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# Traveling-Wave-Tube Efficiency Improvement by a Low-Cost Technique for Deposition of Carbon on Multistage Depressed Collector

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## Summary

A simple method of improving the traveling-wave tube (TWT) and multistage depressed collector (MDC) efficiency has been demonstrated. The efficiency improvement was produced by the application of a thin layer of carbon to the copper electrodes of the MDC by means of a rapid, low-cost technique involving the pyrolysis of hydrocarbon oil in electric arc discharges. Experimental results with a representative TWT and MDC showed an 11 percent improvement in both the TWT and MDC efficiencies as compared to those of the same TWT and MDC with bare copper electrode surfaces. An extended test with a 500-W, continuous wave (CW) TWT and small-sized MDC indicated good stability of the carbon coated electrode surfaces after a relatively small initial degradation in TWT overall and apparent MDC efficiencies.

## Introduction

Significant traveling-wave tube (TWT) and multistage depressed collector (MDC) efficiency improvements have been demonstrated through the use of carbon electrode surfaces in the MDC in place of the machined copper surfaces generally used in MDC's (ref. 1). However, the use of carbon electrodes in MDC's in bulk form requires special fabrication techniques (refs. 2 and 3); and some of the techniques for deposition of thin layers of carbon on metal substrates (ref 4.) are costly, time consuming, and produce very delicate surfaces which require special handling. A simple, potentially rapid and low-cost process for the deposition of roughened carbon on copper substrates has been developed at the NASA Lewis Research Center (ref. 5).

An experimental program involving two representative TWT-MDC combinations was conducted (1) to quantify the efficiency improvements possible and (2) to evaluate the long-term stability of the carbon coating under the intense electron bombardment encountered in small MDC's operated in conjunction with medium power TWT's. This paper presents a description of the carbon deposition process and results of the following:

(1) Measurements of some secondary-electron-emission characteristics of a representative carbon-on-copper surface.

(2) A study of TWT and MDC performance to compare carbon-coated copper electrodes to untreated copper electrodes.

(3) An 850-hr-extended CW test to evaluate long-term stability of the carbon-coated electrode surfaces.

The TWT and MDC performance of carbon-coated copper electrodes was compared to that of untreated copper electrode surfaces by using them in geometrically identical MDC's, operated with the same TWT. Evaluation of the durability of the carbon coating was based on (1) periodic measurements of the MDC performance over the test duration and (2) visual and scanning electron microscope examinations of the MDC electrodes following completion of the test program. Different TWT-MDC combinations were used for the performance comparison and extended tests.

The authors wish to express their gratitude to Arthur N. Curren of the NASA Lewis Research Center for measuring the secondary-electron-emission characteristics of a representative pyrolyzed carbon-on-copper sample, and to Stanley Jopek of NASA Lewis Research Center for optimization of the procedure and applying the carbon coating to the MDC electrodes.

## Carbon Deposition Technique

The technique made use of electrical discharge machining (EDM) equipment, a type of metal cutting tool commonly found in machine shops. EDM is a process performed in an oil bath where rapid, repetitive spark-discharges are normally used to erode an electrically conductive material. However, the operating parameters were changed to convert the metal removal process to a carbon-coating technique. A low-power setting (60 to 70 V and 2 to 3 A) that removed very little material from the copper electrode was used, and the pulse frequency (10 000 Hz) and duty cycle (40 percent) were optimized to roughen the surface and to deposit an adherent carbon film.

Although the exact mechanism is not well understood at this time, the action of the arc-discharge can be described as a controlled explosion occurring between two, oppositely charged electrodes (made of carbon and copper) separated by a narrow, dielectric oil-filled gap. The arcs created an instantaneous, localized heating of the oil, attaining temperatures between 8 000 and 12 000 °C, and turned it into a hot,rapidly expanding plasma (ref. 6).

The high-velocity impact of the ionized materials (electrons, carbon, and other by-products) against the copper electrode surface formed small craters that were simultaneously filled

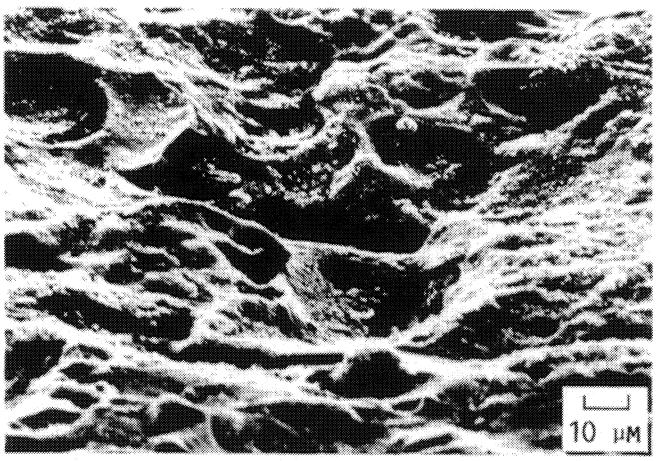



Figure 1.—Scanning electron microscope photomicrograph of a typical arc-pyrolyzed carbon coating on copper surface.

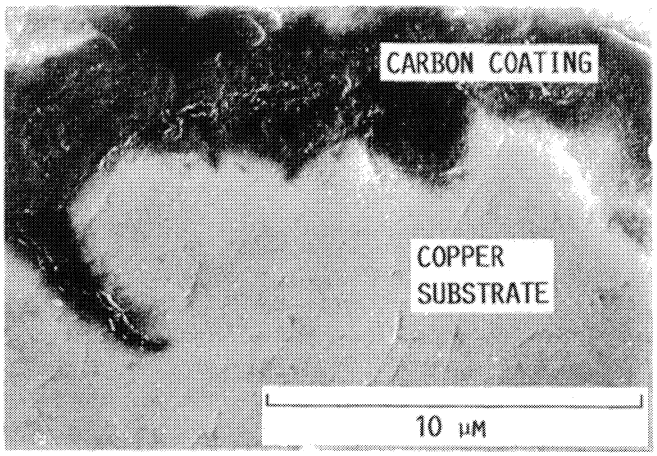



Figure 2.—Scanning electron microscope photomicrograph of a typical cross section of a copper substrate coated with arc-pyrolyzed carbon.

or covered with carbon. The SEM photograph (fig. 1) shows the size and the features of the cratering which gave the arc-pyrolyzed surface a distinctive texture. The formation of the craters contributes to the durability of the coating. The coating resists ordinary scuffing and abrasion due to handling because the carbon fills the tiny cavities where much of the carbon lies below the plane of surface asperities of the copper. Figure 2 is a cross section of the carbon-coated copper substrate. It shows that the irregularities in the roughened copper substrate were will-filled with carbon and that the interfaces between carbon and copper were void-free.

The copper MDC electrode, which served as the anode, was rotated in a fixture relative to an essentially fixed position carbon cathode. This motion provided a flushing action that helped to remove the debris formed during the process. It also assisted in cooling the copper material and minimized overheating and possible warpage. The physical relationship of the copper MDC electrode to the carbon cathode was analogous to writing on a memory disc with a laser. Here, a stationary carbon electrode, because of the arc discharge phenomenon, left a carbonized track on the rotating copper electrode. The width of the track was determined by the size of the carbon electrode. A coating of sufficient thickness was laid down by repeated passes over the same area.

The copper electrode was translated manually relative to the fixed carbon electrode in order to carbonize other areas of the surface. The use of a numerically controlled work-positioning table would eliminate this manual operation, speed up the process, and increase the quality and consistency of the final product. Moreover, it could be programmed to coat MDC electrodes with nonsymmetrical shapes.

The carbon electrode was automatically actuated to move in a direction perpendicular to the copper surface. This was accomplished with a servo-system in order to maintain the set sparking gap. The carbon electrode was consumed at a rapid rate at all locations, wherever the arc-discharges were occurring, and, within a short period, it conformed to the adjacent surface contours of the copper. Therefore, it was not necessary to start with a precisely machined mating electrode. The use of constant spark-gap aided in achieving a uniform, rapidly applied coverage of carbon on the copper surface. The coating was kept thin (about 5 $\mu$m) to ensure better adhesion to the surface. Excluding the setup time, which can vary over a wide range, the actual coating time was in the order of a few minutes for a typical collector electrode.

## Secondary-Electron-Emission Characteristics of Arc-Pyrolyzed Carbon on Copper

The apparatus and experimental techniques described in reference 7 were used to measure some of the secondary-electron-emission properties of a representative sample of arc-pyrolyzed carbon on a copper substrate. Figure 3 shows the total secondary-electron-emission yield as a function of primary electron energy, for various angles of beam impingement (relative to a line normal to the sample surface) on the carbon surface.

Figure 4 shows the reflected primary electron yield index (defined in ref. 7) as a function of primary electron angle, for various angles of beam impingement. The carbon coating procedure produced sharply lower secondary-electron-emission characteristics compared to untreated oxygen-free high conductivity (OFHC) copper (refs. 7 and 8), and were comparable to those of isotropic graphite (ref. 7).

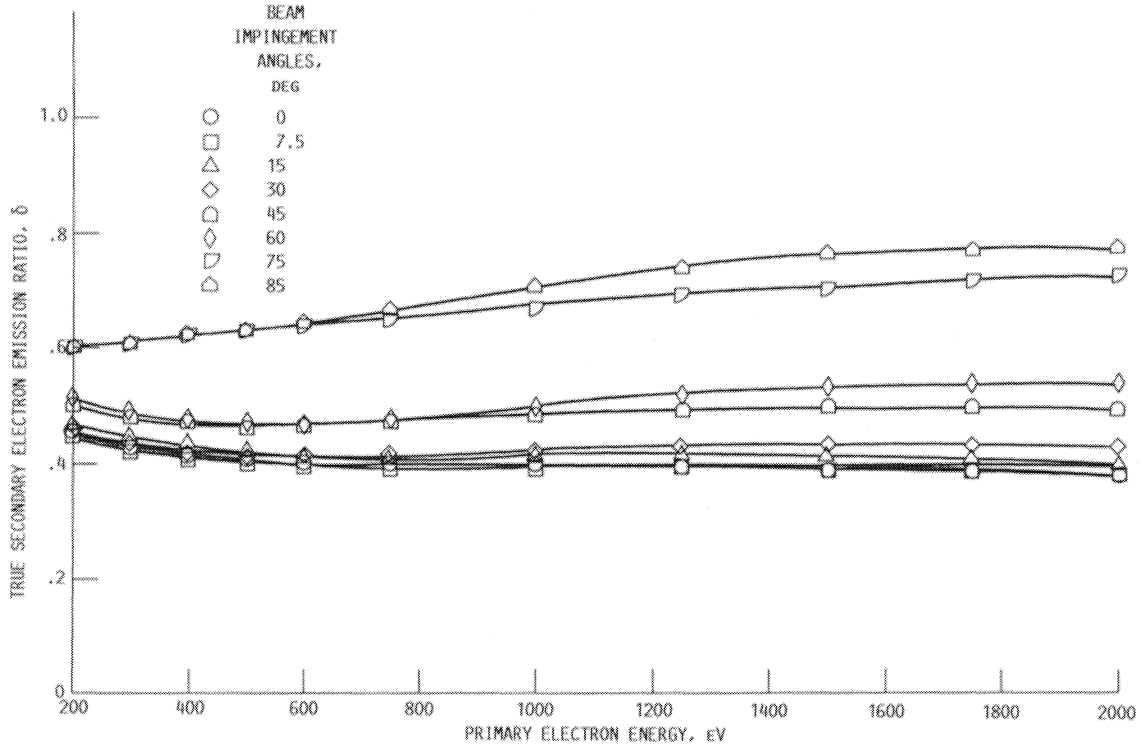



Figure 3.—True secondary-electron-emission ratio as a function of primary electron energy for arc-pyrolyzed carbon on copper.

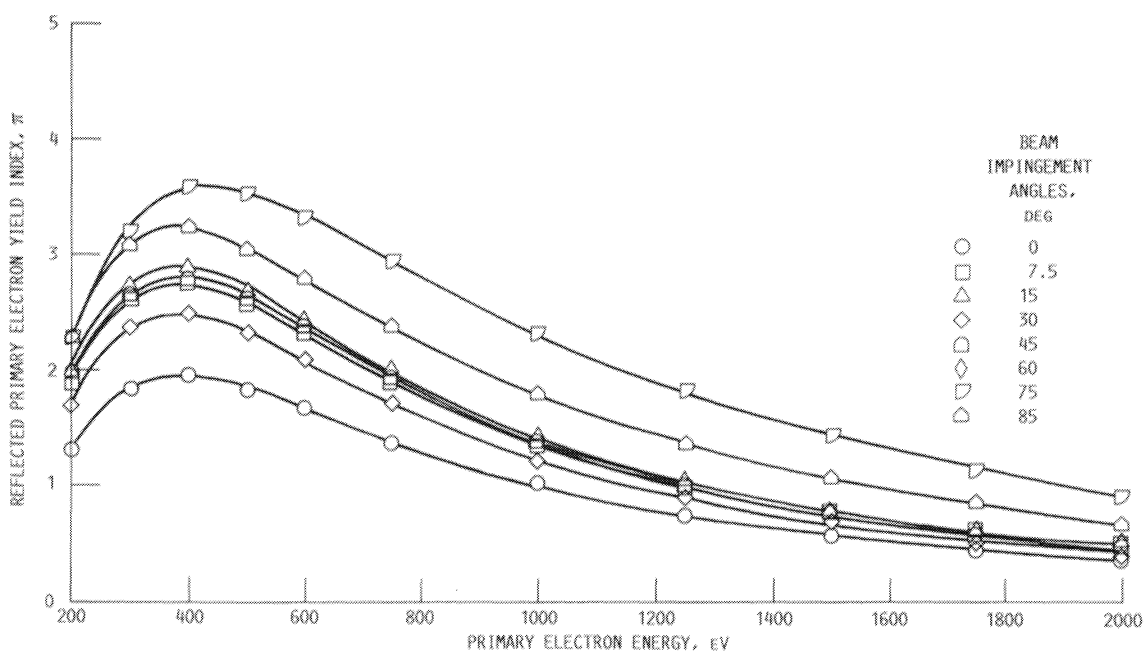



Figure 4.—Reflected-primary-electron yield index as a function of primary electron energy for arc-pyrolyzed carbon on copper.

## Experimental Traveling-Wave Tubes and Multistage Depressed Collectors

The performance comparison test was accomplished with a modified version of a Varian Model 6336A1 TWT, the characteristics of which are shown in table I. For convenience, this TWT is referred to as VA 101 throughout this report. The geometry and characteristics of its MDC, designated as MDC 1, are shown in figure 5 and table II, respectively. The number of collector stages is defined as the number of distinct voltages (other than ground) needed to operate the MDC. MDC 1,

TABLE I.—GENERAL TWT CHARACTERISTICS

| TWT characteristics | VARIAN MODEL 6336A1 (performance comparison test) | T MEC MODEL MTZ-7000 (extended CW test) |
|---|---|---|
| Designation | VA 101 | T MEC 103 |
| Frequency, GHz | 2.5 to 5.5 | [a]4.8 to 9.6 |
| Perveance, $A/V^{3/2}$ | $1.23 \times 10^{-6}$ | $0.4 \times 10^{-6}$ |
| RF output power, (max), W | 840 | 550 |
| Cathode voltage, kV | −6.2 | −9.95 |
| Cathode current, A | .60 | .40 |
| Focusing | Periodic permanent magnet (PPM) | Periodic permanent magnet (PPM) |
| Duty cycle, percent | [b]25 | 100 |

[a]Limited to 6.4 GHz during the CW extended test.
[b]Nominally CW, limited to 25 percent during these tests.

TABLE II.—GENERAL MDC CHARACTERISTICS

| MDC designation | MDC 1 | MDC 3 |
|---|---|---|
| Applicable TWT | VA 101 | T MEC 103 |
| Number of stages | 4 or 3 | 4 |
| Active inner diameter, cm | 2.4 | 2.4 |
| Active height, cm | 3.2 | 3.8 |
| Geometry | (See fig. 5.) | (See fig. 6.) |
| Typical MDC efficiency | Medium | High |

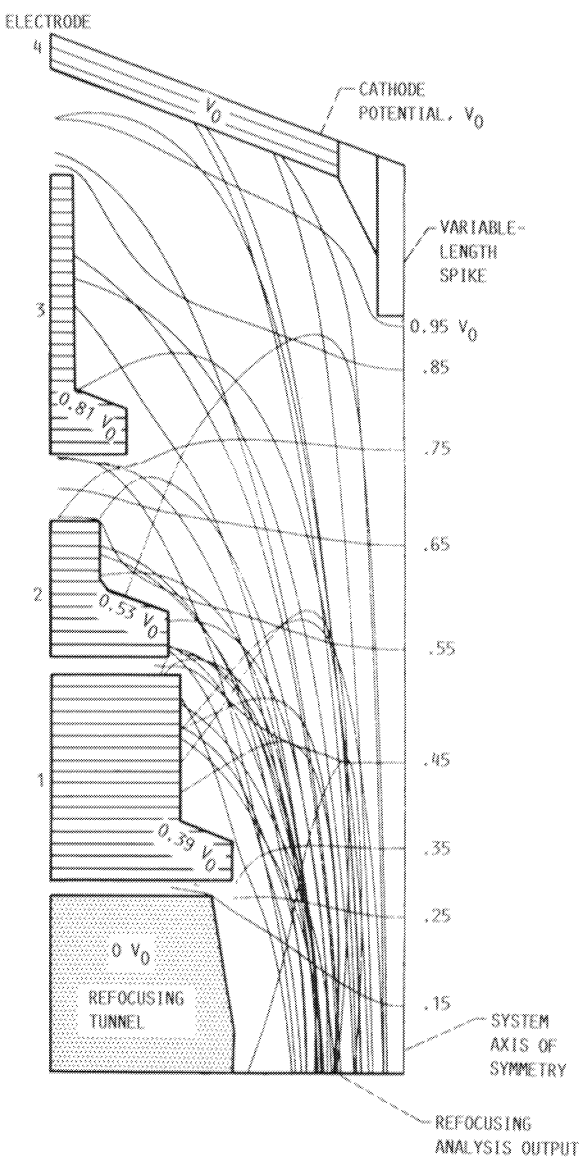



Figure 5.—Geometry of MDC 1 and charge trajectories in collector with TWT operating at saturation.

which does not use a separate electrode at ground potential, was operated in both three and four-stage configurations. In the three-stage configuration, electrodes 1 and 2 were operated at the same voltage.

The extended CW test was performed with a modified version of a Teledyne MEC MTZ-7000 TWT, designated as T MEC 103 in this report. The characteristics of this TWT are shown in table I. The geometry and characteristics of its MDC, designated as MDC 3, are shown in figure 6 and table II respectively.

The TWT and demountable MDC measuring system described in reference 9 was used to optimize and measure the TWT and MDC efficiencies. Because the TWT had an ultrahigh vacuum (UHV) valve (ref. 10) at the end of the refocusing region, the same TWT could be operated with a series of collectors without losing vacuum. (See, for example, figures 4 and 6 of ref. 9.) Traveling-wave tube performance changes from test to test were minimized because no high-temperature TWT bakeout (or removal of the magnets from the periodic permanent magnet (PPM) stack) was required. The TWT RF output power and body power had been measured previously with an undepressed collector (refs. 11 and 12). Consequently, the MDC efficiency, as well as the TWT efficiency, could be measured on subsequent MDC tests as long as the RF performance of the TWT stayed relatively constant.

The MDC's were of demountable design. The MDC 1 electrodes were radiation cooled, while the MDC 3 electrodes were individually water cooled and the thermal dissipation measured. The collectors utilized a metallic spike which

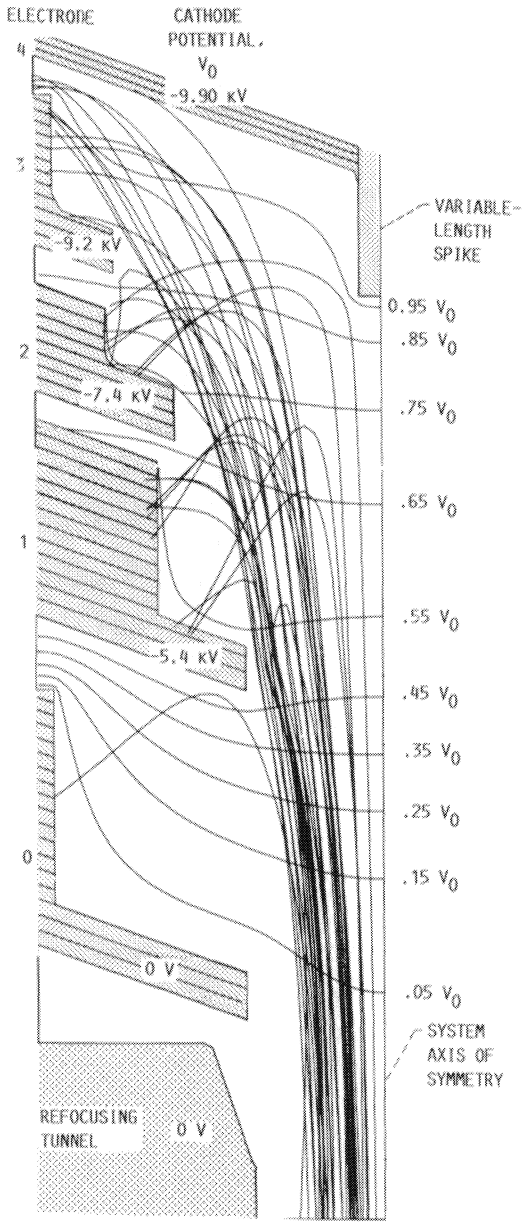



Figure 6.—Geometry of MDC 3 and charge trajectories in collector with TWT operating at saturation in low mode.

protruded through the most depressed electrode. The length of the spike could be varied while the TWT was operating.

The TWT's had a variable refocusing system consisting of two coils. The coil location and current could be varied, while the TWT was operating, to optimize the MDC and TWT efficiencies.

# Experimental Procedure

### Performance Optimization Technique

The TWT and MDC performance was individually optimized for each type of collector electrode surface by using the optimization technique described in reference 9. The variables used to optimize the TWT overall and MDC efficiencies were as follows:

(1) Individual collector stage voltages

(2) Refocusing coil currents and (over a limited range of variability) the coil positions

(3) Length of the variable spike

The VA 101 TWT and MDC 1 efficiencies were optimized for TWT operation at saturation at the operating frequency (4.75 GHz) that yielded the highest electronic efficiency. Data were then taken at saturation across the operating band of 2.5 to 5.5 GHz using this fixed set of refocuser and MDC operating conditions. In addition, data were obtained below saturation and across the linear range of the TWT (at 4.75 GHz) at the same fixed set of refocuser and MDC operating conditions. This procedure was performed independently for both the four- and three-stage versions of MDC 1.

The performance optimization procedure was not used with T MEC 103 and MDC 3. Instead, single TWT-MDC operating points were selected for each phase of the extended test (RF and DC), which resulted in a range of electron bombardment intensities on the various MDC electrodes.

### RF Test Conditions and Duty Cycle

A filtered input drive $P_{in}$ at the fundamental frequency was used throughout these tests. Saturation was determined by using an uncalibrated power meter which (with a low-pass filter) measured RF power only at the fundamental frequency. However, only the total RF power $P_{RF}$, which was dissipated in the water-cooled matched load, was measured, and all TWT overall and electronic efficiencies reported here are based on this $P_{RF}$.

The VA 101 is rated for CW operation. However, to insure that the single tube available would survive the extensive test program, it was operated at a 25 percent duty cycle, with 1.5-msec pulses. The thermal measurements were averages over the pulse time, while the electrical measurements (currents) were instantaneous samples near the end of the pulse. The T MEC 103 was operated in the CW (low) mode for the extended test.

### Collector Electrode Cleaning and Bakeout Procedure

The coating process utilized highly purified oil and high-purity carbon electrode material to minimize contamination. The carbon coated MDC 1 electrodes were cleaned by successive rinses in an ultrasonic cleaner with clean solvent (freon). This method of cleaning was also helpful in removing loosely attached carbon particles. The assembled MDC was baked out in vacuum at approximately 350 °C for 8 hours in the MDC measuring system.

Based on test results with MDC 1 (discussed in the next section) the cleaning procedure for the MDC 3 electrodes was revised. A final rinse cycle in alcohol followed successive rinses in acetone with the ultrasonic cleaner. In addition, the

electrodes were baked out in vacuum at 550 °C for 45 hours prior to assembly of the MDC. The assembly MDC was baked out at approximately 350 °C for 12 hours in the MDC measuring system.

## Experimental Results

### Performance Comparison Test with VA 101 and MDC 1

The TWT overall and MDC efficiencies as functions of frequency at saturation for the carbon-coated and copper versions of MDC 1 are shown in figures 7 and 8 for the four- and three-stage versions, respectively. The average TWT overall and MDC efficiencies across the operating band at saturation are summarized in table III. With the carbon-coated electrodes instead of copper electrodes the overall efficiency was improved by 11 percent for both the four-and three-stage collectors. The collector efficiencies showed a similar improvement.

VA 101 and MDC 1 had been previously used in a sequence of tests involving the use of a number of different forms of carbon as MDC electrode surfaces (ref. 1). The TWT exhibited good repeatability of performance during the arc-pyrolyzed carbon-on-copper tests as compared to those previous tests. Consequently, while a comparison of the carbon-coated to uncoated copper electrodes is stressed here, the performance of the arc-pyrolyzed, carbon-coated MDC can be compared to that of the other forms of carbon reported in reference 1, since the TWT-MDC performance was optimized and evaluated under similar conditions. The TWT and MDC efficiencies obtained with arc-pyrolyzed carbon on copper are almost identical to those obtained with machined isotropic graphite, and only slightly lower than those obtained with textured carbon on copper.

Figures 9 and 10 show the TWT and MDC efficiencies as a function of RF output power at 4.75 GHz for the four- and

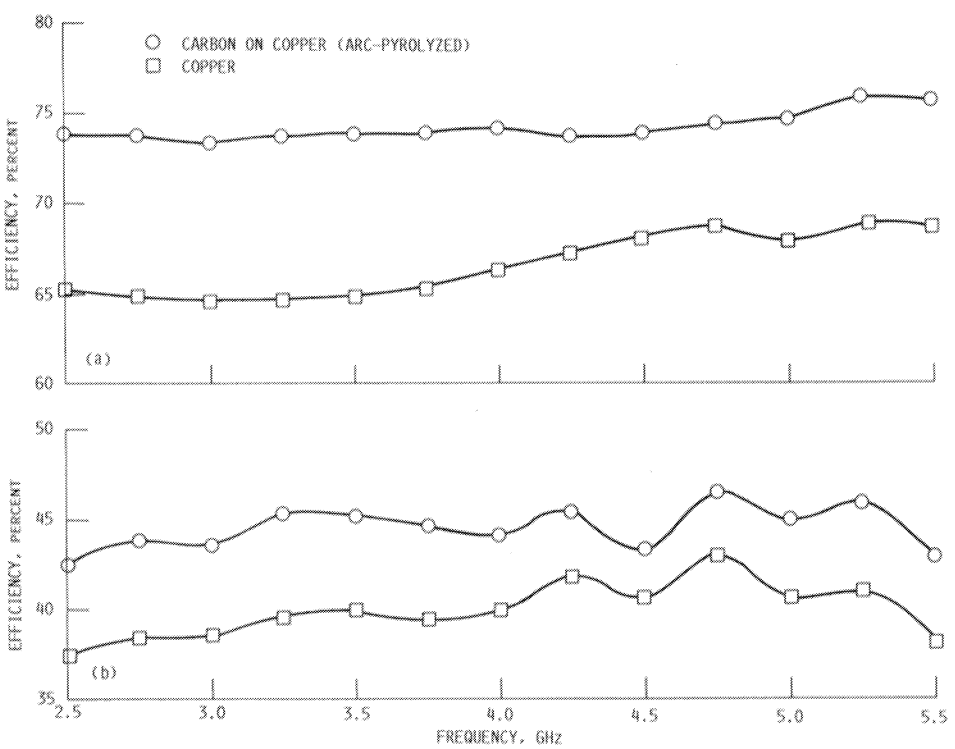
TABLE III.—SUMMARY OF AVERAGE TWT AND FOUR-STAGE COLLECTOR PERFORMANCE AT SATURATION ACROSS 2.5- to 5.5- GHz OPERATING BAND

(a) Four-stage collector

| MDC electrode characteristics | RF efficiency, percent | Overall efficiency, percent | Collector efficiency, percent |
|---|---|---|---|
| Copper | 21.1 | 39.9 | 66.5 |
| Arc-pyrolyzed carbon on copper | 21.1 | 44.5 | 74.2 |

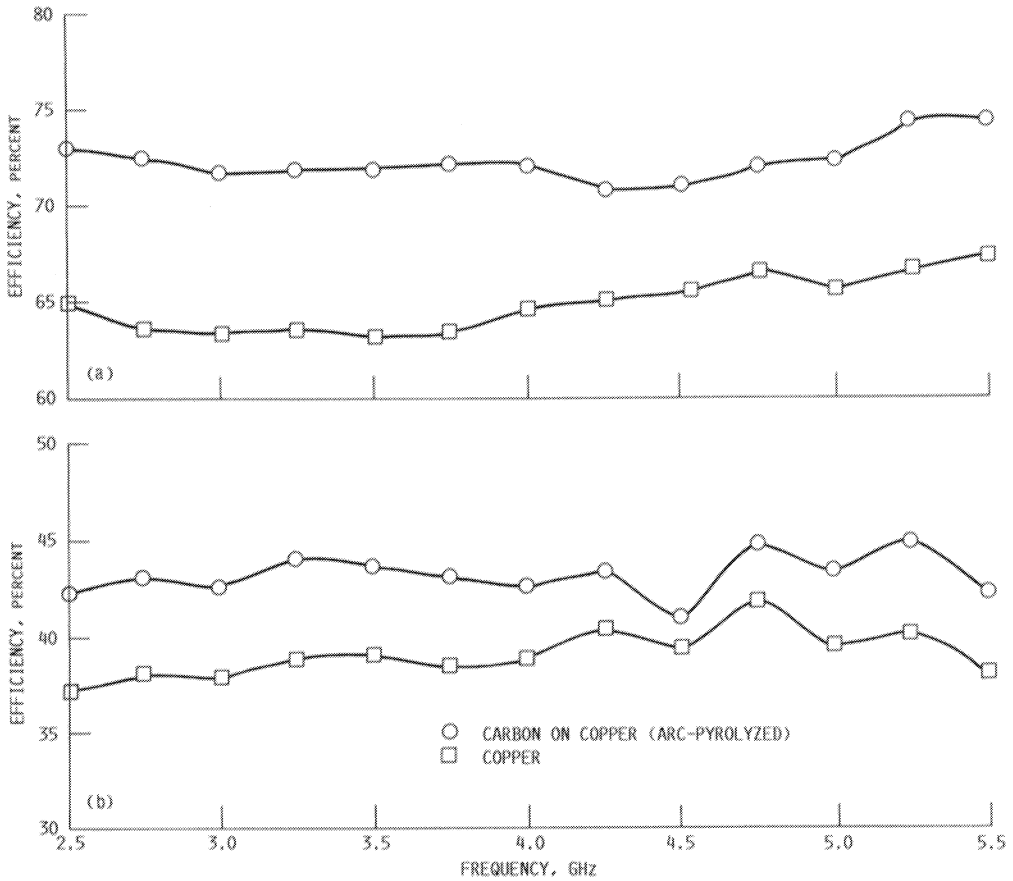
(b) Three-stage collector

| | | | |
|---|---|---|---|
| Copper | 21.1 | 39.1 | 64.9 |
| Arc-pyrolzyed carbon on copper | 21.0 | 43.2 | 72.4 |



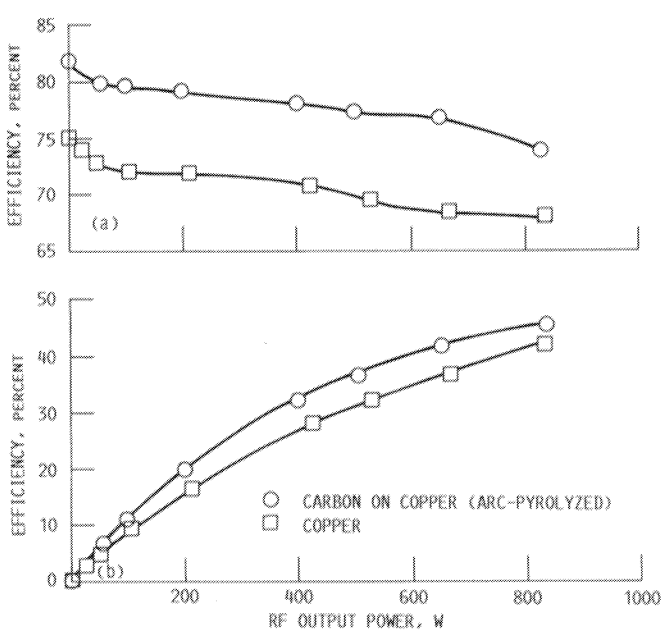

(a) Collector efficiency.
(b) Overall efficiency.

Figure 7.—Collector and overall efficiencies as functions of frequency at saturation for VA 101 and four-stage collector; optimized at saturation at 4.75 GHz.



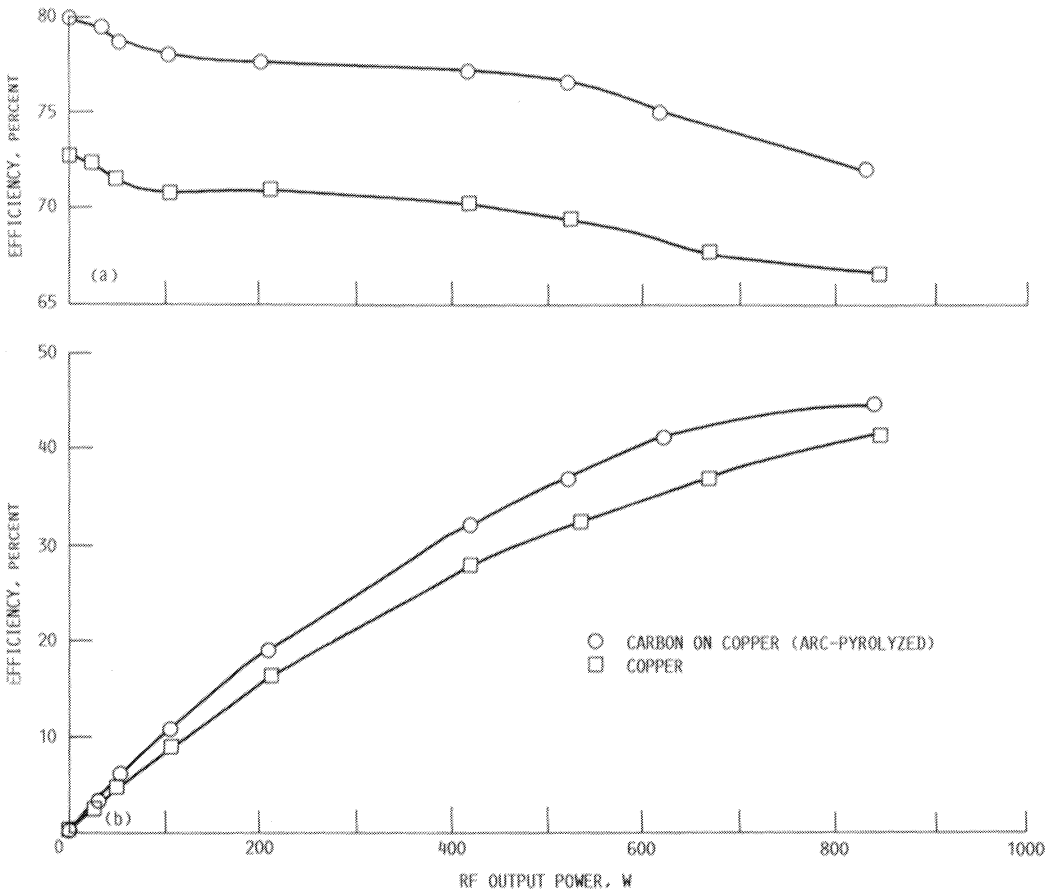

(a) Collector efficiency.
(b) Overall efficiency.

Figure 8.—Collector and overall efficiencies as functions of frequency at saturation for VA 101 and three-stage collector; optimized at saturation at 4.75 GHz.




(a) Collector efficiency.
(b) Overall efficiency.

Figure 9.—Collector and overall efficiencies as functions of RF output power at 4.75 GHz for VA 101 and four-stage collector; optimized at saturation at 4.75 GHz.




(a) Collector efficiency.
(b) Overall efficiency.

Figure 10.—Collector and overall efficiencies as functions of RF output power at 4.75 GHz for VA 101 and three-stage collector; optimized at saturation at 4.75 GHz.

three-stage collectors, respectively, for the same fixed sets of refocusing system and MDC operating conditions that were used to obtain the data at saturation. The collector efficiency increases steadily with decreasing RF output power. The collector efficiencies at the low end of the linear range and for the DC beam are limited by the voltage applied to electrode 3 (see fig. 5), which was optimized for saturation.

The relative improvement in the collector efficiency of the carbon-coated compared to uncoated copper electrodes is approximately constant over the entire range. The relative improvement in the overall efficiency increases steadily as the RF output power $P_{RF}$ and RF efficiency decrease. For example, at $P_{RF} = 200$ W, the addition of the carbon coating improves the overall efficiency by more than 25 percent.

The electrode cleaning and MDC bakeout procedures normally used with bare copper electrodes were applied to the carbon-coated copper electrodes. Higher than normal outgassing and some possible evidence of cathode poisoning were observed during testing of the TWT-MDC, thereby indicating the need for a more stringent cleaning and degassing procedure than is normally used for MDC's with bare copper electrodes. A limited quadrupole residual-gas analyzer survey of gaseous constituents in the vacuum system, when the TWT-MDC were operating, failed to identify any potential sources of the apparent cathode poisoning.

## Extended CW Test with T MEC 103 and MDC 3

An extended CW test was performed with the T MEC medium power TWT and small-sized MDC to test the long-term stability of the electrode surfaces. This test consisted of 500 hours of operation with RF ($P_{RF} \approx 500$ W at 6.4 GHz), followed at 350 hours of operation with the DC beam. The MDC operating voltages and typical values of net current and thermal power dissipated on the MDC electrodes during the test are shown in table IV. The DC beam operation provided the highest intensity of electron bombardment on a single electrode, more than 340 mA of net current and approximately 420 W of dissipated power.

The TWT-MDC exhibited (1) a gradual increase in body current of several milliamperes and (2) a slightly less than 2 percent degradation in the power recovered in the MDC during the first 570 hours of operation. Since the RF performance of the TWT was highly repeatable, it seems likely that small

TABLE IV.—MDC OPERATING VOLTAGES, CURRENTS, AND DISSIPATED POWERS DURING EXTENDED TESTING

(a) RF test, 500 hr ($P_{in}$ = 10.0 mW at 6.4 GHz, $P_{RF}$ ≈ 500 W)

| Collector electrode | Operating voltage,[a] kV | Current, mA | Dissipated power, W |
|---|---|---|---|
| 1 | −5.40 | 155 | 193 |
| 2 | −6.90 | 52 | 107 |
| 3 | −8.90 | 171 | 202 |
| 4 | −9.95 | 2 | 10 |
| (b) DC beam test, 350 hr ($P_{in}$, $P_{RF}$ = 0) | | | |
| 1 | −5.50 | 22 | 89 |
| 2 | −6.90 | 28 | 85 |
| 3 | −8.80 | 342 | 419 |
| 4 | −9.95 | 0 | 0 |

[a]With respect to ground.

changes in the secondary-electron-emission characteristics of the electrode surfaces were partly responsible for the deterioration of collector performance. However, subtle changes in the spent TWT beam due to improved outgassing of the TWT components with time can contribute to the effect. For example, it had been observed during another test program with an 8 to 18 GHz TWT that, early in the test program, CW test results (at higher pressure) produced the following: (1) 1 to 2 percent higher values of power recovered in the collector and (2) lower values of total body current (by several milliamperes) than pulsed results at lower pressures. A similar increase in body current and decrease in recovered power was observed in the extended test of an isotropic graphite MDC (ref. 2). During the last 280 hours of operation with the DC beam the MDC performance improved slightly. The TWT-MDC went through more than 50 on-off cycles during the extended test.

Scanning electron microscope examination of the MDC electrodes after disassembly (e.g., see fig. 1) revealed no cracks in the coating due to thermal cycling, or any unusual features. Visual examination of the electrodes showed areas of discoloration (grayish black rather than black) in locations of both high and low intensity electron bombardment. Similar discolorations have been observed on other tests with carbon black electrode coatings. However, no depletion of the thin carbon coating or points of arc damage were evident.

The MDC electrodes were baked in vacuum at 550 °C before assembly and exhibited very little outgassing on initial TWT-MDC turn-on. Full cathode emission was obtained on turn-on and for the first 250 hours of operation at the nominal operating voltage of the focus (beam control) electrode. However, small adjustments were needed subsequently to keep beam current constant. The extended test was performed in the same vacuum chamber as the performance comparison test with the Varian TWT, during which cathode poisoning (possibly due to inadequate MDC cleaning procedures) was observed. It is possible that the cathode emission of the T MEC TWT could have been affected by trace amounts of impurities left over from the previous test.

## Concluding Remarks

Promising results were obtained with a durable carbon-on-copper electrode coating produced by a rapid and low-cost process with commonly available equipment. The same basic fabrication techniques used for copper electrode MDC's can be used for the carbon coated electrodes. In general, the carbon coating performed well. The TWT and MDC efficiencies obtained compare favorably to those obtained with other forms of carbon. However, considerably more experience with this coating will be required before definitive conclusions on its suitability for ECM and space TWT's can be made. Results to date indicate that a more stringent cleaning procedure and a preassembly high-temperature bakeout may be needed for the coated collector parts to rid contaminants from the carbon deposition process and to minimize outgassing during TWT-MDC processing.

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15. Supplementary Notes

16. Abstract

A simple method of improving the traveling-wave tube (TWT) and multistage depressed collector (MDC) efficiency has been demonstrated. The efficiency improvement was produced by the application of a thin layer of carbon to the copper electrodes of the MDC by means of a rapid, low-cost technique involving the pyrolysis of hydrocarbon oil in electric arc discharges. Experimental results with a representative TWT and MDC showed an 11 percent improvement in both the TWT and MDC efficiencies as compared to those of the same TWT and MDC efficiencies with bare copper electrode surfaces. An extended test with a 500-W, continuous wave (CW) TWT and small-sized MDC indicated good stability of the carbon coated electrode surfaces after a relatively small initial degradation in TWT overall and apparent MDC efficiencies.

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| Carbon-on-copper electrodes; Multistaged depressed collector; Traveling-wave amplifier; Secondary-electron emission | Unclassified–unlimited<br>STAR Category 33 |

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