A Review of the Suppression of Secondary Electron Emission from the Electrodes of Multistage Collectors

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ABSTRACT

A review is presented of more than 20 years of research conducted at NASA Lewis Research Center on the suppression of secondary electron emission (SEE) for the enhancement of the efficiency of vacuum electron devices with multistage depressed collectors. This paper will include a description of measurement techniques, data from measurements of SEE on a variety of materials of engineering interest and methods of surface treatment for the suppression of SEE. In the course of this work the lowest secondary electron yield ever reported was achieved for ion textured graphite, and, in a parallel line of research, the highest yield was obtained for chemical vapor deposited thin diamond films.

INTRODUCTION

The first multistage depressed collector to enter production was designed circa 1971 by Kosmahl [1] for the traveling wave tube (TWT) flown on the Communication Technology Satellite (CTS), also known as Hermes, launched in 1976. Kosmahl's collector had nine stages and was cooled by direct radiation to space. This 12 GHz TWT, which achieved an efficiency of 50% with an RF output power of 200 W, was the highest power transmitter to fly in space until 1988 and enabled the CTS project to achieve its goal to demonstrate for the first time the direct transmission of television signals from space to private homes.

Following the success of CTS, it was immediately obvious that the efficiency of multistage collectors could be enhanced significantly by suppressing secondary electron emission (SEE) from the collector electrodes. Ramins in 1976 observed an improvement in TWT efficiency when soot was applied to the electrodes of a multistage collector [2]. A series of SEE measurements of candidate materials was initiated by Forman with the first publication appearing in 1977 [3]; this work was refined and continued by Curren and others until recently. An apparatus for the detailed measurement of energetic secondary electrons was built by Krainsky with the first results reported in 1992 [4].

When a surface is bombarded by electrons, it will respond by emitting other electrons. The incident electrons are called the primary electrons; therefore, the emitted electrons are the secondary electrons. Typically, secondary electrons are emitted in a spectrum of energies ranging from near zero up to the energy of the primary electron. The distribution of electrons within this energy spectrum is a function of the energy and angle of incidence of the primary electrons as well as the material and surface morphology of the target. Most of the secondary electrons appear in two peaks located at the extremes of the energy distribution. The low energy peak is typically centered around 20 V, and these electrons are frequently referred to as the true secondaries. The electrons distributed near the primary electron energy have typically made elastic collisions with the target; they are frequently referred to as reflected primary electrons. In the apparatus developed by Krainsky, electrons within 20% of the primary energy are collected; therefore, they will be referred to here as energetic secondary electrons.

True secondary electrons degrade collector efficiency, but this effect can be substantially reduced by appropriate electrical design. Energetic secondary electrons can also degrade collector efficiency, but, because they may reenter the slow wave circuit, they represent a risk to the stability of the tube.

MEASUREMENT TECHNIQUES

The apparatus used by Forman [3] is shown in Figure 1. The material to be studied was introduced into a standard Auger spectrometer, which was used to determine the chemical species on the surface of the target and to provide the primary electron beam for the secondary emission measurements at normal incidence. By tuning the cylindrical mirror analyzer to the primary electron energy, a qualitative measure of energetic electron emission was also obtained. The

apparatus also contained a tungsten filament for electron bombardment heating of the target and an ion gun for sputter cleaning and texturing of the target. One half of each sample was typically coated with a layer of soot to serve as a reference. Samples could be translated in three dimensions in front of the electron gun and rotated to face the ion gun for sputter cleaning. Curren and Jensen [5] modified this apparatus to improve the vacuum to 10E-10 Torr, allow variations of the angle of incidence from normal to 85 degrees, and introduced a dc bias voltage on the target to provide a more definitive measure of true secondary emission.

Krainsky's apparatus [4], shown in Figure 2, was designed to study in detail the angular distribution of energetic secondary electrons and to measure the total secondary yield. The angle of incidence of the primary electron beam can be varied from normal to near grazing, while the secondary electrons can be collected over a range of 200 degrees in the half sphere above the target, except for the range within 10 degrees on either side of the primary beam. Primary current was less than 100 nA and the primary spot size was less than 1 mm in diameter. The secondary current was measured using electron counting techniques with a detector/analyzer, fabricated using a channeltron electron multiplier with an aperture and three grids.

ION-TEXTURED SURFACES

Forman [3] observed significant variations in the secondary emission characteristics of some materials following ion sputtering. Curren and his coworkers pursued this effect extensively, producing surfaces with significantly reduced secondary yields using a variety of materials, including copper, pyrolytic graphite, isotropic graphite, carbon on copper and titanium [5-10]. A typical texturing apparatus is shown in Figure 3. An argon ion beam is directed at the target material which is surrounded by a skirt of seeding material, chosen for this purpose because it etches more slowly than the target. Some of the seeding material is sputtered onto the target where it retards the target sputtering locally. The result is a target that is sputtered unevenly, producing a surface morphology such as can be seen in the electron micrograph shown in Figure 4.

By visual inspection these surfaces appear velvety in texture; the textured graphite or carbon surfaces are indeed so black in appearance that they are not readily photographable. A set of textured copper electrodes, fabricated for the Hughes 961H TWT developed for the Cassini mission is shown in Figure 5. In addition to their use in the suppression of SEE, these surfaces have found other applications. For example, textured titanium is being investigated as a surface for the enhancement of the acceptance of surgical implants.

SURFACE COATINGS

Since techniques for the fabrication of devices with copper electrodes are well established, many manufacturers find it desirable to use copper electrodes that have been coated with a low secondary yield material in multistage collectors. Forman [3] reported secondary emission data for copper with a TiC coating, produced by Varian. Curren [7] described a process for sputtering carbon on copper that produced a surface coating similar in appearance to that shown in Figure 5 with a very low secondary yield. Ebihara [11] described a carbon on copper surface applied by optimizing the parameters of the electrical discharge machining process for carbon deposition rather than the customary function of copper removal. This resulted in a highly durable, low secondary yield material shown in Figure 6.

SECONDARY ELECTRON YIELDS

The SEE data presented in the references cited in this paper are summarized in Table 1. These measurements were made by various researchers over an extended period of time using experimental techniques that have evolved as described above. More detail is available in the original sources cited here; typically, the data were presented in a format as shown in Figures 7 and 8. For some of the early data there is some uncertainty in the measurement of the total incident beam current; therefore, the data on the first column is labeled "secondary electron emission ratio", rather than secondary electron yield. For materials with low reflected primary emission this is approximately equal to the yield of low energy secondaries. The primary current was measured using a Farraday cup during the work on textured copper and these values are total secondary yield. Despite the changes in experimental technique over the years, these data are very useful for making relative comparisons between materials.

"Reflected primary electron yield" is presented in the second column of Table I. Referring to Figure 1, this is the ratio of the signal A to the value for soot at 1 keV. Again this is a useful relative measure of the yield of energetic secondary electrons.

ANGULAR DISTRIBUTION OF ENERGETIC SECONDARY ELECTRONS

Examples of the results obtained for measurements of the angular distribution of energetic secondary electrons for copper surfaces are presented in Figures 9 and 10, which illustrate the sharp contrast resulting from ion texturing. The polished copper surface exhibits mostly backward scattering at low incident energies and mostly forward scattering at high energies, while the textured copper surface produces predominantly backward scattering at all energies. The total secondary yield for the two surfaces is presented in Figure 11 where it can be seen that the texturing results in significant reductions in total yield as well as the fraction of energetic secondary electrons. Other data on angular distributions of energetic secondary electrons can be found in [12].

SUMMARY

The experimental techniques, methods of surface preparation and the measured values of SEE for a variety of materials and surfaces of engineering interest have been presented. Of the materials tested, isotropic graphite is most widely used in industry for this application. The measurement of SEE continues as an active area of research at Lewis Research Center, although the current emphasis is on enhancement of emission, rather than suppression. The ion-textured surfaces have also found application in optics and medicine.

ACKNOWLEDGMENT

It would be inappropriate to fail to acknowledge the hard work, imagination and dedication of my colleagues at Lewis Research Center who conducted the research described in this paper.

REFERENCES

1. H. Kosmahl, O. Sauseng, and B. D. McNary, *"A 240-W 12-GHz Space Communication TWT with 56 Percent Overall and 81 Percent Collector Efficiency,"* IEEE Transactions on Electron Devices, Volume ED-20, Number 12, December 1973, pp. 1169

2. P. Ramins, H. Kosmahl, and T. Fox, *"Design and Performance Evaluation of Small, Two-and Four-Stage Depressed Collectors for a 4.8 to 9.6 GHz High-Performance Traveling Wave Tube,"* NASA TM X-73486

3. Forman, *"Secondary-Electron-Emission Properties of Conducting surfaces with Application to Multistage Depressed Collectors for Microwave Amplifiers,"* NASA TP-1097, 1977

4. Krainsky, K. R. Vaden, A. N. Curren, J. A. Dayton, Jr., G. T. Mearini, *"The Angular Distribution of*

Elastically Scattered Electrons and Computed Impact on Collector Performance," IEEE IEDM 92-953, pp. 37.4.1-37.4.4

5. Curren and K. Jensen, *"Beam Impingement Angle Effects on Secondary Electron Emission Characteristics of Textured Pyrolytic Graphite,"* NASA TP-2285, 1984

6. Curren and K. Jensen, *"Secondary Electron Emission Characteristics of Ion-Textured Copper and High Purity Isotropic Graphite Surfaces,"* NASA TP-2342, 1984

7. Curren and K. Jensen, *"Textured Carbon on Copper: A Novel Surface with Extremely Low Secondary Electron Emission Characteristics,"* NASA TP-2543, 1985

8. Curren, K. Jensen, and G. Blackford, *"Secondary Electron Emission Characteristics of Untreated and Ion-Textured Titanium,"* NASA TP-2902, 1989

9. Curren, K. Jensen, and R. Roman, *"Secondary Electron Emission Characteristics of Molybdenum-Masked, Ion-Textured OFHC Copper,"* NASA TP-2967, 1990

11. Ebihara, P. Ramins, and S. Peet, *"TWT Efficiency Improvement by a Low-Cost Technique for Deposition of Carbon on MDC Electrodes,"* IEEE Transactions on Electron Devices, Vol. ED-34, No. 2, Part 2, February 1987

12. Dayton, Jr., I. L. Krainsky, K. R. Vaden, G. T. Mearini, "The Measured Angular Distribution of Elastically Scattered Electrons and Computations of its Effect on Collector Performance," Proceedings of the European Space Agency/NATO Conference in Noordwijk, The Netherlands, April 1997
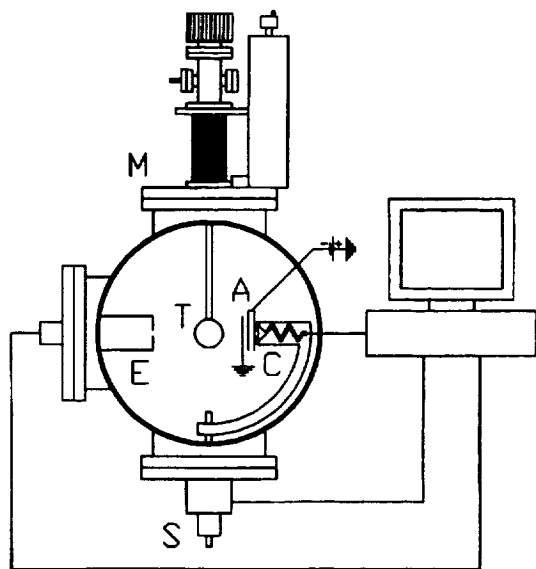
Figure 1 - Secondary-emission measurement equipment

Figure 2 - Schematic diagram of Krainsky's apparatus with component parts labeled (M) manipulator, (A) analyzer, (C) channeltron, (E) electrongun and (S) pumping system
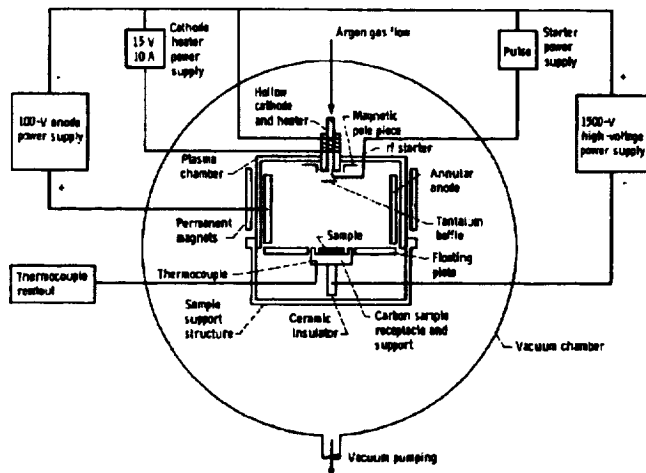

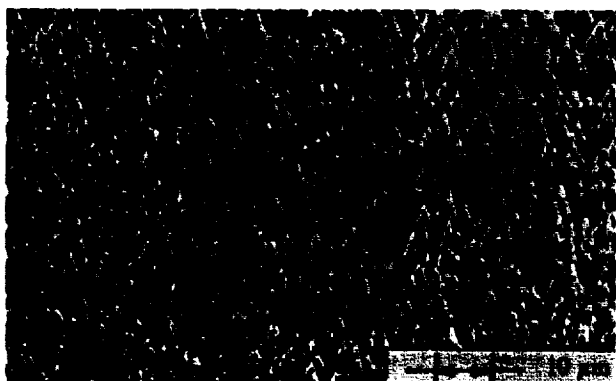**Figure 3 - Schematic of ion-texturing apparatus**

Figure 4 - Photo micrograph of ion-textured copper surface

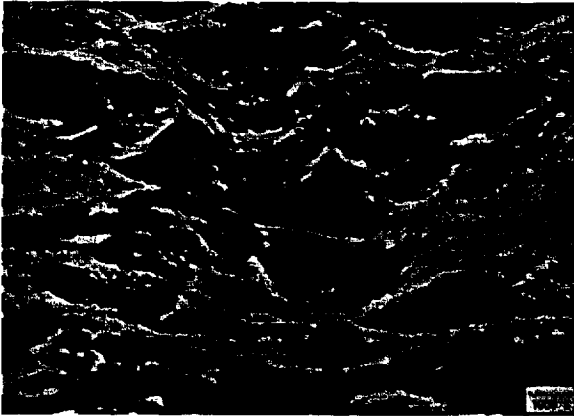**Figure 5 - Ion-textured MDC electrodes in transport container**

Figure 6 - Scanning electron microscope
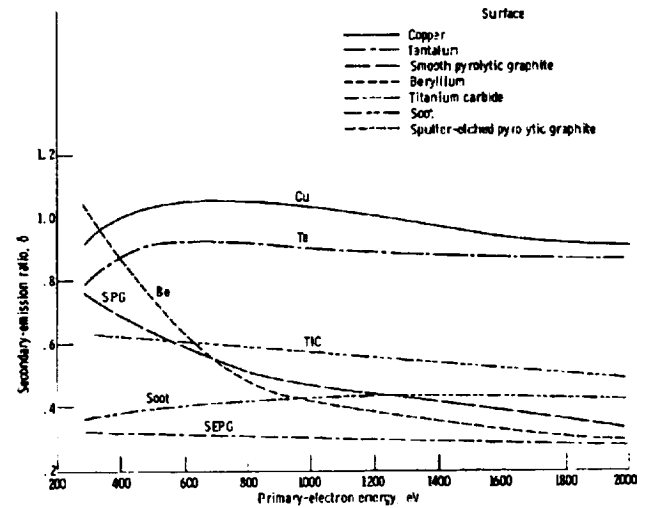photomicrograph of a typical arc-pyrolyzed
carbon coating on copper surface

Figure 7 - Secondary-emission ratio as function of
primary-electron energy for beryllium, copper,
pyrolytic graphite, soot, titanium carbide, and
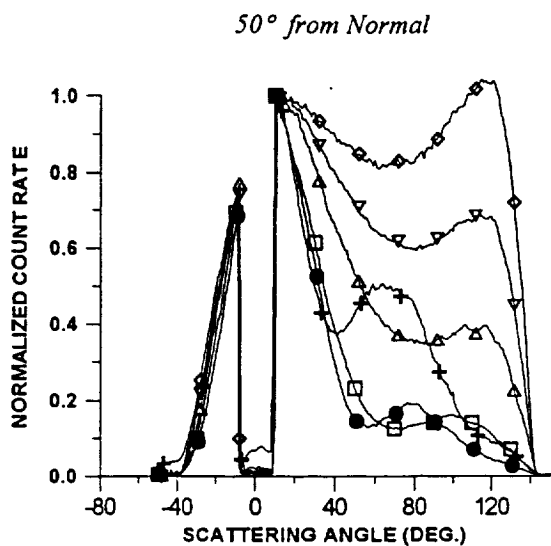tantalum surfaces in range 300 to 2000eV
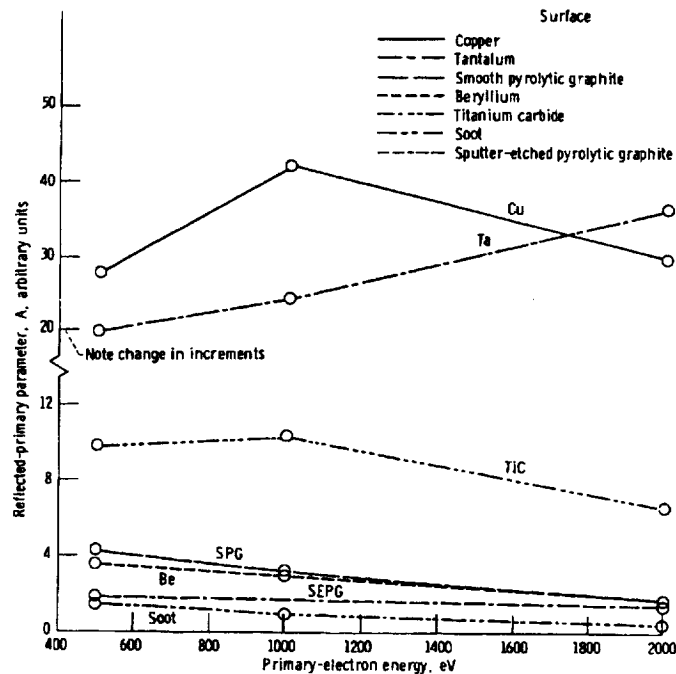
Figure 8 - Reflected-primary parameter A as function of
primary-electron energy for beryllium copper, pyrolytic
graphite, soot, titanium carbide, and tantalum surfaces in
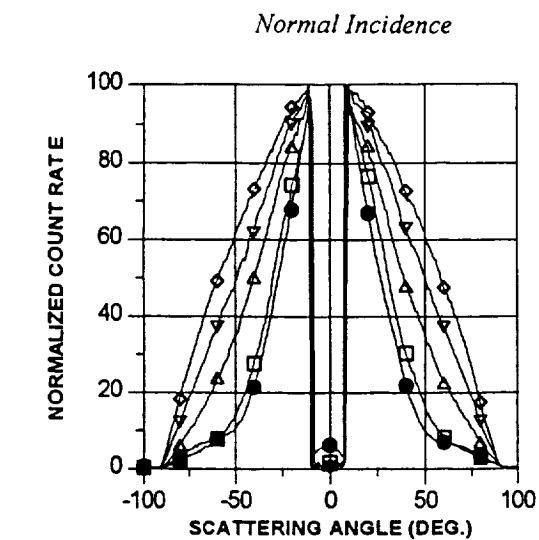range 500 to 2000 eV
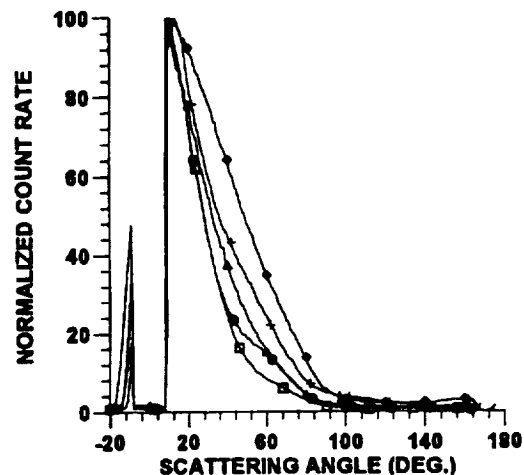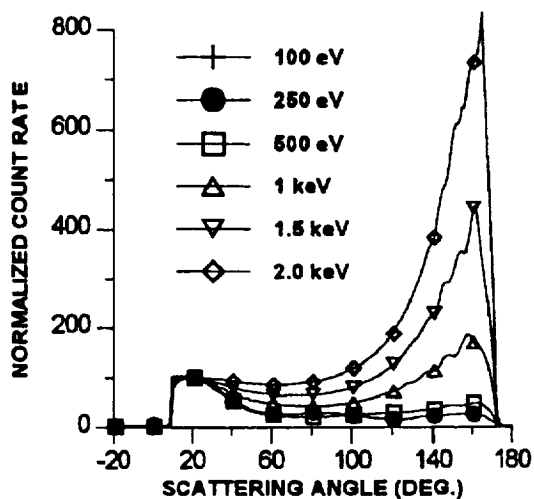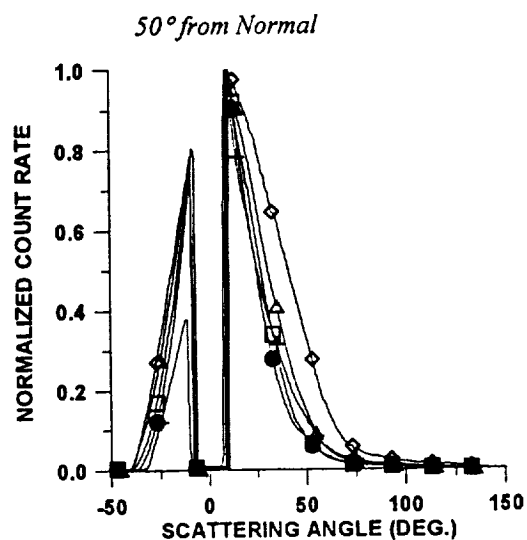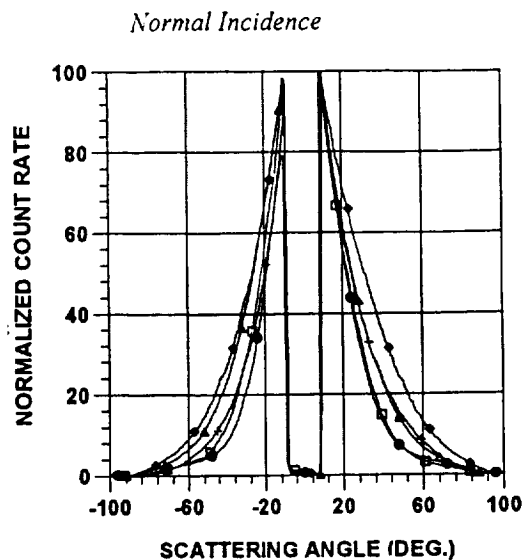
Figure 9 - Normalized angular distribution as a function of incident energy of elastically scattered electrons from a polished copper surface

Figure 10 - Normalized angular distribution as a function of incident energy of elastically scattered electrons from an ion-textured copper surface. The incident energies are designated as in Figure 9
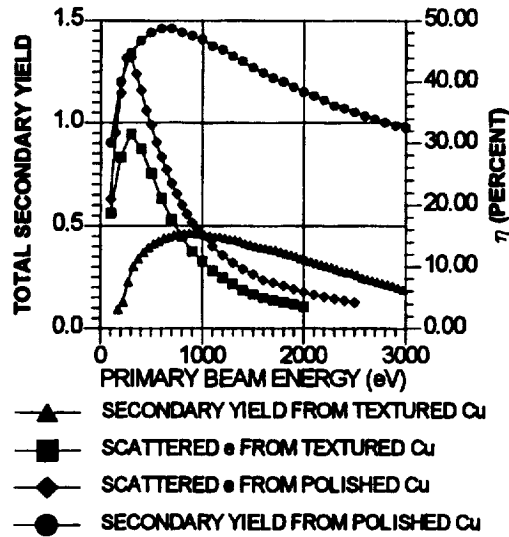
Figure 11 - Total secondary yield and fraction
of yield that is elastically scattered at normal
incidence into the detector at 20 degrees from
normal for polished and textured copper

Table 1- Secondary Electron Emission Characteristics of Candidate MDC Electrode Materials at 500 eV
Primary Beam Energy, Normal Incidence

Material	Secondary Electron Emission Ratio	Reflected Primary Electron Yield Index
Copper (Untreated)	0.94	27.5
Copper (Sooted)	0.33	2.13
Textured Carbon on Copper	0.26	1.60
Pyrolyzed Carbon on Copper	0.41	2.68
Ta-Seeded Ion-Textured Copper	0.39	11.00
304SS-Seeded Ion-Textured Copper	0.34	3.91
Pyrolytic Graphite		
AB Surface (Untreated)	0.82	8.46
AB Surface (Ion-Textured)	0.30	1.10
C Surface (Untreated)	0.49	5.16
C Surface (Ion-Textured)	0.22	0.77
High-Purity Isotropic (POCO) Graphite		
POCO Graphite (Untreated)	0.64	4.65
POCO Graphite (Particle-Blasted)	0.53	3.54
POCO Graphite (Ion-Textured)	0.20	0.51
Ta-Seeded Ion-Textured Titanium	0.40	11.00
Ti C/Copper	0.60	10.0
Ta	0.90	20.3
Be	0.70	3.6