.-O_2	
11/8	7			420	60	7.5	15	45	3 1/2						
	8			420	55	8	15	45	4						
	9			420	55	7.5	15	45	4					1050(H)-1 hr.	Long cracks after anneal
2/11/76	11		LMTAF200-25A	440				45	4	50	0.5				
2/12	12	LMTF50 G-3	LMTAF200-7A	360-450	50-60	7.5	7 1/2-10-20							1015(11)-2hrs. -O_2	All runs with G-3 powder thru APS-23 experienced some powder flow problems
2/12	13		LMTAF200-7A	420-500	50	7.5	10	45	4	45	0.5				
2/12	14		LMTAF200-7A	500	50	7.5	9	50	4 1/2						
3/2	15		LMTAF180(3)	500	50	7.5	10	40	4	60	0.35				Continual stalling of powder feed
3/2	16			500	50	7.5	10	50	4 1/2	50	0.35				
3/8	17			500	60	7.5	30	50	4 1/2	60	0.35				Higher powder feed to relieve blockage
3/8	18			520	50	7.5	30	50	4 1/2	50	0.40				
3/8	19			470-440	50	7.5	30	65	4	50					
3/10	20	(Chambers)	LMTF190(36)	550	60	7.5	30	65	4	50	0.44	700	700	1050(H)-2hrs.	
3/10	21			560-580	50	7.5	30	65	4		0.44				
3/11	22			500	50	7.5	15	50	4		0.6				Slight water leak at gun

ARC PLASMA LOG (Cont'd.)
High Velocity Nozzle
B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Arc	Gas Flow-CFH	Powder	Hopper Speed %	Spray Distance in	* Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
3/11/76	23	LMTF50(Chambers)	LMTF190(36)	450	Ar 50	He 7.5	O_2 10	50	4	50	0.6	700	700	1050(H)-2hrs.	Powder dried overnight @ 80°C - worked
3/15	24	(Fines)		410	50		12	35	4	40	0.44			1050(H)-2hrs.	He gas elimination might have contributed to solution
3/15	25			Broke											
3/15	26			410	50		12	40	4	40	0.45				
3/15	27			410	50		12	40	4	40	0.46				
3/24	28		LMTAF180(33)	530	50		10	40	4 1/2	50	0.40				
3/25	29			470	50		10	40	4	40	0.40				
3/25	30	LMTF50 G-3(Fines)	LMTAF180(33)	480	50		10	40	4 1/2	40	0.40 -	700	700	1050(H)-2hrs Air	Approximately 160 grams of powder sprayed per sample
3/25	31			440-500	50		10	40	4 1/2	32	0.40				
3/25	32			500	50		10	60	4	32	0.65				
3/26	33			500-550	53		10-13	50	4	35	0.48				
3/26	34			575	55		15	50	4	30	0.65				Spitting still continuing at powder gas of 15
3/26	35			520	55		15	50	4	30	0.65			975°(H)-2hrs. Air	Too many samples breaking or fracturing at base
3/26	36			520	50		15	50	4	30	0.65				
3/26	37		Broke												

ARC PLASMA SPRAY LOG
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Roto Feed Hopper Speed %	Spray Distance in	Rate Rot %	Rate Pull in/min	Furnace Chamber	Temperature Holding	Anneal Cycle o/c	Comment
4/6/76	38	LMTF50G-3(fines)	LMTF 195(12)	500	Ar 50	$O_2$10	50	4	35	.65	700	700	1020(H) - 2hrs. 1010(H) - 1 1/2 hrs. ②	Powder flowed very well
4/6/76	39	G-3(fines)	195(12)	500	Ar 50	$O_2$15	50	4	35-30	.60	↓	↓	↓	
4/6/76	40	Broke	195(12)											
4/6/76	41	G-3(fines)	LMTAF 180(33)	500	Ar 50	$O_2$15	50	4	35	.60				
4/6/76	42	↓	LMTF 195(12)	500	Ar 50	$O_2$20	65	4	30	.60				Increase in powder flow parameters wasted less
4/12/76	43		LMTAF 200-7A	400	Ar 38	$O_2$15	55	4	25-30	.58	650	600	1010(11) - 1 1/2 hrs.	4/12, 4/13, 4/14 Babbitt visit
4/12/76	44	↓	200-7A	400	Ar 40	$O_2$20		4			↓	↓	↓	
4/12/76	45		200-7A	400	Ar 40	$O_2$20	60	4	75	.60				Five samples sprayed – four broke
4/12/76	46		200-7A											
4/13/76	47		200-25A	400-+20	Ar 40	$O_2$15	60	4	40	.75				
4/13/76	48	↓	200-25A	340-360	Ar 37 1/2	$O_2$20	60-65	4	40	.70				
4/13/76	49		LMTF 200(2)	370	Ar 35	$O_2$20-24	65	4	50					
4/13/76	50		200(2)	370	Ar 35	$O_2$24	63	4	70	.65				Drastic increase in sample rotation - loading problem
4/13/76	51		200(2)	440	Ar 40-38	$O_2$23-27	60- 65-71	4	75	.75				
4/13/76	52		LMTAF 200(3)	380	Ar 35-33 He 6.5	$O_2$78-30		4	75	.65			975(11) - 2 hrs. ②	Lower arc heat increased deposit and sample survival
4/13/76	53		200(3)	380	Ar 35-38	$O_2$29	60	4	50	.55			1010(H) - 1 hr.	Powder 50 mesh screened
4/14/76	54		200-7A	350-360	Ar 32	$O_2$25	60	4	75	.55				
4/14/76	55	↓	LMTF 195(12)	360	Ar 33	$O_2$23	60	4	75	.55				
4/14/76	56		195(12)	360	Ar 33	$O_2$23	60	4	75	.55				

ARC PLASMA SPRAY LOG (Cont'd.)

High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed	Spray Distance	Rate Rot %	Rate Pull in/min	Furnace Chamber	Temperature Holding	Anneal Cycle o/c	Comment
4/14/76	57	LMTF50G-3(fines)	LMTF 195(12)	360	Ar 33	$O_2$23	60	4	75	0.6	525-550	350	1010-1Hr(H)	
4/14/76	58	↓	LMTAF200-7A	360	Ar 33	$O_2$18	60	4	75	.75	550	↓	↓	
4/14/76	59		200-7A	360	Ar 33	$O_2$18	60	4	75	.75	↓			
4/14/76	60		200-7A	360	Ar 33	$O_2$18	60	4	75	.78				
4/14/76	61		200-7A	360	Ar 33	$O_2$18	60	4	85	0.9				
4/14/76	62		200-7A	360	Ar 33-35	$O_2$18	60	4	85	.8				
4/14/76	63		200-7A	360	Ar 33	$O_2$18	60	4	85	.95				
5/4/76	64	↓	LMTF 195(12)	360	Ar 33	$O_2$18	60	5	75	.78	400	575	1010-10Hrs. (II)	Deposit rate poor at 5 in. Reduced chamber temp. appears to affect deposit more than simply increasing D_S
5/4/76	65		195(12)	360	Ar 45	$O_2$18	60	5	80	.8		↓		
5/4/76	66		195(12)	360-420	Ar 45	$O_2$18	60	6	80	.6				
5/4/76	67		195(12)	380	Ar 33	$O_2$18	60	4-5	75	.66	599-485	525	1010-10Hrs. (II)	
5/4/76	68	50G-3(fines) +325 - 80	195(12)	380-420	Ar 33	$O_2$18-24	70	6	75	.66	425-525	↓		
		Mesh screened	195(12)	300-340				4		.95				
5/4/76	69	53G-2	195(12)	340	Ar 33	$O_2$18-28	70	4	75	1.0	540			Change in powder did not change loading problem.
5/7/76	70	50G-3(fines)	LMTAF 180(33)	360-300	Ar 40	$O_2$18-25	60	4	75	0.6	675			Changed anode from smaller bell shaped bottom to larger 901-11 which turned out to be a disaster for sprayability
		50 mesh screened	LMTF 190(36)								↓			
5/7/76	71	50-G-3(fines)	LMTF 195(12)	360	Ar 40	$O_2$15	70	4	75-40	.6				Substrate rotation at slower speed, hotter substrate
5/7/76	72	↓	LMTF 195(12)	360-340	Ar 38-45	$O_2$25	85	5	75	.6	500-550		1010-16Hrs. (II)	Increased D_S required more arc heat

ARC PLASMA SPRAY LOG (Cont'd.)

High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed	Spray Distance	RATE Rot %	RATE Pull in/min	Furnace Chamber	Temperature Holding	Anneal Cycle o/c	Comment
5/13/76	73 LMTF	53G-2(fines)	LMTAF 200-25A	200-400	Ar 40-60	$O_2$10-30	50-80	4	75	.45	525	550		Tried just about everything, poor deposit
5/13/76	74		200-7A	200-400	Ar 40-60	$O_2$10-30	50-60	4	75	.45	525			Again poor deposit
Low Velocity Nozzle	75		200-7A	300-350-220-330	Ar 40 He 7.5	$O_2$15	40-75 65	4	75	.45	625			Much better deposit w/He. Bricks in rear of furnace opening reduce heat loss to chamber. Very little loading with good deposit
5/13/76 Same as APS68	76	50G-3(fines) + 44u - 177u	195-10A	300-350-330	Ar 40 He 7.5	$O_2$15	50-80 60	4	75	.52	640		1010-16Hrs. (11)	G-3 powder appeared to run better than G-2
5/13/76	77	50-G-3(fines)	195-10A	250-300	Ar 40 He 7.5	$O_2$15	70	4	75-100	.52	650			Red glow at 250 amps but 300 amps was better deposit heat
5/13/76	78	50G-3(fines)	LMTF 200(1)	300-350	Ar 40-45 He 7.5	$O_2$15	70	4 1/2	100	.52	650			Had to increase arc velocity to 45 and heat to 350 for good deposit.
5/20/76	79	53G-2(fines)	200(1)	340	Ar 35	Ar 15	[illegible]	4			600	500	1010-1 1/2Hrs(H)	Dielectric sheared off
5/20/76	80		200(1)	340-320-300	Ar 35	Ar 15-20	[illegible]	4	100	60	600			
5/20/76	81		195(11)	350-320-380-420	Ar 35	Ar 20	[illegible]	4	100	.8-.7	570-600			Increase in arc current increased pulsing
5/20/76	82		195(11)	300-380	Ar 35	$O_2$20-30	70	4	100	.82	600			
5/20/76	83		195(11)	370	Ar 35	$O_2$20	70	4 1/2	100	.65	530-550			
5/20/76	84		195(11)	300	Ar 35	$O_2$15	50-70	4	100	.5	550			Longer small diameter anode

ARC PLASMA SPRAY LOG (Cont'd.)
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed	Spray Distance	RATE Rot %	RATE Pull in/min	Furnace Chamber	Temperature Holding	Anneal Cycle o/c	Comment
6/1/76	APS 85**	LMTF50G-3(fines)	LMTAF180(33)	340	Ar 40*	$O_2$15-20	50	4	100	.9	600	500	1010-1 1/2Hrs(H)	Target area quite red at minimum heat settings - still building on gun end - minimum current settings 320 amps-350 amps
6/1/76	86**		Solid substrate w/one slot-external	350	Ar 40-50-60*	$O_2$20	50-70	4	100	.6-.9			1010-1 1/2Hrs(H)	
6/1/76	87**		Platinum wire forced into slot	350	Ar 50*	$O_2$20	70	4	60-100	1.1			1010-11/2Hrs(H)	No cracking due to wire insert
6/1/76	88**		LMTF 195(12)	360	Ar 50*	$O_2$20	70	4	60	.9			1010-1 1/2Hrs(H)	Sample broke after 1 1/2 in. of deposit
6/1/76	89**		Solid substrate with three slots	360	Ar 50*	$O_2$20	70	4	100-60	1.0			1010-1 1/2Hrs(H)	
6/1/76	90**		LMTAF 195-10A	360	Substrate sheared off in beginning of run									
6/1/76	91**		195-10A	340-350	Ar 55-60*	$O_2$20-23	70	4	100	.6-.8			1010-1 1/2Hrs(H)	Target glow reduced to orange at higher velocity but powder flow had to be increased
6/1/76	92**		LMTF 195(12)	320-340	Ar 60*	$O_2$25	90	4	100	.9-.8			1010-1 1/2Hrs(H)	
6/7/76	93	50G-4(fines)	195(12)	320-400	Ar 40	$O_2$25	70	4	100-60	.32	480-550		1010-1 1/2Hrs(H)	New powder checkout chamber temp low
6/7/76	94		195(12)	350	Ar 40	$O_2$25	70	4	100	.65	525-575		1010-1 1/2Hrs(H)	
6/7/76	95		195(12)	350	Ar 40	$O_2$25	70	4 1/4	100	.63	500-550		1010-1 1/2Hrs(H)	
6/7/76	96		195(12)	350	Ar 40	$O_2$25	70	4	100	1.1	600		1010-1 1/2Hrs(H)	Chamber temp 575°- deposit much better
6/9/76	97**		195(12)	220	Ar 40	$O_2$15	55	4	50	.74	675-700	600	1010-1 1/2Hrs(H)	Motor fuse blew
6/9/76	98**		195(12)	220-260	Ar40	$O_2$15-20	70	4	50	.74	600-730		1010-1 1/2Hrs(H)	Chamber temp up to 700° ○1025° 1 1-2 Hrs. - air

* Regulator pressure of 43 psi

** Modified large opening anode w/Bell end

ARC PLASMA SPRAY LOG (Cont'd.)
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed	Spray Distance	RATE Rot %	RATE Pull in/min	Furnace Chamber	Temperature Holding	Anneal Cycle o/c	Comment
6/9/76	APS 99**	LMTF50G-4(fines)	LMTF195(12)	300	Ar 40	$O_2$20	80	4	50	.9	670-730	600	1010-1 1/2Hrs(H)	Chamber temp. up to 700° 1025° 1-2 Hrs. air
6/9/76	100**	50G-4(fines)	195(12)	300-280-240	Ar 40	$O_2$20	80	4	50	.9	615-700		1010-1 1/2Hrs(H)	1025° 1-2 Hrs. air
6/9/76	101**	50G-4(chambers)	195(12)	280-290	Ar 40	$O_2$20	80-85	4	50	.9	660-730		1010-1 1/2Hrs(H)	Chamber temp. up to 700° 1025° 1-2 Hrs. air
6/9/76	102**		195(12)	280	Ar 40	$O_2$20	70	4	50	.9	600-675			Shroud with O_2 - initially too much O_2, then malfunctioned - inconclusive at this point concerning shroud
6/17/76	103**		195(12)	260	Ar 40	$O_2$20	60	4	50	.4	675	650	1010-1 1/2Hrs(H)	Chambers powder clogged
6/17/76	104**	50G-4(fines)	195(12)	280	Ar 40	$O_2$20	70	4	50	.72				
6/17/76	105**		195(12)	280	Ar 40	$O_2$20-15	70	4	50	.8-.6				Parameters represent pretty standard conditions - deposit affected by build-up on gun
6/17/76	106**		195(12)	275	Ar 40	$O_2$22	70	4	50	.7				
6/17/76	107**		195(12)	275	Ar 40	$O_2$20	70	4	50	.5				Shroud used with no gas
6/18/76	108^{o-o}		195(12)	550	Ar 40 He 7.5	$O_2$10	60	4 1/4	50	.5	800	660		Malfunction because of buildup Chamber temp. very hot, 800°
6/18/76	109^{o-o}		195(12)	550	Ar 40 He 10	$O_2$15	90	4 1/4	50	.5	900	660		900°

** Modified large opending anode w/Bell end
o-o Low temperature anode

ARC PLASMA SPRAY LOG
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed	Spray Distance in	Rate Rot %	Rate Pull in/min	Furnace Chamber	Temperature Holding	Anneal Cycle*	Comments
7/15/76	Δ 110	LMTF50G-4 Chambers	LMTF195(12)	220-600	Ar 40 He 7 1/2	O_2 15	50-70	4	50	.8	800°	600°	1010°-1 1/2 Hrs. (H)	New furnace - Works great - Chamber should be deeper - Anode worked poorly - Powder flowed poorly
7/16/76	Δ Δ 111	LMTF50G-4 fines	LMTF190(36)	320-340	Ar 40	O_2 15-13	60-75	4	50	.6 - .55	725°	600°	1010°-1 1/2 Hrs. (H)	Chamber deepened -better
	Δ Δ 112			380	Ar 40	O_2 13-7 1/2	75	4	50	.8	750	600		
	Δ Δ 113			400-500	Ar 50-45	O_2 15	70	4	50	.7	750	600		
	Δ Δ 114			420	Ar 40	O_2 13	80	4	50	.8	750	600		
	115			380	Ar 35	O_2 15	65	4	50	.92	750	600		Changed from large anode to 901-12 anode (regular)
	116			Substrate cracked - aborted										
	117			400	Ar 35	O_2 15	70	4	50	.85	750	600		Big red glow - But best depositing conditions - even buildup negligible
7/21	118	LMTF50G-4 Fines	LMTAF2007A	400	Ar 40	O_2 15	70	4	50	.77	750	600	1010°-1 1/2 Hr. (H)	Powder flow a problem

* (H) refers to APS holding oven. II and III refer to separate Lindberg furnaces for annealing.

Δ 901-11 Anode modified to feed powder 1/4 in. cooler.

Δ Δ 901-11 Large opening cut back to 30° after powder port.

ARC PLASMA SPRAY LOG (Cont'd.)

High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comments
7/21/76	119	LMTF50G-4	LMTAF180(33)	400	Ar 40	O_2 15	60	4	50	.8	750	600	1010°-1 1/2Hr(H)	Powder flow a problem
7/22	120	LMTF50G-4	LMTAF180(33)	400	Ar 40	O_2 15-19	60-70	4	50	.65-.8	750	600	1010°-1 1/2 Hr(H)	Powder freshly dried overnight @ 80°C
	121	↓	↓	400	Ar 40	O_2 20	70	4	50	.83	750	600	↓	Sample broke halfway sprayed
	122	↓	↓	300	Ar 40	O_2 17	70	4	50	.85	750	600	↓	Reduced current still producing red glow - tho not as bright
	123	↓	↓	300	Ar 40	O_2 18	70	4	50	.85	750	600	↓	
7/26/76	124	LMTF50G-4	LMTAF180(33)	300	Ar 40	O_2 17	75	4	50	.85	750	600	1010°-1 1/2 Hr(H)	
	125	↓	↓	300	Ar 40	O_2 17	75	3 1/2	50	1.0	750	600	↓	D_s decrease improved deposit
	126	LMTF50G-4 Fines	LMTAF180(33)	240	Ar 40***	O_2 17	75	3 1/2	50-40	0.95	750	600	↓	Holding furnace TC still not near samples
	**127	↓	↓	240-500	Ar 40	O_2 17	60	3 1/2	50	0.85	750	600	901-10 Anode did not work with usual parameters	
7/28	128	LMTF50G-4 Fines	LMTF190(36)	200-220	Ar 40***	O_2 17	70	3 1/2	50	0.72	750	700	1010°-1 1/2Hrs(H)-O_2	Current too low - 180 amps
	129	↓	↓	220-240	Ar 40***	O_2 17	70	3 1/2	40-50	.70-.82	750	700	Temp. actually went to 1060 for 10 min.	
	130	↓	↓	230-240	Ar 40	O_2 17	70	3 1/2	50	.87	750	700		7 min spray plus 3 min transfer - 10 mins. total - approx. 34 grams deposited

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** 901-10 Anode-powder port angled forward 55°.

*** Regulator pressure of 40 psi.

ARC PLASMA SPRAY LOG (Cont'd.)
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comments
7/28	131	LMTF50G-4 Fines	LMTF190(36)	250	Ar 40	O_2 17	70	3 1/2	50	.92	750	700	↓	Approx. 34 grams deposited
	132	↓	↓	250	Ar 40	O_2 17	70	3 1/2	50	.95	750	700	↓	
	133	↓	↓	250-840	Ar 50-45	O_2 17	70	3 1/2	50	.95	750	700	↓	Arc gas flow of 50 CFH - Too high
8/3	134	LMTF50G-4 Fines	LMTF190(36)	240	Ar 40	O_2 17	70	3 1/2	50	.80	750	700	1010°-1 1/2 Hr(H) TC moved near	Approx. 121 grams G-4 powder per sample in this run
	135	↓	↓	240-260	Ar 40*	O_2 17	70	3 1/2	50	.95	720	700	samples - Temp actually 1050 - 15 min 1010 - 1 hour	Ⓐ Quick Anneal 135, 138 ① 800° - 40 min ② 1000° - 1 hour
	136	↓	↓	260	Ar 40*	O_2 17	70	3 1/2	50	.98	750	700	↓	
	137	↓	↓	260	Ar 40	O_2 17	70	3 1/2	50	1.0	750	700	↓	
	138	↓	↓	255	Ar 40*	O_2 17	70	3 1/2	50	1.0	740	700	↓	
	139	↓	↓	260	Ar 40	O_2 17-15	70	3 1/2	50	.9	740	750	↓	
8/4	140	LMTF50G-4 Fines	LMTF200(1)	260	Ar 40	O_2 17	60	3 1/2	50	.75	750	700	1010°-1 1/2Hrs. TC located through	
	141	↓	↓	260	Ar 40	O_2 17	60	3 1/2	50	.75	750	700	front brick	
	142	↓	↓	260	Ar 40	O_2 17	60	3 1/2	50	.85	750	700	↓	
	143	↓	↓	260	Ar 40	O_2 17	60	3 1/2	50	.95	750	700	↓	

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ARC PLASMA SPRAY LOG (Cont'd.)

High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comments
8/4	144	LMTF50G-4 Fines	LMTF200(1)	260-280	Ar 40	O_2 17	60	3 1/2	50	.85	750	700	1010^{o}-1 1/2Hrs.	
	145	↓	LMTF195(12)	280	Ar 37 1/2	O_2 17	60	3 1/4	50	1.1	750	700	↓	
	146	↓	↓	280	Ar 37 1/2	O_2 17	60	3 1/4	50	1.5	750	700	↓	
8/26	147	LMTF50G-4 Fines	LMTAF200(2)	280	Ar 37 1/2	O_2 17	60	3 1/4	50	1.0	700	700	No Anneal	Holding Furnace TC located on furnace floor with bead bent into furnace area - Temperature too high - Samples broke because of thermal shock
	148	↓	↓	270	Ar 37 1/2	O_2 17	60	3 1/4	50	1.0	700	650		
	149	↓	↓	270	Ar 37 1/2	O_2 17	60	3 1/4	50	1.0	700	650		
	150	↓	↓	280	Ar 37 1/2	O_2 18	60	3 1/4	50	1.0	700	650		
	151	↓	↓	280	Ar 37 1/2	O_2 18	60	3 1/4	50-40	1-.95	700	650		
	152	↓	↓	280	Ar 37 1/2	O_2 18	60	3 1/4	50	1.0	700	650		
	153	↓	↓	280	Ar 37 1/2	O_2 18 1/2	60	3 1/4	50	0.95	700	875-900	No Anneal	Holding Furnace TC malfunctioned - Temp too high
	154	↓	↓	280	Ar 37 1/2	O_2 18 1/2	60	3 1/4	50	0.95	700	875-900		
	155	↓	↓	280	Ar 37 1/2	O_2 18 1/2	60	3 1/4	50	.95	700	875-900		First sample sprayed from top down
8/31	156	LMTF50G-4 Fines	LMTF190(36)(1/2) LMTAF190-15A(1/2)	290	Ar 36	O_2 18 1/2	60	3 1/4	50	.92	700	650		New chamber elements - New powder dist. wheel
	157	Dried 4 hrs. @ $100^{o}C$	LMTAF200-7A	290	Ar 36	O_2 17	65	3 1/4	50	.92	700	650		
	158			290	Ar 36	O_2 17-15	60	3 1/4	50	.92-.8	700	650	1015^{o}-1 1/2Hr Air	Only bottom to top spray in run - Only sample to crack in anneal

* (H) refers to APS holding oven. II and III refer to separate Lindberg furnaces for annealing.

ARC PLASMA SPRAY LOG (Cont'd.)

High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comments
8/31	159	LMTF50G-4	LMTAF200-7A	290	Ar 36	O_2 17 1/2	65	3 1/4	50	1.0	700	650	1015°-1 1/2Hr Air (II)	
	160			290	Ar 36	O_2 17 1/2	65	3 1/4	50	1.0	700	650		
	161			290	Ar 36	O_2 17 1/2	65	3 1/4	50	1.0	700	650		10 samples sprayed in 2 hrs. - approx. 1025 grams All "downers"
	162			290	Ar 36	O_2 17 1/2	65	3 1/4	50	1.0	700	650		
	163			290	Ar 36	O_2 17 1/2	65	3 1/4	50	1.0	700	650	1015° III-1 1/2Hr-O_2	
	164			290	Ar 36	O_2 17 1/2	65	3 1/4	50	1.0	700	650		
	165			290	Ar 36	O_2 17 1/2	65	3 1/4	50	0.95	700	650		
9/1	166	LMTF50G-4 Fines	LMTF200(2)	200	Ar 36	O_2 17 1/2	65-70	3 1/4	50	0.92	700	650	1015°(II)-1 1/2Hrs-O_2	
	167			280	Ar 36	O_2 17 1/2	70	3 1/4	50	.95	685	650		
	168		LMTF200(1)	280-260	Ar 36	O_2 17 1/2	70	3 1/4	50	.95-.85	700	650		
	169			310	Ar 36	O_2 17 1/2	65-70-80	3 1/4	50	1.2	700	650		
	170			305	Ar 36	O_2 17 1/2	75	3 1/4	50	1.3	700	650		
	171			305	Ar 36	O_2 17 1/2	75-70	3 1/4	50	1.3	700	660		Slight gun buildup at powder feed of 75
	172		LMTAF180(33)	305	Ar 36	O_2 17 1/2	70	3 1/4	50	1.3	700	665		
	173			305	Ar 36	O_2 17 1/2	70	3 1/4	50	1.3	700	665		Top inch blown off but spray completed
	174		LMTAF200-7A	305	Ar 36	O_2 17 1/2	70	3 1/4	45-50	1.3	700	650		Rotation erratic - slower speed
	175			305	Ar 36	O_2 17 1/2	70	3 1/4	50	1.3	700	650		

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ARC PLASMA SPRAY LOG (Cont'd.)
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comments
9/2/76	176 •	LMTF50G-4 Fines	LMTAF180(33)	300	Ar 36	O_2 17 1/2	70	3 1/4	50	1.1	700	650	1015^0(III)-1 1/2Hrs-O_2	First sample after trying undried G-3 powder
	177		LMTAF190-15A	300	Ar 36	O_2 17 1/2-18 1/2	70	3 1/4						
	178			300	Ar 36	O_2 18 1/2-16	70	3 1/4	50	1.0	700	650		
	179		LMTAF180(33)	315	Ar 36	O_2 17	70	3 1/4	50	1.0	710	670		
	180		LMTAF190-15A	320	Ar 36	O_2 17	70	3 1/4	50	1.3	710	665		
	181			320	Ar 36	O_2 17	70	3 1/4	50	1.3	700	665		
	182			310	Ar 36	O_2 17	70	3 1/4	50	1.3	700	665		
	183			300-320	Ar 36	O_2 17	70	3 1/4	50	1.3	700	665		Better deposit at 320 amps
	184			320	Ar 36	O_2 17	90	3 1/4	50	1.4	700	665		Fastest deposit to date
9/14	185	LMTF50G-3 Fines	LMTAF200(2)	320	Ar 36	O_2 16	65	3 1/4	50	1.0	700	650	1025^0(II)-1 1/2Hrs-O_2	No a smooth spray - first sample roughness
	186		LMTAF190-15A	330	Ar 36	O_2 16 1/2	65	3 1/4	50	.7-1.0	700	650		Very wobbly
	187		LMTF195(11)	330-320	Ar 36	O_2 16 1/2	70	3 1/4	50	1.3	700	650		First two substrates broke during spraying
	188			360	Ar 36	O_2 16 1/2	70	3 1/4	50	1.3	700	650		Current crept up
	189			310	Ar 36	O_2 17 1/2	65	3 1/4	50	1.0	700	650	1015^0(III)-1 1/2Hrs-O_2	Continuous trouble up to this point with falling
	190			310	Ar 36	O_2 17	65	3 1/4	50	1.1	700	665		stringers that are 1/2 in. long then fall off
	191			310-340	Ar 36	O_2 18	65	3 1/4	50	.95	720	650		Current surging during run

* (H) refers to APS holding oven. II and III refer to separate Lindberg furnaces for annealing

ARC PLASMA SPRAY LOG (Cont'd.)

High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comments
9/14	192	LMTF50G-3	LMTF195(11)	320	Ar 37	O_2 18	65	3 1/4	50	1.0	700	650	1015^0-1 1/2 Hr-O_2	Arc gas increased to check surging - Sample broke at base - Left in chamber
	193			320	Ar 37	O_2 18	65	3 1/4	50	1.0	700	650		
	194			Sample broke										
9/15	195	LMTF50G-4 Chambers	LMTF195(12)	320	Ar 37	O_2 17-10	65	3 1/4	50	0.85	700	650		Powder gas decrease stopped stuttering feed
	196	-170 Mesh (-88μ)		360	Ar 37	O_2 13	65	3 1/4	50	1.0	700	650		Excellent parameters
	197			360	Ar 37	O_2 13	65	3 1/4	50	1.0	700	660		
	198			340	Ar 37	O_2 13	70	3 1/4	50	1.2	700	665		
	199			350	Ar 37	O_2 13	65	3 1/4	50	0.95	700	665		Low arc gas tank volume influenced current fluctuation
	200			340	Ar 38	O_2 13	65	3 1/4	50	1.0	700	665		Powder ran out - Overlapped in middle
9/21	201	LMTF50G-4 Chambers -88μ	LMTF195(12)	340	Ar 37	O_2 13	65	3 1/4	50	1.2	700	650	1200^0-30 min-O_2	
	202			340-400	Ar 37	O_2 11	65-75	3 1/4	50	1.2	700	650		Current surged
	203			400	Ar 37	O_2 11 1/2	75	3 1/4	50	1.2	700	650		
	204			400-460	Ar 37	O_2 11	65	3 1/4	50	1.1	700	650		Current crept up
	205			440-460	Ar 37	O_2 11	65	3 1/4	50	1.3	700	650		*Excellent deposit*
	206			460-500-440	Ar 37	O_2 11	65	3 1/4	50	1.3	700	650		Current above 460 appeared to melt powder
	207			440	Ar 37	O_2 11	65-75	3 1/4	50	1.3-1.6	700	650	1200^0-30 min-O_2 Controller malfunctioned	
	208			480	Ar 50	O_2 17-13	65	3 1/4	45	0.7				Attempt to similate APS 12 with higher velocity

ARC PLASMA SPRAY LOG (Cont'd.)
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comments
9/21/76	209	LMTF50G-4 -88μ	LMTF195(12)	480	Ar 50	O_2 13	65-55	3 1/4	45	0.8	700	650	1200°(H)-30 min-O_2 Controller malfunctioned	Too much waste overspray at hopper 65
	210	↓	↓	440	Ar 38	O_2 13	65	3 1/4	45	1.3	700	650	↓	
9/23	211	LMTF50G-4 -88μ	LMTAF190-15A	360	Ar 38	O_2 13	65	3 1/4	50	1.1	700	650	1020°(H)-2Hrs-O_2	New TC in holding furnace - Completely sleeved - located close to ceiling over floor hole - APS 212 appeared warped after spraying
	212		LMTAF195-10A	420	Ar 38	O_2 13	65	3 1/4	50	1.2	700	650		
	213			400	Ar 38	O_2 13	65	3 1/4	50	1.2	700	650		
	214			400	Ar 38	O_2 13	65	3 1/4	50	1.0	700	650		Looks warped
	215			400	Ar 45	O_2 13	65	3 1/4	50	0.9	700	650		
	216			400	Ar 45	O_2 13	65	3 1/4	50	0.95	700	650		
	217	↓	↓	400	Ar 45	O_2 13	65	3 1/4	50	1.0	700	650	↓	

* (H) refers to APS holding oven. II and III refer to separate Lindberg furnaces for annealing.

TABLE I

ARC PLASMA SPRAY LOG
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comment
10/6	218	LMTF475G-5 -88μ*	LMTAF190-15A	300	Ar 38	O_2 15	65	3 1/4	50	0.6	700	650	1020°(H)-2Hrs. O_2	Anneal conditions not recorded
	219			400	Ar 38	O_2 14	65	3 1/4	50	1.2				Air in hydraulic line causing poor start
	220			320-420	Ar 38	O_2 14	65-75	3 1/4	45	1.0				Current fluctuating as much as 100 amps
	221			420	Ar 45	O_2 14	65	3 1/4	45	1.1				Wobble forced slower rotation rate
	222			420	Ar 45	O_2 14	65	3 1/4	45	1.1				Higher velocity affects sample rotation and eccentricity
10/11	223	LMTF475G-5 -88μ	LMTAF190-15A	440-450-460	Ar 38	O_2 13	70	3 1/4	50	0.6	710	650	1016°(11)-3Hrs. O_2	Substrate large grained - left in furnace during previous anneal
	224		LMTAF180(33)	450-340	Ar 38	O_2 25	65	3 1/4	45	0.6	710	685		New anode and cathode for this day's run - flame firing upward - needed more powder gas
	225			320-400	Ar 38	O_2 25	70	3 1/4	42	.6-.8	710	680		
10/12	226	LMTF475G-5 -88μ	LMTAF180(33)	360	Ar 38	O_2 25	65	3 1/4	50	0.8	700	-0-	1050°-O_2	Quick anneal - no soak - broke apart - cathode check
10/13	227	LMTF475G-5 -88μ	LMTAF190-15A	320	Ar 40	O_2 30	65	3 1/2	42	0.6	700	650	1000°(11)-5Hrs-O_2	Sample fell in dismount
	228			380	Ar 40	O_2 17	65-70	3 1/2	50	1-0.6	675	650		Seal leak at hopper
	229			380	Ar 40	O_2 17	70	3 1/2	50	1-0.6	675	650		
	230			380	Aborted - Element Failed									
	231	LMTF475G-5 -88μ	LMTAF200(2)	350	Ar 40	O_2 15	65	3 1/4	50	0.6	700	650	1000°(11)-5Hrs-O_2	Powder buildup - broke two substrates
	232			320	Ar 40	O_2 15	50-40	3 1/4	50	0.6	700	650		
	233			320	Ar 40	O_2 15	50	3 1/4	50	0.6	700	650		Left TC malfunctioning
10/14	234	LMTF475G-5 -88μ	LMTAF200(2)	380-400	Ar 40	O_2 20	35	3 1/4	50	0.7	620	650	1000°(11)5 Hrs-O_2	Left TC failed
10/15	235	LMTF475G-5 -88μ	LMTAF195-10A	350	Ar 40	O_2 12	65	3 1/4	50	0.8	750	650		
	236			360	Ar 38	O_2 13-18-22	65	3 1/4	50	0.8	750	650	1000°(11)5Hrs-O_2	
	237			330	Ar 38	O_2 22	65	3 1/4	50	0.8	736	650		Pull rate system will not hold set rate - continually decreases
	238		LMTAF190-15A	320	Ar 38	O_2 22	65	3 1/4	38	0.8	750	650		
	239			365	Ar 38	O_2 23	65	3 1/4	38	0.9-1.0	645	650		
10/22	240	LMTF50G-4 -88μ	LMTAF195-10A	320	Ar 38	O_2 17-22	65-75	3 1/4	50	1.0	660	370		
	241			320	Ar 38	O_2 22	65	3 1/4	50	0.75	625	450	1016°(11)-2Hrs-O_2	Annealed in sand to avoid distortion
	242			320	Ar 38	O_2 22	65	3 1/4	50	0.95-.8	690	483		

* Screened through 170 mesh (88μ)

ARC PLASMA SPRAY LOG (Cont'd.)
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comment
10/22	243	LMTF475G-5 -88μ	LMTF 200(2)		Dielectric Broke									
	244		LMTAF 195-10A	320	Ar 38	O_2 22-28	65-75	3 1/4	42	0.8	645	450		Sample dropped ~ 1/2 in. during spray - overlap
10/26	245	LMTF50G-4 -88μ	LMTAF 195-10A	360	Ar 38	O_2 25	75	3 1/4	50	0.8-0.9	685	485	No Anneal	Ammeter of hopper @ 210 (420) milliamps
	246			320	Ar 38	O_2 25		Sheared Off				560		
	247			320	Ar 38	O_2 25	65	3 1/4	40	1.0	700	650		Jaws appeared to loosen after 1 in. of spraying
	248	LMTF475G-5 -88μ		320	Ar 38	O_2 15	65	3 1/4	50	1.0	685	650		Substrate wobbly - finally broke
	249			320	Ar 38	O_2 15-21	65	3 1/4	40	1.0	700	672		G-5 Powder flowed better than G-4
	250			320	Ar 38	O_2 22	65	3 1/4	42	0.9	700	650		
	251			320	Ar 38	O_2 18	65-50	3 1/4	40	0.7	700	675		Too much wobble for all samples
11/22	252	LMTF50G-4 -88μ + 44μ	Fe_2O_3-Solid	400	Ar 40	O_2 30	65	3 1/4	40	1.0	525	350		First use of graphite Top keeper - unsuccessful
	253		LMTAF 200(4)	380	Ar 40	O_2 15-25	50-65	3 1/2	50	0.4-0.7	620	650	1015°(11)-2Hrs. -O_2	Poor deposit
	254			380	Ar 40	O_2 25-30	55	3 1/4	50	0.5-.65	635	650		Poor powder flow
	255			380	Ar 40	O_2 30-27	60	3 1/4	50	0.5	640	650		Broke in raising - "upper" spray
	256	Not Temp. Conditioned		420	Ar 40	O_2 30	80	3 1/4	50	0.8	700	650		Broke - half sprayed - good deposit - hit obstruction
12/6	257	LMTF50G-4 -88μ	LMTAF200(4)	350	Ar 40	O_2 20	65	3 1/4	50	0.8	660	650	1015°(11)-2Hrs. -O_2	New powder hose - not a good sample - warped
	258		LMTAF195-10A	350	Ar 40	O_2 20	65	3 1/4	50	0.8	675	650		Powder flow improved as spraying continued
	259			350	Ar 40	O_2 20	65	3 1/4	50	0.8	640	600		258, 259 "upper" spray - spitting and too much wobble
12/6	260	LMTF50G-4 -88μ	LMTAF195-10A	350	Ar 40	O_2 16	65	3 1/4	50	1.0	665	600	1015°(11)-2Hrs. -O_2	Blew gun out before spray
	261		LMTAF200(4)	350	40	16	60	3 1/4	50	0.6	660	600		"Upper" spray - ran out of powder
12/9	262	LMTF475G-5 -88μ	LMTAF200(4)	360	40	15-30	65-50	3 1/4	50	0.5	700	720	1015°(11)-2Hrs. -O_2	Powder left in system did not spray well
	263			360	40	25	65	3 1/4	50	1.0	700	720		
	264			360	40	25	50-55	3 1/4	50	0.9	700	710		Sample broke, upper spray
	265			360	40	25	55	3 1/4	50	0.8	700	710	No Anneal	So much wobble that rotation rate just moving - broke in chamber - left to cool
	266			300	40	25	60	3 1/4	50-30	0.8-0.6	700	725		
12/13	267	LMTF475G-5 -88μ	LMTAF200(4)	220	35	13	60	2 7/8	50	0.8	700	600	Aborted because of substrate split	
	268			240	35	13	60	2 7/8	45	1.0	700	600	1015°(11)-2Hrs. -O_2	
	269			230	35	17-10	50-60	2 7/8	50	1.1	700	600		

ARC PLASMA SPRAY LOG (Cont'd.)
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow - CFH Arc	Gas Flow - CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle*	Comment
12/13	270	LMTF475G-5 -88μ	LMTAF200(4)	200	Ar 35	O_2 10	60	2 7/8	45	1.0	675	600	1015°(11)-2Hrs, -O_2	
	271			300-270	35	12	60	2 7/8	45	1.3	700	600	Aborted because of substrate split	
	272			250	35	11	60	2 7/8	45	1.3	700	600		Current too high
	273			220	35	11 1/2	60	2 7/8	45	1.1	685	600		
	274			210	35	12	60	2 7/8	45	1.1	700	700		
12/16	275	LMTF475G-5 -88μ	LMTAF200(4)	240	35	12	60	2 7/8	50	1.0	600	650	1015°(11)-2Hrs-O_2	Spray chamber a bit low in temperature
	276			210	35	17	50-60	2 7/8	50	1.0	690	600		
	277			210	35	12	60	2 7/8	Fwd 50	1.0	650	600		Wobble ~ 1/8 in.
	278			210	35	12	50	2 7/8	50	1.0	655	600		Wobble ~ 1/8 in. Broken near base
	279			210	35	12	50	2 7/8	Rev 45	1.0	690	600		
	280			210	35	12-10	50	2 7/8	50	0.8	675	600		Deposit thinned - "Upper" Spray
	281			210	35	10	40	2 7/8	45	1.0	680	700		
	282		Not Preheated (NP)	210	35	10	50	2 7/8	45	1.3	700	600		Substrate not preheated
	283			210	35	10	50	2 7/8	45	1.2	690	600		Ran out of powder
	284	LMTF475G-5 -88μ	LMTAF201-7A	210	35	10	50	2 7/8	50	1.0	700	600	1015°(11)-2Hrs-O_2	Substrate separation on initiating spray a continuous problem
	285			210	35	10	F50R	2 7/8	50	1.0	700	600		
12/21	286	LMTF475G-5 -88μ	LMTAF201-7A	210	35	O_2 11	50	2 7/8	50	1.1	700	600	1015°(11)-2Hrs-O_2	3/16 in. wobble initially but improved with spraying - back vent brick(Lge) replaced to conserve chamber heat - jaw tension may have decreased - jerky rotation
	287			210	35	12	50	2 7/8	45	1.0	700	600		
	288			220	35	12	50-60	2 7/8	45	1.2	700	600		
	289			220	35	13	50		40	1.1	700	600		
	290			220	35	12	50		40	1.1	710	600		
	291			220	35	12	50-45		40-35	1.0	710	600		Blobs increasing - but deposit good - no change made
	292			Broke after 1/2 in. deposit										
	293		NP	220	35	12-15	45-55		35	1.1-1.5	710	600		No preheat for substrate - (NP)
	294		NP	220	35	15	50		35	1.2	700	600		Current fluctuated briefly
	295		NP	220	35	15	45		35-30	1.1	700	600		Current initially at 200 - poor deposit
	296		NP	220	35	15	60		30	0.7	690	600		Short section for heavy deposit

ARC PLASMA SPRAY LOG
High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Roto Feed Hopper Speed %	Spray Distance in	Rate Rot %	Rate Pull in/min	Furnace Chamber	Temp Holding	Anneal Cycle	Comment
1/6/77	297	LMTF 475 G-5 -88μ 60° Dry	LMTAF 201-7A	220	Ar35	$O_2$15	50	2 7/8	35	0.9	700	900-600	1015°(11)-2Hrs-O_2	Chamber deepened - New Elements - 2 Pair 550W - used
	298	↓	↓	220-240	35	15	50-60	↓	35	1.0	715	650	↓	
	299			240	35	13	60		F35R	1.0	700	650		Rotation reversed at midpoint
	300			220	35	15	50		35	1.0	700	650		
	301			230	35	15-20	50-60		60	1.0	715	650		Higher rotation to reduce substrate separation - ineffective
	302			240	35	15-20	50-60		48	1.0	715	650		
	303		NP*	235	35	20	60		45	1.1	725	650		Retainer clip shift appears to reduce substrate separation
	304		NP	235	35	20	60		45	0.95	725	650		
1/12/77	305	LMTF 475 G-5 -88μ 100° Dry	LMTAF 201-7A NP	230	35	15	50	2 7/8	45	0.9	650	650		
	306	↓	NP	230	35	15-17	50	↓	45	0.9	700	650	1015°(11)-2Hrs-O_2	Heavy substrate Breakage with Powder Gas Initiation
	307		NP	260-230	37	15	50		40	1.1-0.9	725	650		"Upper" Spray
	308		NP	230	35	15-12	50		40	0.95	710	650	1015°(11)-2Hrs-O_2	
2/10/77	309	LMTF 475 G-5	LMTAF 200(4)	310-280	35	25	55	3 3/8	50	0.85	650	600		First Run with Mounting Tube Indirect Drive Assembly and Suspension Plate-Tube jaws not tight enough on substrate-Powder not dry enough New Tube Drive works well
	310	↓	↓	280	35	20	55	↓	50	0.85	650	600		
	311			280	38	20-25	50		35	1.0	710	600		
	312			400	Shut down because of poor deposit conditions									
2/16/77	313	LMTF475 G-5 -88μ	LMTAF 200(4) NP	250	43	20	50	25/8	45	1.0	685	600	1015°(11)-2Hrs-O_2	First use of graphite substrate base and modified new mounting tube
	314	↓	NP	250	43	20	50	↓	45	1.0	700	600	↓	
	315		NP	250	38	20	55-50		35	1.0	700	600		Substrate separating upon initiating spray
	316		NP	250	38	20	50		45	0.85	700	600		

* No preheat (NP)

ARC PLASMA SPRAY LOG (Cont'd.)

High Velocity Nozzle

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Roto Feed Hopper Speed %	Spray Distance in	Rate Rot %	Rate Pull in/min	Furnace Chamber	Temp Holding	Anneal Cycle	Comment
2/21/77	317	LMTF475 G-5 -88µ	LMTAF 200(4) NP*	260	Ar 38	O_2 15	50		40	1.1	700	600		
	318		NP	240	38	15	50-55		45	1.1	720	600		
	319		LMTAF 201-7A NP	220	38	15	55		45	1.05	725	600		Tube reject rod malfunctioned
	320		NP	200	38	14	55-50-60		45	1.1-0.9	725	600		Increased overspray exhaust with heat reduction
	321		NP	220	38	13	50		45	1.0	725	600		Best run parameters for day
	322		NP	220	38	15-10	70-60		45	1.2	600	600		
	323		NP	220	38	13	60		45	1.3	600	600		Substrate half cracked
3/8	324	LMTF475 G-7 -88 +53µ	LMTAF 200(4) NP	270	35	15	70	2 5/8	50	1.5	780-740	600	1015°(11)-2Hrs-O_2	After oven conditioning @100°C, particle size 10%-88u +53u, 60%-53µ +44, 30%-44u. Powder flowing eratically. First use of G-7 powder and uncoated elements in this series
	325		LMTAF 200-7A NP	210-220	35	20	70-65		50	1.3	760	600		
	326		NP	240	35	20	60-65		50	1.2	760-770	600		
3/9	327	LMTF475 G-7 -88 +53µ dried at 100° 4 hrs then screened	LMTAF 202-7A NP	260	35	16	65		50	1.4	725	600		
	328		NP	240	38	15-20	60		50	1.1	760-725	600		
	329		NP	220	38	20-25	60		45	1.0	725-755	600		220 amps appears to be minimum for powder parameters - current fluctuating at flow of 35 CFH of arc gas
	330		NP	280	35	20	60	3.0	45	0.9	735-760	600		
	331		NP	240-250	38	20	60	2 5/8	45	1.0	730-740	600		
	332		NP	260-270	38	20	50	2 5/8	45	1.0	745-765	600		Overspray reduced with hopper speed reduction
3/11	333	LMTF475 G-7 -53 + 44µ	LMTAF 202-7A NP	270-320	38	17-30	50-65		45	1.0	730	600	1015°(11)-2Hrs-O_2	G-7 powder flow erratic at best, but hopper gas leak may be the cause
	334		NP	320	38	30	65		42	1.0	730	600		
	335		NP	320	38	30	65		45	1.2-1.1	730	600		
	336		NP	320	38	30	65		42	1.1	730	600		
	337		NP	350	38	30	65		45	1.1-1.0	730-745	610		Current crept up from 320 - 360
	338		NP	320	38	30	65		45	1.1-0.8	730	600		Conditions poor - hopper leak severe - Graphite plug wobbly

* No preheat (NP)

ARC PLASMA LOG
High Velocity Nozzle
B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	* Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
3/16/77	339	LMTF475G-7(fines)	LMTAF202-7A	260	Ar 38	$O_2$20	60	2 5/8	45	0.5 - 1.0	730	0	1015°(11)-2hrs. -O_2	
3/17	340	-88 + 53 μ		300	38	25	60	2 5/8	45 R	0.6-0.8	725	0		Special run to accommodate movie
	341			300	38	23-20	60-65	2 5/8	40	0.7	725	0	Samples too short	Samples too short
3/30	342	chambers -177 μ	LMTAF202-7A	230	38	17	60	2 3/8	45	1-0.8	725	600	1015°(C)-2 hrs. -O_2	Interrupted spray - current fluctuating - changed cathode
	343			240-280	38	17-25-20	55		45	0.8	725	600	1015°(11)-4hrs. -O_2	
	344			275	38	22	55		45	0.8	725	600		
	345			250	38	22	55-60		45	0.8	750	600	1015°(11)-4 hrs. -O_2	Excessive overspray for all samples
	346	Fines -177 μ		250-220	38	22-25	60		45	0.9-0.8	750	600		First PM session sample Current still fluctuating ± 20 A
	347			250	38	25	60		40 R	0.9	750	600		
	348			220	38	17-20	55		45	0.9	760	600		Changed Ar tank to stop current fluctuation - worked
	349			180	38	22	55-60		45	0.9-0.8	760	600		Flow paramters just about minimum for powder used
	350	LMTF475G-7 chambers -177 μ	LMTAF202-7A	320	38	20-24	60	2 3/8	45	0.9	725	600		New Powder hose
	351			280-320	38	20	55			0.9	725	600		
	352			320	38	20	55			1.1	725			

* 50% = 106 rpm

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
4/4/77	353	LMTF475G-7	LMTAF202-7A	320	Ar 38	O_2 25	60	2 3/8	45	1.1	730	600	1015^0(11)-4hrs. -O_2	Abundant overspray
	354	Fines -177 μ		260-280	38	20-25	55			0.6-0.5	725			Deposit rate slower
	355			320-330	40	25-30	55-70			0.7	725			
	356			300	40	30	70			1.0-0.7	725			
4/8/77	357	LMTF475G-7 Chambers -177 μ	LMTAF202-7A	300	38	16	30-40	2 3/8	45 Fwd	1.0	760	600	1015^0(11)-4hrs. -O_2	Excellent deposit with such low hopper feed
	358			300		20-22-17	40-45			1.0	740			Problem with gun buildup
	359			300		20-25-17	50		45 R	0.9	740			Sample overlap sprayed two or three times Poor run
	360			300		20-15-25	50		45	0.75	740			Erratic deposit 170 gr/sample
	361	Fines -177 μ		250		17-23	50-55		45	1.0	760			Deposit still erratic
	362			240		23	50-60		Rev 45 Fwd	1.0-0.8	760			Rotation changed at midpoint
	363			240		20-25-27	60-65		30	0.8	750			Deposit more erratic 140 gr/sample
4/12	364	G-5 -88 μ	LMTAF202-7A	260-280	38	17-20-26	65	2 3/8	45	0.8	735	600	1015^0(11)-4hrs. -O_2	New powder hose. Spray chamber temp $\Delta T = 70^0$
	365			270		13	70		45	0.9	735			No overspray w/powder gas reduction

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
4/12/77	366	LMTF475G-5 -88 μ	LMTAF202-7A	270	Ar 38	O_2 13	70	2 3/8	45	0.9	750	600	1015^0(11)-4hrs. $-O_2$	
	367					13				0.9	750			Spray very smooth. Like production
	368			250		13	73			0.95	750			
	369			250		13	73			1.0	750			200 gr/sample
	370	G-5/G-7		250		13-15	73			1.0	750			G-5 powder ran out - PM session with G-7 and over-
	371	G-7 -53 +44 μ		260		17	70			0.7	750			lap for bottom half of length G-7 powder deposit slower
	372			240		15	75			0.7	750			for same parameters. New Ar tank for PM session
	373			210		13	75			0.7	750			Buildup occurring on gun
	374			220		13	75			0.75	750			No. 371 broke in dismount
	375			230		13	75			0.65	750			No. 372, 376 broke next
	376			230		15	75			0.75	750			day in taking from furnace No obvious reason
	377	G-5 +88 μ		370-340		17-19	75-70			1.0	750			250gr/sample- Larger particle fraction sprayed faster - not as hot
	378			360		15	75			1.1	750			
4/22	379	G-7 Fines -74 +44 μ	LMTAF203-7A 23407-83	260	38	16	65	2 5/8	45	0.8	750	600	1015^0(11)-4hrs. $-O_2$	Denser graphite plugs used for substrates
	380					16	65			0.9	730			
	381						Sample broke early in spray							
	382						55			0.95	725			Buildup on gun
	383									1.0				
	384					16 1/2				1.0	725			Increased powder gas to eliminate "shooters" -

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	* Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
4/22/77	385	G-7 Fines -77 +44 μ	LMTAF203-7A	255	Ar 38	O_2 17 1/2	55	2 5/8	45	0.9	725	600	1015°(11)-4hrs. -O_2	Still "shooters"
	386					18 1/2				0.9-0.8	735			
	387									0.82-0.78	735			
	388									0.75	735			
4/26/77	389	G-7 Fines +177 +74 μ	LMTAF204-7A	270	38	20-18	57	2 5/8	45	0.70	750	600	1015°(11)-4hrs. -O_2	Smaller bore powder hose used. No obvious difference
	390			265		14-15 1/2	60			0.75	760			Overspray obvious on first sample 185 grams sprayed per sample
	391			260		15-16 1/2	60			0.78	740			
	392			260	37	17	60			0.78	740			This sample had flawed substrate - wobble
	393			240	33 1/2	15	60-50			0.75	750			
	394			215	33 1/2	15	55	2 5/8		0.7	750			Powder flow erratic
	395			240	35	16	55			0.8	760			Gun still loading
	396			230		14-16	53-57			0.7	760			Continual small adjustments needed in powder gas and hopper feed to maintain deposit - sample overlapped - powder ran out after 2" -
	397			230		15	56			0.7	775			
	398			230		15	57			0.7	775			
4/28/77	399	G-7 Fines -177 +74 μ	204-7A	220-280-300	38	16	60	2 5/8	45	0.6	750	600	1015°(11)-4hrs. -O_2 **	All new tanks - poor run - Hopper ammeter high -
	400			300-400-430		15	62			0.6-0.75	750	600		One inch overlap
	401			270		16	55			0.8	725	600		Changed anode and cathode deposit improved

* 50% = 106 rpm ** Anneal set temperature increased 15°

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
4/28/77	402	G-7 Fines -177 +74 μ	LMTAF 204-7A 23407-83	280	Ar 38	O_2 16	55	2 5/8	45	0.9	725	600	1015°(111)-4hrs. -O_2	"Shooters" at end of spray
	403			280		16	50-55			0.75	725	600		Wobble due to plug - gun aim change needed
	404			280		15	55			0.92	725	600		
	405			260		15	50			0.9	725	600		Good run
	406			240		17	55			0.8	725	600		Continuous overspray
	407			240		17	55			0.8	725	600		Slight overlap at end
4/29/77	408	G-7 Fines -177 +74 μ	204-7A 23407-95	300	38	15-17	50-60	2 5/8	45	0.65	725	600	1015°(111)-4hrs. -O_2	Continual fine adjustments needed throughout run on hopper speed and pull rate
	409			280		17	55-60		45	0.65	700	600		
	410			270		16	55-58		45	0.70	750	600		
	411			260		17	60			0.7-0.8	740	600		
	412			260		17	55			0.8	750	600		No adjustment needed
	413			260		17	55			0.75	750	600		"Shooters" still occurring
	414	Broke 2/3 sprayed		260		17	52			0.8	750	600		
	415			260		16-12	60			0.75-0.85	750	600		Deposit improved with powder gas decrease
	416	Fines/Chambers		320		14	52			0.9-0.95	750	600		Chambers dumped in with 60 gr of fines left - no "shooters" but excessive overspray
	417	Chambers		400		14-10	35-40			0.9-1.0	750	600		

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
4/29/77	418	Chambers	LMTAF 204-7A 23407-95	340	Ar 38	O_2 11	45	2 5/8	45	1.05	750	600	1015^0(111)-4hrs. -O_2	Broke before anneal (BBA)
	419		Blew out of mounting tube after 3/4 in. sprayed											
	420	LMTF475G-7 Fines-53 +44 μ	LMTAF204-7A 23407-95	300	38	13	50			0.95-0.8	720	600		Broke in dismount (BID)
	421			345-330		16	45			0.85	725			Broke in defurnacing (BDF)
	422			310	33	15-18	45			0.85	725			Tube rotation a bit eccentric
	423			310	35	15	45			0.85	725			Deposit silhouette not straight
	424			310		15	45-43			0.85	725			"Shooters" as usual after 1"
	425			315		15	45			0.85	730			
	426			315		15	45			0.7-0.80	710			Buildup broke loose after 3" - deposit improved
	427			315		15	42			0.78	675			Right front chamber element shorted
5/5/77	428	G-7 Fines -53 +44 μ	204-7A 23407-95	310	33	12	47	2 7/8		0.80	725		1015^0(11)-4hrs. -O_2	Sample reclaimed (No. 419) with 1" sprayed - lowered arc gas cutoff to 25 CFH - overlap necessary
	429			320	27	12	45			0.8	725			
	430			320-340	33	12-15	45			0.75	725			Deposit improved
	431			340	30	17	40			0.75	725			
	432			340	33	13-12	45-55			0.7-0.9-0.7	725			Frequent adjustments necessary

ARC PLASMA LOG (Cont'd.)
High Velocity Nozzle
B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	• Rot %	• Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
5/5/77	433	G-7 Fines -53 +44	LMTAF 204-7A 23407-95	350	Ar 33	O_2 11 1/2-13	55	2 7/8	45	0.95	725	600	1015°(11)-4hrs. -O_2	Again adjustments - overlap near bottom
	434			350	33	12	55			0.95	725			
	435			340	33	11-15	50-55			0.8	725			
	436			360-340	30	13	40-45			0.9-0.8	725			Buildup affecting aim
	437			340	30	12	50			0.9	725			
	438			350	30	14	50			0.9	725			
	439			350	30	14	47-49			0.8	725			Hopper speed adjustments sufficient to control deposit in last three samples
5/9/77	440	G-7 Fines -88 +53 μ	204-7A 23407-95	350	40	14	45-48			0.75	725			
	441			360	40	18-15	45-48			0.7				Chipped substrate
	442			340	38	16-14	45-55			0.75				Deposit not good so far - on the skimpy side
	443		205-7A 23407-96	340	35	15	55			0.75				
	444			340	31	15-14	50-55			0.8-0.85				
	445			330	31	12	50			0.67				
	446			340	31	12	45			0.72				
	447			340	31	12	41			0.7				Substrate cracked - run aborted
	448			340	31	12	45			0.78				Powder gas of 11 CFH appeared to cause spiraling effect in deposit - 12 CFH OK

• No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
5/9/77	449	LMTF475 G-7 Fines -88 +53 μ	LMTAF205-7A 23407-96	340	Ar 31	O_2 12	42	2 7/8	45	0.78	725	600	1015(11)-4hrs. -O_2	Powder gas of 11 CFH appeared to cause spiraling effect in deposit - 12 CFH OK
	450			340	31	11-12	40-50			0.78				
	451			340	31	12	45-50			0.78				
	452			340	31	12	45			0.78				
5/10/77	453	G-7 Chambers -177 +74 μ	205-7A	340	27	9	33			0.95	720		1015^0(111)-4hrs. -O_2	
	454			350	25	8-8 1/2	32			0.98	720			
	455			320-340	25	8 1/2	32			0.90	725			
	456			350	25	8	34			0.90	725			
	457			340	25	7	33-35			0.95	725			
	458			350	25	9	40			0.85	725			
	459			350	25	10	38			0.85	725			
	460			350	25	10	40-45			0.85	735			
	461			350	25	10	40			0.85	735			
	462			360	25	10	40			0.87	735			
	463			360	25	10	40-43			0.85-0.6	725			
	464			350	25	10	45			0.65-0.85	735			Well sprayed day average 10.5 min/sample Almost no problems
	465			350	27	11 1/2	40			0.9	735			

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
5/11/77	466	G-7 Chambers -177 + 74 μ	LMTAF205-7A	340	Ar 25	O_2 8 1/2-9 1/2	30	2 7/8	45	0.73	750	600	1015(11)-4hrs. -O_2	New Ar tank, slight loading towards end
	467			345	25	9 1/2	27			0.75	735			
	468			345	27	10	30			0.70	735			Adjustments needed continually
	469			330	24	10	30			0.70	740			Overlap in first 1" but smooth thereafter
	470			300	25	10	27			0.72	745			Arc gas flow changes at low end affect flame shape
	471			350	25	10	30			0.75	745			
	472			340	27	15	50			0.7-0.5	715			
5/16/77	473	G-7 Chambers -297 + 177μ	LMTAF205-7A 23407-96	400	25-35	15-20	35	2 7/8	45	0.7	680			BAA (Broke after anneal)
	474			400-350	30	18	32-40			0.75	680			BAA- 30% longitudinal crack
	475			400-360	25	20	40			0.6	670			Overspray necessary
	476	-177 + 74μ		350	25	20-27	35			0.7	720			
	477			330	27	20	35			0.7	670			Shutdown after 1" to change anode and new cathode
5/17	478	G-7 Chambers -297 + 177μ	205-7A	330	27	13	26			0.7	725			New furnace elements all four chambers
	479			340-380	27	14	14-17			0.75-0.6				Many adjustments necessary
	480			340	23	7-12-15	12-15			0.6-0.75				Again deposit problem
	481			350	23	14-11	12			0.7				
	482			350	23	14	12-32			0.6-0.8				Deposit improved with hopper feed increase
	483			350	23-29	13-15	25-32			0.75				Powder buildup

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)
High Velocity Nozzle
B Gear Set

Date	Number	Ferrite	Dielectric **	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed % •	Spray Distance in	* Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
5/17/77	484	G-7 Chambers -297 + 177μ	LMTAF 205-7A	350	Ar 29-23	O_2 15	30-40	2 7/8	45	0.75	725	600	1015(111)-4hrs. -O_2	Powder flow biggest problem
	485			380	28	15	15-60			0.6-1.15				Hopper feed increase solved flow problem
	486			370	27	15	57			1.1				Production type run
	487			360	27	15	57-59			1.1				
	488			360	27	15	60-57			1.0-1.1				
5/18	489	G-7 Chambers -297 +177μ	205-7A	360	27	15	39			1.05	780		1015(11)-4hrs. -O_2	New argon tank
	490			360	27	15	35-44			1.05	750			
	491			360	27	15	42-46			1.1	750			Overspray excessive
	492			360	28	15	45-50			1.1-0.95	750			Overlap necessary
	493			360	28	15	45			1.0	750			
	494			360	28	14	54			1.05	750			
	495			360	28 R	15	56			1.02	750			Overspray in middle of substrate from premount storage
	496			360	28 R	15	53-48			1.05	750			Same overspray from storage
	497			360	28 R	15	58			1.07	750			Spray appears left but deposit best
	498			370	28	15	55			1.09	750			
	499	LMTF 475 G-5 Chambers +88μ	LMTAF206-7A 23407-96	420	35 R	22	75			0.8	750			Excessive overspray and blob spitting
	500			450	38	22	80			0.9-1.25				Again overspray

* 50% = 106 rpm

** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	• Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
5/23	501	LMTF475 G-7 Chambers -177 + 74	LMTAF206-7A 23407-96	360-390	Ar 28	O_2 13	25-32	2 7/8	45	1.1-1.0	750-775	600	1015°(11)-4hrs. -O_2	
	502			350		13	42			1.2	760			Increased hopper speed-Better deposit efficiency
	503			345			32-35			0.9	740			
	504			350			40			0.95				
	505			345			42-45			0.85				
	506			345			43			0.85				
	507			360		13 1/2	50			0.85				
	508			360		13 1/2	49			0.82-0.87				Slight gun adjustment
	509			360		14	47			0.80				
	510			370		14	50			0.75	735			
	511			360		14	50			0.8	740-770			
	512			360		14	45			0.8	730			Longer dismount time - Approx. 2 min. cooling
5/24	513	G-7 Chambers -177 + 74	206-7A 23407-96	400	30	13-15-16	70	3 1/8		0.8	740			New anode - scorch mark - New type cathode 901-14 - Target area orange red
	514			400-450-400	35-28	15	63			0.8	720			
	515			400	28	16 1/2	65			0.9	720			Base target zone whitish red
	516					16 1/2-15	70-65			0.85	720			About 5 minutes in holding oven during powder change - Target glow very hot - also rapid transfer

* 50% - 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric **	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot % *	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
5/24/77	517	LMTF475 G-8 -177 + 74	LMTAF206-7A 23407-96	400	Ar 28	O_2 15	65	3 1/8	45	0.8	760	600	1015°(11)-4hrs. -O_2	
	518					15-16	50-60			0.9	725			Overlap after 2 in. - again rapid transfer
	519			360		15-18	55-65			0.7	720			G-8 not flowing well - frequent adjustments needed
	520					16	50			0.5-0.7	720			Gun buildup and flow adjustments
	521	G-8 Chambers -177 + 74	203-7A 23407-95	320-400	28	13-15-16 1/2	50-65			0.75	735			New cathode
	522			405		17	54-60			0.8	720			Sample had longitudinal or seam crack in middle, 2 in. long
	523	G-8 Fines -177 + 74		410		16 1/2	60			0.75	725		1015°(111)-4hrs. -O_2	When door opened - fell apart and broke - No. 521 also - No. 523 overlapped after 2 in. with powder change - Powder flow problem
	524	G-8/G-5 -88		400	23	13-17	60			0.80	725			
5/31/77	525	LMTF475 G-5 Fines -177 +74	LMTAF205-7A 23407-97	380	30	14	55	2 5/8	45	0.80	750	600		Broke at tweezer contact in dismount
	526			370	27	14	60			0.73	725			Broke same as No. 525
	527		206-7A -96	400	30	14	55			0.75	725			
	528		205-7A -97	400	28	15-13	55	2 7/8		0.75	725			Sample flew apart on dismount
	529		206-7A -96	370-450	35	13	70-60			0.7	725			Current shot up - unsteady deposit conditions

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
5/31/77	530	LMTF475 G-5 Fines -177 +74	LMTAF206-7A 23407-96	360-400	Ar 31	O_2 15	60	2 7/8	45	0.9	725	600	1015^0(111)-4hrs. $-O_2$	Broke at plug in dismount
	531		205-7A 23407-97	450	31	15	65			0.6	725			Powder sprayed eratically with frequent buildup and following hot spots - No. 531 = BID - No. 532 = BAA
	532		206-7A -96	400	32	12	60			0.65	725			
	533			410	30	12	52			0.8	725			BAA - typical, as of lately,
6/1/77	534	G-5 Fines -177 + 74	205-7A 23407-97	350	27	19	50-55	2 3/4		0.7-0.8	725	600		substrate seam crack
	535			340	27	18	47-50			0.72	725			Broke in holding furnace
	536			380	27	16-22	50-65-57			0.8-0.9	690			
	537	Fines/chambers		370		18	45			0.9	695			Deposit via hopper speed influenced by hopper volume
	538	Chambers		350-370			45-47			0.9-0.85	700			
	539			375			39			0.8	700			Substrate cracked - abort
	540			380			48-52			0.9-0.82	700			Chipped substrate
	541		205-7A	380			45			0.85	700			Feed pulsing reduced
	542			380			45-48			0.9	700			Leftfront element gone
6/6/77	543	G-8 Chambers -177 + 74	205-7A 23407-96	370	30	14	42-48	2 7/8		0.72	725	600	1015^0(11)-4hrs. $-O_2$	New elements (4), new Ar, O_2
	544			370			45-48			0.72				First two ran well
	545		LMTF195(12)	360			45-48			0.75				Powder stoppage and substrate sheared off
	546		LMTAF200(4)	390		15	50			0.8-0.75				Deposit shadow irregular
	547		LMTAF205-7A -97	390	30-28		45-48			0.78				Deposit improved with Arc gas change

* 50% = 106 rpm

** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
6/6/77	548	LMTF475 G-8 -177 + 74 μ	LMTAF205-7A 23407-97	380	Ar 28	O_2 15	48-45	2 7/8	45	0.8	725	600	1015^0(11)-4hrs. -O_2	Last 2" very hot
	549			390			48			0.87				Silhouette much smoother last two samples
	550			390			50-53			0.9				
	551			390			48			0.95				Abort
6/7/77	552	LMTF475 G-8 Chambers -177 + 74 μ	LMTAF205-7A 23407-96	370	30	14	46			0.72	745	600		Quick dismount
	553						47			0.85	720			
	554						45-50			0.88	725			
	555						47-50			0.88				Deposit stopped for clean-out and restarted half-way
	556						47-51			0.90				
	557		205-7A -97			14-15	47-53			0.90				BAA -broke after anneal
	558			380		15	50-48			0.87				Broke before anneal
	559			375	29	15	48			0.90				Fast initiation of spray - adjustments throughout
	560			370	30	15	53			0.90				BAA - 80% longitudinal crack
	561			370	28	15	51-55			0.90				
	562	G-5/G-8		380-320	28	15	50-45			0.95-1.1				Ran out of G-8 after 1 1/2"
6/8	563	G-5 chambers -177 + 74 μ	LMTAF207-7A 23407-98	370	30	17	45-47	2 7/8	45	0.95	725	600	1015^0(111)-4hrs. -O_2	Contract speed specification demonstration (SSD) New cathode, anode

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric **	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	* Rate Rot %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
6/8/77	564	LMTF475 G-5 Chambers -177 + 74μ	LMTAF207-7A 23407-98	370	Ar 30	O_2 16	46	2 7/8	45	1.0	725	600	1015°(111)-4hrs. -O_2	
	565				29	16	48			1.05				
	566					16-16 1/2	47-50			1.05				
	567					16-17	45-52			1.1				
	568					16-17	50			1.0				Abort after 1" crack
	569			380		16	50			1.0				
	570			390		18	55			1.0				
	571			395		19	55			1.0				
	572			390			56			1.02				
	573			398			50-52			1.04				End of SSD- excellent mechanical performance
	574			380			55			1.0				
	575			380			57			1.1				Plug broke off in dismount
	576			355			55			1.07				
6/13/77	577	LMTF475 G-8 Fines -177 +74μ	Fe_2O_3 Solid	400	32	20	60	2 7/8	45=96rpm	0.6	725	600	1015°(111)-4hrs. -O_2	Test sample
	578		207-7A 23407-98	400-380	32	20	65			0.6				
	579			390	40	20	63			0.6				Broke in holding furnace
	580			460-360	40-25	20	60			0.65				Aborted-dielectric cracked
	581		205-7A 23407-97	380	28	16 1/2	55			0.5				Aborted - per No. 580
	582			380	30	23	50-55			0.65				Excessive "shooters" - 40 arc gas better

* 50% = 106 rpm

** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
6/13/77	583	LMTF475 G-8 Fines -177 +74μ	LMTAF205-7A 23407-97	380	Ar 35	O_2 18	55	2 7/8	45=96 rpm	0.6	725	600	1015°(111)-4hrs. -O_2	Broke in defurnacing
	584			380	40	20	60-66			0.6				Reduced "shooters"
	585			370	30	20	65			0.62				Sporadic
6/14/77	586	G-8 Fines -177 + 74μ	207-7A 23407-98	340-350	30	16-17	54-57	2 5/8		0.73-0.8	725			Changed to SSD cathode - arc improved - broke in middle
	587			300	28	18	57-67	2 7/8		0.7				Broke per No. 586
	588			360	35	18	57-59			0.7				All three samples sprayed well - breaking or cracking Reason mystifying
	589		205-7A 23407-97	360	30	18-20	63			0.8-0.73				
	590			380	35	20	60-75			0.73				Target hot - deposit slow
	591		23407-98	360	30	10-15	60			0.75				Substrate broke in middle
	592		205-7A 23407-97	360-320	30	15-18	50-60			0.7				Broke in holding brick set
	593			300-280	35-38	21	65			0.7				Stringers reduced at velocity increase
	594			290	38	22	57-62			0.7				Good profile
6/20/77	595	G-8 Fines -177 +74μ	205-7A 2347-97	285-295	38	17	60	2 7/8		0.7	750		No	
	596			300	38	17	60			0.73	730			Sample cracked before dismount - fell apart
	597			310	38	17	60			0.75				Broke per No. 596

* 50% = 106 rpm   ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
6/20/77	598	LMTF475 G-8 Fines -177 + 74μ	LMTAF205-7A 23407-97	310	Ar 38	O_2 17	60	2 7/8	45=96 rpm	0.78	730	600	1015°(111)-4hrs. -O_2	Holding furnace door open to observe seam crack develop
	599			310	38	17	62			0.8		450		Abort
	600						65			0.8	725	510	Survivors	Sample left in spray chamber overnight to cool-cracked
6/22/77	601	G-8 Fines -177 + 74μ	208-7A 23407-98	310	38	23	55-60	2 7/8		0.55	750	700		Broke before door opened New Ar tank
	602		LMTAF190-15A	310	38	19	57-66			0.58				Broke in holding furnace
	603			305	38	19	57-63			0.62				
	604			305	38	19	59-62			0.7			1015°(111)-4hrs. -O_2	Shaky rotation
	605		LMTF200(1)	310-325	39	19	60-64			0.73				
	606			305		19-21	65-67			0.78	725			Broke in furnace - fell over
	607		LMTAF208-7A 23407-98	310		21	65			0.78	730			Flew apart - right element failed
6/27	608	G-7 Fines -44μ	Fe_2O_3 - Solid	300	30-38-28	16-18	55-60	2 7/8		0.65	760	600	1015°(11)-4hrs. -O_2	38 velocity too high
	609		208-7A 23407-98	320	28	18-20	60			0.75	725			Still "shooters"
	610			300		20	60-58			0.7	730			Cracked at seam
	611		LMTAF190-15A	300			68-62			0.7	735			
	612						62			0.78-0.72	725			Seam crack visible at dismount
	613		LMTAF195-10A Solid				60			0.75				

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
6/27/77	614	LMTF475 G-8 Fines -74 + 44μ	LMTAF195-10A	305-330	Ar28-38	O_2 20	60	2 7/8	45=96rpm	0.70	725	600	1015^{0}(11)-4hrs. -O_2	
	615			365-370	38-35 1/2		60-65			0.7				Deposit very smooth
	616		208-7A	360	35	20-22	58-68			0.72				Seam crack at top
6/28/77	617	G-8 Fines -177 +74μ	195-10A	370	40	22-23	65	2 7/8		0.7	770	600	1015^{0}(11)-4hrs. -O_2	New Ar O_2 tanks - Bottom clip
	618			380		23-25	65-70			0.7	725			
	619			380	38	20	60-70			0.73				Bottom clip
	620		208-7A -100	380-420	35-40	20	60-65			0.75				
	621			410	38	20-25	60-65			0.8				Substrate separation excessive (SS)
	622		190-15A	410	36	25	60-65			0.75				SS again noticed - only on last two
	623		LMTAF200(1)	410	36	25	60			0.72-0.77				
	624			420	30	25	60			0.7				SS in first 1 1/2"
6/29	625	G-8 Fines -177 +74μ	190-15A	400	36	20	60	2 7/8		0.7	765	600		Old style cathode 901-110
	626			395	28	15-20	49-60			0.75	725			Buildup caused erratic deposit - BID broke in dismount
	627		195-10A	400	37	20	60			0.7				
	628													
	629													Aborted - cracked substrate
	630		200(4)											

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
6/29	631	LMTF475 G-8 Fines -177 +74μ	LMTAF200(4)	400	Ar 37	O_2 20	60-63	2 7/8	40	0.7	735	600	1015^o(11)-4hrs. -O_2	
	632		LMTF200(2)	400			60		45	0.82	725	600		Looked warped at dismount
	633			380			60-65			0.75				
	634			380			60-67			0.78				No evidence of seam crack throughout day's run
6/30	635	G-8 Fines -177 +74 μ	LMTAF195-10A	365	37	20	60	2 7/8		0.72	750	600	1015^o(111)-4hrs. -O_2	Temperature at target 1350^{o}C
	636			370						0.75-0.72	735			
	637			360						0.74-0.78	745			T_T = 1390^{o}C
	638			355						0.8	740			
	639			345						0.82				Aborted - dielectric cracked
	640			345						0.83				Skimpy substrate half
	641		208-7A -100	335-355						0.8				Long crack upper half - taken hot from holding furnace
	642		195-10A	355						0.82				
	643			350			60-64			0.8				
	644			355			60-64			0.88				
8/4/77	645	G-8 Fines -177 + 74μ	LMTAF190-10A 24650-1	370	38	23	60	2 7/8	45	0.7	760	600	1015^o(111)-4hrs. -O_2	
	646			380		24				0.75	740			Stringers causing target temperature to change -
	647					24				0.8				Broke in defurnacing

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
8/4/77	648	LMTF475 G-8 Fines -177 + 74μ	LMTAF190-10A 24650-1	380	Ar 38	O_2 24-26	60	2 7/8	45	0.85-0.9	740	600	1015^0(111)-4hrs. -O_2	Shadow of seam crack at dismount - broke in defurnacing
	649					26				0.7				Stringer length increasing
	650			380-400	41	26	60-65			0.7				Many adjustments plus two overlaps
	651			390	38	24	63			0.78-0.83				Smoother run but broke in defurnacing
	652			390			65-70			0.85-0.80				Broke in dismount but good sample - stuck in tube-appeared very hot
	653			400			65			0.9				
	654			400		25	65-70			0.9-0.75				Current fluctuation 1" from bot. - deposit hotter than usual
	655			420	40	25	70			0.7				Sub cracked - abort
	656			410	38	25	67-72			0.78				Powder running out
	657			400	38	23-20	60-65			0.75		400		Only 1/4" bite in plug for No. 658, 659 to try and eliminate substrate separation
	658					20	60			0.73	770			
	659					20-21	60-65			0.65-0.70	740			
	660					21	60			0.75-0.80				Many adjustments in last two samples, 659, 660
	661					22	60			0.75-0.80				Shut down and cleaned Gun bore - improved
	662						60-63			0.78-0.85				Broke in defurnacing
	663			420			65			0.88				
	664			420			65			0.91				

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)
High Velocity Nozzle
B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot* %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
8/9/77	665	LMTF475 G-8 Fines -177 + 74μ	LMTAF190-10A 24650-1	405	Ar 37	O_2 22	65	2 7/8	45	0.88	740	400	1015°(111)-4hrs. -O_2	
	666			420			65			0.85				
	667			410			65			0.85				More adjustments
	668			430			65-68			0.88				Target very hot
8/11/77	669	G-8 -177 + 74μ	190-10A	400	38	22	60	2 7/8	45	0.72	740	500	1015°(111)-4hrs. -O_2	
	670						60			0.72				Slight bow in substrate half
	671		191-10A				60			0.76				*Seam crack before dismount* - Broke in dismount
	672						60			0.75				Same as No. 671
	673		190-10A Solid				60			0.78				Control check sample
	674		191-10A	360	30	22-24	60			0.75				Broke in chamber 1" from completion
	675					24	60			0.75				Excessive separation - broke
	676				33		60			0.75				Broke after 2" as No. 675
	677				36		60		40	0.75				Broke while spraying - seven in a row of new 191-10A
8/15/77	678	G-9 Fines -177 + 74μ	204-7A 23407-95	280	38	19	67	2 7/8	45	0.65-0.7	750	200**	1015°(111)-4hrs. -O_2	Broke at base - stored in No. 3 position
	679			285			65			0.7-0.85	740			
	680						65			0.85	745			More "shooters" this run
	681			375			65			0.8-0.85	750			Seam crack appeared after two samples sprayed

* 50% = 106 rpm   ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
8/15/77	682	LMTF475 G-9 F -177 + 74μ	LMTF 200(1) 23407-95	290	Ar 38	O_2 20	65-70	2 7/8	45	0.7	740	200	1015^0(11)-4hrs. -O_2	Run not as good as 1-3
	683			290-310	37	20	65			0.7-0.78	740			
	684		LMTAF191-10A	315	37	20	65			0.8	740	200***		Broke in defurnacing
	685			310						0.8	730			Broke in defurnacing
	686			315						0.75	740			Blew off 1" from completion
	687			330			65-70			0.8-0.75	740			Occasional hot spots
	688			325			70			0.92	750			*Broke in defurnacing*
8/17/77	689	G-9 Fines -177 + 74μ	191-10A	290	40	20	65			0.7-0.65	765	500	1015^0(11)-4hrs. -O_2	New Ar and N_2 tanks - Graphite top plug No. 689, 690
	690			295	41					0.65	765			
	691			290	38					0.75-0.80	740			Hot spot 1" from bottom
	692			280						0.75				Increased "shooters" due to powder buildup at flame sides
	693									0.75-0.78				
	694									0.75-0.8				Substrate separation
	695									0.78				
	696									0.8				
	697		LMTAF207-7A							0.8-0.75	720			Cracked just before dismount
	698		LMTAF191-10A							0.75				Substrate separation excessive
	699									0.75				

* 50% = 106 rpm ** No preheat *** Furnace turned off

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
8/22/77	700	LMTF475 G-8F -177 + 74μ	LMTAF191-10A	280	Ar 38	O_2 17	60	2 7/8	45	0.68	780	500	1015°(111)-4hrs.-O_2	Substrate separation excessive before mounting
	701						62-65			0.68	765			New anode cathode (SSD)
	702		Aborted after 1 1/2"				65.			0.7				Lower velocity tried - poor deposit
	703			300			60			0.7				Steady deposit
	704								45-40	0.72	760			Excessive wobble
	705								40	0.7				
	706								40	0.7				Current crept up to 320 for 1/4" deposit
	707				39		65		40-45	0.7	770			Hot spots and frequent adjustments - Ar tank 60 FT^3
	708						60-65		45	0.72	750			
	709			315			65		43	0.72	780			
8/23/77	710	LMTF475 G-9 Fines -177 +74μ	LMTF200(1)	290	38	19	60	2 7/8	43	0.70	790	215	1015°(11)-4hrs.-O_2	Holding furnace elements worn out
	711						60-63			0.75	790	210		
	712						60-63			0.7	790	215		
	713						63			0.75				
	714		LMTAF191-10A				60			0.73				"Stringers" from beginning becoming more troublesome
	715			285			60			0.7				40 amp increase for 1/4" - Deposit erratic
	716			280			60			0.7				

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
8/25/77	717	G-9 Fines -177 + 74μ	LMTAF191-10A 24650-2	285	Ar 38	O_2 19	60-65	2 7/8	43	0.7	780	500	1015°(111)-4hrs. -O_2	New holding furnace elements
	718			290-345			62			0.72	760			Current fluctuated
	719			295-280			62			0.7				
	720			280		20	62			0.72				
	721						62			0.73				
	722						62			0.73				
	723						64			0.75				Broke at plugin dismount
	724			290			65-69			0.75				
	725						65			0.78	770			
	726						63			0.73	780			Adjustments necessary to maintain deposit -
	727			300-360		20-25	65-80			0.65	780			Overlapped 1" from bottom - Powder low
8/31/77	728	LMTF475 G-9F -177 + 74μ	LMTAF191-10A 24650-2	300	Ar 38	O_2 19	65	2 7/8	43	0.75	800	500	1015°(111)-4hrs. -O_2	New cathode, Ar tank
	729			300						0.7	790			
	730			280-380						0.75	770			Current fluctuations early in run
	731			290						0.8	790			
	732			290						0.88	780			
	733			300						0.9	780			Broke at plug in dismount
	734			290						0.8	780			Deposit erratic due to current fluctuations
	735			280						0.8	770			
	736			290						0.88	790			

ARC PLASMA LOG (Cont'd.)
High Velocity Nozzle
B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rot %*	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
8/31/77	737	LMTF475 G-9F -177 + 74μ	LMTAF191-10A 24650-2	290-300	Ar 38	O_2 19-20	65	2 7/8	43	0.8	780	500	1015°(111)-4hrs. -O_2	
	738			300		20				0.8				
	739			290						0.9				Current still fluctuating
	740			290						0.8				Broke at plug in dismount
9/22/77	741	G-9 Fines -177 + 74μ	LMTAF192-10A 24650-8	280	38	20	65	2 7/8	43	0.75	790	500		Broke in dismount current fluctuated at end
	742			200						0.75	780	515		
	743			255						0.77				Again current fluctuation
	744			260						0.77				
	745			270						0.78				Well sprayed but cracked at seam before dismount
	746			260	Ar 38	O_2 20	65	2 7/8	43	0.88	780	515		
	747			255			67			0.88				
	748			260-240		20-21	68			0.85				
	749			245		21	68			0.85				
	750			245			68			0.87				Fluctuation in the middle again
	751			245			66			0.83	790			
	752			250			67			0.83				Broke after anneal
	753			260			67			0.85				

* 50% = 106 rpm ** No preheat

ARC PLASMA LOG (Cont'd.)

High Velocity Nozzle

B Gear Set

Date	Number	Ferrite	Dielectric**	Current Amps	Gas Flow-CFH Arc	Gas Flow-CFH Powder	Hopper Speed %	Spray Distance in	Rate Rot* %	Rate Pull in/min	Furnace Temperature Chamber	Furnace Temperature Holding	Anneal Cycle	Comment
9/23	754	G-9 Fines -177 + 74μ	LMTAF 192-10A 24650-8	275	Ar 38	O_2 20	57	2 7/8	43	0.72	820-790	510	1015°(111)-4hrs. -O_2	
	755			275			60-65			0.82	785	515		
	756			295			63			0.89	775			Broke while cooling
	757			290			67			0.92	795			
	758			285			65			0.83	790			
	759			320			63			0.83	790			Power fluctuated throughout run - broke in machining
	760			260		20-21	60-63			0.82	800			
	761			260		21	65			0.9	800			
	762			275			65-67			0.92	810			
	763			290			67			0.95	810			Seam crack, then broke in dismount
	764			290		21	61			0.82	810			
	765			280			62			0.83	810			

*50% = 106 rpm ** No preheat

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APPENDIX IV

ELECTRONICS COMMAND
TECHNICAL REQUIREMENTS

SCS-478
30 September 1974

ARC PLASMA SPRAYED PHASE SHIFTER ELEMENTS

1. SCOPE

1.1 This specification establishes the manufacturing methods for the production of arc plasma sprayed ferrite phase shifter elements for C-band non-reciprocal waveguide phase shifters for phased array antennas.

2. APPLICABLE DOCUMENTS

MIL-STD-202 - Test Methods for Electronic and Electrical Component Parts.

3. REQUIREMENTS

3.1 Physical dimensions. - The overall dimensions of the preliminary phase shifter element are illustrated in Figure 1.

3.1.1 Length. - The length of the final production phase shifter element ferrite-dielectric composite shall be 5.145 inches.

3.1.2 Dielectric dimensions. - The cross-sectional dimensions of the dielectric shall be 0.150 x 0.120 ± 0.001 inches. The dielectric shall have a 0.040 x 0.020 inch hole the length of the dielectric, in the center of the insert. The hole which is required for the switching wires of the phase shifter may either be formed within the dielectric or by using two (2) dielectric halves, each with a cross-sectional dimension of 0.150 x 0.060 inches, in which a slot can be cut, to form the hole when the halves are placed together. The initial length of the dielectric shall have to be longer than 5.145 inches, in order that it extends beyond the ferrite deposit.

3.1.3 Ferrite dimensions. - Ferrite shall be sprayed around the dielectric, such that the thickness of the deposit is enough to machine back to 0.050 ± 0.001 inches on each side. To determine the proper spraying parameters of Paragraph 3.8, all spraying shall be conducted on the same dielectric as that used in the dielectric insert.

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MANUFACTURING METHODS AND TECHNOLOGY MEASURE FOR ARC-PLASMA-SPR--ETC(U)
DEC 77 J J GREEN, H J VANHOOK, R J MAHER   DAAB07-75-C-0043
UNCLASSIFIED   S-2287   NL

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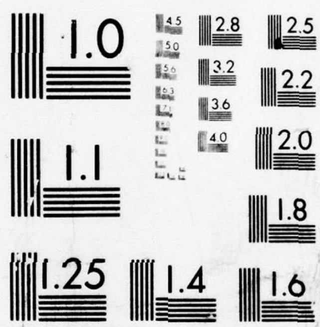

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

3.2 Properties of dielectric. - The dielectric shall have a loss tangent, tan δ, less than 0.0008, and a dielectric constant, K, greater than 18. The dielectric should exhibit a coefficient of linear expansion similar to that of the deposited ferrite.

3.3 Properties of the ferrite powder. - The lithium ferrite powder to be sprayed, shall be a free flowing sprayed dried powder with the capability of high feed rates, greater than 10 gms/min. The conglomerate particle size should vary from 5 to 100 microns in size.

3.4 Properties of deposited ferrite. - The magnetic properties of the arc plasma deposited ferrite shall exhibit the following characteristics:

3.4.1 The coercive force at room temperature shall be such that 90% of the required differential phase shift shall be obtained with at least 15 amperes of driving current.

3.4.2 Remanence at room temperature shall be such as to produce at least 340 degrees of differential phase shift, with driving current of 15 amperes.

3.4.3 Dielectric loss tangent of the ferrite at X-band shall be less than 0.0008.

3.4.4 Dielectric constant of the ferrite at X-band shall be greater than 15.

3.4.5 Temperature dependence over the range of -30 to 85°C.

3.4.5.1 The remanence shall not vary more than ± 10% over the temperature range.

3.4.5.2 The saturation magnetization shall not vary more than ± 10% over the temperature range.

3.5 Physical characteristics of composite. - The bond between the ferrite and the dielectric shall be such as to inhibit insertion loss spikes, and should not deteriorate over the temperature range of 3.4.5.

3.6 Physical handling. - The phase shifter elements, after machining, shall be capable of withstanding normal physical handling during assembly to the test jig, during the measurements, and removal from test jig.

3.7 Device requirements. - The following device requirements will be used as a guide to establish the reproducibility and yield of the device using the arc plasma spraying process, and are not intended to be the specifications of this program.

3.7.1 Frequency - 5.2 to 5.7 GHz.

3.7.2 Insertion phase - Mean $\pm 16^{\circ}$ at 5.45 GHz.

3.7.3 Differential phase shift - Mean $\pm 10^{\circ}$ at 5.45 GHz.

3.7.4 Insertion loss - less than 1.0 dB over the frequency range as specified in 3.7.1.

3.8 Arc plasma spraying parameters. - The following arc plasma spraying parameters will be determined and recorded:

3.8.1 Arc gas - Type of arc gas or mixture and the flow rate.

3.8.2 Carrier gas - Type and flow rate.

3.8.3 Working distance - The distance from gun to dielectric.

3.8.4 Powder feed - Powder feed in lbs./hr.

3.8.5 Oven temperature - Temperature of oven at start and during spraying.

3.8.6 Other spraying variables - Modification such as nozzle design, etc.

3.9 Device reproducibility. - The measurements conducted under Paragraph 3.7 shall be used to establish the reproducibility of the arc plasma spraying process.

3.10 Microwave test fixture. - A test fixture will be fabricated to accommodate the phase shifter element, such that each element can be located into this test fixture and the measurements of Paragraph 3.7 can be conducted. Appropriate transitions will be fabricated to match waveguide WR-187 (.872" x 1.872") to the test fixture (.250" x .750") to facilitate the testing required.

4. QUALITY ASSURANCE PROVISIONS

4.1 Inspection. -

4.1.1 Responsibility for inspection. - The contractor is responsible for the performance of all inspections specified herein. The contractor may utilize his own facilities or any commercial laboratory acceptable to the Government. The tests shall be performed under the supervision of a technically qualified Government representative. Inspection records of the examinations and tests shall be kept complete and available to the Government.

4.2 Classification of inspection. - Inspection shall be classified as follows:

(a) First article inspection (does not include preparation for delivery) (See 4.3).

(b) Quality conformance inspection (See 4.4).

4.3 First article inspection. - This inspection shall consist of all the tests included in the Government approved test procedure to show compliance with the requirements of Section 3. No failures shall be permitted.

4.3.1 Schedule of tests. -

(a) 20 each - Determination of Remanence and Coercive Force at room temperature (See 3.4.1 and 3.4.2).

(b) 10 each - Determination of Remanence and Coercive Force over the temperature range (See 3.4.5).

(c) 10 each (from b above) - Determination of Insertion Loss, Insertion Phase, and Differential Phase Shift over the specified frequency range at room temperature.

(d) 2 each (from c above) - Determination of Insertion Loss, Insertion Phase, and Differential Phase Shift over the specified frequency and temperature ranges.

4.4 Quality conformance inspection. - This inspection shall be performed on samples selected from the pilot production as specified in the bid request and contract.

5. PREPARATION FOR DELIVERY

5.1 Preparation for delivery shall be in accordance with best commercial practices.

PBN-78-90

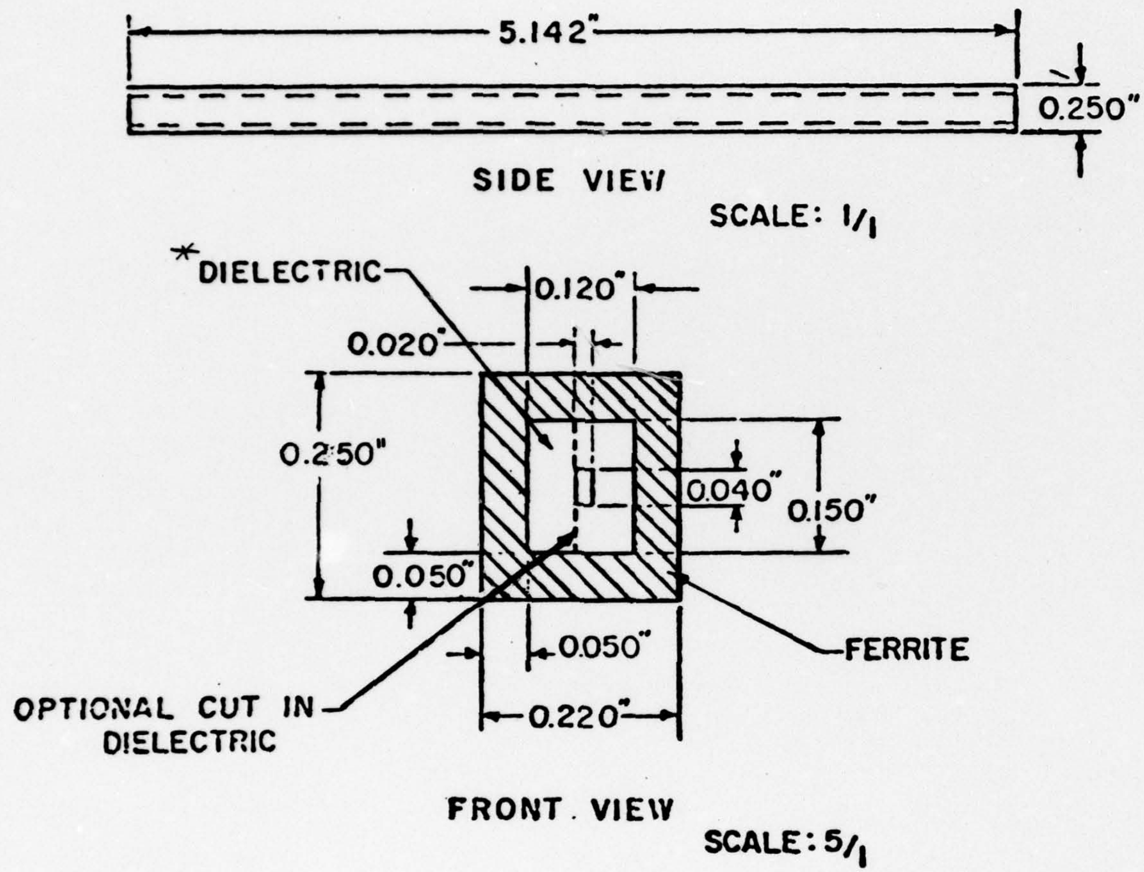

Figure 1 Arc Plasma C-Band Phase Shifter (Tolerance ± 0.001 in.).

* Dielectric core geometries of either center or exterior dots are acceptable.

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