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DC HIGH VOLTAGE BREAKDOWN CHARACTERISTICS
OF
304L AND 304LMC SST ELECTRODES

A Thesis

Presented to

The Faculty of the Department of Chemical and Materials Engineering
San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Michael P. Dolak, Jr.

December 2004

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ABSTRACT

DC HIGH VOLTAGE BREAKDOWN CHARACTERISTICS OF 304L AND 304LMC SST ELECTRODES

By Michael P. Dolak, Jr.

Conditions that affect High Voltage Breakdown were examined to propose process changes to improve production yield at Communications & Power Industries. Cathodes of 304L/LMC were evaluated for their ability to sustain DC High Voltage potentials in UHV ($\sim 10^{-8}$ torr). Testing followed a 7-day exposure in a class 100K cleanroom with cleaning or non-cleaning. Cleaned 304LMC displayed an increase in E_b over non-cleaned by a factor of ~ 1.7 . Cleaned 304L gave large data scatters versus non-cleaned. SEM photomicrographs displayed a greater surface concentration of inclusions for 304L versus 304LMC. This may account for the disparity in results for 304LMC and 304L. 304LMC may be more sensitive to micro-particle contamination. 304L may be less sensitive to contamination. Copper transfer from the anode to the 304L/LMC cathodes support the micro-particle breakdown theory proposed by Cranberg (1952). The E_b results for 304LMC support the use of low inter-metallic materials indicated by Hawley (1963).

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CHAPTER 1

INTRODUCTION

High Voltage (HV) Breakdown problems have been associated with Vacuum Electronic Devices (VED's) since the Varian brothers developed the first commercial devices in the late 1940's. The problem is associated with Continuous Wave (CW) and Pulsed Klystrons, Traveling Wave Tubes (TWT), and Coupled Cavity Traveling Wave Tubes (CCTWT). These devices offer RF amplification for Particle Accelerators, Ground Based Radar and Tracking Stations, X-ray amplifiers for radiation treatment and TV transmission.

Figures 1-3 contain the basics of Klystron relationships to other linear beam devices, basic operation design and specific High Voltage Breakdown problem area(s), respectively. Figure 2 presents a basic design of a Klystron, which is comprised of a Gun, an Interaction Structure (commonly referred to as the Body) and a Collector. The P_{in} and P_{out} elements refer to the incoming and out going RF signal. The basic workings of this device involve the interaction of P_{in} with an electron beam, which is provided by the Gun. The Gun contains a thermionic emitter, which when heated to $\sim 1000^{\circ}\text{C}$, produces a continuous or pulsed beam of electrons, depending on the application. The beam is at first compressed by the Focus Electrode and Modulating Anode as shown in Figure 3. However, if left unattended, the electron space charge repulsive forces would spread the beam. It is in the Interaction Structure, displayed in Figure 2, where the beam maintains its linearity and diameter through the use of external

permanent magnets or solenoids. It is also in the Interaction Structure where the electrons form bunches and interact with P_{in} to provide amplification. This amplification can be as high as 50 dB (or 10^5 times). Once the amplification has been completed the RF signal leaves the Klystron (P_{out}). The electron beam is then collected in the collector and its kinetic energy is dissipated as thermal heat energy.

Figure 1. Family Tree of Linear-Beam Tubes [1].

Figure 2. Basic design of a typical Klystron [2].

Figure 3. Overview of a Pierce Gun [3]. (Arrows and text box inserted)

Briefly, HV breakdown is associated with the electrical breakdown of the vacuum insulation ($\sim 10^{-8}$ torr) between electrodes during testing or operation in the field. The event is associated with an arcing phenomenon, which causes material from one of the electrodes to evaporate and deposit on the opposite electrode. The result is an electrical leak, which destroys the high voltage standoff of the device. The problem has been studied for several decades and while progress has been made, the phenomenon is still undergoing extensive investigation.

These HV vacuum breakdown problems have occurred with Communications & Power Industries (CPI) VA-889F and AWACS Klystron product lines intermittently over the past several years. Figures 4 and 5 display

the systems that these Klystrons are integrated into as well as the actual VED's (Klystrons) which amplify the microwave signals during system operation.

Figure 4. SPS-49 Shipboard Radar (upper left) and the VA-889F Klystron (lower left). AWACS Airborne Reconnaissance System (upper right) and VKR-7940 Klystron (lower right). Photographs courtesy of CPI.

Figure 5. PHALANX 20 mm Gun Platform (upper left) and VKU-7785E1 Klystron (lower left). Tomahawk cruise missile (upper right) and VA-896D Klystron (lower right). Photographs courtesy of CPI.

High Voltage Breakdown that leads to electrical leakage can occur during 50 kV DC Hi-Pot testing prior to RF acceptance testing. Five such occurrences from 2/98 to 2/99 have resulted in an average rework cost of \$33,000 per VED, for a total cost of \$165,000. This does not represent the “opportunity lost” cost for the resources expended, which could have been better served elsewhere. Moreover, if the failure trend was extrapolated, the expected failure rate for FY 1999-2000 would be expected to have been 13%. Some design changes have occurred during FY 2000-2001, which have reduced the frequency of the failures.

The design changes addressed geometrical flaws that exposed sub assemblies to higher localized fields (electrical field enhancement), with failure sites associated with HV breakdown. However, the problem has not been addressed in-depth. Certain inherent issues exist regarding the properties and processing of the materials used to fabricate the VED assemblies. Among these is the cleanliness of the subassemblies during fabrication. CPI typically performs subassembly fabrication in a class 100,000 (100K) cleanroom.

At CPI periodic electrical leakage can occur during 50 kV DC Hi-Pot testing of the Cathode/Ceramic and Mod Anode & Input Cavity (I/P) Cone as part of the acceptance procedure for the VA-889F Klystron. Figure 6 displays a failed OFE Copper Mod Anode and a 304L SST I/P Cavity Cone. Figure 7 shows a close up photograph of the SST I/P Cavity Cone. Figure 8 presents a Scanning Electron Microscope (SEM) image of a film deposited on the OFE Mod Anode after HV breakdown. It was believed that the film material emanated from the 304L SST I/P Cavity Cone. Figure 9 displays an Energy Dispersive X-Ray (EDX) analysis of the deposited film and the base material as well as an analysis of the 304L SST. Interestingly, the concentration of the Mn in the film is higher than in the parent 304L SST material. Conversely, the Fe and Cr content in the deposited film are lower in concentration than in the parent 304L SST.

This can be supported thermodynamically whereby the graphical data prepared by RCA in 1962 [4] indicates that for the pressures (10^{-8} torr) and temperatures of interest (800°C – 1500°C) Mn has a vapor pressure $\sim 10^4$ times

that of Fe, $\sim 10^5$ times that of Cr, and $\sim 10^7$ times that of Ni, which are the primary elements in 304L SST. As an example the following calculation reveals the fact that Mn is the dominant element in the film of Figure 8 and supported by EDX results of Figure 9. For example at $T = 800^\circ\text{C}$ (the melting range of 304L SST is $1400\text{--}1450^\circ\text{C}$ [5]).

$$P_{\text{Mn}} = 7 \times 10^{-4} \text{ torr (0.0225 Mn atomic fraction in 304L SST)} = 1.58 \times 10^{-5} \text{ torr (1)}$$

$$P_{\text{Cr}} = 2 \times 10^{-9} \text{ torr (0.2255 Cr atomic fraction in 304L SST)} = 4.51 \times 10^{-10} \text{ torr (2)}$$

$$P_{\text{Fe}} = 2 \times 10^{-9} \text{ torr (0.7520 Fe atomic fraction in 304L SST)} = 1.50 \times 10^{-9} \text{ torr (3)}$$

$$P_{\text{Ni}} = 5 \times 10^{-10} \text{ torr (0.0170 Ni atomic fraction in 304L SST)} = 8.52 \times 10^{-12} \text{ torr (4)}$$

Figure 6. VA-889F Mod Anode (left) and I/P Cavity Cone) right. Note: Dark metallic blush observed on Mod Anode tip. EDX analysis indicated a high concentration of Mn (see Figures 8 and 9)

Figure 7. Close-up photograph of HV Breakdown site on 889F I/P Cavity Cone.

Figure 8. SEM Photomicrograph (~1100X) of film deposited on a VA-889F OFE Cu Mod Anode.

Figure 9. EDX analysis of film deposited on OFE copper Modulating Anode (left) and the parent material of the 304L SST I/P Cavity Cone (right).

It should be noted in Figure 8 that the HV breakdown occurred during in-process Hi-potting from 0-50kV. The Mod Anode was at negative or cathode potential. The I/P Cavity Cone of Figure 7 was at positive or anode potential. The 304L SST material during HV breakdown that is comprised of positive Mn^{2+} , Cr^{3+} and Fe^{3+} ions would be expected to transfer to the Mod Anode surface that was at negative potential. It is noticed in Figure 9 that Ni does not appear in the film deposited on the Mod Anode. This is probably due to the extremely low vapor pressure of Ni and surface sensitivity of the SEM. The Field Strength at breakdown (E_b) was estimated to be 5 MV/m.

The following expressions from Kubaschewski and Evans [6] can also be used to calculate the elemental vapor pressures from 298K to the melting point in a typical 304L SST material. Whereas,

$$\log(P_{\text{Mn}}) = -14850/T - 2.52\log(T) + 17.88 \quad (5)$$

$$\log(P_{\text{Cr}}) = -21200/T - 1.56\log(T) + 15.75 \quad (6)$$

$$\log(P_{\text{Fe}}) = -21080/T - 2.14\log(T) + 16.89 \quad (7)$$

Rearranging and solving for P at T = 800 °C (1073K) and considering the contribution of each element by its atomic fraction in 304L SST, the following results are obtained:

$$P_{\text{Mn}} = 5.65 \times 10^{-6} \text{ torr} \quad (8)$$

$$P_{\text{Cr}} = 6.21 \times 10^{-10} \text{ torr} \quad (9)$$

$$P_{\text{Fe}} = 4.23 \times 10^{-10} \text{ torr} \quad (10)$$

$$P_{\text{Ni}} = 7.64 \times 10^{-12} \text{ torr} \quad (11)$$

The previous expressions are valid for an overall ambient background pressure. The vacuum pressure in the failed device in Figure 6 was $\sim 10^{-8}$ torr. These expressions correlate that Mn would be expected to be the dominant species in the film of Figure 8 as indicated by the EDX analysis of Figure 9.

The Fowler-Nordheim expression was utilized to compare experimental pre-breakdown current and voltage data to determine if in effect, the arc initiation is due to electrode surface microprotrusions and field emission. Additionally, the Fowler-Nordheim equation can be used to estimate the field emission area and the field enhancement factor. SEM/EDX and Auger analysis was used to characterize the emission sites of the base metals and other spurious contaminants, and their concentration thresholds, if present. The same tools were then used to characterize possible materials and process solutions and

their effectiveness at eliminating or suppressing High Voltage Breakdown problems.

The objective of this study was to evaluate the effect of microparticle contamination on an electrode surface and the resultant ability of the electrode to hold High Voltage potentials in vacuum. Additionally, the effect of cleaning processes in removing micro-particles will be evaluated to determine if improvements in High Voltage standoff can be achieved. A comparison between two grades of stainless steel, 304L (low carbon grade) and 304 LMC (low carbon and manganese grade), will be evaluated in a side by side comparison to evaluate the ability of these materials to hold high voltage potentials after undergoing the aforementioned processing. Residual Gas Analyzer (RGA) equipment will be used to monitor gas evolution prior to, during and after the breakdown event.

The following chapters will present an historical background including theoretical models and related theories in Chapter 2. Research Hypothesis, Experimental Procedure, Experimental Results, Discussion of the Experimental Results and Conclusions with Recommendations to improve High Voltage Breakdown thresholds for electrodes under high vacuum insulation will be presented. Limitations of this experimental study will also be discussed. Additionally, recommendations for future work to expand further knowledge of the HV breakdown phenomena will be presented.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 Historical Background

Phenomena associated with HV Breakdown were first investigated by Wood [7] in 1897. Wood observed arc discharges on platinum wires and spheres under vacuum that led to material erosion. Subsequent studies were conducted by Earhart in 1901 [8]. Earhart studied the effects of spark discharges on metal plates in ambient and CO₂ atmospheres. Also, studies were conducted by Hobbs in 1905 [9], and Millikan and Sawyer in 1918 [10]. These initial investigations established a pre-breakdown condition(s) where a vacuum gap has a small but finite current, which increases with increasing voltage prior to the final breakdown event. Investigators throughout the years have been able to make progress regarding the causes of field emission, ohmic emission, thermionic emission and how they relate to high voltage breakdown. It was discovered that localized field enhancement would occur for a given applied voltage. Contributing factors were found to be the residual gas pressure, geometry of the electrode surfaces and metallic microprotrusions, and in-process contamination of the base electrode material, etc. [11].

Several theories regarding the cause of the electrical breakdown were developed in the 1960's. Two basic electrode related mechanisms were considered in an attempt to model field emission and high voltage breakdown. "Cathode-initiated" (electrode at negative bias) breakdown is thought to occur

when a metallic microprotrusion on the opposite anode (electrode at positive bias or ground) becomes thermally unstable due electrical field enhancement. This results in the material being evaporated, followed by ionization that forms a localized micro-plasma with positive metallic ions, and then being accelerated across the vacuum gap potential, and coating the negative electrode [12].

“Anode-initiated” (electrode at positive bias or ground) breakdown is thought to occur when the anode surface is heated locally by the stream or beamlet of electrons being emitted by the cathode microprotrusion. At some critical level of power density, the anode material is vaporized causing an arc between the electrodes with the resultant insulation breakdown [13].

Briefly, the phenomena of High Voltage Breakdown in a vacuum can be described as an arcing event which is initiated at some critical voltage potential during operation of the VED. For small gaps (< 1 mm), Hawley, *et al* [14], have stated that prior to the breakdown event, pre-breakdown currents are observed which can be indicative of thermionic emission, field assisted thermionic emission or field/cold emission. The I vs. V graph of Figure 10 display a schematic representation of HV breakdown.

Figure 10. The typical form of the non-ohmic current-voltage characteristics of a high voltage vacuum gap [15]. (Text box inserted)

The duration of the breakdown current discharge in Figure 10 is of special interest. Mesyats, Puchkarev and Murzakaev investigated the arc discharge time for copper electrodes in ultra high vacuum (UHV) [16, 17]. The average arc duration time was found to vary from 10^{-8} s to 10^{-7} s for a breakdown current of 1.8 A. The data was compiled from >100 measurements by Murzakaev in a similar but independent study [18]. Juttner and Freund compiled data on the average arc burning time as a function of current for various electrode materials [19]. Their results are presented in Figure 11. For copper electrodes the arc time increases from ~0.1 s at ~17 A discharge current to ~1 s at ~52 A of discharge current. Fu [20] also indicated that rougher surfaces and Kesaev [21] indicated that higher temperatures give increasing arc time lengths.

Figure 11. Mean arc burning time $\langle \tau_b \rangle$ as a function of arc current for different materials [19].

2.2 Theoretical Models

2.2.1 Metallic Microprotrusion (MM)

Figure 12 presents three models that have been proposed to explain the causes of High Voltage Field Emission breakdown in a vacuum. The first model is referred to as the Metallic Microprotrusion (MM) model. Millikan and Lauritsen first proposed this model in 1928 [22]. It explains that an applied electric field can be enhanced by metallic microprotrusions emanating from a broad-area cathode. This enhancement in turn leads to electrons being emitted from the tip of the metallic micro-protrusion. When sufficient field enhancement is attained (≥ 100 MV/m), localized current densities can lead to an increase in temperature. This in turn can cause evaporation of the metal which can form a micro-plasma discharge leading to breakdown. It is thought that the positive metallic ions when

stripped of their valence electrons can then be accelerated across the vacuum gap and if sufficient kinetic energy exists, can cause anode surface damage. Conversely, a breakdown condition may arise from the positive metallic ions depositing as a thin film ($\sim 10^{-6}$ inches) and if deposited on an insulating surface would decrease the surface resistivity of the insulator to a point where breakdown would occur.

2.2.2 Metal-Insulator-Vacuum (MIV)

In Figure 12, the second model is referred to as the Metal-Insulator-Vacuum (MIV) model. Allen and Latham first proposed this model in 1978 [23]. Latham explains that the emission phenomena can be viewed as a micron-sized electronic device embedded on a broad surface cathode. The MIV model describes field emission being primarily caused by electron trapping and ultimate exchange and discharge at the Metal-Insulator surface. Electron energy band diagrams are useful in visualizing the emission regime as displayed in Figure 13.

2.2.3 Metal-Insulator-Metal (MIM)

The third model is referred to as the Metal-Insulator-Metal (MIM) model. It was first proposed by Athwal *et al*, in 1985 [24]. It incorporates all of the features of the MIV model but adds a conducting surface attached particle that provides local field enhancement to the Metal-Insulator interface. It attempted to explain how artificially introduced graphite flakes onto a Cu electrode would cause low field (< 10 MV/m) electron emission.

While all of these models have been correlated by experimental evidence to some degree, none has achieved complete acceptance as the dominant explanation for HV breakdown. In fact these models may collectively interact to produce the failure mechanism(s) at the electrode surface [25].

Figure 12. Schematic illustration of three possible micro-emission regimes, or electron "pin-holes". (a) the Metal-Insulator-Vacuum (MIV) regime, (b) the Metal-Insulator-Metal regime, and (c) the Metallic-Microprotrusion (MM) regime, [26].

Figure 13. An illustration of the quantum mechanical tunneling mechanism by which a field-emitted electron may escape, or tunnel, from the surface of a metal. It shows the modified high-field potential barrier outside the surface (solid line), where the contributions of the image potential and the applied field ($E \sim 3 \times 10^9$ V/m) are shown by the broken and the broken-solid lines, respectively. In addition, the wave function of a tunneling electron is depicted. Finally, the inset illustrates the low- and high-temperature electron energy distribution $dN_e/d\varepsilon_e$ within the metal. [27]

2.3 Field Emission Theory

2.3.1 Fowler-Nordheim Theory

Fowler and Nordheim proposed another theory that was developed to explain Metallic Field Electron Emission (M-FEE) in 1928 [28]. It uses a quantum mechanical approach to describe the tunneling probability of electrons through a potential barrier in an ideal metal as influenced by a high-applied electric field in vacuum as illustrated in Figures 12c and 13. It has been applied to predict pre-breakdown currents from a single idealized metallic

microprotrusion in a vacuum gap, under increased applied electric fields. The following expression was derived:

$$J = AE^2/\Phi \exp(-B\Phi^{3/2}/E) \quad (12)$$

Where, J is the current density expressed in A/m^2 , E is the applied electric field in V/m , and Φ is the ideal metal work function in eV . With the previous expressed units, the constants A and B have the following numerical values:

$$A = 1.54 \times 10^{-6} \quad (13)$$

$$B = 6830 \quad (14)$$

This law predicts a very small current for fields below a few gigavolts/meter (GV/m). A steep rise in current is then predicted above this limit.

2.3.2 Deviations from Fowler-Nordheim Theory

Dyke and Trolan [29] in 1953 discovered that for current densities greater than $J = 10^{12} A/m^2$, theory to experimental correlation breaks down. They theorized that space charge effects came into play and that the emitting metal tip morphology would change by blunting or melting due to Joule heating effects. Duke and Alferieff [30] further contended that if the emission current density was kept below $10^{12} A/m^2$, the emitting tip would remain stable, provided that vacuum was maintained at $\leq 10^{-8}$ mbar (7.5×10^{-8} torr). At pressures higher than 10^{-8} mbar (7.5×10^{-8} torr), condensed gaseous species would alter the potential energy barrier of the emitting electrons and the result would be a varying current density.

For such an emitter the microscopic field can be enhanced according to the following expression:

$$E_m = \beta E = \beta V/d \quad (15)$$

Here, E_m is the enhanced electric field at the tip of the microprotrusion (in Volts/meter), β is the geometric field enhancement factor due to the microprotrusion, and E (or V/d) is the applied electric field (Volts/meter) for plane parallel gap electrode geometry.

This expression can be substituted into the general Fowler-Nordheim (FN) equation in terms of measurable parameters I and V , whereby the following is derived:

$$\ln(I/V^2) = \ln[1.54 \times 10^{-6} A_e \beta^2 / \phi d^2] - (6830 d \phi^{1.5} / \beta) (1/V) \quad (16)$$

Here, I is the pre-breakdown emission current (Amperes), A_e is the emission area (m^2), ϕ is the work function of the emitter material (eV), and d is distance between the electrodes (m).

A plot of $\ln(I/V^2)$ vs. $1/V$ will give a straight line with a slope of:

$$d(\ln(I/V^2))/d(1/V) = - 2.84 \times 10^9 d \phi^{1.5} / \beta \quad (17)$$

The intercept can be found at:

$$[\ln(I/V^2)]_{V=\infty} = \ln[1.54 \times 10^{-6} A_e \beta^2 10^{4.52\phi-0.5} / \phi d^2] \quad (18)$$

Equations (16) and (18) are useful in determining β and A_e . Values for β and A_e , which have been reported experimentally, range from 200-800 for β and 10^{-9} to $10^{-18} m^2$ for A_e [31].

Figure 14 presents a Fowler-Nordheim plot of an actual VED during in-process acceptance testing. The negative slope is indicative of F-N field emission.

Figure 14. Fowler-Nordheim plot of a VA-889F S/N 1195 during 50 kV Hi-pot testing. The current plotted was before breakdown that did not occur. VED was processed.

Trump and van de Graaf [32] in DC studies describe a “total voltage” breakdown mechanism(s) which involve positive ion emission by electron impact and the reverse mechanism of electron emission by positive ion impact and photon impact. They went on to differentiate between field emission breakdown at low voltages (and high field gradients) and high voltages.

Mesyats refers to HV breakdown in what is termed Explosive Electron Emission (EEE). Briefly, EEE is predicated on a cathode material experiencing high energy concentrations in microvolumes due to Joule heating by way of field emission. He refers to these breakdown currents as comprised of discrete packages of electrons that he named as “ectons” [33].

Cox [34], and Cox and Williams [35, 36] were able to isolate field emitters on roughly machined ultrasonically cleaned and degassed copper and stainless steel electrodes. Their intent was to measure the current from micro-points and then estimate the Fowler-Nordheim parameters of the micro-emitters. The dependence of the emission current did obey the F-N equation, however the appearance of emission areas was not determined by micro-points alone. They examined a single emitter under 2×10^{-8} mm-Hg (torr) pressure, with emission currents of 10^{-8} A and an applied electric field (E_A) of 4.8×10^6 V/m. The field enhancement factor (β_E) was calculated to be 735 and the emission area (A_E) was 0.5×10^{-11} cm². Mesyats in review, concluded that these estimated parameters could be provided by a conical microprotrusion of 29 μ m in height and a tip radius of 0.02 μ m [37].

2.4 Microparticle Theory

2.4.1 Surface Contaminant Effects

Cox and Williams [36] using direct SEM observations of the emission centers identified dielectric inclusions as the emission source that were approximately 5 μ m in diameter. When the electric field was increased to

1.24×10^7 V/m the current dropped to 10^{-11} A. They concluded that this was related to dielectric surface contaminants being removed [36]. β_E was calculated to be on the order of 200 for uncontaminated areas. However, their SEM analysis concluded that the observed microprotrusions could not give such high values of β_E . They did observe that in the non contaminated areas, emission centers corresponded to grain boundary and micro-protrusion interfaces. Cox and Williams estimated that these structures could not produce a field enhancement factor greater than 30-100. They surmised that these regions had reduced work functions on the order of 2-3 eV. Similar estimations were drawn by Fabiniak, *et al* [38], and Llevellin-Jones [39] in experiments involving observed emission current.

2.4.2 Microparticle Effects

Cranberg first proposed in 1952 that loosely adhering micro-particles, which attain a critical surface charge density, could accelerate across the electrode gap and impact on the target anode [40]. He referred to microparticle induced breakdown as a “clump” mechanism. Cranberg, in examining the results of HV breakdown studies from other workers, found that the breakdown voltage V_b , was proportional to the square root of the electrode gap ($d^{1/2}$) for plane parallel electrodes. Following this, other researchers have proposed that if the kinetic energy of the particle was high enough to initiate an explosive discharge of the target material, a localized micro-plasma could be formed, leading to the insulation breakdown of the vacuum gap. In flight micro-particle

velocities were estimated to be from 280-900 m/s [41]. Figure 15 presents a schematic representation of micro-particle impact and an SEM photomicrograph displaying electrode surface craters due to impact.

Figure 15. (Top) Microcrater regimes produced by microparticles whose impact velocities (i) only marginally exceed the critical value v (≤ 300 m/s), and (ii) are well in excess of v_c , such that there is extensive plastic deformation and progressive melting of the impacting materials (after Rudolph). (Bottom) A scanning electron micrograph of the type of high impact velocity microcrater illustrated in Fig 7.26(ii). [42]

Rudolph [43] in 1969 and in later studies by Dietzel, *et al* [44], in 1972 indicated that when micro-particle velocities exceed 500 m/s an additional

mechanism of localised melting can occur. This is coupled with the initial severe plastic deformation of the the impinged electrode. The melting of the electrode material can lead to secondary microparticles and crater shape as illustrated in Figure 16.

Figure 16. A schematic representation of the creation of (a) a “primary” microparticle by the field-stripping of a protruding microfeature, and the “coronet” effect in which a shower of “secondary” microparticles result from a high velocity impact of a primary microparticle, (b) Primary and secondary microparticles. [45]

The physical evidence of micro-particles in the early studies centered on topographical examination of the electrode surfaces after the HV breakdown event. Anderson in 1935 using optical spectroscopy methods and dissimilar electrode materials, found physical evidence of “foreign” materials being present on an electrode surface which corresponded to the opposite electrode after HV breakdown (46).

Padamse indicated that particles themselves can cause field emission if bound strongly to the electrode material. RF and DC studies have indicated that emitters are micron sized particles with chemistry different from that of the parent electrode material [47]. However, the percentage of particles which do emit at a given field strength is relatively small. Padamse and Knobloch [48] found that while all field emitting sites were associated with micro-particles; only a small percentage was found to cause field emission. At field strengths of < 100 MV/m only 5-10% of the microparticles observed were emitters. Particle geometric field enhancement factors (β) for the particles studied were approximately 50. This was below the Fowler-Nordheim approximations of 700. They hypothesized that other factors were contributing to whether a particle will emit or not. The three most salient factors were the detailed geometry of the microparticle, condensed gas on the particle and the interaction between the particle and insulating layer on the electrode surface.

Pupeter, Gohl, Habermann, *et al.*, [49] studied the effect of particle emission on niobium substrates. Their group studied various surface effects such as roughness and cleanliness. Their results indicated that the field emission mechanism was not strongly dependent on surface roughness but did correlate with surface cleanliness. Pre-breakdown field strengths of up to 300 MV/m were reported. In a separate study, Habermann *et al.*, indicated that the field emission on flat niobium substrates was influenced by gas adsorbates and metallic surface oxides. They also indicated that the substrate/microparticle

interfacial properties can play a role [50]. Knobloch [51] in studies on RF vacuum breakdown indicated that even under excellent vacuum conditions, adsorbed gasses or surface plasmas can significantly reduce HV breakdown levels.

Regarding microparticle geometry, Jimenez, *et al* [52] found that microparticle size plays an insignificant part in determining the field emission threshold. However, the detailed surface morphology is important in determining the field emitting characteristics of the micro-particle. Figure 17 presents examples of the particle morphology. They examined irregular or jagged shaped and smooth spherical Ni and Fe particles (10-20 μm sized irregular and 5-10 μm smooth), on Nb and Au substrates. They found that irregular shaped particles had threshold field emitting limits of below 50 MV/m, while those of the spherically smooth particles had limits of 120 MV/m.

Figure 17. SEM micrographs of two intentionally introduced nickel particles from a field emitter study: (a) jagged shape and emitting (b) smooth and non-emitting up to 120 MV/m. [52]

2.5 Gas Effects

Padamse and Knobloch [48] further contended that emission sites can be activated by the presence of oxygen gas that condenses on a micro-particle at 2K in a Superconducting RF Cavity. Temperature (2K to 300K) and oxygen (partial pressure not specified) cycling indicated that reactivation of the same site occurred under applied fields of 16-18 MV/m. Figure 18 displays temperature maps of 1500 MHz cavities up to 26 MV/m.

Figure 18. (a) Temperature maps of a 1500 MHz cavity. The surface is emission-free at 26 MV/m. (b) Emitters appear when the cavity is exposed to oxygen. (c) Emitters are no longer active after cycling to room temperature. (d) The same emitters reappear when exposed to oxygen a second time. [48]

In 0-50 kV DC experiments using ultra-high vacuum (10^{-10} torr) to low vacuum (10^{-3} torr), Bloomer and Cox [53] contended that the break down field

strength (E_B) was independent of the electrode separation (d) but strongly dependent on the material and the ability to condition the electrodes. This conditioning effect was thought to be due to the “sputtering” away of field emitting micro-protrusions on the electrode surfaces by ionized gasses.

L. Laurent, *et al* [54], conducting work on pulsed RF breakdown for X-band transmission cavities found that gas emission from the grain boundaries of metals may contribute to HV breakdown. Figure 19 shows preferential breakdown sites observed at the grain boundaries of the OFE (Oxygen Free Electronic Grade) copper cavity walls. Outgassing the cavities improved performance. Sharp edges or step discontinuities in the metals (surface roughness) was believed to provide localized geometric field enhancement.

Figure 19. SEM shows preferential breakdown along grain boundaries at field levels of ~ 150 MV/m for a pulse duration of $1.5 \mu\text{s}$ for the cavity noses that were not vacuum fired (a) 1st experiment (b) 2nd experiment. [54]

Duke and Alferieff [30] proposed several models to explain emission enhancement due to the presence of adsorbed gas. It was believed that an adsorbed layer on a microparticle can induce “resonant tunneling” of electrons

from the substrate/microparticle/gaseous interfaces to vacuum. The large range of reported emission area (A_e) values might be accounted for by the various condensed gaseous species on emission sites. Conversely, “gas conditioning” of electrodes has been successfully used to extinguish emission sites to allow for higher applied electric fields [55-57]. Helium gas was injected into the electrode gap with controlled currents in the low μA levels with an increasing electric field. This was a “staged” process whereby the emission currents are allowed to decrease over time at a constant electric field. This process is repeated until the operating voltage is achieved. It was believed that metallic-microprotrusions were sputtered away by the action of the gas ions. This is a common technique used in the VED industry today.

Interestingly, Bajic, *et al* [58], found that different gas species have optimal “conditioning” effects for a particular applied voltage. Figure 20 illustrates gas conditioning voltage and temperature effects. Thermal cycling in the range of 200-300 °C was found to reactivate previously gas-conditioned sites on high vacuum electrodes. With this in mind, it was recommended that gas conditioning be the final *in-situ* vacuum process for electrodes and that operating temperatures should not exceed 100 °C.

Figure 20. The general properties of the gas conditioning phenomenon, highlighting in a) the “temperature” effect, and in b) the “voltage” effect. [58]

Kobayashi, *et al* [59], using ASTM F-68 Class 1, 3 and 5 degassed OFE copper electrodes concluded that electrode gas content was an important factor in determining the breakdown field strength. They used an *in-situ* Ar ion beam sputtering system in the vacuum test chamber to clean the electrodes prior to testing. Breakdown current was limited to 10 A. The Class 1 material displayed higher field strength per breakdown than the Class 5 material. Kobayashi attributed this to the greater purity (i.e. lower porosity content) of the Class 1 material. Reported increases in field strength after 500 breakdown events were 19.6 MV/m to 183 MV/m for the Class 1 material; 18.9 MV/m to 175 MV/m for Class 3 and 18.5 MV/m to 118 MV/m for Class 5. In studying the effect of the *in-situ* Ar ion beam cleaning using Class 1 material, it was found that the *in-situ*

cleaned material had higher field strengths per breakdown than material, which was not *in-situ*, cleaned. However, there was no discernible difference between the two cases for the initial breakdown event(s).

Hackham and Altcheh [60] studied the effect of the ambient gas pressure on breakdown voltage for a given electrode gap distance using both DC and AC conditions. They found that for AC conditions the breakdown voltage was independent of pressure from 10^{-6} to 10^{-2} mbar (7.5×10^{-7} to 7.5×10^{-3} torr) for gap distances of 0.13 mm (.005 in.) to 2.03 mm (0.080 in.). Their DC findings indicated that for the same pressures the breakdown voltage was independent only for a gap distance at 0.13 mm (.005 in.). Their results are presented in Figure 21.

Figure 21. The pressure effect, illustrated by a family of plots showing how the DC (dashed lines and open symbols) and AC (solid lines and closed symbols) breakdown voltages of a pair of plane-parallel Cu-electrodes depend on the pressure and gap separation. (From Hackham and Altceh, with permission). [61]

Figure 22 presents a non-ohmic I vs. V graph that illustrates the difference in pre-breakdown currents for different vacuum pressures. This was previously highlighted in Figure 10. Latham [62], noted that this “noise” level may be evidence of current spikes identified as “microdischarges”. The duration of the spikes can run from 50-1000 μs . As the pressure increases and the applied voltage (V) approaches the breakdown voltage (V_b) these pre-breakdown spikes grow in magnitude.

Figure 22. The effect of pressure on the DC current-voltage characteristics of a typical HV gap (dashed line). Curve 1: $P \geq 10^{-9}$ mbar. Curve 2: $P < 10^{-6}$ mbar. [62]

Arnal [63], Pivover and Gordienko [64], Mansfield [65], Boersch *et al* [66], and Powell and Chatterton [67] presented several mechanisms in an attempt to explain the cause of the pre-breakdown microdischarge phenomena, in the middle of the last century. One contention was that they could be evidence of

“explosive” electron emission or microparticle assisted breakdown. A second explanation offered that gas ionization resulting from surface adsorbed ambient gasses following sample bake out could be a source.

Gerasimenko [68], offered a third explanation that a positive and negative ion exchange mechanism emanates from contaminant deposited films. He explained that a cascade effect can occur when a vacuum ambient positive ion is created in the gap. This can accelerate and impact the cathode resulting in negative ion creation. The result is negative ion impact at the anode with the generation of more positive ions. He concluded that if the ion multiplication factor is > 1 at both electrodes, the resultant generation of the ions would lead to the observed pre-breakdown micro-discharge current. Figure 22 also illustrates that the phenomena is more pronounced at higher vacuum pressures.

2.6 Electrode Material

The choice of materials for use as High Voltage electrodes is important. In general, the material should possess the capability to withstand high vacuum conditions ($\geq 10^{-8}$ torr) at the operating temperatures of the device.

Thermodynamically, these materials should have low partial vapor pressures under the temperature and vacuum conditions of the high voltage environment.

Materials of choice range from 304L Stainless Steel, Titanium alloys such as IMI Ti-318, OFE copper, and nickel. Molybdenum has also been used at CPI. The resistance to oxidation is an important criterion because the oxide insulation layer could decrease the breakdown voltage threshold according to the MIV

model coupled with microparticle contamination [69]. Hawley [70] also indicated that the use of low concentrations of intermetallic materials can give improved high voltage thresholds.

2.7 Cleaning Processes and Fabrication Environment

Methods to remove adhering micro-particles prior to exposure of the substrate electrodes to high electric fields have utilized high-pressure Water Rinsing (HPR) [71]. Results of testing indicated that field emission was reduced after such processing. Maintenance of Class 100 cleanrooms during the fabrication and integration of High Voltage Vacuum Devices had a positive effect at reducing micro-particle contamination and increasing the field emission breakdown voltage [71]. Padamse reported that for DC studies conducted at the University of Geneva, test samples prepared in a non-clean room environment, had a greater areal concentration of emission sites than for similar samples prepared in a class 100 clean room at the Wuppertal Institute [71]. Surface preparation techniques such as chemical polishing has been shown to have positive effects in improving the High Voltage Breakdown resistance for superconducting Nb cavities [49].

CHAPTER 3

RESEARCH APPROACH

The approach taken was strictly empirical as no quantitative model exists which can explain the overall High Voltage Breakdown phenomenon. This research was driven by actual High Voltage Breakdown problems associated with Communication & Power Industries (CPI) product line. Therefore, the materials chosen and processing thereon followed present CPI production baselines. It is expected that the results of this research will be used to recommend new materials and/or processing to increase the threshold voltage field strength of CPI's product line and improve the yield and profitability of the manufacturing activity. However, theoretical models were used when applicable, to correlate the findings and give direction to further research activity.

Several baseline materials that comprise the various electrode materials used in CPI's product line were evaluated. These were OFE copper, 304L SST, and 304LMC SST. The various chemical compositions were taken from the metallurgical surveys that the manufacturers supply on a lot and heat basis. The overall manufacturing cycle was surveyed to determine the in-house processing and environments, which these materials would experience in a typical fabrication cycle. The initial testing utilized the information gathered during the survey to prepare and process the initial test samples and provide a baseline for future comparison testing.

SEM and EDX analysis was used before and after testing to identify and map potential emission sites. These sites were characterized as to roughness

(from machining operations) and surface particles that resulted from the environmental exposure (insulating or non-insulating). Electro polished SEM photomicrographs, provided by Leo Garbini of CPI in a previous study, were examined to identify grain boundaries and exposed insulating inclusions such as MnS and Cr₂O₃. This latter technique was used in parallel to regular machined surfaces as a preliminary examination indicated that insulating inclusions in the metal matrix are near impossible to distinguish at normal machined finishes.

The chemical composition of the test materials from the suppliers was used to determine the concentration of high vapor pressure materials in the respective test materials. EDX analysis also presented a relative distribution of high vapor pressure materials present in the test materials. AES analysis was employed for identification of the chemical composition of the breakdown sites and the immediate surroundings for chemical mapping.

Following the results of the baseline testing, the subsequent testing evaluated the effect of the as machined surface finishes, time exposure to a 100K clean room environment, and solvent cleaning. The data that was taken focused on the various field strengths attained prior to and including HV breakdown. The plot of the Breakdown Field Strength, E_b (V_b/d) vs. test trial established the value of the selected materials and processing to withstand HV breakdown, and which material(s) and processing would provide the most robust assembly for use in manufacturing the devices. In addition, SEM and EDX

analysis was used to determine the composition and morphology of emission sites for comparison to the current theoretical models.

There are certain limitations of this experiment that need to be mentioned. The amount of experimental data points for each trial was 5 or less. The time involved to conduct one trial, which included pre-test sample preparation, insertion into the vacuum chamber, seal-in, followed by pump down from ambient pressure to $\sim 10^{-8}$ torr, took ~ 24 hours. The overall test effort took over 3 months to complete, including aborted tests due to test protocol violation. As previously stated, the intent of this study was to provide recommendations to CPI on material and process improvements.

For in-process testing at CPI, typical sample sizes generally run from as few as 3 to 5 test samples for process improvement recommendations. A test sample size of 5 follows ASTM D 1002, Lap Shear Test Procedure protocol. As this study was limited in financial scope, and knowing that follow-on AES testing by Charles-Evans Associates and consultation fees would consume $\sim 30\%$ of the assigned budget, it was determined that an individual sample size of 5 would be sufficient to make the aforementioned recommendations.

CHAPTER 4

RESEARCH HYPOTHESES

The literature search has indicated that material quality and surface conditions strongly affect the HV Breakdown phenomena. It has also been the experience of the author that identifying surface conditions on electrodes are an important first step in addressing HV Breakdown problems associated with CPI's product line. Therefore, any hypotheses in determining possible causes for HV Breakdown should center on characterizing the materials used, environmental conditions of the materials during fabrication and cleaning processes used to fabricate HV vacuum devices.

It is therefore hypothesized that materials that have low concentrations of insulating inclusions (i.e. Cr_2O_3 , Cr_3C_2 , MnS) should have higher threshold field strengths prior to breakdown. Following this, the same materials that have undergone environmental exposure and contamination (i.e. SiO_2 , Al_2O_3) should have lower field strengths prior to breakdown. Finally, the same materials that undergo cleaning processes after environmental exposure should have higher threshold field strengths prior to breakdown than those which do not undergo the cleaning processes. A series of experiments will be conducted to investigate the relationship of HV Breakdown as to the inherent quality of the material, environmental exposure, and the effects of cleaning those materials post environmental exposure.

CHAPTER 5

EXPERIMENTAL METHODOLOGY

5.1 Material Test Sample Selection

The materials that were evaluated as electrodes were 304L Stainless Steel, 304LMC Stainless Steel and Oxygen Free Electronic (OFE) Grade copper. The cathode materials used were 304L and 304LMC with a nominal surface finish of 32 μ -inch (SUR 32). The anode material was OFE Cu with a nominal surface finish of 64 μ -inch (SUR 64). The applicable surface finish was chosen to replicate the surface finish of the anode in the fabrication of the high voltage gun assembly. A radius of 0.050 inch was machined into the SST cathodes to reduce edge field enhancement.

The 304L and 304LMC test coupons were machined from 0.25 inch rod stock. The OFE Cu test coupons were machined from 3.0 inch bar stock. Typical as received chemical properties and hardness of the stainless steel materials used as cathodes in the experiment are given in Table 1. Typical as received chemical properties and hardness of the OFE copper material used as anodes in the experiment are given in Table 2.

Table 1. As received chemical comparison of 304L (Allegheny Ludlum Steel) and 304LMC (Carpenter Specialty Alloys) SST. Values are in wt.%. Material meets CPI Materials and Process Manual specification.

	Comp	C	Mn	P	S	Si	Ni	Cr	Fe	Ti	Mo	Cu	N
Type	Spec.												
304L HRB 87	ASTM A 182	0.024	1.88	0.029	0.0003	0.43	8.3	18.3	Bal	-- --	0.21 ----	0.25 ----	0.10
304LMC HRB 80	ASTM A-167	0.009	0.04	0.01	0.01	0.09	9.95	18.5	Bal	-- --	---- ----	----	0.01

Table 2. As received chemical composition of OFE Cu (Hitachi Cable, Ltd.). Material meets CPI Materials and Process Manual specification. Values for elements other than Cu are in ppm.

Spec	Cu	Bi	Cd	Pb	Hg	O2	P	Se	S	Te	Zn	Sb	As	Fe	Mn	Ni1	Ag	Sn
ASTM F 68 HRF 77	99.995 wt. %	<1	<1	4	<1	2	2	<1	6	<1	<1	2	1	4	0.5	1	10	1

5.2 Test Apparatus

CAUTION

In conducting any testing in and around High Voltage Power Supplies, it is imperative that the operator have a thorough knowledge of the Safety issues involved and training in the use of such equipment.

The author was trained as a Qualified Person 1 (QP1), which is the minimum skill set to operate High Voltage equipment at CPI. It is strongly recommended that personnel undergo similar training in the event that this or similar experiments are replicated.

The test apparatus utilized was CPI's High Voltage Breakdown Analyzer. Figure 23 illustrates the overall test setup. This is a vacuum test device that can attain 10^{-8} torr base pressure or lower. Two turbo pumps maintained the vacuum pressure. The main pump is a Varian model Turbo V-250 (250 l/s) backed up by a Varian model Turbo V-70 (70 l/s) pump. A Residual Gas Analyzer (RGA) was utilized during testing to verify the presence of potential ionized gasses. The RGA used was a QX 2000 manufactured by Leybold Inficon, Inc. The pressure

was monitored by a Varian Ionization Gauge Model No. 0564-K2500-303. The power supply utilized to monitor the voltage and current responses was a Tektronics 177 used with a Tektronics 577 curve tracer that provided 0-1600 VDC. After the test samples were loaded into the chamber, the distance between the electrodes was controlled by an internal micrometer with an accuracy to ± 0.0005 inch over 3 inches of traverse.

This test device can operate in either a constant gap (variable applied voltage) or variable gap (constant applied voltage) mode. In the constant gap mode the extensometer can position the cathode sample to a set distance from the anode sample. In the variable gap mode, which was used in the present study, the micrometer positioned the cathode sample approximately 0.050 inches away from the anode sample. The voltage is then set to a constant value of approximately 1600 volts.

The voltage was applied across the gap by an external feed through that connects the micrometer/cathode in the circuit. The anode would be at ground potential. The cathode to anode gap distance was decreased until the breakdown event (voltage drops and current increases) was observed on the Tektronics 577 Curve Tracer. Figures 24 and 25 display the vacuum chamber test setup.

Figure 23. High Voltage Breakdown Analyzer test setup (Courtesy of CPI).

Figure 24. Close-up of Vacuum Test Chamber for High Voltage Breakdown Testing.

Figure 25. Detail of vacuum envelope displaying the Anode and Cathode plane parallel geometry and the nominal environmental conditions in the chamber.

5.3 Test Specimen Preparation

Approved clean room gloves were used to handle all of the Cu anodes and SST cathodes after machining. All Cu anode and SST cathode test specimens were individually ultrasonically cleaned in reagent grade acetone for ten minutes followed by ultrasonically cleaning in reagent grade isopropyl alcohol for ten minutes prior to environmental exposure in the Class 100,000 (100K) cleanroom. The coupons were not annealed or vacuum degassed following machining or cleaning. The anode specimens were not exposed to a Class 100K cleanroom environment, following cleaning. The 304L and 304LMC

specimens were separated into test bins and sealed to prevent spurious contamination.

The geometry of the anode and cathode(s) when opposing each other as depicted in Figure 25, simulates a plane parallel electrode configuration. This simplifies the calculation of the electric field strength at breakdown, whereby $E_b = V_b/d$. Here, V_b is the gross applied breakdown potential (Volts) in the gap, d is the gap distance (meters), and E_b is the electrical field strength at breakdown (Volts/meter)

5.4 Cathode Test Specimen Environmental Conditioning

The 304L and 304LMC specimens that were separated into test bins were then exposed to a Class 100K cleanroom environment for 7 days. At the end of the seven days the coupons were removed from the clean room and were individually stored in a snap-on plastic box which had been solvent cleaned with electronic grade isopropyl alcohol. Each box was identified with an alphanumeric label for traceability. The individual coupons were randomly selected for SEM/EDX analysis prior to testing to determine the amount and type of airborne contamination on the surface of the coupon. Figure 26 presents the process flow diagram of the test sample preparation and conditioning.

Figure 26. Process flow diagram displaying machining, cleaning and environmental conditioning prior to HV breakdown testing.

5.5 Test Procedure

The test apparatus was positioned in the beam optics lab at CPI, which maintains an approximate class 100K cleanroom environment. The 304L and 304LMC test coupons were randomly selected from their respective test bins and a clean or non-clean test sequence was initiated. To minimize any environmental fallout, the 304L or 304LMC test coupons designated as “cleaned” were given a final acetone followed by an isopropyl alcohol cleaning with lintfree Kimwipes®. This was followed by blow drying with dry, filtered N₂, just prior to positioning in the test apparatus. The OFE Cu anodes were also given a final acetone and isopropyl cleaning prior to positioning into the test chamber and were also blow dried with dry, filtered N₂. The time required to complete the final solvent cleaning, position the test specimens and perform the final seal-in and begin pump down was approximately ten minutes.

The test apparatus achieved a 10⁻⁸ to low 10⁻⁷ torr total pressure after 24 hours of continual evacuation. At this time the Inficon RGA analyzer was opened and turned on as well as the Vac Ion Gauge. This caused total pressure to climb to 10⁻⁶ torr. The test apparatus was allowed to stabilize again in the mid-10⁻⁸ torr level. Degassing of the RGA analyzer and the Vac Ion Gauge perturbed the total pressure again and another period of pressure stabilization was undertaken until mid-10⁻⁸ torr was reached. The RGA was then monitored for the gas partial pressures in the vacuum chamber.

A calibration trial was undertaken before each test sequence to determine the “zero” position of the extensometer/cathode and anode. This was accomplished by using a Simpson Model 372 Ohm Meter. The ohmmeter range selected was 10 k Ω . The ohmmeter was attached to the anode and cathode (with anode as ground), the micrometer was driven until a deflection was noticed on the analog gauge. A reading was then taken on the radial micrometer gauge. This was repeated three times and if the reading was ± 0.0005 inches; the position was recorded as the “zero.”

Each test scenario was separated into appropriate bins and coded with an alphanumeric to identify each test sequence. Yellow CAUTION barrier tape surrounded the entire working area. With the cathode test specimen 0.050 inches from the anode, the power supply feed throughs were connected to the vacuum test chamber and the voltage was increased to approximately 1.6 kV DC. The polarity of the applied voltage ensured that the cathode specimen was negative with the anode at ground. The actual applied voltage as read on the Tektronics 577 Curve Tracer was recorded. The “zero” position, beginning total pressure and starting micrometer position was recorded. The RGA was then monitored to record the gaseous response at breakdown. The micrometer was then engaged to slowly drive the cathode towards the anode. The point at breakdown was achieved when the curve tracer set point deflected sharply from its position. The final breakdown current was also noted and recorded. The power supply was then immediately shut off and the applied voltage dial returned

to zero. All beginning and ending power supply attachments were carefully grounded with a ground stick per CPI's QP-1 Electrical Worker Safety procedures prior to approaching the test setup. The final operating pressure was recorded.

The power supply was then disconnected from the test chamber and the micrometer distance was recorded. The RGA response was also recorded for later downloading to an Excel file. The ohmmeter was attached to the electrical feed-throughs to verify that the same "zero" point was achieved. If the same zero point was not repeatable the test was nullified. The turbo vacuum pumps were turned off and allowed to stabilize. The test chamber was then opened and the OFE copper anode and stainless steel cathode was removed for subsequent SEM/EDX and Auger analysis as required. The test specimens were wrapped in lintfree Kimwipes© and packaged in a corresponding alphanumeric labeled plastic container to prevent additional environmental fallout. The sequence of tests was conducted randomly in that "cleaned" and "non-cleaned" 304L and 304LMC stainless steel cathodes were intermixed in the testing sequence.

CHAPTER 6

EXPERIMENTAL TEST RESULTS

6.1 HV Breakdown Test Results

Figure 27 and Table 3 presents the overall test results of the breakdown experiments. Due to an experimental error, trial 5 for the 304LMCc (cleaned) was omitted. Figure 27 indicates that the 304LMC cathodes displayed the most significant sensitivity to environmental exposure. The average E_b difference between cleaned (304LMC c) and non-cleaned (304LMC nc) is 6 MV/m). This represents an improvement in the field strength at breakdown by a factor of 1.7. The standard deviation for both trials was < 1 . The test results for the cleaned (304Lc) and non-cleaned (304Lnc) 304L cathodes bear further examination. The 304L cleaned specimens had an average E_b of 15.14 MV/m. The standard deviation of approximately 5.0 MV/m is indicative of the large scatter in the data. The non-cleaned 304L specimens had an average E_b of 12.5 MV/m with a standard deviation of 0.63. The absolute error for all trials is displayed graphically.

Figure 27. Breakdown Field Strength (E_b) vs. Trial for non-cleaned (nc) and cleaned (c) 304L and 304LMC SST cathodes.

Table 3. HV Breakdown test results of non-cleaned and cleaned 304L and 304LMC SST Cathodes

	OFE Cu Anode	OFE Cu Anode	OFE Cu Anode	OFE Cu Anode
Sample No.	304LMC nc	304LMC c	304L nc	304L c
1	9	14.04	12.1	17.3
2	7.06	15.26	11.9	9.9
3	7.34	13.47	13.2	22.7
4	8.14	13.64	12.1	12.2
5	9.14	ABORTED	13.2	13.6
E_{avg}	8.14	14.10	12.52	15.14
Std. Dev.	0.94	0.81	0.63	4.99

6.2 Cleaning Effects

Figure 28 shows the pre and post cleaning of a typical 304L or 304 LMC cathode surface. It is evident from the SEM photomicrographs that the solvent cleaning procedure as used in section 5.5 was effective at removing the airborne contamination.

Figure 28. Pre and Post Cleaned 304 LMC SST Cathodes after exposure to a Class 100K cleanroom for 7 days.

6.3 Contaminant Analysis

6.3.1 Microparticle Analysis

Figure 30 displays the typical materials present as surface micro-particle contaminants identified by EDX analysis prior to testing. Briefly, EDX is a low surface sensitive analytical technique that emits primary electrons that penetrate a material to $\sim 10,000$ angstroms ($\sim 1 \mu\text{m}$) in depth. The secondary emitted particles are x-rays whose energies are characteristic of the material being

sampled. Elements that can be detected by EDX range from Na to U or Atomic Mass Units (AMU) from 11 to 92 [72]. Figure 29 presents a schematic representation of the EDX analytical technique. EDX is usually used in conjunction with the SEM.

Figure 29. Simultaneous use of SEM and EDX. [73]

The contaminant material appears to be primarily Si bearing compounds, possibly SiO_2 . These are typical air-borne compounds that are found in Class 100K cleanrooms. The typical size of the micro-particles ranged from 5 to 25 μm. Exposed surfaces typically can attract airborne hydrocarbons as well. However, EDX is not sensitive to materials that have Atomic Mass Units (AMU) of 10 or less. Oxygen that has an AMU of 8 would not be expected in an EDX analysis as well as carbon with an AMU of 6. Auger Electron Spectroscopy (AES)

analysis later confirmed that carbon was present on the surfaces. AES analysis also indicated high concentrations of carbon bearing compounds in the breakdown sites after testing.

Figure 30. SEM photomicrograph and corresponding EDX analysis of a typical particle found on a 304LMC SST cathode after exposure to Class 100K Clean room for 1 week.

6.3.2 Intermetallic Rating Results

Figure 31 gives the comparison in the areal concentration of the intermetallic inclusions between typical 304L and 304LMC materials. A modified ASTM E 45 protocol [74] was used to determine the average areal concentration of inclusions on the 304L and 304LMC micrographs provided by Leo Garbini of CPI. For measurements in the heavily “included” regions in Figure 29; the

method gave an average result of $\sim 12 \times 10^3 / \text{cm}^2$ and $\sim 6 \times 10^3 / \text{cm}^2$ for typical 304L and 304LMC materials, respectively.

It is also evident from Figure 31 that the surfaces for 304L and 304LMC have areas of relatively inclusion free material as well. Typically, inter-metallic inclusions form and then migrate to the grain boundaries. The grain boundaries are not in evidence in these photomicrographs.

Figure 31. Areal inclusion distribution of a typical as received and electropolished 304L (left) and 304LMC (right) SST material(s). SEM photomicrographs courtesy of Leo Garbini of CPI.

Figure 32 displays a typical inclusion found in 304L SST and an actual SEM photomicrograph of an experimental breakdown site in trial sample T2 (304LMCnc). An EDX analysis of the crater and inclusion is also presented. It is observed that the crater material and inclusion display different chemical composition as noted in the EDX spectrum (top right). The crater rim material displays a typical SST spectrum of Fe, Ni and Cr (dots) on the right hand side of the spectrum. The inclusion shows Cr rich regions with an absence of Fe and Ni (shaded). The Cr peak overlaps between the crater and inclusion spectral

analysis in the middle. It is unknown whether the inclusion is Cr_2O_3 or Cr_3C_2 .

The sensitivity of EDX is limited to materials between the atomic mass units (AMU) of lithium (Li) to uranium (U) [72]. As oxygen and carbon have AMUs of 8 and 6 respectively, these elements would not be displayed in the presented spectrum.

It is interesting to note in Figure 32 that the dimensions of the inclusion (bottom left) are approximately the same as the inclusion in the center of the crater (bottom right). This was derived by noting the scale on an SEM photomicrograph from Charles Evans & Associates of the inclusion in 304LMC sample T2 (bottom right), and comparing to the photomicrograph on the bottom left. The AES analysis is detailed in section 6.6.

Figure 32. An actual HV breakdown site displaying an inclusion in 304LMC T2 (top left at 2800X) and the EDX analysis of the breakdown site (top right). Electropolished surface of a typical 304L SST displaying a single inclusion (bottom left), courtesy of L. Garbini of CPI and the 304LMC T2 sample (bottom right) SEM photomicrograph (Charles-Evans & Assoc.) comparing dimensions.

6.4 Pressure Effects on HV Breakdown

The vacuum pressure was monitored during testing as previously noted. The comparison of E_b to the operating test pressure was performed to determine if any correlation existed. Figure 33 presents the results of E_b versus the

operating test pressure for the tests conducted. It is apparent from Figure 33 that no correlation exists over the range of pressure from 1.3×10^{-8} to 1.2×10^{-7} torr.

Figure 33. E_b versus Pressure.

6.4.1 Residual Gas Analysis (RGA)

An analysis of the RGA data indicated that the predominant gaseous species noted at breakdown were CO, CO₂, H₂O, and H₂. It should be noted that the gas species designated C* is a generic term that refers to light hydrocarbons with the general formula of C_nH_{2n+2}. Appendix B presents the gaseous response prior to, during, and after the breakdown event. Additionally, the cleaned and uncleaned 304L and 304LMC cathodes were analyzed on the RGA and

compared within and between each test group. Figures 34 through 37 present the results.

Figure 34. Gas Species vs. ΔP ($P_{\text{Max}} - P_{\text{Prebreakdown}}$) for selected SST Test Cathodes.

Figure 34 shows that the non-cleaned 304LMC (T7) had the greatest evolution of CO, CO₂, and H₂ at breakdown. This result would be expected as the microparticle contamination could provide increased surface area for gas adsorption and desorption at breakdown. Conversely, the non-cleaned 304L (T24) displayed a much lower amount of gas evolution for all species than the non-cleaned 304LMC.

A possible explanation for the discrepancy may lie in examining the OFE Cu anode surface roughness for samples T7 and T24. Sample T7 had a nominal surface roughness of 49 μ -inch and T24 had a nominal surface roughness of 21 μ -inch. The greater roughness of T7 indicates that a greater surface area exists for a given radial traverse, as compared to sample T24. This could supply a greater area for gas adsorption on the anode surface for sample T7 than T24. A similar argument can be made for anode samples T8 and T23. Their nominal surface roughness was 25 μ -inch and 27 μ -inch for samples T8 and T24, respectively. As their total gas response was similar to sample T24 it is reasonable to assume that their areas for gas adsorption would be expected to be less than anode sample T7.

The cleaned 304LMC (T8) had a much lower evolution of gases for all species than the non-cleaned 304LMC (T7), with the exception of H₂O. Comparing T8 to the cleaned 304L (T23) it is also apparent that a larger evolution of gas for all species is seen for T8 versus T23.

Figure 35 presents the normalized ΔP versus gas species from the selected trials. The normalized ΔP was calculated by subtracting the individual gas species pre-breakdown partial pressure from the maximum breakdown partial pressure and then dividing by total pre-breakdown pressure. It is noted that the gas species C*, N₂, Ar and O₂ did not show any appreciable change due to the HV breakdown. However, H₂O, CO, CO₂, and H₂ did show a response as a result of the HV breakdown event. H₂O showed a decrease in normalized ΔP

from -0.05 to -0.29 for the four trials. CO is observed to increase from ~ 0.02 to ~ 0.18 for the four trials. CO₂ decreased from -0.005 to -0.07 for three of the four trials. H₂ increased from 0.03 to 0.17 in three out of four trials and decreased to -0.02 in one of four trials.

Figure 35. Gas Species vs. Normalized $\Delta P [(P_{\text{Max}} - P_{\text{Prebreakdown}})/(P_{\text{Total}})]$.

Figure 36 presents the gas species response (ΔP), and HV breakdown field strength (E_b) versus the experimental trials. The ΔP and E_b for the non-cleaned (T7) and cleaned (T8) 304LMC cathodes indicates that as the gas response for CO increases from $\sim 3 \times 10^{-10}$ torr to $\sim 2.25 \times 10^{-9}$ torr, and increases for H₂ from $\sim 4 \times 10^{-10}$ torr to $\sim 2.8 \times 10^{-9}$, E_b decreases from ~ 14 MV/m to ~ 9 MV/m. The standard deviations for the non-cleaned and cleaned 304LMC samples were 0.94 and 0.81, respectively. This indicates a low order of data scatter. The

results indicate that E_b for 304LMC SST is sensitive to gas response at breakdown.

The results for the non-cleaned (T24) and cleaned (T23) 304L SST samples display a different total ΔP and E_b response. The total gas response for non-cleaned and cleaned 304L is less than that for non-cleaned and cleaned 304LMC. The non-cleaned 304L (T24) did show a greater gas response than cleaned 304L (T23) for CO from $\sim 0.5 \times 10^{-10}$ torr to $\sim 2.0 \times 10^{-10}$ torr. The response of H_2O went from 0.04×10^{-10} to 0.11×10^{-10} torr from samples T23 to T24. H_2 is seen to increase from $\sim$ zero to $\sim 2.5 \times 10^{-10}$ for samples T23 to T24.

Figure 36. Comparison of ΔP and E_b vs. SST Cathodes.

The comparison of ΔP and E_b for the non-cleaned and cleaned 304L tests samples, show an inverse relationship, when compared to 304LMC. Here, E_b decreases from ~ 13.5 MV/m to ~ 9.5 MV/m for sample T24 to sample T23. However, this correlation is suspect when the standard deviations of the Non-cleaned and cleaned 304L trials is examined. The standard deviation for the non-cleaned 304L trial was 0.63 while the standard deviation for the non-cleaned 304L was ~ 5 . The non-cleaned trials displayed a very low order of data scatter. Conversely the cleaned 304L trials displayed a large scatter. Therefore, it is difficult to draw any correlations for gas response to E_b for samples T23 and T24.

Figure 37 presents the Normalized ΔP and E_b versus test results. This graph is similar to 36 with the addition of the E_b axis. It is observed that H_2O decreases for all four trials and does correlate that the cleaned 304L/LMC samples displayed a smaller normalized decrease than for non-cleaned 304L/LMC samples. With the exception of sample T23 all trials display a positive increase in normalized H_2 . Also, the cleaned 304L/LMC samples displayed a lower positive (or negative) normalized ΔP response for the generation of CO, than non-cleaned 304L/LMC. Similar results are seen for CO_2 .

Figure 37. Comparison of Normalized ΔP and E_b vs. SST Cathode.

The normalized ΔP figures show that overall, H_2O and CO_2 decreased as a result of the HV breakdown event and that CO and H_2 increased. The question arises regarding the chemical reactions that could cause a decrease or increase in the partial pressures of the gas species. Secondly, what is the source of the gas species in the gap? Either the gas was present in the gap due to the vacuum ambient and/or resulted from the adsorbed gas molecules on the OFE Cu and 304L/LMC electrodes. The latter question will try to be answered by an *a priori* argument in section 6.4.2.

Equations 19-27 present possible chemical reactions at the cathode and anode surfaces during HV breakdown:

In considering these equations an observer would look for reactions that would consume H_2O and to a lesser degree CO_2 , and also look for reactions that would generate H_2 and CO . Equation 19 displays carbon (C_{s}) and H_2O as reactants with H_2 and CO as products. Equation 23 displays CO_2 being reduced to CO by the action of an electron (i.e. breakdown current). Equation 27 shows CO as one of the products. It can be assumed that equations showing O_2 can be discounted in the present study as Figures 34-37 indicate that O_2 did not display any significant response during the HV breakdown event. Reactions displaying O^{-2} and H^+ ions as products, could play a part in the HV breakdown event as an additional source of ionic current or plasma generation. The preference as to which reaction(s) would dominate the overall reactions would be dependent thermodynamically on the kinetics and chemical potentials of the individual reactions.

6.4.2 Mean Free Path (MFP) Calculations

In determining the source of the gas species analyzed in section 6.4.1, calculations of the mean free path for H₂, H₂O, O₂, CO, CO₂, N₂, and Ar was conducted. The gas volume and the resultant diameter was estimated from van der Waal's coefficients [75] and equation of state. Where,

$$[P + a(n/V)^2](V/n - b) = RT \quad (28)$$

The constants **a** and **b** are values characteristic of an individual gas. Van der Waal's equation of state approaches the ideal gas law $PV = nRT$ as **a** and **b** approach zero. Constant **b** is representative of the gas volume. Modeling a gas molecule as a hard sphere, the volume can be calculated from:

$$V = b/N_A \quad (29)$$

Where **V** is the volume of the gas (m³), **b** is van der Waal's constant (m³/mole) and N_A is Avogadro's number. From equation 18 the diameter **d**, can be calculated from:

$$d = (6V/\pi)^{1/3} \quad (30)$$

When the diameter of the gas molecule is known the Mean Free Path can be calculated from:

$$\lambda = RT/2^{1/2}\pi d^2 N_A P \quad (31)$$

Here, λ is the mfp (m), $R = 82.057 \text{ m}^3\text{-atm/mole-}^\circ\text{K}$, T is the temperature of interest (298 ^oK), d is the diameter (m) of the particular gas molecule, $N_A = 6.023 \times 10^{23}$ molecules/mole and P is the pressure of interest (atm).

Table 4 presents the calculated MFP results. The partial pressures selected were from the highest value for all trials attained by the individual gas species prior to HV breakdown. The shortest mean free path of the gas species H₂O is 3.8 miles. From Table 4, taking the largest starting gap distance of 0.10 inches during vacuum pump down, the probability that vacuum chamber ambient H₂O would be present in the breakdown gap is 4.2×10^{-7} . Therefore, it may be assumed that the change in pressures observed during all of the HV breakdown experiments is due to adsorbed surface gases on the cathode and anode.

Table 4. Calculated Mean Free Path of Gasses present in the Vacuum Test Chamber and the Probability that the gasses would be present in the gap (d) during HV breakdown.

MFP	H ₂	H ₂ O	O ₂	CO	CO ₂	N ₂	Ar
cm	2.36×10^6	6.10×10^5	1.1×10^8	1.92×10^6	2.62×10^6	4.63×10^7	9.7×10^7
in.	9.35×10^5	2.40×10^5	4.25×10^7	7.56×10^5	10.3×10^5	1.82×10^7	3.8×10^7
mi.	14.8	3.8	670	11.9	16.3	288	603
d _{gap} (in.)	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Probability	1.0×10^{-7}	4.2×10^{-7}	2.4×10^{-9}	1.3×10^{-7}	9.7×10^{-8}	5.5×10^{-9}	2.6×10^{-9}

6.5 Effect of Surface Finish on HV Breakdown

The roughness of the OFE anode and the corresponding E_b value was compared to determine if any correlation existed between the breakdown field strength and surface roughness. These anodes were taken from all tests completed using both cleaned and non-cleaned 304L and 304LMC cathodes. As noted in section 5.3 and 5.5 the Cu anodes were not subject to environmental exposure and were always cleaned with acetone and isopropyl alcohol prior to testing. The nominal machined surface was 64 micro-inch. It is known that this value can vary by as much as +/- 25 micro-inch. A series of three profilometer

(Mitutoyo Sufitest 401) readings were conducted on each OFE Cu anode and averaged. The average roughness value was plotted versus the E_b value.

Figure 38 presents the results.

Figure 38. Breakdown Field Strength vs. Roughness of the OFE Cu anode for all trials.

It is readily apparent that no real correlation exists between the anode surface roughness and E_b . However, it is interesting to note the SEM photomicrographs of a typical OFE Cu anode at 490X in Figure 39. This particular SEM scan reveals the typical damage morphology after HV breakdown testing. The scan displays the micro-roughness of the anode surface, which is characterized by a series of ridges and grooves.

Figure 39. Typical damage morphology of an OFE Cu anode (top row) and 304LMC sample T4 cathode (middle row). EDX analysis (bottom photomicrograph) of Cu particles of left photomicrograph (middle row), 304LMC sample T4.

The top row displays typical damage on an OFE Cu anode. It is interesting to note that there appears to be some correlation between the breakdown event and the machine high spots on the perimeter of the damaged area of the left side photomicrograph (top row). Also, several of the large craters tend to follow the machined pattern. A close-up detail is presented on the right hand side (top row). In the right hand photomicrograph (middle row) of Figure 39 it is also noted that the elliptical geometry of the breakdown area follows the general machined pattern of the 304LMC cathode. It maybe possible that the breakdown energy favors the machined high spots, initially, but as the breakdown energy increases over time, the overall damage is such that no gross correlation of E_b with roughness is seen as displayed in Figure 38.

The bottom photomicrograph of Figure 39 also displays an EDX analysis of the Cu particles displayed on the left photomicrograph of the middle row. The particles have a strong Cu fingerprint that is much different than the crater parent material of Fe, Cr and Ni in 304LMC. It may be assumed that the Cu particles originated from the opposite OFE Cu anode and transferred as a result of the HV breakdown event. It is also noticed below the top crater where the Cu particles reside that a series of stacked crater damage is observed. It is possible that as the HV breakdown event proceeded, successive melting and cooling of the craters provided field enhancement and helped sustain the breakdown.

6.6 Auger Analysis (AES)

Auger Electron Spectroscopy (AES) was conducted on a 304LMC cleaned (T4) and its corresponding Cu anode, and a 304LMC not cleaned (T2) and its corresponding Cu anode to quantify the surface chemistry of the materials after HV breakdown testing. Briefly, AES is a high vacuum surface sensitive analytical technique that gives a depth profile of 10 to 30 angstroms (10^{-10} m). If used in conjunction with Ar sputtering, depths of 800 angstroms or more can be achieved. The technique derives atomic concentrations by analyzing emitted Auger electrons upon material excitement from primary impacting electrons. Detection limits of AES are on the order of 1000 ppm. (~ 0.1 atomic %) [76].

Figures 40-44 presents the results of AES analysis conducted by Charles-Evans & Associates [77]. The equipment used was a Physical Electronics PHI670 Scanning Auger Microprobe. Figures 40 and 41 present the AES results of the Cu anodes for sample T2 (304LMC SST cathode not cleaned) and sample T4 (304LMC SST cathode cleaned).

It should be noted that in Figures 40-44, the AES peaks for carbon maybe arbitrarily high due to environmental fallout. There was a time delay of ~ 3 weeks from the end of the HV breakdown testing until the samples were submitted to Charles-Evans & Associates for AES testing. Although the samples were carefully handled with clean room gloves and packaged in linfree wipes and sealed in a clean plastic box, spurious carbon compounds can nonetheless accumulate on the samples.

Figure 40. Auger Analysis of Cu Anode (T2 304LMC not cleaned).

Figure 40 shows high concentrations of carbon from 0 to 150 angstroms of depth in the damaged (areas A1, A2 and A3) and control regions not damaged. Copper shows a strong peak at 100 angstroms depth in the areas A3 (damaged area 3). In an additional control (not damaged) area AA3 of Figure 40, Cu is the dominant element at a depth of 150 angstroms. Oxygen is noticed in low concentrations across the spectrum and would be evidence of CuO that is inherent to copper surfaces. There is also trace amounts of Cl, Na, K, Mo, and Fe.

Figure 41. Auger Analysis of Cu Anode (T4, 304LMC cleaned).

Comparing Figures 40 and 41, it is noticed in Figure 40 that the Cu anode (T2, 304LMC not cleaned) contains Cl, Na, K, Mo and Fe, but in very low concentrations. A check of the material certification for 304LMC in Table 1 indicates that Cl, Na, K and Mo are not present. With the exception of Cl, the other elements would not be expected to travel from the 304LMC cathode, if present at breakdown, given their valence state (positive ions) and the polarity of the test with the cathode at negative bias. Figure 41 does not display any of these elements and only show C, O and Cu as the elements present. Charles-Evans indicated that Cl, Na, and K are usually evidence of “handling” contamination. However, as all samples were continually handled using approved clean room gloves, the source of the contamination is unknown for

Figure 40. Carbon is the dominant contaminant for both Cu anodes and is present to a depth of 800 angstroms in the control area (undamaged). Part of the source of carbon maybe the time delay from HV breakdown testing to AES testing that was approximately 3 weeks. Pure Cu is seen in the control A2 area at a depth of 800 angstroms.

Interestingly, Si was not detected on the Cu anode that was opposite the non cleaned 304LMC cathode in Figure 40. If Si bearing microparticles as shown in Figure 28 did accumulate a critical surface charge and transfer to the Cu anode they may have been pulverized at impact. The result could be that their concentration levels were below the AES detection limits of 0.1 atomic %. The detected Si bearing compounds were on the order of 5 μm to 25 μm in diameter. As their initial surface concentrations on the non cleaned 304LMC cathodes were unknown, it is difficult to estimate what the transfer potential would be. It is also possible that no Si bearing compounds transferred from the non-cleaned 304LMC cathodes to the Cu anodes during HV breakdown.

Figures 42 and 43 present the AES analysis of the non-cleaned (T2) and cleaned (T4) 304LMC SST cathodes, respectively. Both figures show very similar chemical responses with carbon present in the A2 and A1 damaged areas up to 200 angstroms in depth. The source of this carbon would be due to the AES test time delay and a contribution from the 7-day environmental exposure in the Class 100K clean room prior to HV breakdown testing for non-cleaned sample T2. The damaged area A1 of the cleaned sample T4 in Figure

43 does show evidence of Fe and Ni at a depth of 50 angstroms. The damaged area A2 of the non-clean T2 sample of Figure 42 does not show Fe and Ni until 200 angstroms of depth is reached. It is also noted that carbon has a high concentration up to 100 angstroms depth for T2, whereas, the T4 sample begins to show a decay in carbon from 50 to 100 angstroms. This could be evidence of the cleaning effectiveness of sample T4. As the 304LMC clean and non-cleaned trials displayed low standard deviations for all tests, this would correlate with the E_b values of 15.3 MV/m and 7.1 MV/m for samples T4 (cleaned) and T2 (non-cleaned), respectively. The control areas (not damaged) of Figures 42 and 43 have very similar chemical responses related to 340LMC SST for Cr, Fe and Ni.

Of special interest is the presence of Cu across the depth spectrum for both cleaned and non-cleaned 304LMC samples in Figures 42 and 43, in the damaged areas A2 and A1. There is no evidence of Cu in the control (non-damaged) areas, with the exception of the control area at 0 angstroms depth in Figure 42. This would correlate with Anderson's [46] observation of different electrode material transferring to the opposite electrode during HV breakdown.

Figure 42. Auger Analysis of 304LMC non-cleaned (T2, $E_b = 7.1$ MV/m), damaged Area (A2) and undamaged Area (Control).

Figure 43. Auger Analysis of 304LMC cleaned (T4, $E_b = 15.3$ MV/m), damaged area (A1) and undamaged area (Control).

Figure 44 presents the AES analysis of the crater and inclusion for 304LMC sample T2, observed by SEM and analyzed by EDX in Figure 32 (top row). The crater rim section displays a high concentration of carbon with a steady decay from 0 to 200 angstroms depth. At 200 angstroms the response again is similar to the native elements of Cr, Fe and Ni for 304LMC SST. The presence of O is probably due to the thin oxide layer usually present on SST.

Figure 44. Auger Analysis of 304LMC not cleaned (T2, $E_b = 7.1$ MV/m). Inclusion and Crater Rim Depth Profile.

For the inclusion analysis carbon is seen to decay in concentration from 0 to 200 angstroms. Of interest is the increase in Cr and O from 0 to 200

angstroms of depth. At 200 angstroms depth, the peak height ratios are evidence of the chemical stoichiometry of either Cr_3C_2 or Cr_2O_3 (text box insert). Using a Mitutoyo digital micrometer, the measured peak height stoichiometry of CrC was $\text{Cr}_1\text{C}_{0.53}$ and the CrO ratio was $\text{Cr}_1\text{O}_{1.25}$. Multiplying both formulas by 2 gives results of $\text{Cr}_2\text{C}_{1.06}$ and $\text{Cr}_2\text{O}_{2.5}$. Multiplying both original formulas by 3 gives results of $\text{Cr}_3\text{C}_{1.59}$ and $\text{Cr}_3\text{O}_{3.75}$. It appears that the compound is trending towards Cr_2O_3 . However, in order to make a more quantitative estimation, the AES depth profile would have to be appreciably extended beyond 200 angstroms.

6.7 Field Gradient and Capacitive Potential Energy Analysis

Figure 45 displays the field gradient analysis computed by Brad Stockwell of CPI for a theoretically applied potential of 1600 volts and a gap distance of 0.004 inch using MAXWELL 2D. The analysis indicates that the electric field is magnified at the geometrical transition between the planar and radiused areas of the cathode. The increase in E_b is on the order of 0.3 MV/m. Interestingly, the typical breakdown areas observed in both 304L and 304LMC cleaned and non-cleaned cathodes, were near the radiused portion of the cathodes.

Brad Stockwell using MAXWELL 2D also computed the capacitive stored energy for trials 304LMC non-cleaned (T3) and cleaned (T6) and also 304L non-cleaned and (T26) and cleaned (T25). The hypothetical trial is also presented. The results are presented in Table 5.

Figure 45. Contours of Electric Field Magnitude. Each line represents 0.25 MV/m. (Generated by Brad Stockwell of CPI, with permission).

Table 5. Calculation of E_{bavg} , E_{bpeak} , Capacitance and Potential Energy for selected 304L and 304LMC SST Cathodes. Courtesy of Brad Stockwell, CPI.

Sample	d_{gap} (inch)	V_b (Volts)	E_{bavg} (MV/m)	E_{bpeak} (MV/m)	Capacitance (pF)	Potential Energy (μJ)
Hypothetical	0.004	1600	15.8	16.1	2.5	3.3
304LMCnc (T3)	0.008	1560	7.7	8.0	1.8	2.1
304Lnc (T26)	0.005	1540	12.1	12.5	2.2	2.7
304Lc (T25)	0.003	1570	20.6	20.9	3.0	3.7
304LMCc (T6)	0.0045	1540	13.5	13.8	2.4	2.8

6.8 HV Breakdown Mass and Energy Balance Estimation

An estimation of the energy transfer that caused melting in the 304L, 304LMC cathodes and OFE copper anodes can best be approximated by conducting a mass and energy balance about the melted areas. By knowing the heats of fusion for SST and copper, the energy transfer during the breakdown event ($iVt + 1/2CV^2$) and the volume of material melted, a first order approximation can be made for an energy balance. SEM dimensions of the melt regions of the OFE Cu anodes and 304L/LMC SST cathodes for samples T3, T6, T25, and T26 are presented in Appendix C. The melt areas were estimated by breaking up the melt regions into “best fit” geometric figures of squares, rectangles, triangles, circles and ellipses. The estimated melt areas were multiplied by the estimated depth of melt of ~0.1 mm to achieve the melt volume. This latter value was arrived at by doing a depth of profile scan on the SEM.

The following equation was used to calculate the energy balance:

$$E_{\text{Total}} = 1/2CV^2 + iVt = E_{\text{MELT}} + \Sigma E_i \quad (32)$$

Where:

$1/2CV^2$ = Potential energy of breakdown gap due to stored electrode surface charges.

iVt = Energy transfer during the HV Breakdown event resulting from electron (current) discharge.

E_{MELT} = Heat of Fusion for OFE Cu and 304L/304LMC SST.

ΣE_i = Other energy contributors, to be defined.

The capacitive energy value for $1/2CV^2$ for the various cases was presented in Table 5. As the calculated values are in the μJ (10^{-6} J) range, it appears that their contribution would be insignificant, since the following calculated results for iVt are in the mJ (10^{-3} J) range. However, it is known that the capacitive potential energy discharge precedes the iVt discharge and so “sets the stage” for the overall HV breakdown event. The concentration of the capacitive discharge energy in the micro-volume melt areas may also contribute to pre-heating the electrode breakdown surfaces.

The iVt energy contribution was estimated from the voltage/current waveform on the Tektronics 577 curve tracer. The final breakdown voltage (V_b) for each trial was observed and recorded. The iVt energy values are presented in Table 6. The breakdown current (i_b) was also observed and recorded for each trial. The range of breakdown current was $40\ \mu\text{A}$ to $60\ \mu\text{A}$. The time of the event was based on the author’s reaction time to turn off the power supply toggle switch. This value was estimated to be $\sim 0.1\ \text{s}$.

The E_{MELT} value for the Cu samples was taken from tabulated values in the A.S.M Metals Handbook for H_{FUSION} with a value of $12.1\ \text{J/g}$ [78]. As the chemical composition of 304L and 304LMC are similar, a nominal value for the estimated H_{FUSION} was used. This value was derived from the A.S.M Metals Handbook for H_{FUSION} of the main elemental species of Fe, Cr, Ni, and Mn [78]. Once the values of the pure elements was known, a rule of mixtures calculation was conducted based on the weight fractions of the elements in 304L/LMC SST

with an estimated value of 18.2 J/g. The values for the density of OFE Cu and 304L/LMC was taken from CPI's Materials and Process Manual [79]. When the H_{FUSION} , melt volume, and density are known the following equation was used to calculate the E_{MELT} for OFE Cu and 304L/LMC SST:

$$E_{MELT} = \rho v H_{FUSION} \quad (33)$$

Where, ρ is the density (g/cm^3) of the material of interest, v is the melt volume (cm^3) of the material of interest, and H_{FUSION} is the heat of fusion (J/g) for the material of interest. Table 6 presents the estimated energy balance results.

Table 6. Energy balance results for selected 304L, 304LMC and OFE Cu after HV Breakdown

		E melt	E total	
I	Sample	H_{FUSION} (cu+sst) mJ	$iVt + 1/2CV^2$ (mJ)	Eleft (mJ)
50micro-amps	304LMCnc T3	2.5	7.8	5.3
50 micro-amps	304Lnc T26	2.0	7.7	5.7
50 micro-amps	304LMCc T25	0.3	7.9	7.6
50 micro-amps	304LMCc T6	0.4	7.7	7.3
60micro-amps	304LMCnc T3	2.5	9.4	6.9
60micro-amps	304Lnc T26	2.0	9.2	7.2
60micro-amps	304LMCc T25	0.3	7.9	7.7
60micro-amps	304LMCc T6	0.4	9.2	8.8
40micro-amps	Sample T3	2.5	6.2	3.7
40micro-amps	Sample T26	2.0	6.2	4.2
40micro-amps	Sample T25	0.3	6.3	6.0
40micro-amps	Sample T6	0.4	6.2	5.8

As a first order approximation the results indicate that 2 out of 4 H_{FUSION} values for OFE Cu combined with 304L/LMC SST are in the same order of magnitude when compared to E_{TOTAL} . The other two cases were an order of

magnitude below the E_{TOTAL} estimation. The current range of 40 – 60 μA is presented for comparison.

It should be noted that the greatest margin of error is estimating the melt volume followed by the estimation of time (t) for the HV breakdown event. The melt volume was difficult to estimate due to the non-homogeneity of the melt regions. The time interval of the breakdown event was estimated at 0.1 seconds. This is based on the author's reaction time from observing the sharp decrease in voltage and increase in current at the breakdown event to shutting off the power supply toggle switch. Another unknown factor is the inherent capacitive nature of the Tektronics 177 power supply. Practically all electrical circuits have a degree of capacitive discharge related to the time constants of the circuitry. This indicates that even after the toggle switch was turned off, there still could be some capacitive discharge adding to the HV breakdown event. As the value of this discharge is unknown, it was omitted for the present energy balance analysis. Future studies should attempt to quantify this factor.

6.9 Fowler-Nordheim Analysis

An analysis of the pre-breakdown current and voltage was conducted for non-cleaned and cleaned 304L SST cathodes. These materials were chosen with the understanding that micro-particles on the non-cleaned samples can promote field emission according to Padamse and Knobloch [48]. Also, as displayed in Figure 31, it is apparent that the 304L material has a greater areal concentration of insulating inclusions. Figure 32 also displayed that these

inclusions can be centers of emission and would be similar to the MIV model put forth by Allen and Latham [23]. A cleaned 304L sample was analyzed to determine if any significant difference could be seen between cleaned and non-cleaned due to a lack of micro-particle contamination. Figure 46 presents the results.

Figure 46 does not show the linear negative slope that would indicate Fowler-Nordheim type field emission for all three samples tested. Therefore, the observed emission is not Fowler-Nordheim field emission. The next step was to conduct a voltage versus current plot. These results are presented in Figure 47.

Figure 46. Fowler-Nordheim Plot of Cleaned and Non-Cleaned 304L SST Cathodes

The results indicate that the V versus I relationship follows Ohm's Law where:

$$V = IR \quad (34)$$

Here V is the pre-breakdown applied potential (Volts), I is the pre-breakdown current (Amperes) and R is the resistance (Ohms). The resistance can be calculated from the slope of Figure 47, where:

$$R = \Delta V / \Delta I \quad (35)$$

The calculated resistance was approximately 978 mega-ohms. The best fit lines (linear) were calculated from a sum of the least squares application in Microsoft Excel.

It is seen that the pre-breakdown emission is ohmic for all three trials analyzed. This is indicative of a resistive film on the electrodes. The nature of this film maybe due to the micro-particle and carbon contamination, as displayed in Figures 30 and 40-44, respectively. Another factor to consider would be the inherent surface resistance of the OFE Cu and 304L SST electrodes, post machining.

Figure 47. V versus I Plot of Cleaned and Non-Cleaned 304L SST Cathodes ($R \sim 978$ mega-ohms).

As stated in section 5.3 the OFE Cu and 304L/LMC test specimens were not annealed before testing. It is well known that the resistivity of a metal can be increased with increasing cold work. As the test anodes and cathodes were subject to machining operations, there as received hardness values would be expected to increase from HRF 77 for Cu anodes and HRB 87 and HRB 80 for the 304L and 304LMC cathodes, respectively. This increased hardness would be a maximum at the electrode surfaces. Hardness testing was not conducted post machining and so a quantitative interpretation of the change in hardness is unknown.

CHAPTER 7

DISCUSSION OF EXPERIMENTAL RESULTS

7.1 HV Breakdown

The results for the HV breakdown tests displayed in Figure 27 indicate that the 304LMC clean material after exposure to microparticle contamination, had a significant increase in E_b by a factor of ~ 1.7 over that of non-cleaned 304LMC. Cleaning the samples prior to HV breakdown testing was effective in removing the contamination as evidenced in Figure 28. The results of the non-clean 304LMC indicate that micro-particle contamination negatively affects its ability to attain high field strengths. This is indirectly supported by the results of Cranberg [40] for micro-particle induced breakdown and directly by the effect of cleaning methods surveyed by Padamse and Knobloch [71]. The recommended use of low inclusion and/or contaminant pure materials by Hawley, *et al* [70] and Kobayashi, *et al* [59] is also supported by the test results for cleaned 304LMC. The results of the non-cleaned 304LMC, indicates that strict process controls are needed when utilizing this material in a fabrication environment.

The large scatter observed for the non-cleaned 304L where $E_{bavg} = 15.1$ MV/m with a σ of ~ 5 indicates the removal of the microparticle contamination may uncover areas of inclusion “rich” and “lean” sections of the metal matrix. This is supported by Figure 31 that displayed the inclusion areal concentration of an as received 304L and 304LMC. It was estimated that the 304L material has ~ 2 times the inclusion concentration of 304LMC in the heavily included areas. It

was also noticed that there were areas that were relatively inclusion free for 304L. If these “islands” of inclusion free material are distributed in the metal matrix; cleaning off the microparticle contamination can expose these areas. The result could be that observed in Figure 27, where large values of E_b can result along with low values. It is also possible that the machining operation can break off and remove inclusions as well.

The results for non-cleaned 304L indicate that microparticle contamination gives a lower average E_b than the results for cleaned 304L. However, the σ was very low at 0.63 compared to ~ 5 for cleaned 304L. The microparticle contamination appears to negatively affect the high voltage performance of 304L. However, the average E_b results are larger than non-cleaned 304LMC test trials. The factors leading to this somewhat counter intuitive result bears further examination.

7.2 Gas Pressure Effects

The results of E_b versus Pressure of Figure 33 indicated that the breakdown field strength was independent of the experimental vacuum pressure. Hackham and Altcheh [60] demonstrated that for DC high voltage breakdown studies using plane parallel Cu electrodes, the breakdown voltage was independent of pressure from 10^{-7} to 10^{-2} mbar (7.5×10^{-7} to 7.5×10^{-3} torr) pressure at a gap distance of 0.13 mm (~ 0.005 inches). Breakdown pressures in the present experiments ranged from 2.0×10^{-8} to 1.2×10^{-7} torr and nominal breakdown gaps ran from 0.003 to 0.008 inches. This supports the results of

Figure 33. There is also additional evidence from the MFP calculation conducted in section 6.4.2. It was calculated that the probability of a vacuum ambient H₂O molecule being present in the vacuum gap at breakdown was 4.2×10^{-7} .

The RGA analysis of section 6.4.1 specific to the normalized ΔP and E_b vs. SST Cathode of Figure 37 indicated that H₂O and CO₂ was consumed and that H₂ and CO was generated during the breakdown event. Knowing the independence of E_b to the ambient vacuum pressure and the MFP, it was determined that the reduced and produced gasses most probably came from the surfaces of the Cu anodes and SST cathodes at breakdown. The non-clean 304LMC and to a lesser extent, non-clean 304L had greater gas generation than cleaned. This is possibly due to the additional surface area of microparticles for adsorption and desorption of gas. This result correlates with the microparticle gas adsorption contention by Duke and Alferieff [30].

The possible chemical reactions at the electrode surfaces resulting from HV breakdown may indicate an additional source of breakdown current as a result of gas ion generation. This would be supported by the gas adsorption plasma generation mechanism put forth by Knobloch [51]. The influence of gas adsorbates effecting HV breakdown resulting from field emission is also supported by Habermann.

7.3 Surface Roughness Effects on HV Breakdown

The results of E_b versus surface finish in section 6.5 and Figure 38 indicate that the HV breakdown was independent of surface roughness. This

result is also correlated by Pupeter, *et al* [49]. However, the SEM photomicrographs of Figure 39 indicated that there was evidence of preferential breakdown sites at the high machined ridges of the electrode surfaces. There is also indication that the overall breakdown damage areas (melted regions) generally follow the machined surface direction. This is seen in both the Cu anode and SST cathode of Figure 39. It is known that high spots and sharp corners will have field enhancement according to the following expression.

$$E_m = \beta E = \beta V/d \quad [15]$$

Here E_m is the enhanced electric field due to the local geometry, E is the applied field (or V/d) and β is the geometric field enhancement factor. It is apparent from Figure 39 that the high spots or ridges from the as machined surface have a greater affinity for the initial electrical arcing than does the grooves. This is evident from the small electrical arc marks which are present on the ridges but which are absent in the grooves.

Another examination of the SEM scan at 300X in Figure 39 may explain why there is no overall correlation between the field strength at breakdown E_b , and the surface roughness. This photomicrograph shows a large breakdown area, with several large arc craters in the center of the breakdown region surrounded by smaller arc craters on the periphery of the breakdown region. The total energy transfer during this event which is sufficient to cause melting of both the anode and cathode material, as evidenced by the melt regions of the craters, is not instantaneous.

It is probable that during the initial phase of the breakdown event the energy transfer is only sufficient to damage or melt a small volume of material. This would be evidenced by the high spots of the OFE anode displaying the relatively small melt regions. As aforementioned, these are areas of field enhancement and would most likely receive the initial energy transfer. As the breakdown event proceeds a greater amount of energy per unit time (E/t) or power, is transferred from the cathode to the anode. A cascade of energy transfer occurs that can then melt a greater volume of material, as evidenced by the large arc craters in the center of the damaged areas in Figure 39. The overall energy transfer from cathode to anode at the initiation of the breakdown event to completion may be viewed as a Gaussian distribution. A hypothetical distribution of breakdown energy versus time is presented in Figure 48.

Figure 48. Hypothetical Representation of Breakdown Energy versus Time.

The region indicated by the arrow would constitute the initial energy transferred to the electrode surface (anode) after the initiation of the breakdown event. The area under this marked region is small, relative to the overall power deposited. If all the data points (arc marks and melt regions) in Figure 39 can in

general be represented by the waveform in Figure 48, then the initial energy transfer, while favoring the geometric high spots of the machined surfaces during the initial breakdown event, is dominated by the overall energy transfer. Therefore, as the breakdown event proceeds the HV breakdown energy transfer obliterates the geometrically enhanced regions and cascades to the point where the volume of material melted is greater than the initial “ridged” regions. As a result it would not be expected that E_b would be correlated with surface roughness, overall.

7.4 Electrode Material Transfer

The results of the EDX analysis indicating Cu particles on 304LMC sample T4 in Figure 39 and the results of the AES analysis in section 6.6, specifically Figures 42 and 43, indicate that Cu transferred from the anode to cathode surface during HV breakdown. This material transfer phenomena was also observed by Anderson using different electrode materials in a similar experiment [46]. This Cu microparticle transfer may also promote the HV breakdown event as proposed by Cranberg [40]. Furthermore, if the kinetic energy of the Cu microparticles was sufficient to promote the melting of the 304L/LMC material at impact this would be correlated by the findings of Rudolph [43] and Dietzl *et al* [44]. However, as the in-flight Cu microparticle velocities are unknown, it is impossible to correlate whether sufficient kinetic energy was achieved.

Figure 30 displayed a typical air borne microparticle contaminant that deposited on the 304L/LMC cathodes during the 7-day 100K clean room exposure. The EDX analysis indicates that it is a Si containing compound, most likely SiO_2 . The AES analysis did not reveal any evidence of Si on the OFE Cu anodes. It is possible that if the Si containing compounds did transfer, they were below the analytical threshold of AES. It is also possible that they did not transfer from the SST cathode to the Cu anode at all.

7.5 Other Possible HV Breakdown Mechanisms

The EDX analysis of Figure 32 and the AES analysis of Figure 44 indicated that the inclusion in the center of the observed crater for 304LMC cathode T2 contained high concentrations of Cr. The stoichiometric exercise in section 6.6 indicated that the inclusion could be Cr_2O_3 . Regardless of its chemical composition, it appears to be a high dielectric material or semiconductor surrounded by the metal matrix of the 304LMC material. This is somewhat similar to the MIV mechanism in Figure 12a, first proposed by Allen and Latham [23]. Cox and Williams [36] also identified dielectric inclusions as emission sources in their SEM observations, as well. The extent to which this emission site or similar existing sites not observed, but present, contributed to the overall HV breakdown event is not known. Nonetheless, it is evidence that such sites exist and are electron emission centers.

7.6 The Nature of the HV Breakdown Current

The various Figures presented, showing crater like damage on the 304L/LMC cathodes post HV breakdown, are evidence of electron emission sites. The variety in sizes of the craters that are on the order of 5 μm to 50 μm imply that the arc current is not a cohesive or a uniform beam. These multiple emission sites indicate that the total arc current maybe comprised of discreet cylindrical packages of emitted electrons. If so, this would support Mesyat's description of non-coherent emission currents that he termed as "ectons" [33].

7.7 Mass and Energy Balance Implications

A mass and energy balance was conducted in section 6.8 to achieve a first order approximation of the energy required to melt the OFE Cu anodes and 304L/LMC cathodes. It was seen that the required melt energies are of or close to the same order of magnitude as the HV breakdown energy due to iVt and $1/2CV^2$ contributions. Equation (32) is presented for reference.

$$E_{\text{Total}} = 1/2CV^2 + iVt = E_{\text{MELT}} + \Sigma E_i \quad (32)$$

Understanding that there is an energy debt for the cases analyzed and results presented in Table 6, equation (32) can be expanded to define and include other possible energy variables to the right hand side of equation (32).

$$E_{\text{total}} = 1/2CV^2 + i_eVt = HF + 2H_{\text{CONDUCTED}} + H_{\text{VAPMETALS}} + H_{\text{IONMETALS}} + H_{\text{IONGAS}} + H_{\text{RADIATION}} + (1/2mv^2)_{\text{MICROPARTICLES}} + i_{\text{ION}}Vt + \Sigma E_i \quad (33)$$

Where:

$1/2CV^2$ = capacitive potential energy, i_eVt = breakdown discharge energy due to

the breakdown current, voltage and HV breakdown time duration, H_F is heat of fusion of metals at melting, $2H_{COND}$ is the non-melt heat conducted away during heating to the melting temperature of a metal and cooling down after solidification, $H_{VAPMETALS}$ is the heat of vaporization of metals, $H_{IONMETALS}$ is the heat of ionization of metals, H_{IONGAS} is the heat of gas ionization, $H_{RADIATION}$ is the heat of photon generation resulting from the arc current, $1/2mv^2$ is the K.E. due to impacting microparticles, $i_{ION}Vt$ is an additional breakdown energy contribution resulting from gas ionization and breakdown voltage acceleration over the breakdown time, and ΣE_i is other energy contributions that could result from other mechanisms not yet defined.

As mass and energy are conserved in all reactions according to the laws of conservation for mass and energy (with the exception of nuclear reactions), equation (33) is a valid description of the overall HV breakdown event studied. This equation could be used in a design of experiments methodology.

CHAPTER 8

CONCLUSIONS

The cleaning method prior to testing was effective in increasing E_b for microparticle contaminated 304LMC SST. It apparently removes the microparticle mechanism that impacts non-clean 304LMC SST, resulting in a lower E_b . Cleaning of purer vacuum materials can statistically remove loosely adhering microparticle.

The cleaning method prior to testing gave results with a high degree of data scatter for 304L SST. This is possibly due to exposing inclusion “free” or rich material. Also, machining may remove or cover inclusions. Microparticle contamination for non-clean 304L appeared to reduce the scatter of E_b but with greater average results than non-clean 304LMC. This result bears further investigation.

The use of purer and clean materials in the HV vacuum envelope of VEDs is recommended. However, for 304LMC SST effective and consistent process controls need to be in place in the production environment. Fabrication of VED subassemblies in a class 100 facility instead of a class 100K environment should provide a more robust vacuum envelope under high electric field applications.

Vacuum degassing of HV electrode materials prior to assembly may not be beneficial, *IF* subassemblies are to be exposed to ambient conditions. The 304L/LMC test specimens that were cleaned prior to HV breakdown testing

would still adsorb ambient gas molecules during pump down that took ~24 hours to complete

The mass and energy balance equation can be used for design of experiments. The isolation of the variables of interest, in a well designed experiment, could provide additional insight into the complex yet fascinating nature of High Voltage vacuum breakdown.

CHAPTER 9

RECOMMENDATIONS FOR FUTURE RESEARCH

Use the energy balance to evaluate individual contributions from micro-particle impact ($1/2mv^2$), temperature measurements of the damaged areas to quantify $H_{\text{conduction}}$, H_{fusion} , etc.

Conduct *in situ* vacuum experiments to evaluate microparticle contaminated and non-clean 304L SST as well as electropolished 304L SST and 304LMC SST. This would involve vacuum annealing (degassing); then selected contaminants and/or selected gasses could be deposited/injected in a multi-chambered vacuum chamber and finally HV breakdown tested. The same test setup should also provide *in situ* vacuum capability for EDX and AES analysis, within the same test apparatus. This is similar to experimental designs conducted by Pupeter *et al* [49], Habermann *et al* [50], and Kobayashi *et al* [59].

Evaluate the effects of Ba deposited on electrodes and the resultant HV breakdown effects due to lower work functions on metal substrates. This is germane to the VED industry. Also, investigate the effect of “greened” 304L/LMC SST that undergoes wet H_2 firing to promote Cr_2O_3 films on the surfaces. This is a current controversy in the VED industry with proponents aligning themselves with the “to green” or “not to green” opinions. Of interest here is that the Cr_2O_3 film would strongly correlate with the MIV emission mechanism displayed in Figure 12a, as proposed by Allen and Latham [23]. This experiment should investigate the extent of “greening”, as to the thickness levels of this high

dielectric film versus E_b . The processes to achieve this insulating film should be thoroughly documented.

It is recommended that the test sample size be increased to achieve a more statistically meaningful population of HV breakdown data.

Conduct experiments to evaluate the effect of fully annealed and heavily cold worked (i.e., machined surfaces in present study) on HV breakdown due to increased surface resistivity of the cold worked specimens.

The use of test equipment that would record more accurate measurements of breakdown current and time is also recommended.

REFERENCES

1. A.S. Gilmore, Jr., Klystrons, From notes presented in a technical seminar at CPI, p. 1, (01/25/99).
2. A.S. Gilmore, Jr., Klystrons, From notes presented in a technical seminar at CPI, pp. 1-6 (01/25/99).
3. A.S. Gilmore, Jr. Klystrons, From notes presented in a technical seminar at CPI, p. 2-5 (01/25/99).
4. R.E. Honig, "Vapor Pressure Data for the Solid and Liquid Elements," RCA Review, Vol. XXIII, **4**, pp. 567-587 (1962).
5. A.S.M. Metals Handbook – Desk Edition, H.E. Boyer and T.L. Gall, eds., (ASM: Metals Park, Ohio), p. 1-67, (1997).
6. O. Kubaschewski, and E.L. Evans, Metallurgical Thermochemistry, (Pergamon Press, New York, 1958), pp. 326-335.
7. R.W. Wood, "A new form of Cathode Discharge and the Production of X-rays, together with some notes on Diffraction," Phys. Rev. Ser. I, **5**, 1-10 (1897).
8. R.F. Earhart, "The Sparking Distances between Plates for small Distances," Phil. Mag., **1**, 147-159 (1901).
9. G.M. Hobbs, "The Relation between P.D. and Spark-length for Small Values of the latter," Phil. Mag., **10**, 617-631 (1905).
10. R.A. Millikan, and R.A. Sawyer, "Extreme Ultra-Violet Spectra of Hot Sparks in High Vacua," Phys. Rev., **12**, 167-170, 1918.
11. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, (Academic Press, London, UK, 1995) pp. 4-7.
12. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, (Academic Press, London, UK, 1995) pp. 6-7.
13. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, (Academic Press, London, UK, 1995), p. 7.
14. R. Hawley, A.A. Zaky, M.E. Zeine, "Insulating Properties in High Vacuum," Proc. IEE, Vol. 112, **6**, pp.1237-1248 (1968).

15. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, (Academic Press, London, UK, 1995), Fig. 2.3, p. 24.
16. G.A. Mesyats, and V.F. Puchkarev, "Current Density and Lifetime of a Vacuum Arc Spot," Proc. XIX Intern. Conf. on Phenomena in Ionized Gases, Belgrade, 1989, pp. 16-23.
17. V.F. Puchkarev, and A.M. Murzakaev, "Current Density and the Cathode Spot Lifetime in a Vacuum Arc at Threshold Currents," J. Phys. D: Appl. Phys., 1990, **23**, pp. 26-35.
18. A.M. Murzakaev, "Nonstationary Processes in the Cathode Spot of a Vacuum Arc in at Near-Threshold Currents," Thesis, Institute of High Current Electronics, Tomsk, 1990.
19. B. Juttner and E. Freund, Beitr. Plasma Phys., **15**, pp. 47-61, (1975).
20. Y.H. Fu, J. Phys. D: Appl. Phys., **22**, pp. 94-102, (1989).
21. I.G. Kesaev, Cathode Processes in Electric Arcs, Nauka-Publishers, Moscow, (1968).
22. R.A. Millikan, and C.C. Lauritsen, Proc. Nat. Acad. Sci. (US) **14**, pp. 45-49, (1928).
23. N.K. Allen, and R.V. Latham, J. Phys. D: Appl Phys, **11**, pp. 55-57, (1978).
24. C.S. Athwal, K.H. Bayliss, R. Calder, and R.V. Latham, IEEE Trans. Plasma Sci., **13**, pp. 226-229, (1985).
25. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, (Academic Press, London, UK, 1995).
26. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, Academic Press, Inc., (1995), p. 118, Figure 4.1.
27. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, Academic Press, Inc., (1995), p. 120, Figure 4.2.
28. R.H. Fowler, and L. Nordheim, "Electron Emission in Intense Electric Fields", Proc. Roy. Soc. London, **A119**, pp. 173-181, (1928).
29. W.P. Dyke, and J.K. Trolan, Physics Review, **89**, 799, (1953).

30. C.B. Duke, and M.E. Alferieff, "Field Emission through Atoms adsorbed on a Metal Surface", J. of Chemical Physics, **46**, pp. 923-937, (1967).
31. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, (Academic Press, London, UK, 1995), pp. 26-28.
32. J.G. Trump, and R.J. van de Graaf, J. of Appl. Phys., **18**, pp. 327-332, (1947).
33. G. A. Mesyats, Explosive Electron Emission, URO-Press., Ekaterinburg, Russia (1998), p. iv.
34. B.M. Cox, J. Phys. D: Appl. Phys., v. 8, pp. 2065-2073, (1975).
35. B. M. Cox and W.T. Williams, J. Phys. D: Appl. Phys., 1977, v. 8, pp. 2065-2073, (1977).
36. B.M. Cox and W.T. Williams., "Anomalous Field Emission Sites on Polished Electrodes," Proc. VII Int. Symp. On Discharges and Electrical Insulation in Vacuum, Novosibirsk, USSR, 1976, pp. 176-180.
37. G. A. Mesyats, Explosive Electron Emission, URO-Press., Ekaterinburg, Russia (1998), p.
38. T.J. Fabiniak, L. Jedynak and R.A. Dodd, J. Appl. Phys., v. 42, pp. 2240-2246, (1971).
39. F. Llevellin-Jones, Ionization and Breakdown in Gases, CO Ltd., London: Sons Inc., NY, (1966).
40. L. Cranberg, "The Initiation of Electrical Breakdown in Vacuum," J. Appl. Phys., **23**, 518-22 (1952).
41. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, Academic Press, London, UK, (1995), pp. 247-249.
42. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, Academic Press, Inc., (1995), p. 283-4, Figures 7.26 (top) and 7.27 (bottom).
43. V. Rudolph, Z. Naturforsch, **24a**, pp. 326-331, (1969).

44. H. Dietzel, G. Neakum, and P. Rauser, J. Geophys. Res., **77**, pp. 1375-1395, (1972).
45. R. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, Academic Press, Inc., (1995), p. 237, Figure 7.2.
46. H.W. Anderson, Elect. Eng., **54**, pp. 1315-1320, (1935).
47. H. Padamse, "Overview of Advances in the Basic Understanding of Dark Current and Breakdown in RF Cavities," Cornell University, Nuclear Studies, Newman Lab, Ithaca, NY, IEEE, pp. 2884-2888, (1998).
48. H. Padamse, and J. Knobloch, "The Nature of Field Emission From Microparticles and the Ensuing Voltage Breakdown," CP474, High Energy Density Microwaves, The American Institute of Physics, pp. 212-48, (1999).
49. N. Pupeter, A. Gohl, T. Habermann, A. Kirschner, E. Mahner, G. Muller and H. Piel, "Influence of Surface Roughness and Preparation, Bulk Purity and Heat Treatment on Electron Field Emission from Nb and Nb₃Sn," Particle Accelerators, **53**, pp. 77-96, (1996),
50. T. Habermann, A. Gohl, D. Nau, G. Muller, H. Piel and M. Wedel, "Influence of Adsorbates and Surface Compounds on the Field Emission of Niobium", Particle Accelerators, **61**, pp. 401-415, (1998).
51. J. Knobloch, Advanced Thermometry Studies of Superconducting RF Cavities. PhD thesis, Cornell University, (1997).
52. M. Jimenez, R.J. Noer, G. Jouve, J. Jodet, and B. Bonin, "Electron Field Emission from Large-area Cathodes: Evidence for the Projection Model," J. Phys. D: Appl. Phys., **27**, pp. 1038-1045, (1994).
53. R.N. Bloomer and S.M. Cox, Vacuum, Vol. 18, **7**, (1968).
54. L. Laurent, G. Scheitrum, A. Vlieks, C. Pearson, G. Caryotakis and N.C. Luhmann, Jr., "Pulsed RF Breakdown Studies," SLAC-PUB-8409, March 2000.
55. D. Alpert, D.A. Lee, E.M. Lyman, and H.E. Tomaschke, J. Appl. Phys., **38**, 880-1, (1967).
56. S.Y. Ettinger, and E.M. Lyman, Proc. III-ISDEIV, pp. 128-33, (1968).
57. G.P. Beukema, Physica C., **61**, pp. 259-75, (1972).

58. S. Bajic, A.M. Abbot, and R.V. Latham, IEEE Trans. Elec. Insul., **24**, pp. 89-86, (1989).
59. S. Kobayashi, Y. Saito, Y. Nagai, and Y. Yamamoto, "XVth. International Symposium on Discharges and Electrical Insulation in Vacuum". Darmstadt, Germany, September 6-10, 1992.
60. R. Hackham, and L. Altcheh, J. Appl. Phys., **46**, pp. 627-636, (1975).
61. R.V. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, Academic Press, Inc., (1995), p. 40, Figure 2.12.
62. R.V. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, Academic Press, Inc., (1995), pp. 24-25 and Figure 2.4.
63. R. Arnal, Ann. Phys. (France), **10**, pp. 830-873, (1955)
64. L.J. Pivover and V.I. Gordienko, Sov. Phys-Tech. Phys., **7**, pp. 908-912, (1963).
65. W.K. Mansfield, Brit. J. Appl. Phys., **11**, pp. 454-461, (1960).
66. H. Boersch, H. Hamisch, and S. Wiesner, Z. Agnew. Phys., **13**, pp. 450-456, (1961).
67. H.P.S. Powell, and P.A. Chatterton, Vacuum, **20**, pp. 419-429, (1970).
68. V.I. Gerasimenko, Sov. Phys.-Tech. Phys., **13**, pp. 107-112, (1968).
69. R.V. Latham, High Voltage Vacuum Insulation – Basic Concepts and Technological Practice, (Academic Press, London, UK, 1995).
70. R. Hawley, B. Loy, and R. Craik, "Phenomena occurring at Electrically Stressed Metallic Surfaces in Long Gaps in Vacuum," Nature, **197**, p. 274 (1963).
71. H. Padamse, and J. Knobloch, "The Nature of Field Emission From Microparticles and the Ensuing Voltage Breakdown," CP474, High Energy Density Microwaves, The American Institute of Physics, p. 244, (1999).
72. L.C. Feldman and J.W. Mayer, Fundamentals of Surface and Thin Film Analysis, PTR Prentice-Hall, Inc., Englewood Cliffs, N.J., p. 353, (1986).

73. A. Sherman. Chemical Vapor Deposition For Microelectronics. Noyes Publications, (1987), p. 191, Figure 14.
74. ASTM E 45-87, "Standard Practice for Measuring the Inclusion Content in Steel," (1987).
75. CRC Handbook of Tables for Applied Engineering Science, 2nd Edition, R.E. Bolz and G.L. Tuve, eds., CRC Press, Inc. Baton Rouge, Fla. p. 53, Table 1-17, (1987).
76. L.C. Feldman and J.W. Mayer, Fundamentals of Surface and Thin Film Analysis, PTR Prentice-Hall, Inc., Englewood Cliffs, N.J., p.270 and p.353, (1986).
77. Charles-Evans & Associates, "Scanning Auger Microprobe Analysis Report for CEA# B6934," C.L. Weitzsacker, Ph.D., analyst, p. 5, (05/10/00).
78. A.S.M. Metals Handbook – Desk Edition, H.E. Boyer and T.L. Gall, eds., (ASM: Metals Park, Ohio), pp. 144-45, (1997).
79. CPI Materials and Process Manual, Micro Wave Tube Division, sections 006 & 009, (1990).

APPENDIX A

SAMPLE CALCULATIONS AND ERROR ANALYSIS

Field strength (E_b) at breakdown:

$E_b = V/d$ For sample T3, $V = 1560$ volts and $d = 0.008$ inch.

Then $E_b = (1560\text{volts}/0.008\text{inch})(39.37\text{inch}/1\text{meter})(1\text{MV}/10^6\text{meters}) = 7.7 \text{ MV/m}$

Error Analysis in $E_b = V/d$

For “worst case” $V = 1600 \pm 10$ volts and $d = 0.008 \pm 0.00005$ inches =
.0000203 $\pm$ 0.000001 meters

$$\begin{aligned}\text{Error} &= 7.7\text{MV/m} \times \{(10/1600)^2 + (0.000001/0.0000203)^2\}^{1/2} \\ &= \pm 0.05 \text{ MV/m}\end{aligned}$$

Mean Free Path for H_2O (see Table 7):

$$V = b/N_A$$

$$d = (6V/\pi)^{1/3}$$

$$\lambda = RT/2^{1/2}\pi d^2 N_A P$$

$$E = iVt = (50 \times 10^{-6} \text{ A})(1600 \text{ V})(0.1 \text{ s}) = 8.0 \text{ mJ}$$

$i = 50 \pm 10 \mu\text{A}$, $V = 1600 \pm 10$ volts, $t = 0.1 \pm 0.02$ seconds.

$$\begin{aligned}\text{Error} &= 8.0 \text{ mJ} \times \{(10/50)^2 + (10/1600)^2 + (0.02/0.1)^2\}^{1/2} \\ &= \pm 0.3 \text{ mJ}\end{aligned}$$

Table 7. MFP Calculation and Probability of H₂O

H2O	H2O	Units
P=	5.38E-09	torr
P=	7.08E-12	atm
R=	82.057	cm ³ .atm/mole.o K
T=	298	oK
V=	141.3	cm ³
No	6.02E+23	atoms/mole
n=	24637226104	
n'	174361118.9	
root2	1.414213562	
s	4.60E-08	cm
s ²	2.12E-15	
pi	3.14127	
MFP=	6.10E+05	cm
	6101.188244	m
	20016.77839	ft
	240201.3407	in
	3.791056513	mi.
Probability	4.16317E-07	

Table 8. Mass and Energy Balance Calculations for 304L sample T3

Estimation of Energy to melt OFE and SST			
		cal/g	J/g
304L cathode T3	Hfusionssst =	76.06	18.1791006
Copper	Hfusioncu =	50.6	12.093906
	Density cu	8.96 g/cm3	8.96
	density sst	7.94 g/cm3	7.94
Atotal	0.000159512	T3	
Vtotal (cm^3)	1.59512E-06	304L SST	
	Joules	a1	0.000551
Emelt = rhoVH	0.000172849	a2	0.0000986
Cu anode T3	Acopper (cm^3)	a3	4.90823E-06
a1	0.000452343	a3	0.00000012
a2	0.0008712	a4	1.96329E-07
a3	0.000064	a5	1.96329E-07
Atotal	0.001387543	a6	1.50E-06
Vtotal (cm^3)	1.38754E-05	Atotal	0.000656521
		Vtotal (cm^3)	6.56521E-06
			Joules
Emelt Cu	0.001503561	Emelt 304L	0.000947636
		Ettotal	0.002451197

APPENDIX B

RGA RESPONSE OF 304L AND 304LMC SST

Table 9. RGA profile of 304L Sample No T24 (Not Cleaned)

Gas Species	Pre-Breakdown Pressure (torr)	Post-Breakdown Pressure (torr)	Max Change in Pressure (torr)	ΔP ($P_{MAX} - P_{PRE}$) (torr)
H ₂ O	1.74×10^{-10}	1.74×10^{-10}	1.85×10^{-10}	0.11×10^{-10}
CO	0.43×10^{-10}	0.44×10^{-11}	2.66×10^{-10}	2.23×10^{-10}
CO ₂	4.39×10^{-11}	4.34×10^{-11}	6.55×10^{-11}	2.16×10^{-11}
H ₂	0.77×10^{-10}	0.77×10^{-10}	3.31×10^{-10}	2.54×10^{-10}
C	0.42×10^{-11}	0.43×10^{-11}	1.75×10^{-11}	1.33×10^{-11}
N ₂	1.28×10^{-12}	1.16×10^{-12}	5.53×10^{-12}	4.25×10^{-12}
Ar	1.23×10^{-12}	0.73×10^{-12}	1.41×10^{-12}	0.18×10^{-12}
O ₂	0.93×10^{-12}	1.21×10^{-12}	0	-0.93×10^{-12}

Table 10. Normalized RGA response of 304L Sample No T24 (Not Cleaned)

Gas Species	Normalized P_{PRE}	Normalized P_{POST}	Normalized P_{MAX}	Normalized ΔP ($P_{max} - P_{pre}$)
H ₂ O	0.5	0.5	0.21	-0.29
CO	0.12	0.13	0.30	0.18
CO ₂	0.13	0.12	0.07	-0.06
H ₂	0.22	0.22	0.38	0.16
C	0.012	0.012	0.02	0.008
N ₂	0.004	0.003	0.006	0.002
Ar	0.004	0.002	0.002	-0.002
O ₂	0.003	0.004	0	-0.003

Table 11. RGA response of 304L Sample No T23 (Cleaned)

Gas Species	Pre-Breakdown Pressure (torr)	Post-Breakdown Pressure (torr)	Maximum Change in Pressure (torr)	ΔP ($P_{MAX} - P_{PRE}$) (torr)
H ₂ O	2.38×10^{-10}	2.38×10^{-10}	2.42×10^{-10}	0.04×10^{-10}
CO	0.49×10^{-10}	0.49×10^{-10}	1.04×10^{-10}	0.55×10^{-10}
CO ₂	4.80×10^{-11}	4.75×10^{-11}	5.60×10^{-11}	0.8×10^{-11}
H ₂	0.92×10^{-10}	0.92×10^{-10}	1.05×10^{-10}	0.13×10^{-10}
C ⁺	4.26×10^{-12}	4.37×10^{-12}	6.01×10^{-12}	1.75×10^{-12}
N ₂	1.65×10^{-12}	1.96×10^{-12}	2.45×10^{-12}	0.8×10^{-12}
Ar	5.62×10^{-13}	6.04×10^{-13}	1.49×10^{-13}	-4.13×10^{-13}
O ₂	1.34×10^{-12}	0.79×10^{-12}	1.05×10^{-12}	-0.3×10^{-12}

Table 12. Normalized RGA Response 304L Sample No T23 (Cleaned)

Gas Species	Normalized P_{PRE}	Normalized P_{POST}	Normalized P_{MAX}	Normalized ΔP ($P_{MAX} - P_{PRE}$)
H ₂ O	0.53	0.55	0.47	-0.06
CO	0.11	0.11	0.21	0.10
CO ₂	0.11	0.11	0.11	0
H ₂	0.21	0.21	0.23	0.02
C ⁺	0.01	0.01	0.01	0
N ₂	0.004	0.004	0.005	0.001
Ar	0.001	0.001	0.0003	-0.0007
O ₂	0.003	0.002	0.002	-0.001

Table 13. RGA response of 304LMC Sample No T7 (Not Cleaned)

Gas Species	Pre-Breakdown Pressure (torr)	Post-Breakdown Pressure (torr)	Max Change in Pressure (torr)	ΔP ($P_{MAX} - P_{PRE}$) (torr)
H ₂ O	5.38 X10 ⁻⁹	5.44 X 10 ⁻⁹	5.52 X 10⁻⁹	0.14 X 10⁻⁹
CO	1.43 X10 ⁻⁹	1.45 X10 ⁻⁹	3.76 X 10⁻⁹	2.27 X10⁻⁹
CO ₂	1.0 X10 ⁻⁹	1.0 X10 ⁻⁹	1.25 X 10⁻⁹	0.25 X10⁻⁹
H ₂	1.44 X10 ⁻⁹	1.47 X10 ⁻⁹	3.36 X 10⁻⁹	2.89 X10⁻⁹
C [*]	1.02 X10 ⁻¹⁰	1.04 X10 ⁻¹⁰	1.76 X 10⁻¹⁰	0.74 X10⁻¹⁰
N ₂	6.0 X10 ⁻¹¹	6.1 X10 ⁻¹¹	8.81 X 10⁻¹¹	4.25 X10⁻¹²
Ar	3.27 X10 ⁻¹¹	3.29 X10 ⁻¹¹	4.19 X 10⁻¹¹	0.18 X10⁻¹²
O ₂	1.63 X10 ⁻¹¹	1.65 X10 ⁻¹¹	2.19 X 10⁻¹¹	0.56 X10⁻¹¹

Table 14. Normalized RGA response of 304LMC Sample No T7 (Not Cleaned)

Gas Species	Normalized P _{PRE}	Normalized P _{POST}	Normalized P _{MAX}	Normalized ΔP ($P_{MAX} - P_{PRE}$)
H ₂ O	0.57	0.57	0.39	-0.18
CO	0.15	0.15	0.30	0.15
CO ₂	0.10	0.10	0.09	-0.1
H ₂	0.15	0.15	0.24	0.09
C [*]	0.011	0.011	0.008	-0.002
N ₂	0.006	0.006	0.005	-0.001
Ar	0.003	0.003	0.003	0
O ₂	0.002	0.002	0.002	0

Table 15. RGA response of 304LMC Sample No. 8 (cleaned)

Gas Species	Pre-Breakdown Pressure (torr)	Post-Breakdown Pressure (torr)	Max Change in Pressure (torr)	ΔP ($P_{MAX} - P_{PRE}$) (torr)
H ₂ O	4.05 X10 ⁻⁹	14.28 X 10 ⁻⁹	4.30 X 10⁻⁹	0.25 X 10⁻⁹
CO	1.30 X10 ⁻⁹	1.37 X10 ⁻⁹	1.73 X 10⁻⁹	0.43 X10⁻⁹
CO ₂	7.34 X10 ⁻¹⁰	7.69 X10 ⁻¹⁰	8.03 X 10⁻¹⁰	0.69 X10⁻¹⁰
H ₂	1.51 X10 ⁻⁹	1.62X10 ⁻⁹	2.01 X 10⁻⁹	0.50 X10⁻⁹
C ⁺	0.86 X10 ⁻¹⁰	0.93 X10 ⁻¹⁰	1.21 X 10⁻¹⁰	0.35 X10⁻¹⁰
N ₂	5.47 X10 ⁻¹¹	5.91 X10 ⁻¹¹	6.64 X 10⁻¹¹	1.17 X10⁻¹¹
Ar	3.18 X10 ⁻¹¹	3.31 X10 ⁻¹¹	3.53 X 10⁻¹¹	0.35 X10⁻¹¹
O ₂	2.95 X10 ⁻¹¹	3.11 X10 ⁻¹¹	3.14 X 10⁻¹¹	0.19 X10⁻¹¹

Table 16. Normalized RGA response of 304LMC Sample No. 8 (cleaned)

Gas Species	Normalized P _{PRE}	Normalized P _{POST}	Normalized P _{MAX}	Normalized ΔP ($P_{MAX} - P_{PRE}$)
H ₂ O	0.52	0.52	0.47	-0.05
CO	0.17	0.17	0.19	0.02
CO ₂	0.094	0.093	0.088	-0.006
H ₂	0.19	0.19	0.23	0.04
C ⁺	0.011	0.011	0.013	0.002
N ₂	0.007	0.007	0.008	0.001
Ar	0.004	0.004	0.004	0
O ₂	0.0038	0.038	0.0034	0

APPENDIX C

SEM PHOTOMICROGRAPHS USED FOR MELT VOLUME CALCULATIONS

SEM photomicrographs displaying measured areas and depth used to estimate melt volumes of the OFE Cu anodes and SST cathodes. The following SEM photomicrographs were produced using an Hitachi S-2600N SEM.

Figure 49. SEM photomicrograph of 304LMC (T3) post HV Breakdown measurement area 1.

Figure 50. SEM photomicrograph of 304LMC (T3) post HV breakdown measurement area 2.

Figure 51. SEM photomicrograph of OFE Cu (T3) anode post HV Breakdown with measurements.

Figure 52. SEM photomicrograph of 304LMC (T6) SST cathode post HV breakdown with measurement of area 1.

Figure 53. SEM photomicrograph of OFE Cu (T6) anode post HV breakdown with measurement of area 1.

Figure 54. SEM photomicrograph of OFE Cu (T6) anode post HV breakdown with measurement of area 2.

Figure 55. SEM photomicrograph of 304L (T25) SST cathode post HV breakdown with measurement of area 1.

Figure 56. SEM photomicrograph of 304L (T25) SST cathode post HV breakdown with measurement of area 2.

Figure 57. SEM photomicrograph of OFE Cu (T25) anode post HV breakdown with measurement of area 1.

Figure 58. SEM photomicrograph of OFE Cu (T25) anode post HV breakdown with measurement of area 2.

Figure 59. SEM photomicrograph of 304L (T26) SST cathode post HV breakdown with measurement of area 1.

Figure 60. SEM photomicrograph of 304L (T26) SST cathode post HV breakdown with measurement of area 2.

Figure 61. SEM photomicrograph of OFE Cu (T26) anode post HV breakdown with measurements.

APPENDIX D

FOWLER-NORDHEIM and I vs. V ANALYTICAL WORKSHEETS

Table 17. Fowler-Nordheim analytical spreadsheet of 304L T27 cleaned, used to produce Figure 46.

304L T27 Cleaned						
volts	current (I)	V ²	1/V ²	LN(I/V ²)	1/V	LN(I/V ²)
40	0.00000005	1600	0.000625	-24.189	0.025	-24.189
80	0.000000045	6400	0.00015625	-	0.0125	-
160	0.00000008	25600	3.9063E-05	-	0.00625	-
200	0.000000103	40000	0.000025	-	0.005	-
280	0.00000017	78400	1.2755E-05	-	0.003571	-
400	0.00000027	160000	0.00000625	-	0.0025	-
440	0.0000003	193600	5.1653E-06	-	0.002273	-
560	0.000000485	313600	3.1888E-06	-	0.001786	-
600	0.00000051	360000	2.7778E-06	-	0.001667	-
680	0.0000006	462400	2.1626E-06	-	0.001471	-
720	0.000000645	518400	1.929E-06	-	0.001389	-
800	0.00000075	640000	1.5625E-06	-	0.00125	-
1000	0.00000095	1000000	0.000001	-	0.001	-
1200	0.00000125	1440000	6.9444E-07	-	0.000833	-
1400	0.00000133	1960000	5.102E-07	-	0.000714	-
1550	0.0000015	2402500	4.1623E-07	-	0.000645	-

Table 18 . Fowler-Nordheim analytical spreadsheet of 304L T25 cleaned, used to produce Figure 46.

304L T25 Cleaned						
volts	current (I)	V ²	1/V ²	LN(I/V ²)	1/V	LN(I/V ²)
20	0.00000005	400	0.0025	-	0.05	-
				22.80271		22.80271
80	0.00000006	6400	0.00015625	-	0.0125	-
				25.39297		25.39297
160	0.00000009	25600	3.9063E-05	-	0.00625	-
				-26.3738		-26.3738
200	0.000000115	40000	0.000025	-	0.005	-
				26.57497		26.57497
280	0.00000016	78400	1.2755E-05	-	0.003571	-
				26.91767		26.91767
400	0.00000025	160000	0.00000625	-	0.0025	-
				27.18473		27.18473
440	0.000000275	193600	5.1653E-06	-	0.002273	-
				27.28004		27.28004
560	0.0000004	313600	3.1888E-06	-	0.001786	-
				27.38767		27.38767
600	0.0000005	360000	2.7778E-06	-	0.001667	-
				27.30252		27.30252
680	0.0000005	462400	2.1626E-06	-	0.001471	-
				27.55284		27.55284
720	0.00000065	518400	1.929E-06	-	0.001389	-
				-27.4048		-27.4048
800	0.00000075	640000	1.5625E-06	-	0.00125	-
				27.47242		27.47242
1000	0.0000009	1000000	0.000001	-	0.001	-
				27.73638		27.73638
1200	0.000001	1440000	6.9444E-07	-	0.000833	-
				27.99566		27.99566
1400	0.00000125	1960000	5.102E-07	-	0.000714	-
				28.08082		28.08082
1550	0.0000014	2402500	4.1623E-07	-	0.000645	-
				28.17106		28.17106

Table 19 . Fowler-Nordheim analytical spreadsheet of 304L T26 not cleaned, used to produce Figure 46.

304L T26 Not Cleaned						
volts	current (I)	V ²	1/V ²	LN(I/V ²)	1/V	LN(I/V ²)
40	0.00000005	1600	0.000625	-24.189	0.025	-24.189
80	0.000000045	6400	0.00015625	-	0.0125	-
160	0.00000007	25600	3.9063E-05	25.68066	0.00625	25.68066
200	0.000000105	40000	0.000025	-	0.005	-
280	0.00000017	78400	1.2755E-05	26.62512	0.003571	26.62512
400	0.00000027	160000	0.00000625	-	0.0025	-
440	0.0000003	193600	5.1653E-06	26.66594	0.002273	26.66594
560	0.000000475	313600	3.1888E-06	-	0.001786	-
600	0.000000525	360000	2.7778E-06	26.85705	0.001667	26.85705
680	0.0000006	462400	2.1626E-06	-	0.001471	-
720	0.00000065	518400	1.929E-06	27.10777	0.001389	27.10777
800	0.00000075	640000	1.5625E-06	-	0.00125	-
1000	0.00000095	1000000	0.000001	27.19303	0.001	27.19303
1200	0.00000113	1440000	6.9444E-07	-	0.000833	-
1400	0.00000138	1960000	5.102E-07	27.21582	0.000714	27.21582
1550	0.00000155	2402500	4.1623E-07	-	0.000645	-
				27.25373		27.25373
				-		-
				27.37052		27.37052
				-27.4048		-27.4048
				-		-
				27.47242		27.47242
				-		-
				27.68231		27.68231
				-		-
				27.87345		27.87345
				-		-
				27.98188		27.98188
				-		-
				28.06928		28.06928

Table 20. I vs. V analytical spreadsheet, used to produce Figure 47.

T27c	T26nc	T25c	
I (Amps)	I (Amps)	I (Amps)	Volts
4.5E-08	4.5E-08	6E-08	80
0.00000008	7E-08	9E-08	160
1.03E-07	1.05E-07	1.15E-07	200
0.00000017	1.7E-07	1.6E-07	280
0.00000027	2.7E-07	2.5E-07	400
0.0000003	0.0000003	2.75E-07	440
4.85E-07	4.75E-07	4E-07	560
0.00000051	5.25E-07	5E-07	600
0.0000006	0.0000006	5E-07	680
6.45E-07	6.5E-07	6.5E-07	720
0.00000075	7.5E-07	7.5E-07	800
0.00000095	9.5E-07	9E-07	1000
0.00000125	1.13E-06	0.000001	1200
0.00000133	1.38E-06	1.25E-06	1400
0.0000015	1.55E-06	1.4E-06	1550