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Performance of a Multistage Depressed Collector With Machined Titanium Electrodes

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Summary

The performance of a multistage depressed collector (MDC) with machined titanium electrodes was evaluated in conjunction with an 800-W, 8- to 18-GHz traveling-wave tube (TWT) and was compared with the performances of geometrically identical copper and isotropic graphite electrode MDC's operated with the same TWT. The titanium electrode MDC produced a modest (about 3 percent) improvement in the MDC and TWT overall efficiencies as compared with the copper electrode MDC, but its performance was substantially lower than that of the isotropic graphite electrode MDC.

Introduction

Multistage depressed collectors (MDC's) are passive devices that recover a substantial part of the kinetic power in the spent beams of microwave tubes and make possible the attainment of very high overall tube efficiencies (ref. 1). One factor that can limit the attainment of very high MDC efficiencies is the presence of backstreaming secondary-electron emission (SEE) current from the electrode surfaces. Such deleterious backstreaming is always present even though modern MDC's provide (by design) electrostatic suppression of low-energy secondaries generated on most MDC electrode surfaces. In the commonly used, machined copper electrode MDC's, such backstreaming secondaries can reduce the collector efficiency from several percent to more than 15 percent (ref. 2). These losses can be substantially reduced by (1) roughening the electrode surfaces on a microscopic scale (ref. 3), (2) applying low (SEE) yield coatings (refs. 3 and 4), and (3) using lower SEE yield bulk electrode materials (such as isotropic graphite).

Practical considerations will determine which particular technique (if any) will best serve the needs of any given microwave tube application. The magnitude of the efficiency improvement must be weighed against (possibly) greater cost or complexity, reduced reliability, risk of long-term performance changes, and other factors. Consequently, even electrode materials that might yield only a modest improvement in efficiency are of interest if they possess other desirable qualities as well. Titanium, in its bulk form, is an example of such a material. Its secondary-electron yield characteristics (ref. 5) suggest only a modest efficiency improvement over copper. However, it has several other potential advantages, such as the following:

(1) It can be brazed directly to alumina and beryllia ceramics because of its favorable thermal expansion characteristics, and it is compatible with the rugged and compact MDC assembly design worked out for isotropic graphite MDC's (ref. 6).

(2) Its presence inside the vacuum envelope of the traveling-wave tube (TWT) may lead to enhanced pumping by volume absorption of certain residual gases and may make possible the elimination of appendage pumps.

(3) It provides a very stable electrode surface, which is not easily susceptible to arc damage.

This report presents the performance of a representative TWT equipped with a machined titanium electrode MDC and compares it to the (previously measured) performance of the same TWT with copper and machined isotropic graphite electrode MDC's.

Symbols

f	operating frequency, GHz
I_0	beam current, A
P_b	body power, sum of RF circuit losses and intercepted-beam power in forward direction, W
P_{col}	collector power, $V_0 I_0 - P_{RF} - P_b$, W
P_{RF}	total RF output power, W
P_{rec}	power recovered by MDC, W
V_0	cathode potential with respect to ground, V
η_c	TWT circuit efficiency, $P_{RF}/(P_{RF}$ + circuit losses), percent
η_{col}	collector efficiency, P_{rec}/P_{col}, percent
η_e	electronic efficiency, η_{RF}/η_c, percent
η_{ov}	TWT overall efficiency, $P_{RF}/(dc$ input power), percent
η_{RF}	RF efficiency of TWT, $P_{RF}/V_0 I_0$, percent

Experimental TWT and MDC's

The general characteristics of the TWT used in these tests are shown in table I. (This TWT will be referred to as VA 101 throughout this report.) The very high electronic efficiency and high perveance of VA 101 combine to produce wide ranges of electron energies and angles in the spent beam (ref. 7). The

TABLE I.—GENERAL TRAVELING-WAVE-TUBE CHARACTERISTICS

TWT Model	Varian 6336 Al
Designation	VA 101
Frequency, GHz	2.5 to 5.5
Cathode voltage, kV	−6.20
Cathode current, A	0.60
Perveance, $A/V^{3/2}$	1.23×10^{-6}
Electronic efficiency, η_e, percent	26 max
Focusing	PPM[a]
Duty cycle, percent	[b]25

[a]Periodic permanent magnet.
[b]Nominally CW, limited to 25 percent during these tests.

range of computed electron energies at the input to the MDC is 2.4 to 7.4 keV. The gridded gun of the TWT probably introduces additional beam ripple and contributes to the wide range of electron angles at the MDC input. The TWT had a variable spent-beam-refocusing system consisting of two coils. VA 101 is rated for continuous wave (CW) operation. However, to ensure 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 active geometry of the four-stage depressed collector is shown in figure 1. Both the titanium and the copper collector electrodes were individually water cooled by brazed-on copper cooling lines, and the thermal power dissipated on each was measured. The graphite collector electrodes were radiation cooled. The graphite and the titanium collector electrodes were used in the "as-machined" state. The copper collector electrodes, which had been coated with carbon black for an earlier test, were lightly bead-blasted to remove any remaining traces of carbon. It is believed that such bead blasting of a machined metal surface does not measurably modify the secondary electron emission characteristics and would yield collector efficiencies very close to those for machined copper electrodes. The variable length spike was constructed of stainless steel in all cases.

The number of collector stages is defined as the number of distinct voltages, other than ground, needed to operate the MDC. The MDC was operated in both three- and four-stage configurations. In the three-stage configuration, electrodes 1 and 2 were operated at the same voltage.

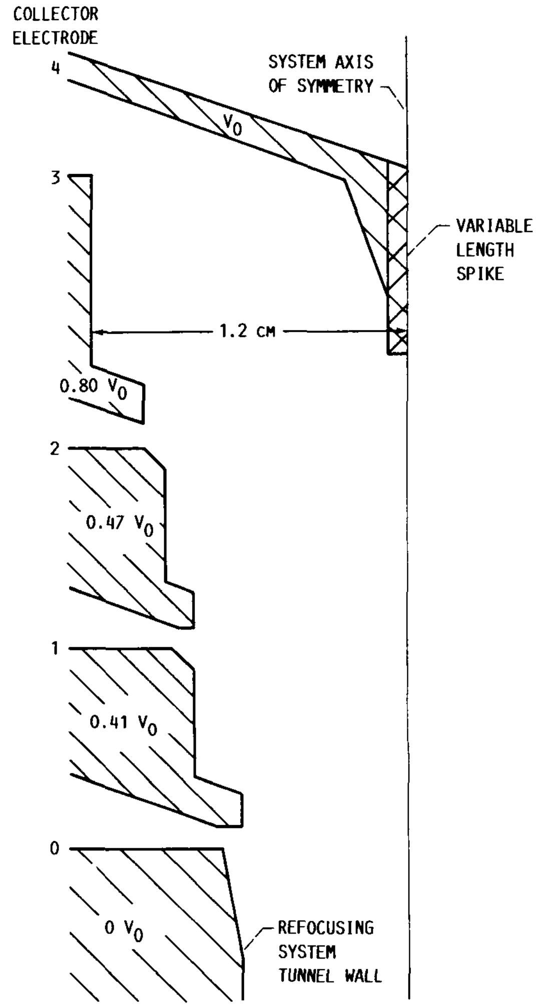

Figure 1.—Geometry and applied potentials of 2.4-cm-diameter four-stage depressed collector.

Experimental Arrangement and Procedure

Apparatus

The demountable MDC evaluation system shown in figure 2 was used to optimize and measure the TWT and MDC efficiencies. Because the TWT had an ultrahigh vacuum (UHV) valve at the end of the refocusing region, the same TWT could be operated with a series of collectors without losing vacuum (ref. 8). TWT 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 P_b had been measured previously with an undepressed collector (ref. 9). 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 use of the same TWT (as opposed to the use of a number of TWT's of identical design) was of considerable importance in this study. It has been previously observed that TWT's of identical design can exhibit significantly different $P_{RF}(f)$ and $P_b(f)$ characteristics, and thus it would have been impossible to resolve the differences in collector efficiencies of the order of 1 percent that were obtained in this study by using the same TWT.

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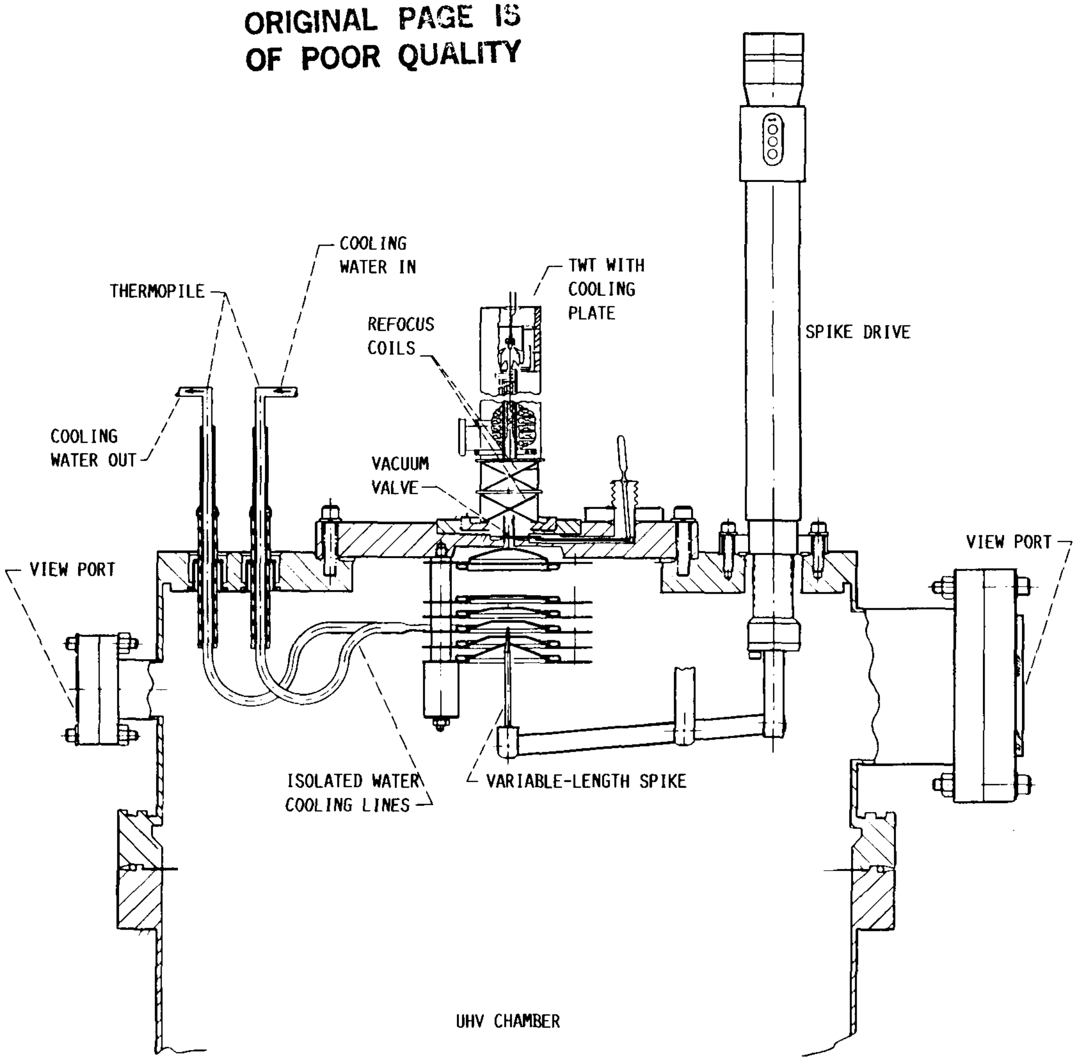

Figure 2.—Schematic of demountable MDC evaluation system.

Performance Optimization Technique and RF Test Conditions

The TWT and MDC performances were individually optimized for each collector electrode material by using the optimization technique described in reference 10. The following variables were used to optimize the TWT overall and MDC efficiencies:

(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 TWT and MDC 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 at the fixed set of refocuser and MDC operating conditions. The performance of the TWT with the titanium electrode MDC was compared to those obtained previously with geometrically identical copper and isotropic graphite electrode MDC's (ref. 2). The tests with the graphite, copper, and titanium MDC's were the 10th, 12th, and 18th, respectively, with VA 101. The fact that they were not performed sequentially added to the difficulty of obtaining repeatable TWT performance $P_{RF}(f)$ for all three tests.

Filtered input drive at the fundamental frequency was used throughout these tests. Saturation was determined by using an uncalibrated power meter that 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 thermal measurements were averages over the pulse time, whereas the electrical measurements (currents) were instantaneous samples near the end of the pulse.

Multistage Depressed Collector Test Results

In testing of the titanium electrode MDC, some problems were encountered in duplicating the previous TWT performance. When the TWT-MDC processing (outgassing) had been completed it was observed that the saturated RF output power at 4.75 GHz (the optimization condition) was slightly low, and some adjustments were made to the PPM stack to increase the power to the required level. In the subsequent performance optimization of the refocusing system profile, collector voltages, and spike length, it was noticed that a decrease in the beam current I_0 of up to 1-1/2 percent from the nominal value (600 mA) did not significantly affect the recovered power P_{rec} or the RF output power, suggesting that virtually all of the incremental beam current above about 591 mA was intercepted early on the RF circuit. It is hypothesized that a gas buildup during a two-year storage period (with the UHV valve closed but no pumping of any kind on the TWT vacuum envelope) may have contributed to this effect, which had not been observed on previous tests. Since the RF output power was fully up to nominal, the subsequent performance optimizations and evaluations were performed at the slightly lower than nominal beam currents of 590 to 591 mA.

The saturated RF output power as a function of frequency for the isotropic graphite, copper, and titanium electrode MDC tests is shown in figure 3. The repeatability is very good over the frequency range of 2.5 to 5.0 GHz. At 5.25 and 5.0 GHz, however, there are some significant differences. Consequently, although TWT-MDC performance data were obtained over the entire operating band of 2.5 to 5.5 GHz, the performance comparisons presented herein are based on only the data in the frequency range of 2.5 to 5.0 GHz, where the repeatability in P_{RF} was very good.

The overall and collector efficiencies as functions of frequency are shown in figures 4 and 5, respectively, for the four-stage version of the MDC. The corresponding efficiencies for the three-stage version are shown in figures 6 and 7. The individually optimized MDC voltages are shown in table II.

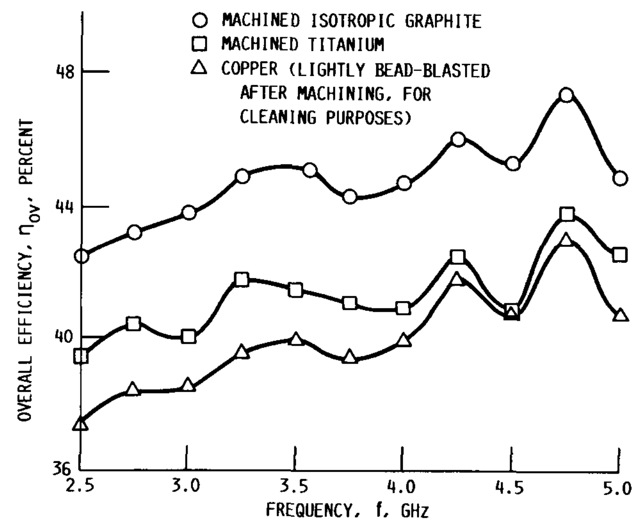

Figure 4.—Overall efficiency as function of frequency with four-stage depressed collector and VA 101 operating at saturation (optimized at 4.75 GHz).

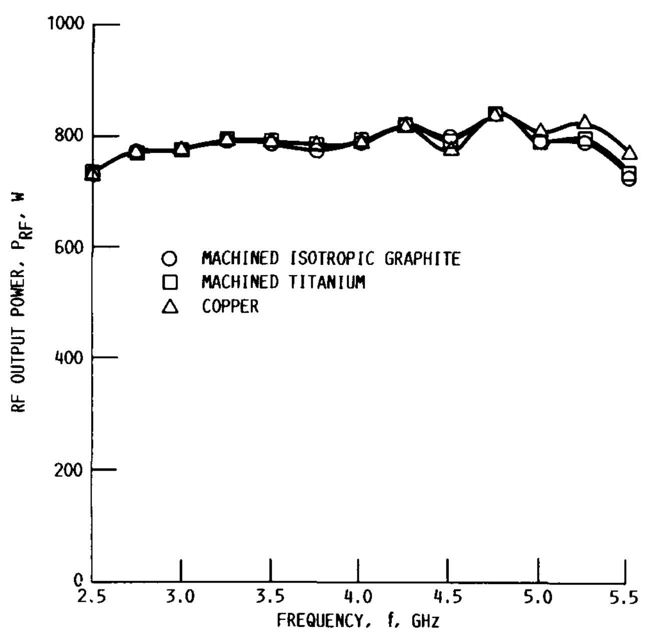

Figure 3.—RF output power as function of frequency for TWT VA 101 and four-stage depressed collector.

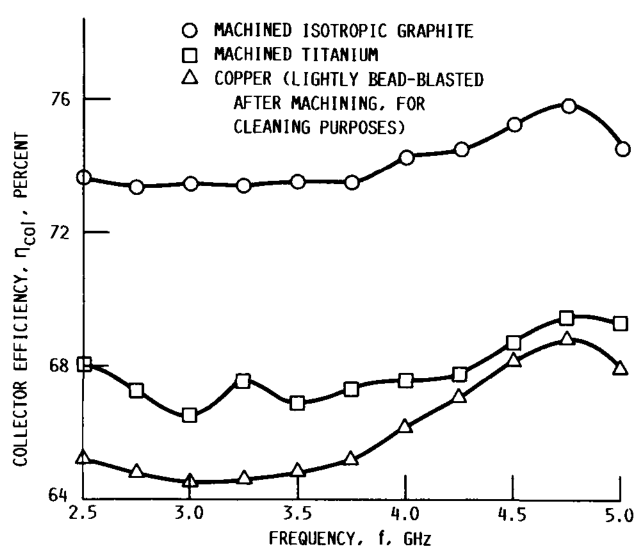

Figure 5.—Four-stage depressed collector efficiency as function of frequency with VA 101 operating at saturation (optimized at 4.75 GHz).

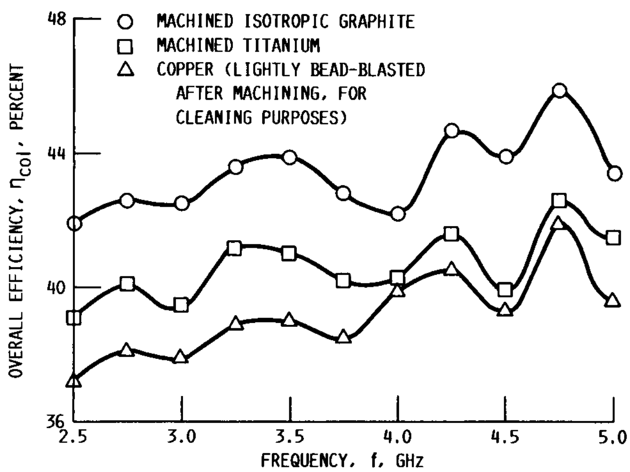

Figure 6 .— Overall efficiency as function of frequency with three-stage depressed collector and VA 101 operating at saturation (optimized at 4.75 GHz).

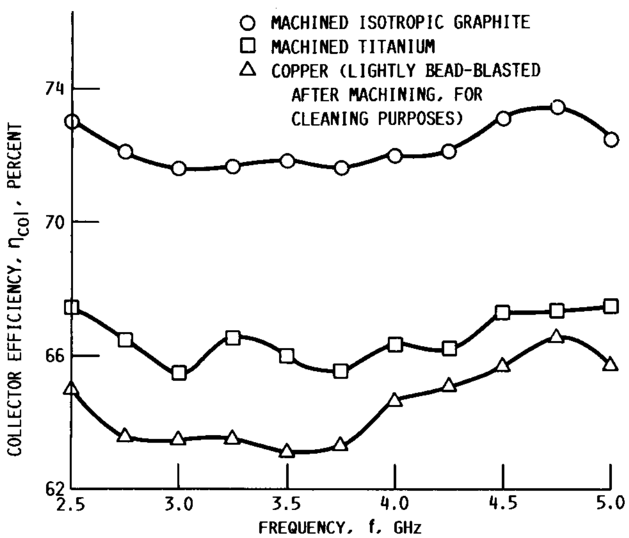

Figure 7.—Three-stage depressed collector efficiency as function of frequency with VA 101 operating at saturation (optimized at 4.75 GHz).

The results are summarized in table III. The relative improvement in η_{ov} and η_{col} of the graphite and titanium electrode MDC's, as compared with the copper electrode MDC, are summarized in table IV. The slightly higher average TWT RF efficiencies during the test with the titanium electrode MDC are due to slightly lower values of beam current (590 to 591 mA, as discussed previously), and these higher efficiencies result in slightly exaggerated relative improvements in the TWT overall efficiency of the titanium electrode, as compared with the copper electrode MDC test. At identical values of RF efficiency, the relative improvements in overall efficiency would be slightly smaller than the relative improvement in collector efficiency. Overall, therefore, the titanium electrode MDC produced a modest improvement in both the MDC and TWT overall efficiencies of about 2-1/2 to 3 percent. However, its performance was significantly below that of the isotropic graphite electrode MDC.

These results are based on using identical values of body power $P_b(f)$ for all three tests. Previously (ref. 2), small

TABLE II.—SUMMARY OF OPTIMIZED MDC VOLTAGES WITH VA 101 OPERATING AT SATURATION

(a) Four-stage collector

MDC electrode characteristic	Optimized voltage, normalized to V_0			
	Electrode 1	Electrode 2	Electrode 3	Electrode 4
Machined isotropic graphite	0.420	0.511	0.837	1.0
Machined titanium	.412	.472	.799	1.0
Copper[a]	.410	.467	.796	1.0

(b) Three-stage collector

MDC electrode characteristic	Optimized voltage, normalized to V_0			
	Electrode 1	Electrode 2	Electrode 3	Electrode 4
Machined isotropic graphite	0.439	0.439	0.828	1.0
Machined titanium	.430	.430	.796	1.0
Copper[a]	.420	.420	.794	1.0

[a]Subsequently bead blasted for cleaning purposes—see text.

TABLE III.—SUMMARY OF AVERAGE TWT VA 101 AND MDC PERFORMANCE ACROSS 2.5- TO 5.0-GHz OPERATING BAND AT SATURATION

(a) Four-stage collector

MDC electrode characteristic	RF TWT efficiency, η_{RF}, percent	Overall TWT efficiency, η_{ov}, percent	Collector efficiency, η_{col}, percent
Machined isotropic graphite	21.2	44.7	74.1
Machined titanium	21.5	41.4	67.9
Copper[a]	21.1	39.9	66.1

(b) Three-stage collector

MDC electrode characteristic	RF TWT efficiency, η_{RF}, percent	Overall TWT efficiency, η_{ov}, percent	Collector efficiency, η_{col}, percent
Machined isotropic graphite	21.1	43.4	72.3
Machined titanium	21.5	40.6	66.6
Copper[a]	21.1	39.1	64.5

[a]Subsequently bead blasted for cleaning purposes—see text.

TABLE IV.—SUMMARY OF TWT OVERALL AND MDC EFFICIENCY IMPROVEMENTS FOR CARBON AND TITANIUM COMPARED WITH COPPER MDC ELECTRODE SURFACES FOR VA 101

MDC electrode characteristics	Four-stage MDC		Three-stage MDC	
	TWT overall efficiency improvement relative to copper, percent	MDC efficiency improvement relative to copper, percent	TWT overall efficiency improvement relative to copper, percent	MDC efficiency improvement relative to copper, percent
Machined isotropic graphite	12.0	12.1	11.1	12.0
Machined titanium	[a]3.6	2.6	[a]4.0	3.2

[a]Relative improvement exaggerated by higher average TWT RF efficiency during test with titanium MDC—see text.

adjustments had been made in the $P_b(f)$ values to account for small differences (from test to test) in the measured RF output power P_{RF} due to very small differences (variations) in the TWT operating parameters (V_0, I_0). The rationale of this procedure is that incremental increases (or decreases) in the $P_{RF}(f)$ from nominal would result in small increases (or decreases) in the TWT circuit losses and, therefore, in $P_b(f)$. This assumes a constant circuit efficiency $\eta_c(f)$. This procedure was not followed here since some of the RF performance, $P_{RF}(f)$, variations (eg., 4.5 and 5.0 GHz) were larger than could be accounted for by small V_0 and I_0 variations and might involve small dimensional changes in the RF structure or output coupler, which could in fact result in changed $\eta_c(f)$. Such changes in $\eta_c(f)$, however, are probably relatively small as long as there is no degradation in the average RF performance of the TWT. Moreover, the MDC efficiency is relatively insensitive to changes in circuit efficiency. Consequently, although the computed collector efficiency (based on $P_b(f)$ values from the bench test) might be off slightly at any one frequency, it is believed these "variations" would largely average out over the wide operating band, as long as the average RF performance of the TWT was not degraded. The TWT-MDC performance, however, was also computed with individually adjusted values of $P_b(f)$ for all three tests, according to the previously used procedure. On the basis of average results across the operating band, the results with and without the P_b adjustments were virtually identical. The average results relative to copper were also computed over the entire 2.5 to 5.5 GHz range and were found to be very similar to those in table IV.

Concluding Remarks

The performance of a titanium electrode MDC was evaluated and compared with the performances of geometrically identical copper and isotropic graphite electrode MDC's operated with the same TWT. The titanium electrode MDC produced an improvement in both the TWT overall and MDC efficiencies in the range of 2-1/2 to 3 percent as compared with the copper electrode MDC, because of the lower secondary-electron emission characteristics of titanium. Its performance, however, was significantly lower than that of the isotropic graphite electrode MDC.

The modest efficiency improvement by itself may not be of sufficient magnitude to warrant replacing the commonly used copper electrodes with titanium ones. However, titanium has other highly desirable properties as well. These include thermal expansion characteristics compatible with alumina and beryllia ceramics (which greatly simplify direct joining by brazing) and volume absorption of the hydrogen, oxygen, and nitrogen residual gases found in TWT-MDC vacuum envelopes. Taken together, the desirable properties of titanium seem to warrant further development and evaluation of titanium electrode MDC's, especially in the backup role in the event that the isotropic graphite electrode MDC's do not (for one reason or another) find wide application.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, November 8, 1988

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16. Abstract

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