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AFAL-TR-75-117

MATRIX CATHODE DEVELOPMENT

Warnecke Electron Tubes, Inc.

January 1976

Technical Report AFAL-TR-75-117
Final Report for Period 15 February 1974 to 1 June 1975

AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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This technical report has been reviewed and is approved for publication.

FOR THE DIRECTOR

Donald S Rees

DONALD S. REES
Actg. Chief
Microwave Technology Branch
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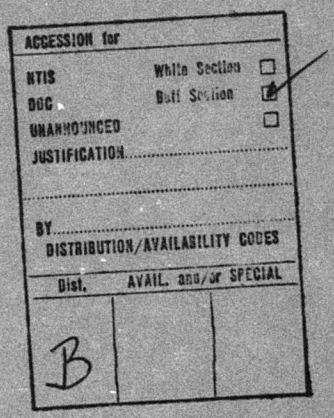

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REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: AFAL-TR-75-117	2. GOVT ACCESSION NO. -
	3. RECIPIENT'S CATALOG NUMBER: -
4. TITLE (and Subtitle): Matrix Cathode Development.	5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report. Period: 2/15/74 to 6/15/75
	6. PERFORMING ORG. REPORT NUMBER: EP-8528
7. AUTHOR(s): Günter Dohler; Frederick Scafuri	8. CONTRACT OR GRANT NUMBER(s): F33615-74-C-1087
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Warnecke Electron Tubes, Inc., 175 West Oakton Street, Des Plaines, Illinois 60018	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2,002 0216
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Air Force, Air Force Avionics Laboratory, Air Force Systems Command, Wright Patterson Air Force Base, Ohio 45433	11. REPORT DATE: January 1976
	12. NUMBER OF PAGES: 93
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*: DCASR Chicago, O'Hare International Airport, P. O. Box 66475, Chicago, Illinois 60666	15. SECURITY CLASS. *(of this report)*: Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

"Distribution limited to U.S. Government agencies only; test and evaluation; July 1975. Other requests for this document must be referred to Air Force Avionics Laboratory, AFAL/DHM, Wright-Patterson Air Force Base, Ohio 45433."

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

AF-0216

18. SUPPLEMENTARY NOTES

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

Thermionic Emitters
Matrix Cathodes
Oxide Cathodes

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

This report describes the results of an investigation on the Medicus Matrix Cathode material. This study, sponsored by the U.S. Air Force under contract No. F33615-74-C-1087, was conducted simultaneously by three laboratories.

– Air Force Avionics Laboratories, under the direction of G. Medicus.

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– Warnecke Electron Tubes, Inc.

– Spectra-Mat Inc., as subcontractor to Warnecke, under the direction of G. Thornber.

In order to correlate the efforts made by the three laboratories, three meetings between the respective responsible personnel were held during this phase of the program.

The results obtained show the potential of the new cathode, since high current levels at relatively low operating temperature have been observed under cw and pulse operation. The current decay during pulse operation is less pronounced than in oxide cathodes, the emission homogeneity is excellent when compared to tungsten impregnated cathodes, and the inherent high ductility of the cathode material leads to inexpensive production fabrication of cathodes, especially of those requiring highly complex geometry and tight tolerances.

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SECTION I

INTRODUCTION

1.1 Requirements

A large number of cathodes have been studied and are used in several different electron devices. The requirements for the cathode depend on their application and certain characteristics of a cathode can be important in one device and negligible in others.

The main characteristics of a cathode are:

a. Current density in cw and under pulsed (decay) conditions

b. Operating temperature (heat factor or emission efficiency)

c. Homogeneity

d. Sparking current

e. Poisoning

f. Evaporation

g. Operational Life

h. Shelf Life

i. Price

– Homogeneity of emission is an important characteristic for the CFA; for it is well known that an inhomogeneous emission leads to instability of a crossed-field beam. In TWT's, an inhomogeneous emission leads to difficulties in the focalization essential for PPM focussing and can lead to increased noise in low noise tubes.

– The sparking current is the upper limit of current density in cw and pulsed operation, and the decay of the current is increased if the operating current approaches the sparking current. The sparking current is a function of pulse width and duty cycle.

– Cathodes with low work functions are generally more sensitive to poisoning. Poisoning may occur during operation and during heater turn-off. Contamination during non-operating needs a reactivation during operation[1]. For some applications, this cannot be tolerated, e.g., for expendable power sources, where the operational life is between 1-30 minutes.

– High evaporation rates lead to contamination of the isolators and limits the life. It is unknown whether the evaporation rate is a function of the current drawn from the cathode. The required life of cathodes can be less than several hours for expendables, to several thousand hours for ECM tubes, to several

hundred-thousand hours for space communication systems.

In many modern systems, the cathodes have to be immediately operational after shelf-life of several years with no excessive outgassing and poisoning. Outgassing of the cathode during turn-on and poisoning depend largely on the environment and processing of the tube. However, extended processing and activation requires time, and cathodes withstanding poisoning and low getter action at low temperatures are preferable in many applications.

1.2 Nickel Matrix Cathodes

Nickel matrix cathodes are fabricated by post impregnating methods, where a metal powder is potted on a nickel base, or are fabricated by preimpregnating methods where a mixture of Ni and Carbonates are potted on the nickel base. Table I shows the different cathodes and their main fabrication characteristics.

Table I. Nickel-Matrix Cathode

TYPE	AUTHOR	MANUFACTURING	CHARACTERISTIC TREATMENT
MESH CATHODE	BELL TELEPHONE CO.[2]	POST-IMPREGNATED	CARBONATES SOAKED IN IN NI-MESH NI-BASE
MUSH CATHODE	BELL TELEPHONE CO.[3]	POST-IMPREGNATED	ACTIVATOR, SINTERING IN H_2 (600°) AND NITROGEN (1000°)
BN - CATHODE (BARIATED-NICKEL)	BECK[4]	PRE-IMPREGNATED	ACTIVATOR Zr H_2 OR ACTIVE Ni
FRITTED CATHODE	FREYTAG[5]	POST-IMPREGNATED	THIN LAYER OF CARBONATE ON THE EMITTING SURFACE ACTIVE Ni
FRITTED CATHODE	RYBAS ET Al.[8]	PRE-IMPREGNATED	Zr - Ni POWDER BETWEEN Ni-BASE AND THE EMITTING LAYER.
NICKELATE CATHODE	EDWAROS AND SMITH[6]	PRE-IMPREGNATED	FORMATION OF Ba NiO_2 AT 1250°C
MEDICUS CATHODE	MEDICUS[7]	PRE-IMPREGNATED	ROLLING AND ANNEALING
COATED POWDER CATHODE	MAURER AND PLEASS[9]		DEPOSITION OF Ni ON CARBONATE GRAINS

The main advantages of the matrix cathodes relative to the oxide cathodes are higher emission densities at a slightly higher operational temperature, and higher resistance to poisoning and to sparking. Furthermore, they are generally less expensive then the tungsten impregnated cathodes.

1.3 Medicus Cathode

The Medicus cathode is characterized by a rolling and annealing cycle. Preimpregnated Ni and alkali earth carbonates are sintered on a nickel base and rolled to about half the thickness in several steps. Between each step, the cathode substrate is annealed. The result is a very ductile material which can be plastically formed to the desired shape cathode.

Preliminary measurements made with the original Medicus cathode material showed the cathode material to exhibit a very homogeneous emission pattern and to emit a current density of 10 Amps/cm^2 under pulse condition.

In this report, the results of a study on the Medicus cathode made at Warnecke Electron Tubes, Inc., are described. The work was done in collaboration with Dr. G. Medicus of the Avionics Laboratory, Dayton, Ohio, and with Mr. W. Thornber of Spectra-Mat. Only a few measurements related to the physics of the cathode are described. Microprobe and Auger spectroscopy studies of the cathode surface as well as measurements of the work function homogeneity across the surface could not be made at Warnecke because of the equipment limitations.

SECTION II

FABRICATION OF THE MEDICUS MATRIX CATHODE

2.1 Proposed Fabrication Processes and Techniques

In order to correlate efficiently the studies to be pursued simultaneously at the Air Force Avionics Laboratories (Wright-Patterson Air Force Base), at Spectra-Mat, Inc., and at Warnecke Electron Tubes, Inc., a meeting was held at the beginning of this program to define and to propose fabrication processes and techniques required for the fabrication of the Medicus Matrix cathode material. The meeting was attended by Dr. L. Yarrington (Air Force Project Engineer of the program), by Dr. G. Haas from the Naval Research Laboratories, by Mr. M. Zinn, U.S. Army Electronics Command, Fort Monmouth, and by the representatives of the three responsible Laboratories. The following decisions were made and the following starting processes and techniques were defined during this meeting.

2.1.1 Materials and Material Preparation.

The cathode substrate material is to be fabricated from a passive nickel which Warnecke will purchase and distribute to Spectra-Mat and to the Avionics Laboratories in form of 5 cm x 5 cm x .8 mm Nickel 270 sheets. If, during the program period, a material of smaller thickness should be required, the primary sheets of .8 mm thickness could be rolled down to the desired thickness. Also, Warnecke was requested to stock .4 mm passive Nickel 270 sheets on a supplementary basis.

The nickel substrate will be cleaned and roughened to insure adherence of the NiO and the earth alkaline carbonate powders which are to be applied at a later point. Dr. G. Medicus recommends that the nickel be prepared by removing a superficial layer from the surface by an abrasion technique which is to scrape the metal with an aluminum pot shard until the surface has lost its gloss, but still looks metallic. Warnecke proposed to roughen and clean the nickel with an alumina vapor blaster, operated at around 30 psi, to wash the surface with water and to degrease the substrate in an ultrasonic trichlorethylene vapor degreasor. Warnecke will then fire the nickel at 950° for 10 mn in a wet hydrogen atmosphere. This method will anneal the nickel and remove any residual organic contaminates.

If further surface roughness is found to be necessary, high purity nickel powder could be sparsely sieved onto the surface and sintered onto the Ni-substrate at 1000°C for 15 minutes in dry hydrogen. Warnecke will provide 325 mesh, 99.995% pure nickel powder to Spectra-Mat and Dr. G. Medicus (Avionics Laboratories). The remaining materials to be used are: NiO powder, $BaCO_3$, and a triple mixture of Ba/Sr/Ca carbonates in weight proportion of 57/39/4.

The NiO powder will be mixed, either with the $BaCO_3$ or the triple carbonate powders in a weight ratio of 3 to 1. Both the $BaCO_3$ and the tricarbonate cathodes will be studied in parallel.

The complete NiO and carbonate powder mixture will be ball-milled for 48 hours by using porcelain balls and a porcelain container. Enough distilled water should be added to allow the mixture to run down the vertical wall of the container.

After ball-milling, the NiO carbonate mixture is air dried at 80°C. The resulting cake will be ball-milled until the particle size is smaller than 177 μm (U.S. Sieve Series No. 80).

2.1.2 Cathode Material Fabrication.

The NiO carbonate mixture obtained previously is sieved onto the prepared nickel substrate until a loose 5 mm thick layer is obtained. The powder layer is then covered with a clean household aluminum foil (shiny side in contact with the powder) and pressed by hand at a pressure of 5 to 10 psi, using a household rolling pin. The powder is then sintered in a dry hydrogen, sulfur-free atmosphere at 950°C ±20°C for 20 minutes in a cycle shown in Figure 1. It was clear to all participants of the meeting that further experimentation with the sintering cycle will be required, especially concerning the temperature profile (time and temperature).

Immediately after sintering, the cathode material will be rolled to 50% of its initial thickness, and then annealed in a dry hydrogen, SO_2 free atmosphere, with a thermal cycle as shown in Figure 2.

Immediately after annealing, the cathode material will be rolled again to 50% of its thickness in a direction perpendicular to the direction of the first rolling. The cathode material is then annealed once again, using the same thermal cycle, see Figure 2.

2.1.3 Emission Test Vehicle.

From the meeting, it evolved that each Laboratory measuring the emission characteristics of the cathode material, will design and fabricate its own test vehicle and will use its own cathode configuration to best fit the needs and capabilities of that Laboratory. However, it was agreed that each diode test vehicle will incorporate a water cooled OFHC copper anode, fired in a wet hydrogen atmosphere for at least 15 mn. The diode test vehicle will incorporate a movable shutter to protect the anode from contamination during the cathode activation cycle. Furthermore, the cathode temperature will be monitored with a thermocouple, preferably a W-WRh. The thermocouple shall be placed near to but not on the cathode surface. If glass cannot be avoided, then the glass must be heated extensively prior to operation to prevent the evaporation of contaminants during operation. Any pinch-off used to seal the vacuum should be metallic (no glass tip-offs). Some suggested cathode configurations are shown in Figures 3 and 4.

2.1.4 Cathode Activation.

Before the insertion of the cathode into the test vehicle, the cathode surface shall be cleaned. Dr. Medicus suggested to brush the surface of the cathode with a fine glass fiber brush until the surface is shiny. G. Medicus would supply Spectra-Mat and Warnecke with the required fiber glass brushes.

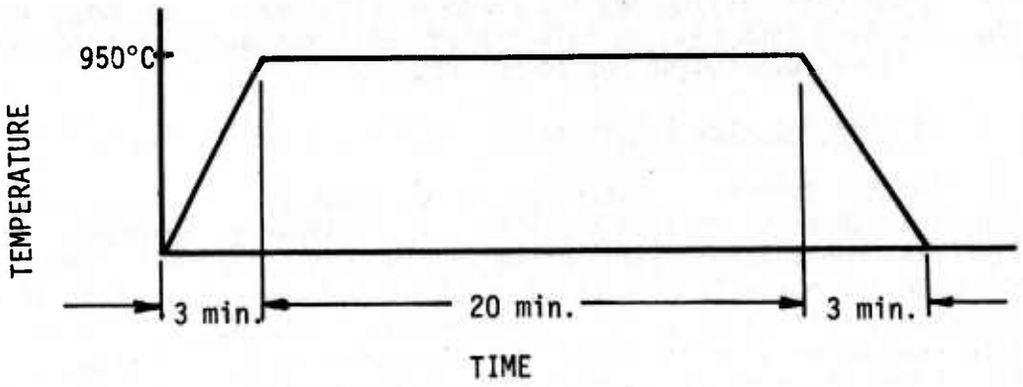

Figure 1. Proposed Sintering Cycle of the NiO/Carbonate Mixture on the Nickel Substrate in Dry H_2, SO_2 Free Atmosphere. The Temperature Tolerance is ±20°C.

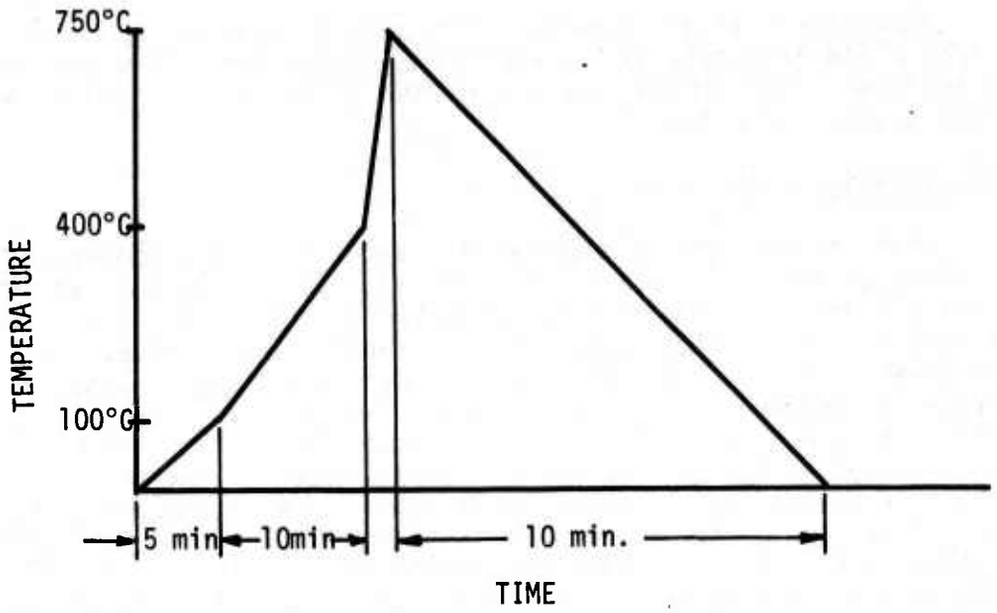

Figure 2. Proposed Cathode Annealing Cycle in Dry H_2, SO_2 Free Atmosphere. The Temperature Tolerance is ±20°C. The Rise of Temperature from 400°C to 750°C is as Fast as the Furnace will Permit. The Temperature Drop from 750°C is governed by the Furnace Cool Down Rate.

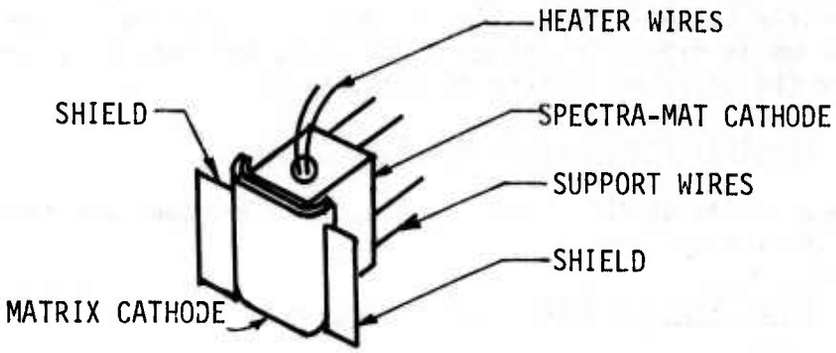

Figure 3. Cathode Configuration as Proposed by Warnecke. The Matrix Cathode is Bent Around a Spectra-Mat Cathode and Spotwelded to the Sides. A shield is Attached to Mask Off the Plane Emitting Surface.

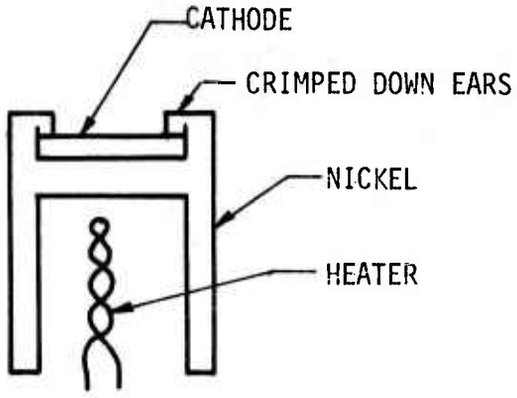

Figure 4. The Cylindrical Cathode as Proposed by G. Haas. It is a 1/8" Nickel Cylinder with a Blind Hole Machined in One End and A Heater Inserted. The Cathode is Fixed to the Blind End by Crimping Down Ears.

The tentative activation cycle was determined, as given in Figures 5 and 6. First, the test vehicle is to be baked out, as shown in Figure 5. After bake-out, during the cooling cycle, the cathode heater is turned on when the test vehicle reaches 250°C. The cathode will then be heated following the procedure shown in Figure 6. After a hot shot, the cathode is cooled down to 950°C, where the emission current is switched on.

2.2 Actual Fabrication Processes and Techniques

The description of the actual fabrication processes and techniques is being made in the following.

2.2.1 Materials and Material Preparation.

Table II shows the kind and the purity of the materials, which have been used for the fabrication of the Medicus cathode material. Note that these materials have been purchased and distributed to the two other Laboratories by Warnecke Electron Tubes, Inc. At a later point of the program, however, "Mischcrystals" have been purchased and used by Warnecke.

Table II. Material and Chemical Composition used on for Cathode Construction.

Material	Company	Purity	
NiO	Fischer	99.9%	
$BaCO_3$	Fischer	99.8%	
$CaCO_3$	Fischer	99.8%	
$SrCO_3$	Matheson	99.7%	
Ni Powder (325 Mesh, 44μ)	ESP	99.995%	
Nickel 270		99.98%	
Tricarbonate (Mischcrystals)	Sylvania	Chloride	10^{-5}
		Heavy Metals	10^{-5}
57.2% $BaCO_3$		Iron	10^{-5}
38.8% $SrCO_3$		Nitrate	9×10^{-3}
4% $CaCO_3$		Sodium	4×10^{-3}
		Sulfate	3×10^{-5}
		Water Solubles	6×10^{-4}
		Insolubles	10^{-4}

The Nickel 270, when received has a hardness: 70 R_b
when annealed in dry H_2 at 950° for 10 min: 43 R_b
when rolled from 5.3x5.3x.08 cm to 11.1x5.3x0.38 cm: 84 R_b
when annealed in dry H_2 at 950° for 10 min: 14 R_b

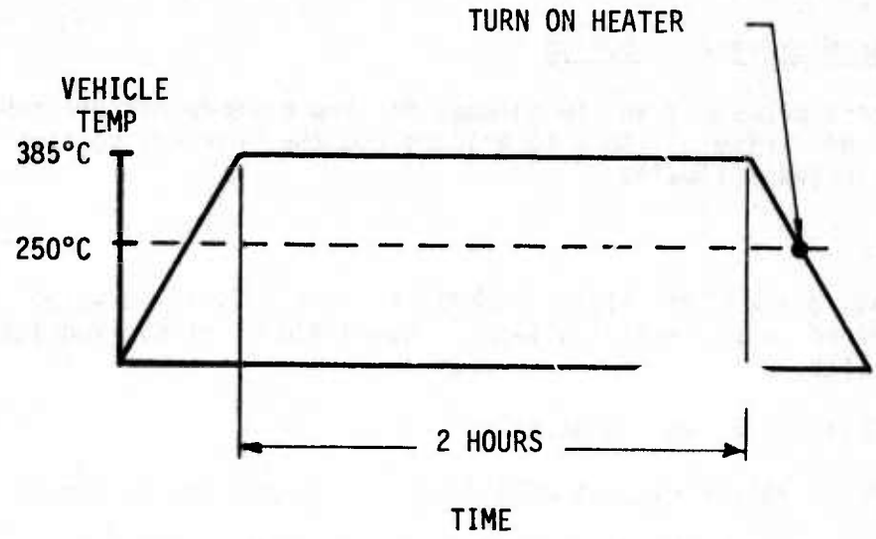

Figure 5. Bake-Out Temperature Cycle of the Test Vehicle. Initial Heating and Cooling Slopes are Consistent with Good Vacuum Practices. at 250°C The Cathode Heater is Turned On.

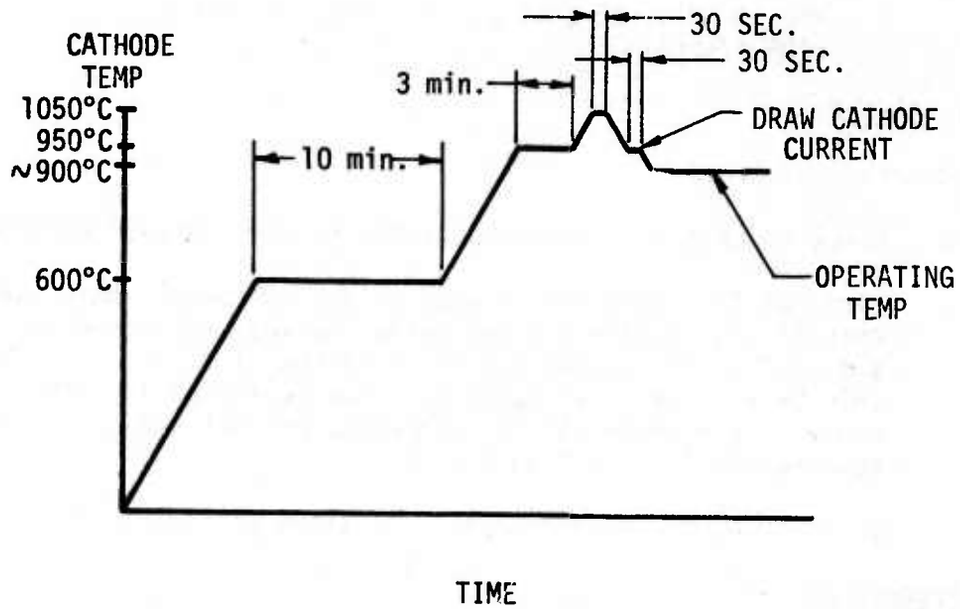

Figure 6. Cathode Temperature Cycle. The Heating Rates to 600°C and 950°C are Chosen such that the Vacuum System does not get Overloaded. Cathode Current is Drawn at 950°C on Cool Down Side of Heating Curve. The Cathode is then Lowered to an Operating Temperature to be Determined.

2.2.2 Cathode Mixture Preparation.

Different processes and techniques for the cathode mixture fabrication have been used. Five of those techniques and the relevant conclusions will be discussed in the following.

Process 1:

a. 453.3 ±.2 g NiO +151 ±.2 g $BaCO_3$ + 750 ml distilled water mixed in procelain ball-jar. Added 300 ml of cyclindrical balls.

b. Ball milled for 24 hours.

c. Dried in air oven at 80°C in ball mill jar for 24 hours.

d. Ball-milled dried powder for 24 hours. Material powder in ball-mill jar.

e. Heated in vacuum oven for 18 hours at 25°C and ball-milled again—still having packing after 18 hours on ball-mill.

f. Removed 1/2 the number of balls and ball-milled again for 18 hours.

g. Removed contents from jar and forced through the following sieve series:

#10 (2 mm), #20 (841 μ), #40 (420 μ), #80 (174 μ), #200 (74 μ).

Process 2:

a-d. Same as Process 1.

e. Break up cake by mortar and pestle to pass through #80 sieve.

f. Fired at 550-600°C for 30 min. in dry hydrogen. Note that this firing temperature was varied between 550°C and 950°C, and then fired between the above values of 550°C and 600°C. This temperature was chosen in order to reduce the NiO. However, the earth alkali carbonates are not reduced at this temperature (see Section 2.2.3).

Break-up by mortar and pestle and sieve with #200 sieve.

Process 3:

a. 453.3 ±.2 gr NiO + 151.1 gr of mixture of $BaCO_3$ (57.2%), $SrCO_3$ (38.8%), and $CaCO_3$ (4%), and add 750 ml of distilled water (mix in porcelain ball jar).

b. Continue all steps as in Process 2. (Steps b-g)

Two other alterations should be mentioned here, namely ball mill without water, and the use of "Mischcrystals".*

Process 1 corresponds to the fabrication processes and techniques as defined during the meeting discussed above (see Section 2.1). The results obtained by using Process 1 are relatively poor, namely:

a. Poor adherence of the emission material to the nickel substrate.

b. Large cracks found on the surface of the emission material.

c. Poor emission density.

d. Relatively poor emission homogeneity.

It was found that the reason for obtaining these results could be traced back to the shrinkage of the material during sintering. Therefore, tests were conducted to control the shrinkage during sintering.

2.2.3 Shrinkage.

In order to determine the shrinkage characteristics of the cathode material during sintering, each component material was fired independently from the other components. The weight loss versus the firing temperature in dry hydrogen for 30 minutes was recorded for the different materials and for the fabrication of the Medicus Matrix Cathode. The results have been plotted in Figure 7. At high firing temperatures, the weight reduction observed on the earth alkali-carbonates corresponds to the transformation of these carbonates into oxides. From Figure 7, it follows that the transformation of:

- NiO into Ni is achieved in 30 mn at $T < 600°C$
- $CaCO_3$ into CaO is achieved in 30 mn at $T \approx 700°C$
- $SrCO_3$ into SrO is achieved in 30 mn at $T \approx 900°C$
- $BaCO_3$ into BaO is achieved in 3 hours at $T \simeq 900°C$

From these results, it follows that the preparation of the powder after ball milling requires a drying temperature of about 500°C in order to reduce the NiO but not the carbonates. The sintering process, however, requires a higher temperature, and it should be kept in mind here that a sintering temperature above 700°C will transform the carbonates into oxides. If the carbonates are transformed into oxides, the weight will change in air due to the hygroscopy of the earth alkali oxides. However, heating the hydroxides above 100°C will result in the evaporation of water. Since $Ca(OH)_2$ is transformed in calcium oxide at or above 600°C, the formation of hydroxides does not seem critical to the fabrication process. Note that, for Mischcrystals* of earth alkali-carbonates the transformation into oxides occurs after 30 mn at 900°C.

* Mischcrystals are obtained by a common precipitation of all three earth alkali components in the derived mixture.

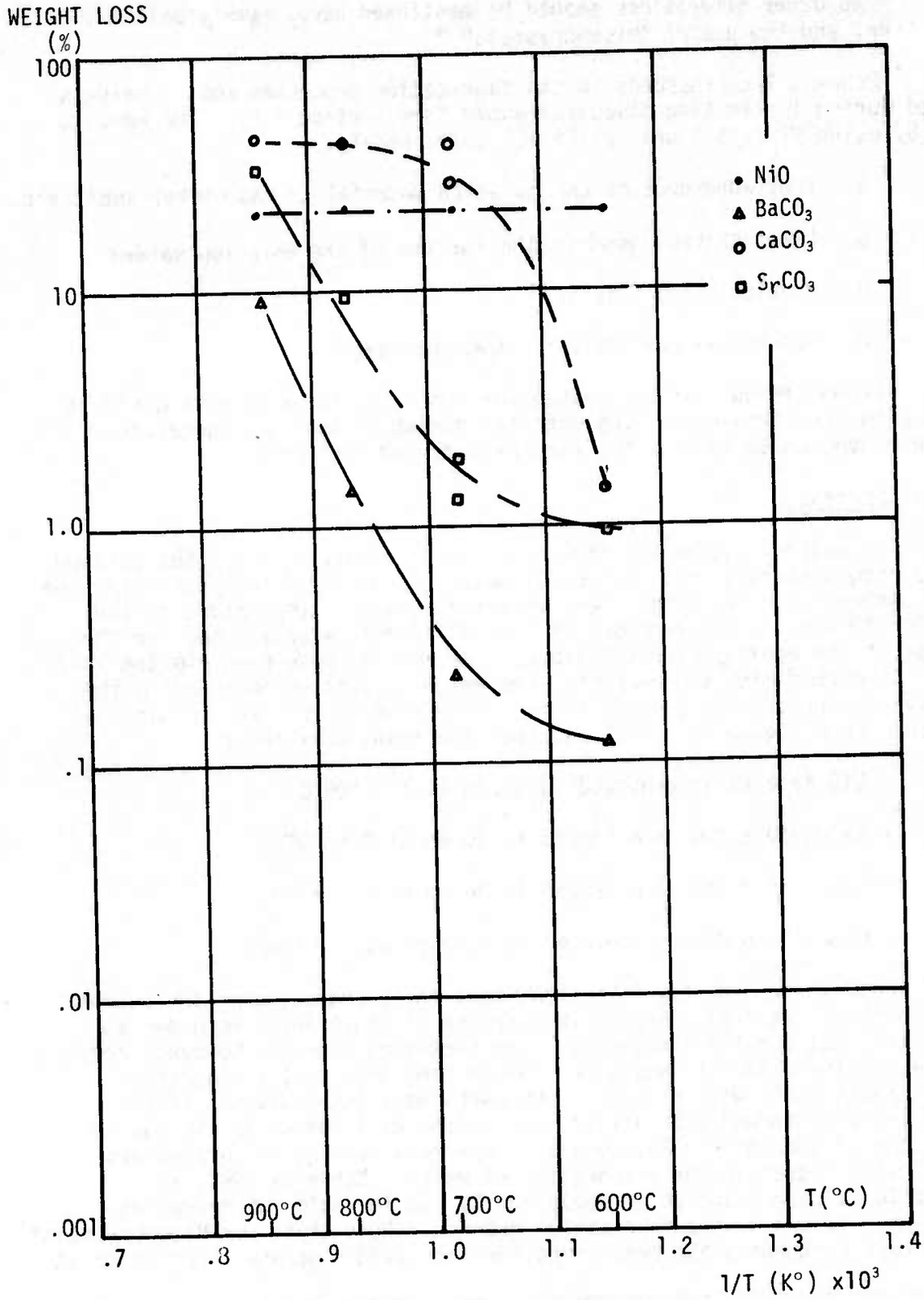

Figure 7. Weight Loss of Cathode Mixture Materials During a 30 mn Firing as a Function of Firing Temperature Cycle.

2.2.4 Preparation of Ni-Substrate (Base Material).

Passive Ni 270 is used as base material (substrate). The Ni-base material is rolled to the proper thickness. Before the process of sintering the cathode material onto the Ni-substrate, the base material (substrate) is subject to a cleaning process.

The following processes and techniques are used for the preparation of the base material (substrate).

a. If necessary, the Ni-substrate is rolled to the desired thickness.

b. The rolled Ni-substrate is thoroughly cleaned by degreasing ultrasonicly in trichlorethylene.

c. The Ni-substrate is annealed at 950° for 10 mn in dry hydrogen.

d. 325 mesh nickel powder (44 μm) of about 1 layer of thickness is sintered onto the substrate at 950°C for 30 mn in dry hydrogen.

2.2.5 Sintering of the Cathode Material.

The following processes and techniques are used for sintering the cathode material onto the cleaned and prepared Ni-substrate.

a. The black cathode material powder is sieved onto the Ni-substrate with a sieve-mesh #150 until a layer of about 5 mm is obtained.

b. The material is compressed with a rolling pin to a thickness of about 200-250 μ (No aluminum used).

c. The material is sintered onto the substrate in dry hydrogen. The sintering temperature was varied between 550°C and 1000°C. To avoid the transformation of carbonates into oxides, the sintering temperature is proposed to be kept below 650-700°C. At the end of this study program, the sintering temperature was kept between 550°C and 650°C for a sintering time of 30 mn. As shown in Figure 7, the carbonates are practically not transformed during this sintering cycle. (The minimum Ni-annealing temperature is 650°C.)

2.2.6 Rolling and Annealing.

Rolling and annealing are two of the intrinsic characteristics of the Medicus Matrix Cathode. Different cycles of rolling and/or annealing have been studied during the period of this program. Rolling to a thickness reduction of about 50% can be achieved either in one single rolling step or in several incremental rolling steps. A too fast thickness reduction per rolling step has been found to lead to cracks of the cathode material layer. If too

many rolling steps are used, the time of the fabrication increases and age hardening occurs (see Section 2.3.3). The best compromise has been found to use a five step rolling cycle, reducing the thickness of the cathode during each step by an amount varying from 24 μm to 100 μm maximum. The total variation of thickness after the five steps is to be about 50%.

The annealing cycle, which follows immediately after the rolling cycle, has also been varied during this program. The annealing cycle and the annealing temperature are being discussed in the next section. For the fabrication of the cathode, 2 or 3 rolling-annealing cycles have been found to be a best compromise. However, Spectra-Mat uses a different cycle, which is described in the attached final report by Wynn and Thornber.

2.2.7 The Annealing Temperature.

It has been found that the annealing temperature is a very important and critical parameter for the fabrication and the quality of the cathode.

Vacuum firings, wet and dry hydrogen firings have been investigated with the result that vacuum and wet hydrogen firings unvariably lead to cathodes with very homogeneous surfaces, nearly without cracks, but with poor electronic emission characteristics.

For mesh cathodes, McNair[3] used the following cycle:

- From room temperature to 600°C: dry hydrogen.
- From 600°C to 1000°C to 600°C: nitrogen.
- From 600°C to room temperature: dry hydrogen.

Warnecke has used this cycle, with the result that "Cauliflowers" and cracks were developed on the cathode surface, as shown in Figure 8 (McNair did not observe these effects). Furthermore, "puff-balls" and "asparagus" could be observed, on both $BaCO_3$ and tricarbonate cathode types.

Figure 9 shows a typical tricarbonate cathode after a 10 mn vacuum firing cycle at 850°C. It is known[10] that $BaCO_3$ forms a compound $BaO—BaCO_3$ during its transformation from a carbonate to an oxide. This compound melts at around 800°C when rapidly heated.* This phenomenom has lead the cathode industry to use mischcrystals instead of pure $BaCO_3$ for the fabrication of cathodes. Since neither "cauliflowers" nor "puff-balls" are observed when Mischcrystals are used, Warnecke replaced the powder mixture of earth-alkali-carbonates with mischcrystals. The result is shown in Figure 10, which shows a mischcrystal cathode fired at 1000°C in dry hydrogen for 2 hours.

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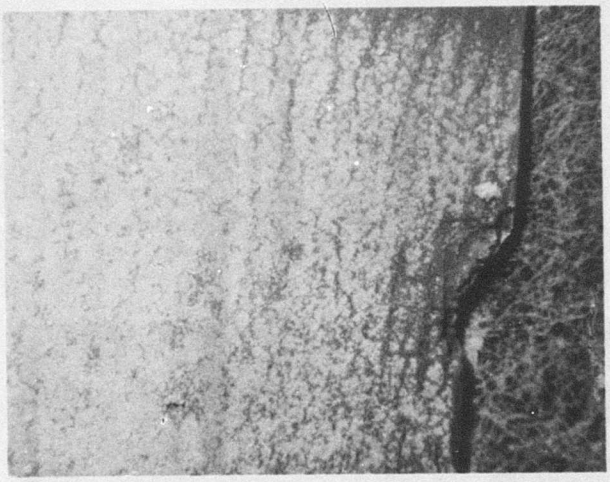
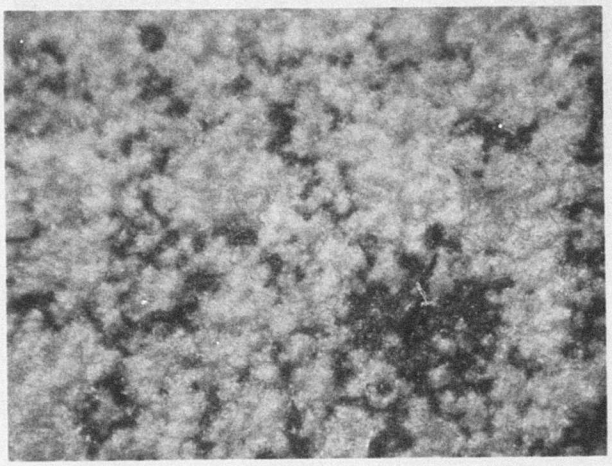
*G. Medicus describes the melting of $BaCO_3$ powder which "later solidifies quickly under violent boiling and bubbling" to a whitish dust (Report on in-house work, from March 1974, Avionics Laboratories).



10X Magnification



70X Magnification

Figure 8. Pictorial Results of Special Firing Schedules on W-6.

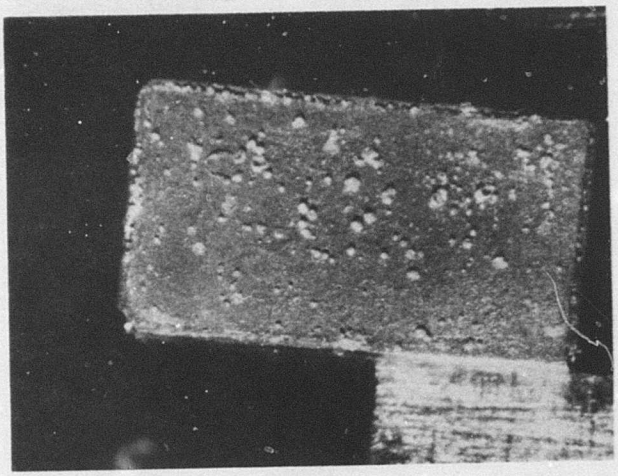
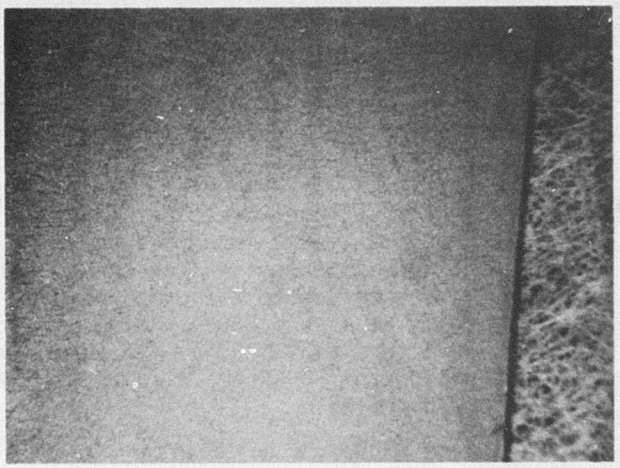
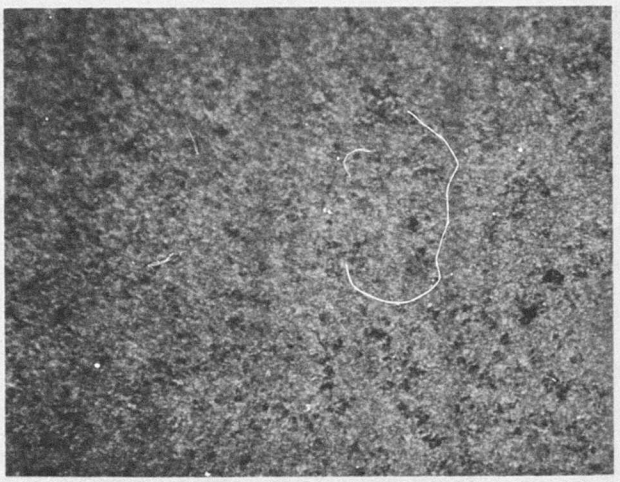


Figure 9. Tricarbonate Cathode Vacuum Fired at 850°C. 10X Magnification



10X Magnification



70X Magnification

Figure 10. W-11 Cathode After 1000°C Firing.

As shown in Figure 7, $CaCO_3$ is totally transformed into CaO if an annealing temperature just below 700°C is used. At the same temperature, $SrCO_3$ and $BaCO_3$ are practically untransformed. This corresponds also to the following observations made:

- All (non-mischcrystal) cathodes exhibiting homogeneous surfaces with no "cauliflowers","puff-balls", or equivalent inhomogeneities, were annealed at temperatures below 700°C.

- Non-mischcrystal cathodes annealed at higher temperatures exhibited the above mentioned imperfections. It is therefore believed that the imperfections described are not due to the hydroxides, but are due to the compound $BaO—BaCO_3$ which violently boils at around 800°C. Since the transformation of $BaCO_3$ to BaO occurs above 750°C, the annealing temperature proposed and adopted by Warnecke is between 600°C and 700°C for 30 mn in dry hydrogen.

2.2.8 Conclusion.

Table III summaries the different variations in processes and techniques investigated during the period covering this program. The same table also shows the recommended processes and techniques for the fabrication of the Medicus Matrix Cathode. The recommended processes sometimes are considerably different from those used by Spectra-Mat and described in their final report (attached). The main differences between Spectra-Mat's and Warnecke's recommendations are shown in Table IV.

Figure 11 shows the surface of a Spectra-Mat cathode as delivered by Spectra-Mat to Warnecke, and Figure 12 shows the surface of a cathode fabricated by Warnecke using the aforementioned processes. Figure 13B shows the surface of a Spectra-Mat cathode after a few hours of heating at 900°C in vacuum. Figure 13A shows the surface of cathode fabricated at Warnecke after having operated at 1100°C for 50 hours.

2.3 Mechanical Properties of the Medicus Cathode

2.3.1 Cross-Sections.

Microphotographs have been taken to determine the homogeneity of the cathode. Figure 14 shows the $BaCO_3$ cathode W-3 and the tricarbonate cathode W-4 (in a 3:1 mixture with NiO). Both cathodes were fired in dry hydrogen at 900°C. In cathode W-3, $BaO—BaCO_3$ compounds and large crystals were formed which could not be broken by ball milling process. Therefore, after passing through a #145 sieve, the ratio of NiO and $BaCO_3$ was higher than 3:1. A relatively low amount of BaO is in cathode W-3. The emission of this cathode was poor. In the W-4 cathode of Figure 14, more emissive material passed through the sieve, the density of the earth-alkali-oxide is larger and relatively homogeneous. A current density of more than 6 Amps/cm^2 under pulse conditions (pulse length ~100 μsec, duty ~.5%—3%) at 960°C was obtained with this cathode.

Table III. Investigated and Recommended Fabrication Processes and Techniques (Warnecke)

	VARIATIONS	RECOMMENDED PROCESS
Carbonates Mixture	$BaCO_3$ $BaCO_3$ - $SrCO_3$ - $CaCO_3$ 57.2% - 38.8% - 4% 62.4% - 34% - 3.6% 66.5% - 29.4% - 4.1% Mischcrystals 57.2% - 38.8% - 4%	Mischcrystals 57.2% - 38.8% - 4%
Nickel Thickness	Nickel 270 (passive) .25 mm - .125 mm	Nickel 270 .19 mm
Mixture - NiO - Carbonates	3:1 2.7:1 1.8:1	2.7:1
Mixture Heat Treatment	400-900°C Dry Hydrogen	450 - 550° Dry Hydrogen
Sintering Temperature	500-1000° Dry Hydrogen 550-650° Wet Hydrogen 550-650° Vacuum	600-750 Dry Hydrogen
Pressing before rolling 10^4 psi	No pressing Pressing	Pressing
Rolling and Annealing	(1 rolling - 1 annealing) 3 - 5 times (5 rollings - 1 annealing) 3 - 5 times	(5 rollings - 1 annealing) 2-3 times
Annealing Temperature	550-1000°C Dry Hydrogen Wet Hydrogen Vacuum	550-700 Dry Hydrogen
Thickness of the layer before sintering	.275 - .5 mm	Recommended .275 - .3 mm
Final thickness of Matrix Material		100 - 140 µm

Table IV. Difference Between Spectra-Mat's and Warnecke's Fabrication Techniques and Processes.

	SPECTRA-MAT	WARNECKE
Substrate Thickness	.75 mm	.19 mm
Firing Temperature of the Mixture	50°C	500-550°C
Sintering	800°C during 25 min. Room temperature 950°C during 30 min.	600-700°C (30 mn)
Rolling	1 Rolling to reduce to 50% of thickness	5 Rollingsto reduce to 50% of thickness
Annealing Temperature	As sintering	600-700°C

Figure 15 shows the cross section of a cathode before and after 70 hours of operation with a current density of 5 Amps/cm^2 in cw at 1025°C. The carbonates (black areas) are dense compared to the nickel powder. A good emission was obtained. Figure 16 shows the cross section of a cathode which had a current density of more than 20 Amps/cm^2 under pulse conditions at 880°C. The carbonates are homogeneous and the carbonate to nickel ratio is still high.

Figure 17 shows the cross-section of a cathode recently received from Spectra-Mat. The matrix (emissive) material is thinner than the emissive material of Warnecke cathodes and the thickness varies over the surface by about a factor of 2. Emission tests have not been made as of yet with this cathode.

Figure 18 shows a mischcrystal cathode. Large islands of nickel are visible. The emission was poor, (a few Amps/cm^2), and the cathode was difficult to activate.

There seems to be a good correlation between the microphotographs of the cross section and the emissivity of the cathode. Therefore, microphotographs may be used as a quality control of the cathode fabrication.

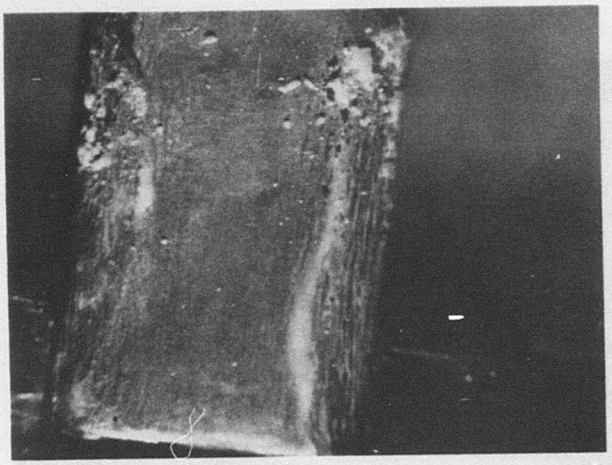


Figure 11. Spectra-Mat Cathode
10X Magnification

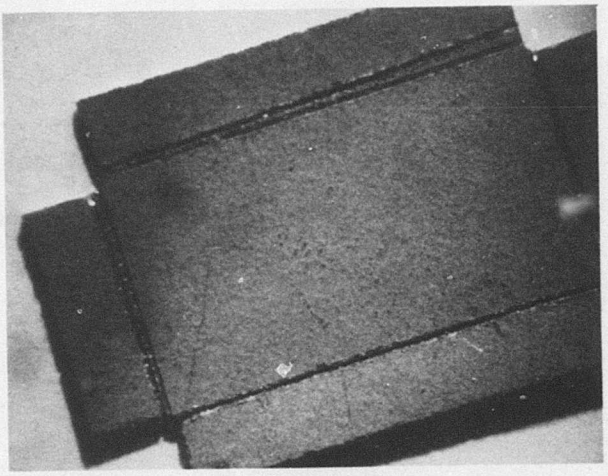
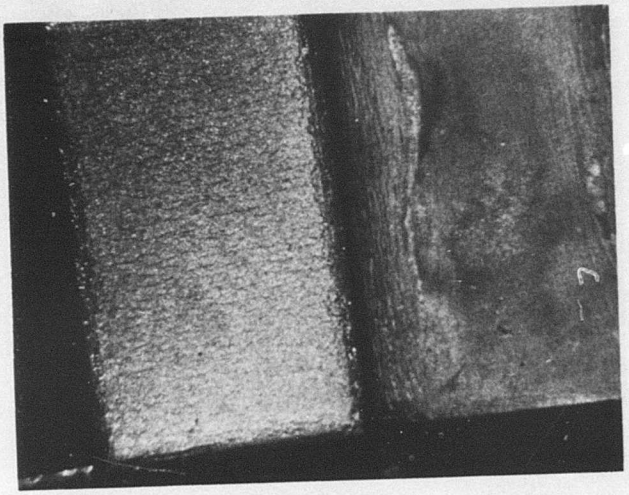


Figure 12. Warnecke Cathode Surface
10X Magnification

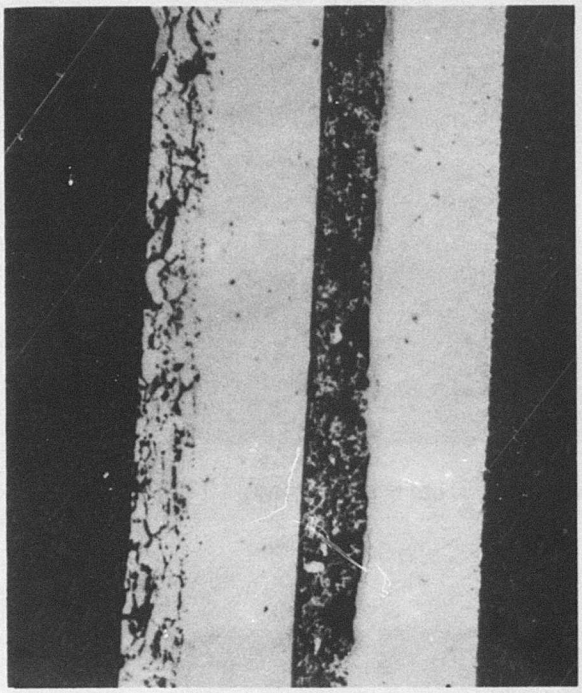


(A) (B)

Figure 13.

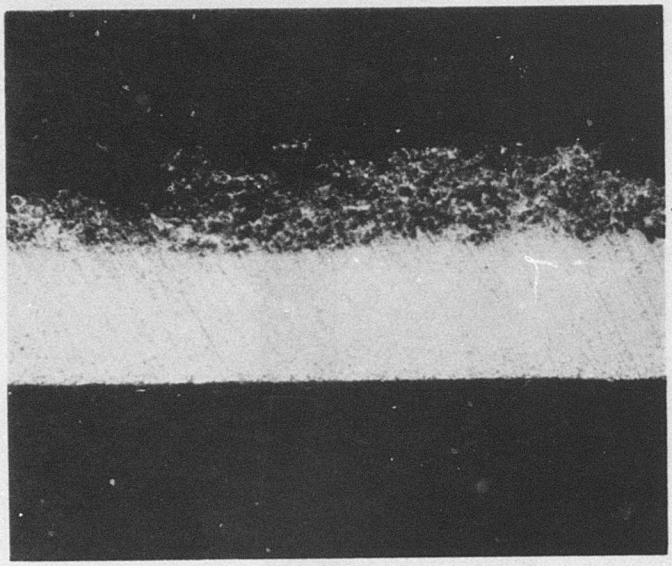
(A) Warnecke's W-11 Cathode Surface 10X Magnification.

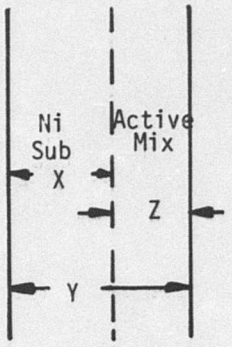
(B) Spectra-Mat's Cathode at 10X Magnification.



W-3 W-4

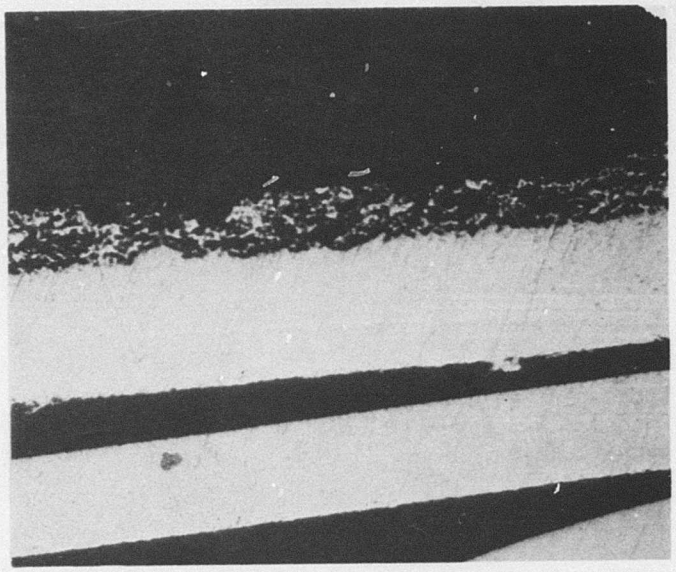
Figure 14. Cross-Section Area of Warnecke's Cathodes W-3 & W-4 at 120X Magnification.

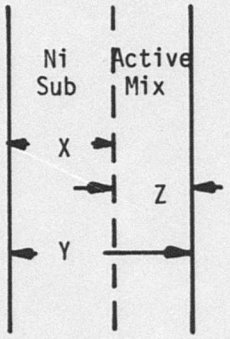




Y = 303μ
X = 171μ
Z = 132μ

Cross-Section of W-5 Before Testing. 120X





Y = 247μ
X = 169μ
Z = 78μ

Cross-Section of W-5 After CW Testing 120X

Figure 15. Cross-Section of W-5 Before and After Testing.

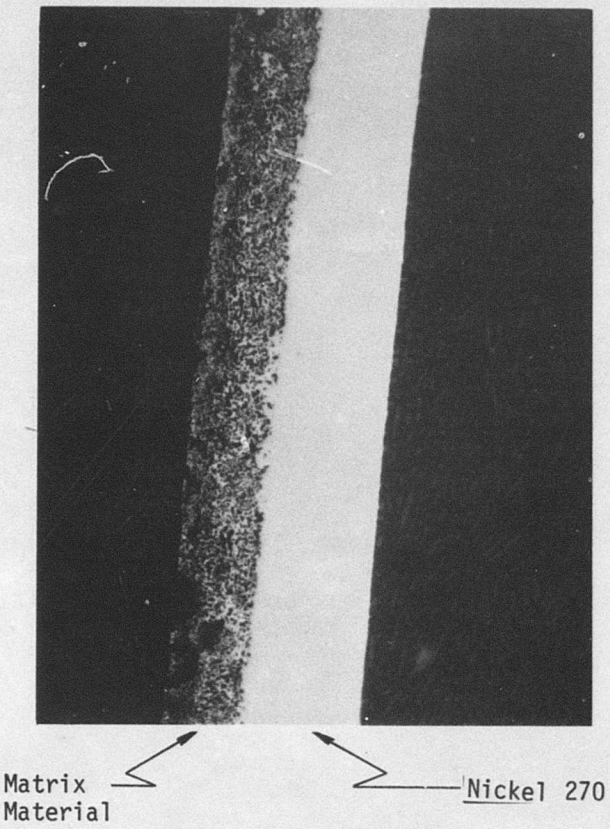


Figure 16. Cross-Section of Warnecke's W-8 at 120X Magnification.

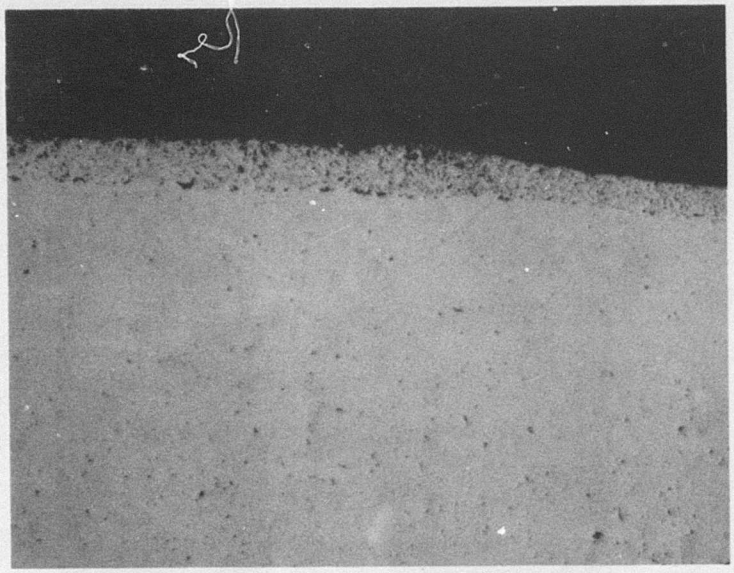


Figure 17. Cross-Section of Spectra-Mat Cathode at 120X Magnification.

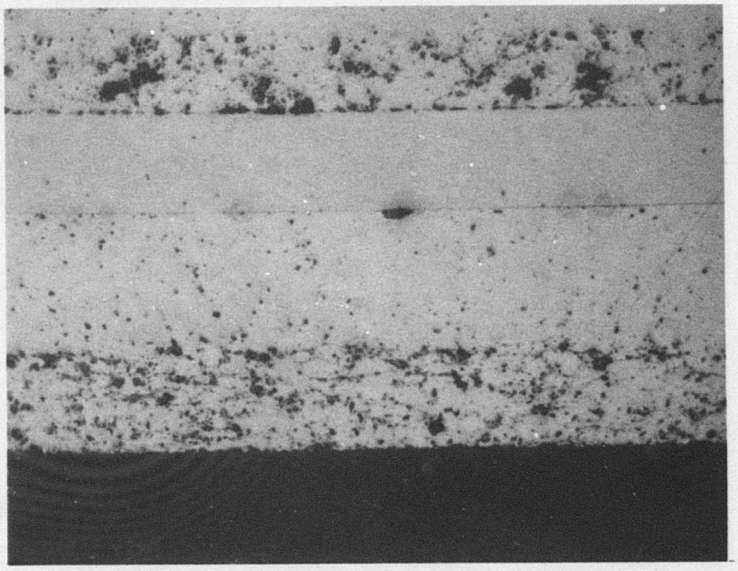


Figure 18. Mischcrystal Cathode Cross-Section at 120X Magnification.

2.3.2 Surface Finishing.

One of the advantageous characteristics of the Medicus cathode is its intrinsic flatness, which, for many tubes (microwave triodes, low noise tubes) is an important parameter. The finishing of the Medicus cathode was measured to be about .6-.9 μm before operation, and about 1 μ after operation.

Very flat oxide cathodes, specially developed for having high flatness (printed cathodes), have a finishing of about 2-3 μm.[11] Tungsten cathodes impregnated with Barium aluminate, have a better finishing than the Medicus cathodes (.4-.5 μm).

2.3.3 Hardness and Ductility.

Supposedly, the Medicus cathode material is a very ductile material and, as such, can be easily deformed plastically. Since the ductility of a given material is inversely proportional to its hardness, the hardness, e.g., the Rockwell number R_b, is a measurement of the ductility. On the other hand, more work has to be applied for thicker substrates. This is one of the reasons that the nickel substrates used were reduced to 200 μm or less in thickness.

The first cathodes fabricated both at Avionics Laboratories and at Warnecke were ductile, and bending of the cathode sheet did not produce cracks. However, the material did harden with storage time. A new annealing cycle reduced the hardness again without changing the electronic emissivity of the cathode material.

An investigation was started recently to study the age-hardening relationship, and preliminary tests were conducted with a Wilson surface hardness tester (1/16" diameter ball) and a Tukon microhardness tester made by Wilson. A rhombus shaped diamond, called Knoop indenter, is used to indent the surface of the material under test. The size of the indented "print" on the material is used as hardness measurement. The size is calibrated as a function of the applied weight to the indenter. The resolution obtained is excellent of the order of 30 μ.

Hardness measurements were performed over the cross section of the cathode, perpendicular to the Ni substrate and Matrix cathode material. Figure 19 shows the cross-section of the cathode W-11. The different rhombuses printed on the cathode are locations at which the hardness of the material was measured. As can be seen, the hardness is lower in the matrix cathode material than in the nickel base substrate (larger indentation). Figure 20 shows the hardness (in Rockwell numbers) as a function of the distance from the substrate surface.

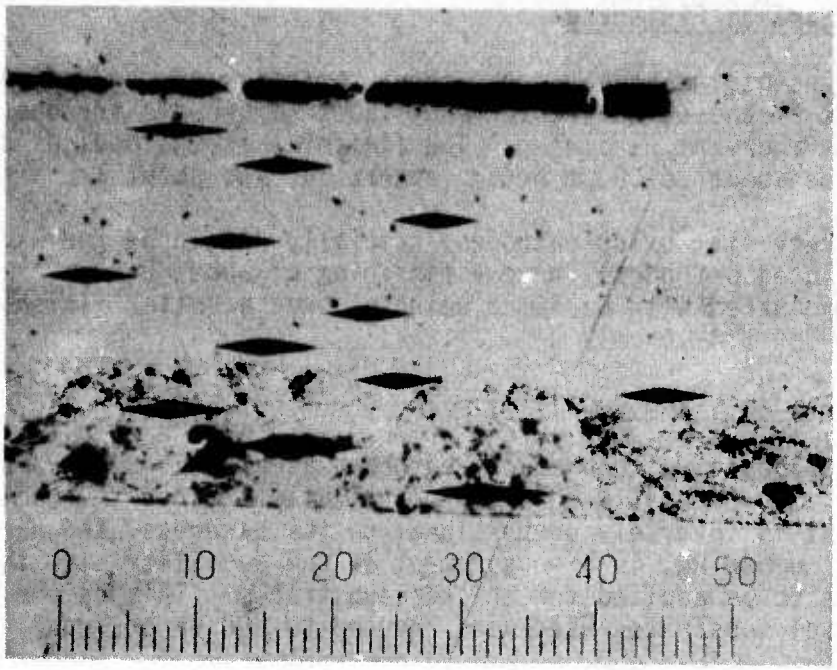


Figure 19. Cross-Section of Cathode W-11 with Knoop Indentations for Measuring Hardness (120X Magnification).

The hardness is constant and about R_b = 70 within the nickel substrate, and drops continuously to about R_b = 12 near the edge of the cathode material (matrix). Note that there is one measurement point made near to the interface between nickel substrate and matrix, indicating $R_b \approx 55$. It is not clear at this point, whether or not this is an error of measurement or whether or not there exists near to the interface (between nickel substrate and matrix) a maximum possibly due to a diffusion process during annealing and/or sintering. It should be noted here that the measured hardness varies over the large area of the cathode, probably due to the inhomogeneity of the matrix material (voids and inhomogeneous distribution of carbonates). Measurements made on the (flat) surface of the cathode material (matrix) have shown large variations in hardness, the Rockwell number varying from zero (void) to 70. Furthermore, for some cases as in Figure 19, the nickel substrate is clearly harder than the cathode (matrix) material, in other cases, the matrix material is harder than the nickel substrate. If the hardness of the matrix material is measured to be relatively high, the cathode is brittle, and it becomes nearly impossible to plastically deform the cathode.

For a given cathode, the hardness measurements of the nickel substrate is generally more consistent (and constant) than those performed on the matrix material. However, the hardness measurements made on many different cathodes also shows strong variations, which may or may not be due to different annealing and sintering cycles. Although the preliminary measurements

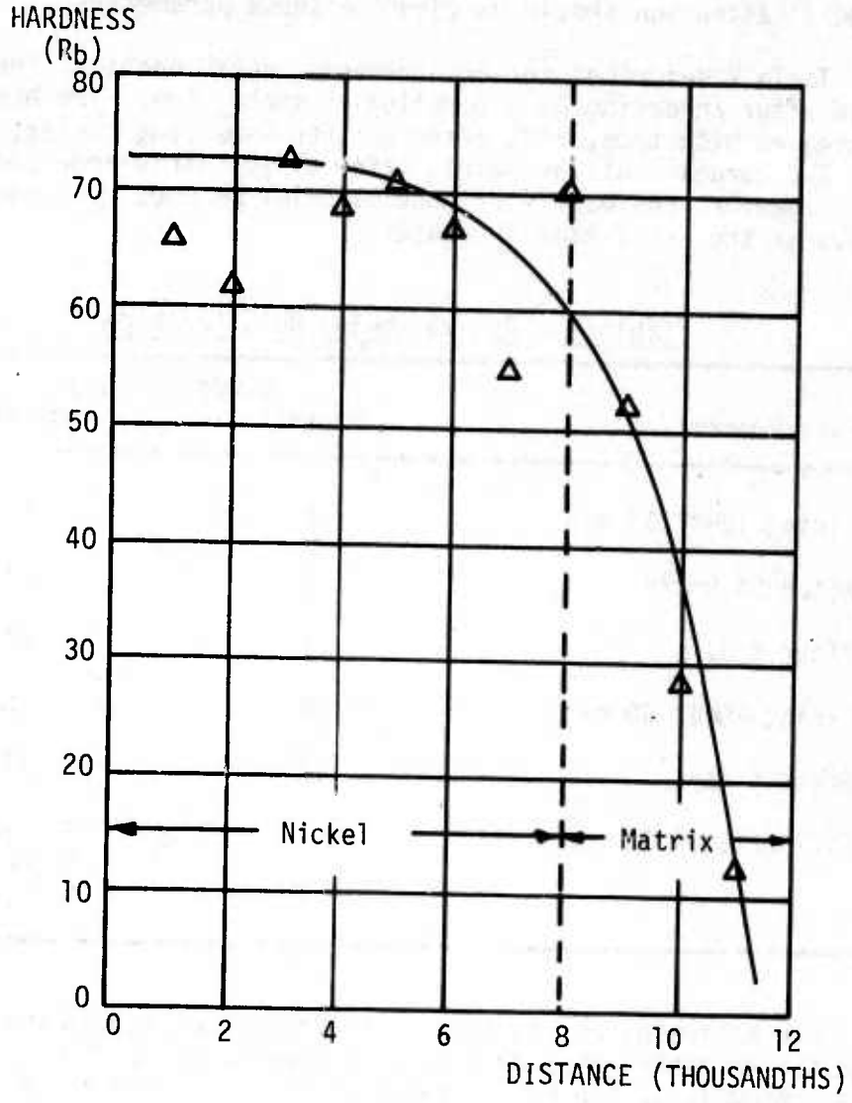


Figure 20. Hardness in Rockwell B Over Cross-Section of Cathode W-11.

made do not seem to be consistent as of yet, the results obtained on the cathode W-11 and shown in Figure 19 are relevant and indicate a smooth consistent variation of the hardness across the cross-section. Further investigation is required in this area, especially when considering that the hardness is a function of temperature, annealing and sintering cycles and of the rolling cycle. Special attention should be given to these parameters.

Table V describes the age-hardening relationship. The hardness was measured after annealing as a function of shelf time. The hardness of the Ni-base increased with time, and, after another annealing cycles, became once more soft. The hardenss of the matrix material is nearly independent on the shelf life. However, the matrix cathode material becomes more porous and more inhomogeneous as the shelf time increases.

Table V. Age-Hardening Relationships.

Last Process	Hardness [R_b] Nickel	Matrix
Firing 1000° 30 min.	~0	79
After 24 hours	6	84
After 6 days	27	84
Firing 1000° 30 min.	~0	35
After 6 days	40	57
Firing 1000° 30 min.	~0	Variable between 0 and 100 over the surface

Age hardening occurs only if compounds are formed within the nickel, and the formation of such compounds seemsto occur during the annealing time, since compounds of the matrix material diffuses into the nickel. Age hardening and increase of porosity of the matrix material limits the number of annealing cycles as well as the temperatures and time the material is subjected to.

It is believed that, under controlled rolling, annealing and sintering cycles, the microhardness tester presented here will be an excellent tool for quality control of the Medicus cathode fabrication.

2.3.4 Defects and Imperfections.

G. Medicus has described in detail different defects and imperfec-

fections he has observed on the surface of the fabricated cathodes.* These defects and imperfections have also been observed on cathodes fabricated at Warnecke, and they will be discussed in the following.

2.3.4.1 Cauliflower, Puff-Balls, Etc.

White excrescences in the form of cauliflowers, blooming, puff balls, etc. are growing out of the cathode surface after annealing (under certain conditions). These defects are more or less homogeneously distributed over the surface (see Figures 8 and 9, for example). G. Medicus describes a certain number of experiments which lead to a reduction of the cauliflower problem.

At Warnecke, no cauliflowers have been observed when the annealing temperature was held below 700°C for an annealing time shorter than 120 minutes. Furthermore, cauliflowers were not observed under annealing temperatures up to 1000°C when Mischcrystals were used for the fabrication of the cathode. Cauliflower growth is excessive when $BaCO_3$ is used and/or the material is heated rapidly above 800°C. Under fast heating conditions, G. Medicus observed a melting of $BaCO_3$, which is attributed to the formation of a compound ($BaO—BaCO_3$). This effect was discovered in the early days of oxide cathodes, and can be avoided by the use of Mischcrystals triple carbonates.

It is believed that the "cauliflower" problem has been resolved, in spite of the fact that some phenomena described by Dr. Medicus cannot be explained with this simple theory based on the formation of a melting $BaO—BaCO_3$ compound.

2.3.4.2 White Haze.

"Often, when the active cathode surface is exposed to air, a 'white haze' can be observed, i.e., the layer becomes non-uniform in a direction perpendicular to the surface." The white haze has been attributed by G. Medicus to the formation of hydroxides.

Such a white haze has also been observed under certain conditions at Warnecke, however, immediately after firing. Furthermore, the recent cathode delivered by Spectra-Mat to Warnecke also exhibits this white

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*G. Medicus, "Improvement of uniformity of Active Layers", Report in-house work from March 1974—August 1974, Avionics Laboratories, Dayton, Ohio. (Wright-Patterson Air Force Base).

haze on certain areas of the cathode. The emission pattern observed from this cathode, however, shows that the emission density of areas with white haze is greater than the emission density of areas without white haze. It has also been observed at Warnecke that the activation of white haze areas is faster and easier than areas of the cathode without white haze. It is thus not determined whether the white haze should be eliminated (defect) or whether it should be developed on the surface of the finished cathodes.

It is still believed that the white haze is a diffusion of earth alkali oxides (annealing temperature above 800°C) to the surface, which, in air, are transformed into earth alkali hydroxides (in agreement with Medicus). However, the hydroxides are transformed in oxides at temperatures above 600°C (see Section 2.2.3), thus enhancing the electronic emission density. With earth alkali oxides on the surface of the cathode, a much faster activation should occur as described by Freytag and Huber[5] who used the "voile" on the matrix cathode to increase the emission density and decrease the time for cathode activation.

2.3.4.3 Cracks.

When the active layer is strongly bonded (sintered) to the substrate, the shrinking of the active layer of the cathode during sintering can produce cracks on the surface. The cracks are more frequent and larger if the matrix layer is thick. Therefore, a maximum thickness for the matrix material exists. When the cracks are relatively large, an inhomogeneous emission pattern as shown in Figure 21 is observed. (Microcracks are not visible on the emission patterns.)

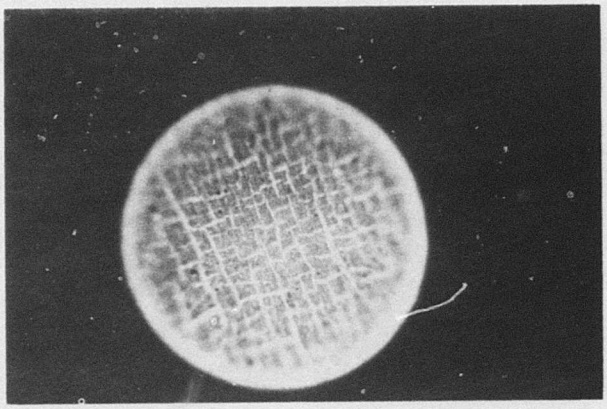


Figure 21. Inhomogeneous Emission Pattern with Cracks on the Surface.

It is believed that crack formation can be reduced by optimizing the rolling-annealing cycles. However, it is also believed that microcracks cannot be completely avoided.

2.3.4.4 Warping.

If the cathode is thin and a good bond exists between Ni-substrate and Matrix material, then warping of the cathode can occur nearly without cracks, especially when exposed to air for hours or days. The warping does not happen if, after annealing, the cathode is pressed between parallel plates for a few days. G. Medicus has found that the "white haze" areas warp more easily and faster than those areas without white haze.

It is believed that warping is not a fundamental problem, since pressing of the cathode between two parallel plates can eliminate the warping of the cathodes in production.

2.3.5 Conclusion.

During the course of this program related to the fabrication of the Medicus Matrix cathode, a certain number of problems have been found and defined. Those mechanical problems directly related to the fabrication techniques have only been resolved partially, although some primary direction of attack have been found and described. The cauliflower, puff-balls, blooming, cracking and warping problems are believed to have been solved, and seem to be understood. The white haze "defect" is believed to be advantageous from the electrical performances point of view. The ductility and thus the hardening of the material is still a major problem, since no direct correlation between hardness measurements and production process control could be determined. Some fabrication processes and techniques could be recommended, but much more work is needed in these areas if the fabrication of the cathode is to be highly reproducible and highly reliable.

SECTION III

TEST EQUIPMENT AND TEST VEHICLE

The temperatures given within this report have been measured with a Tungsten-Rhenium-Tungsten Thermocouple. (Some temperature measurements were made with the use of a pyrometer.) The thermocouple was calibrated at the following temperatures: melting ice, boiling water, melting tin and nickel. The indications of the thermocouple did not vary by more than 5% from the respective calibration temperatures. For most of the electrical measurements (which are described later) the Medicus Matrix cathode material was mounted (spotwelded) onto a used, rectangular, tungsten impregnated cathode so that the fabrication of heater and cathode assemblies were avoided during the numerous tests performed. For cw-operation and, under certain conditions, in pulse operation, the cathode material was mounted onto a newly designed circular cathode fixture which was incorporated into the emission test vehicle. The diameter of the emitting cathode surface in this case was 3.2 mm.

Figure 22 shows the schematic of the test vehicle which has been used for testing the emission homogeneity. The rectangular cathode was placed in front of a cylindrical "Pierce-Electrode" the potential of which was adjusted for best presentation onto the phosphor screen. Close to the Pierce Electrode a first anode was used for adjusting the emission of the cathode.

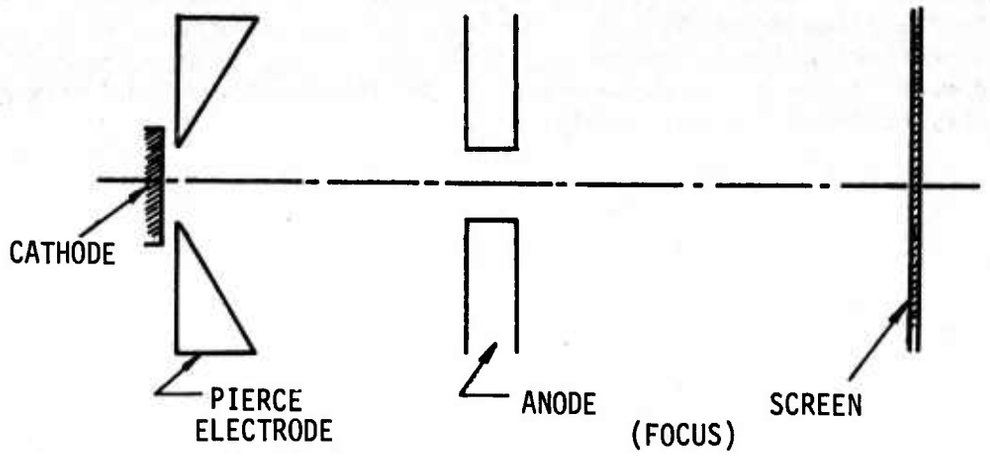


Figure 22. Schematic of the Emission Homogeneity Test Vehicle.

The screen was located at about 7" away from the anode (under certain conditions, the screen could be moved within the vacuum system, so that the distance of the anode to the screen could be varied. The magnification, which occurred due to a cross-over of the beam within the lens system, was determined to be about 30 for a "normalized" set of potential and spacing values. Higher magnification could be obtained, and the smallest resolution element clearly visible on the screen was estimated to be about 20 μm under "normalized" conditions.

The observation and recording of the emission homogeneity pattern is based on the differentiation between areas with low saturation current and areas with higher saturation current. If one assumes that the temperature across the cathode area under observation is constant, and that the test vehicle is well aligned with the cathode, then this test truly represents a picture of the emission homogeneity of the cathode. However, since higher potentials have to be applied to the electrodes if the pattern is to be observed at operation temperature (high saturation currents) and since the phosphor screen is subject to easy burn-out, the test pattern generally does not corresponds to the pattern one would observe at real operation temperature. Tests have been performed under pulse conditions and by reducing the spacings to a safe minimum. Preliminary results clearly indicate that the pattern observed at higher temperatures (close to operation temperature) are similar to those patterns described in this report.

Figure 23 shows schematically the test vehicle designed and fabricated for current emission tests. During the activation of the cathode, a shutter in front of the OFHC-copper anode is close in order to avoid contamination of the anode. The anode is water cooled, and all isolating parts have been made out of ceramics. This test vehicle was designed to be demountable for fast removal and insertion of cathodes.

Due to the high capacities of the cw test vehicle, the experiments describing the pulse operation were made in a glass vehicle, which limited the duty of the pulsing to about .05-3%. In both the cw and pulse test vehicle cases, a vac-ion pump was permanently attached to the vehicle for continuous pumping during tests.

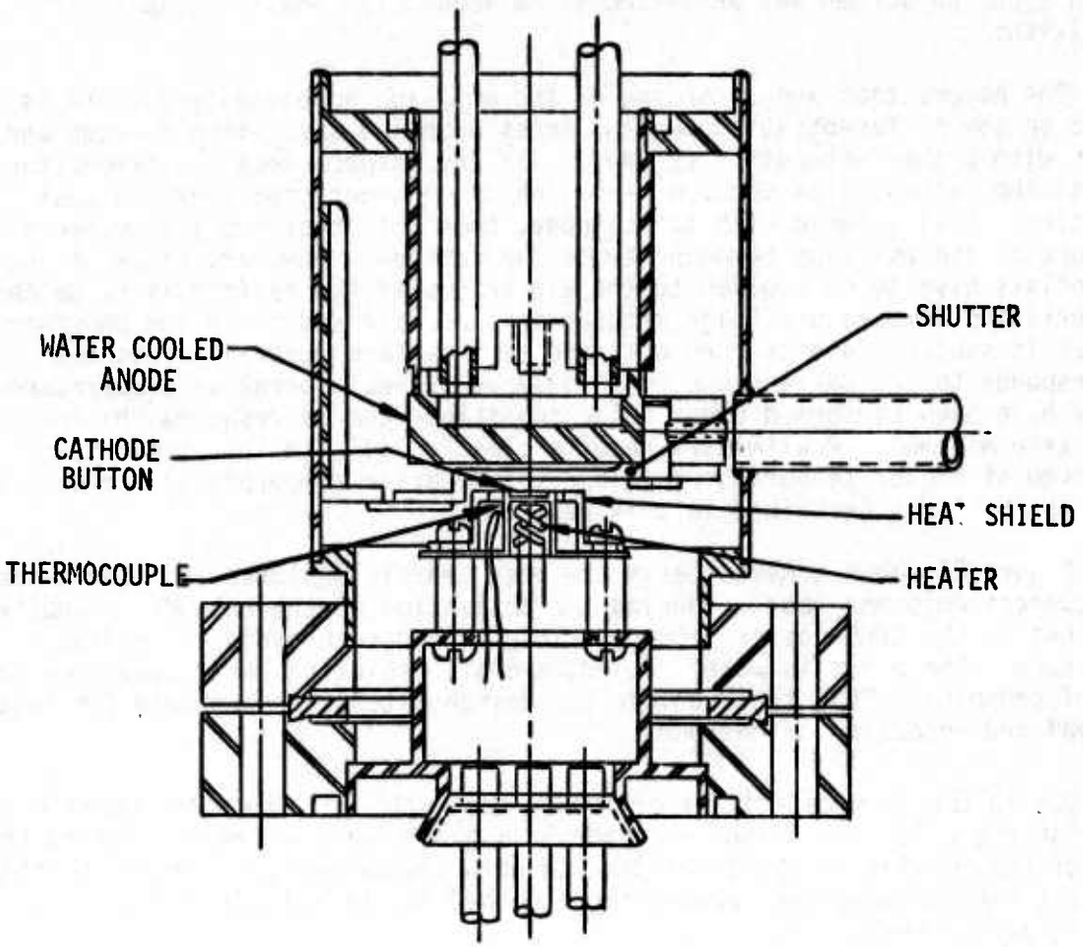


Figure 23. Matrix Cathode Test Diode.

SECTION IV

CATHODE ACTIVATION

The activation of the cathode is still a main subject of concern and study. Also, the existing literature on nickel matrix cathodes describes the concerns and difficulties observed for activating these cathodes. The formation of nickel matrix cathodes has been described to be relatively long, sometimes lasting for a period of a few days. To reduce the activation time, several procedures have been given in the literature.

- Introduce active materials during the fabrication of the cathode, such as Boron, Silicon, Zirconium, Zirconium Hydrides, etc. No tests have been made at Warnecke during the period of this program.

- Activation of the cathode in rare gas atmospheres as proposed by G. Medicus. An experimental conducted at Warnecke was partially successful but laborious. No further investigation on this subject has been made because of difficult processing for production applications.

- Use of a "voile"[5] on the cathode surface. This method could be applied to the Medicus Matrix cathode.

The activation cycles mostly used during this period were those related to the activation of "normal" oxide cathodes. In general, the formation of the cathode was laborious, and consumed generally an extended amount of time. The best result as yet has been obtained by the following procedure. The cathode temperature is slowly increased to 800°-900°C by keeping the vacuum below 10^{-6}torr. After the pressure has dropped below 10^{-8} torr, a cw current of a few mA/cm^2 is drawn for about 24 hours. The temperature of the cathode is then raised to a maximum of 1080°C for a few hours, and then reduced to the operating temperature (750°-1000°C).

SECTION V

ELECTRICAL TESTS

The quality of a cathode depends on its current emission capability and its temperature, although other parameters are important, such as emission homogeneity, life, sparking current, etc. The emission characteristics vary from cathode to cathode, especially during the development phase of a new cathode. During this program, some of the cathodes fabricated exhibited very poor emission capabilities. However, some of the cathodes fabricated exhibited "good" emission characteristics, and these are being described in this report. This has the advantage to show the capabilities of the cathode, and immediately explains the need for a refinement of the fabrication processes and techniques. The emission characteristics of the Medicus Matrix cathode have been measured by mounting the cathode into a simple diode structure. The emitted current is then a well defined function of the voltage applied to the anode, the temperature of the cathode and the environmental conditions. The emission current as a function of the anode voltage determines a current voltage characteristic which can be divided into three different regions, namely,

a. the "Anlaufstrom" region, where the applied voltage is negative.

b. the space charge region, where the current emitted is proportional to the 3/2 power of the applied voltage.

c. the saturation region, where the current characteristics deviate from the space charge region (b).

Each of those regions give some information of the physical nature of the cathode, and have been measured and analyzed. With the exception of the "Anlaufstrom" region, where the results have not been consistent, especially because of the inadequacy of the proper activation cycle (beginning of the program), the results are presented in the following.

5.1 Space Charge Characteristics

Figures 24 to 27 show the experimental results of the current voltage characteristic for the following cathodes:

- Warnecke Cathode W-5 (Figure 24), the microphotographs of which are shown in Figure 15. The characteristic has been measured under pulse conditions, with .5% duty and a pulse width of 100 μs. The current measured has been limited by the capabilities of the pulse equipment.

- Warnecke Cathode W-8 (Figure 25). The characteristic was measured under cw conditions.

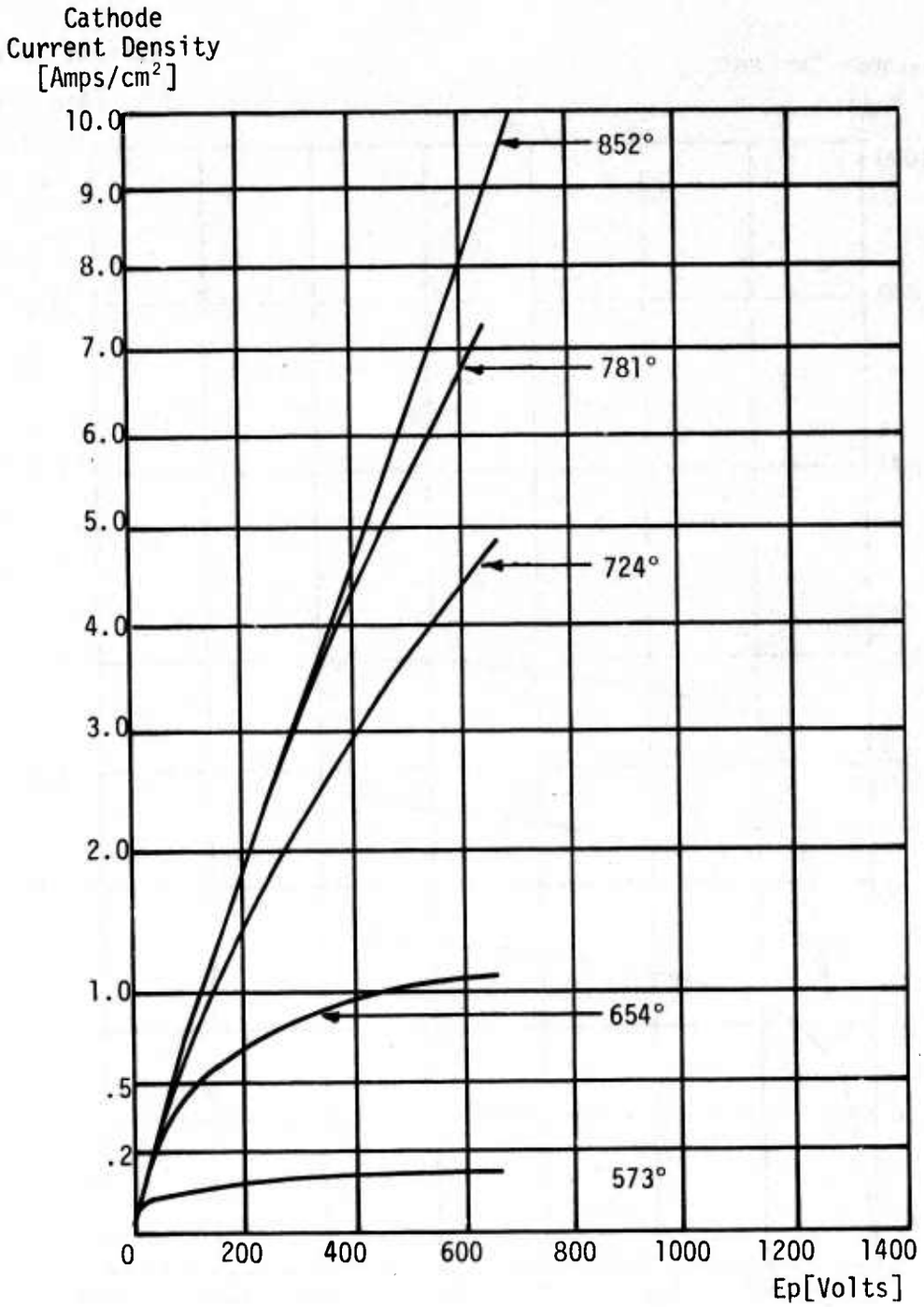


Figure 24. $I^{2/3}$ Voltage Characteristics of W-5 at Different Temperatures (Pulsed Conditions).

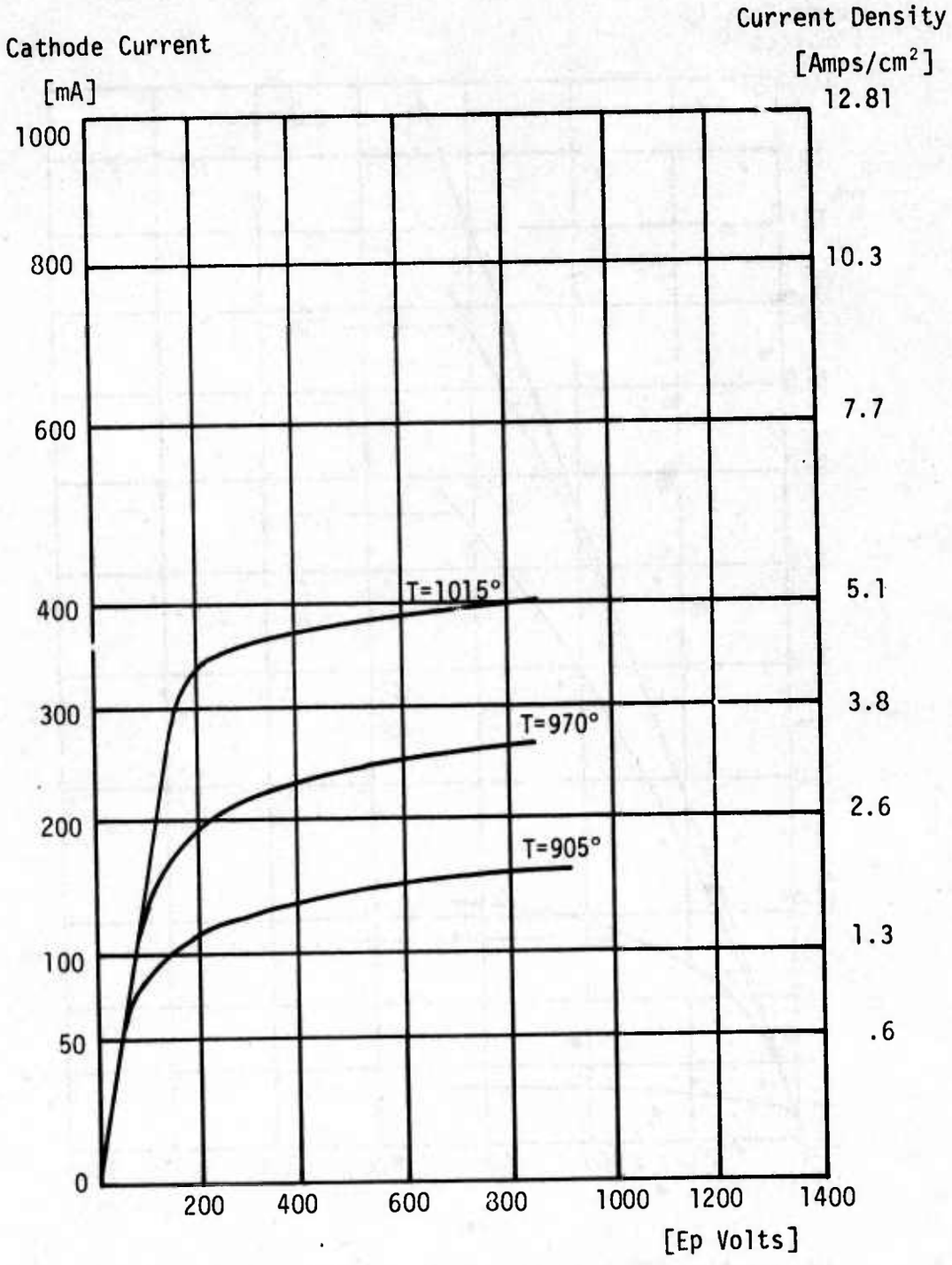


Figure 25. $I^{2/3}$-V Characteristics of W-8 in CW Operation.

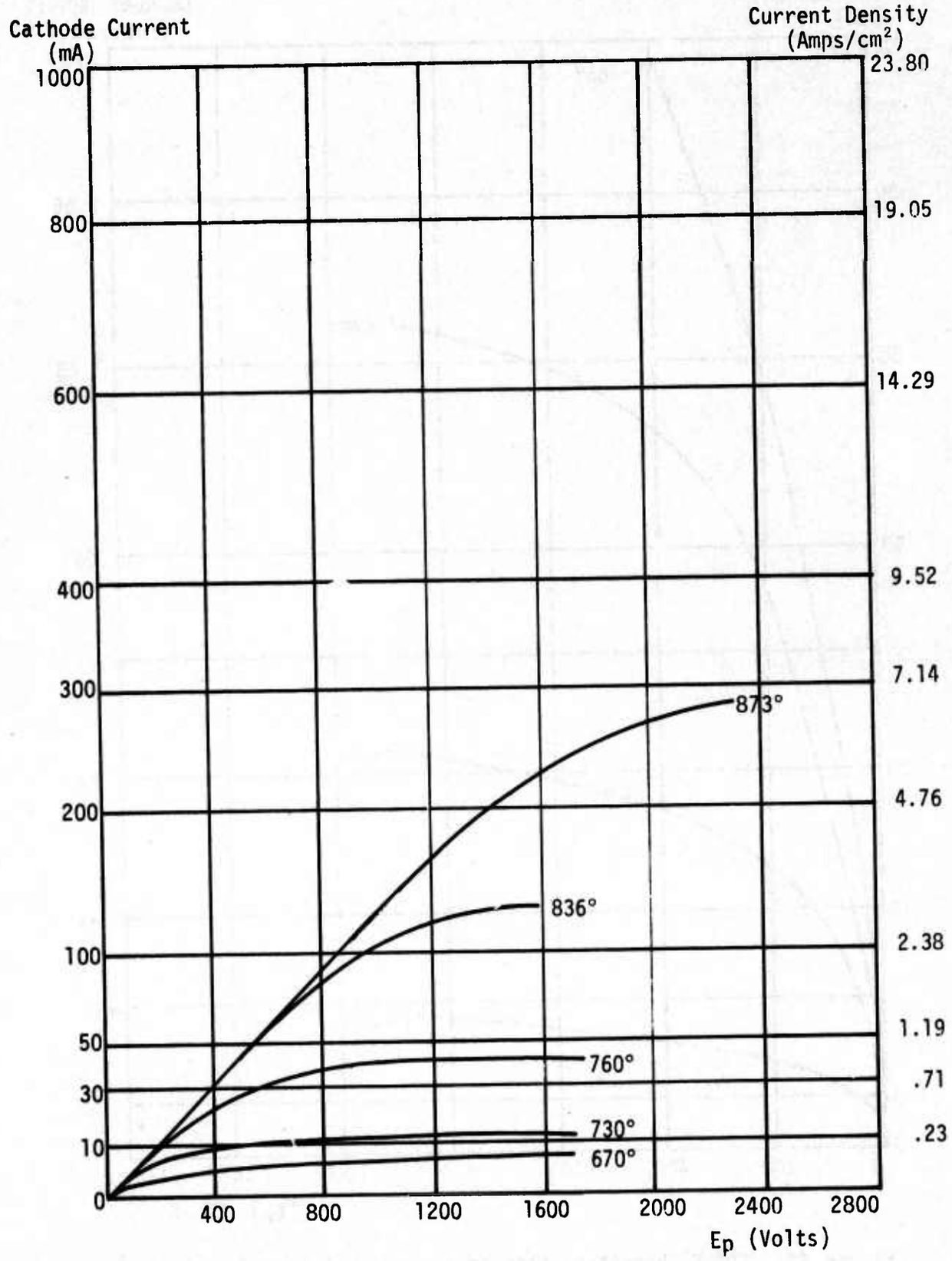


Figure 26. Spectra-Mat Cathode, CW Test.

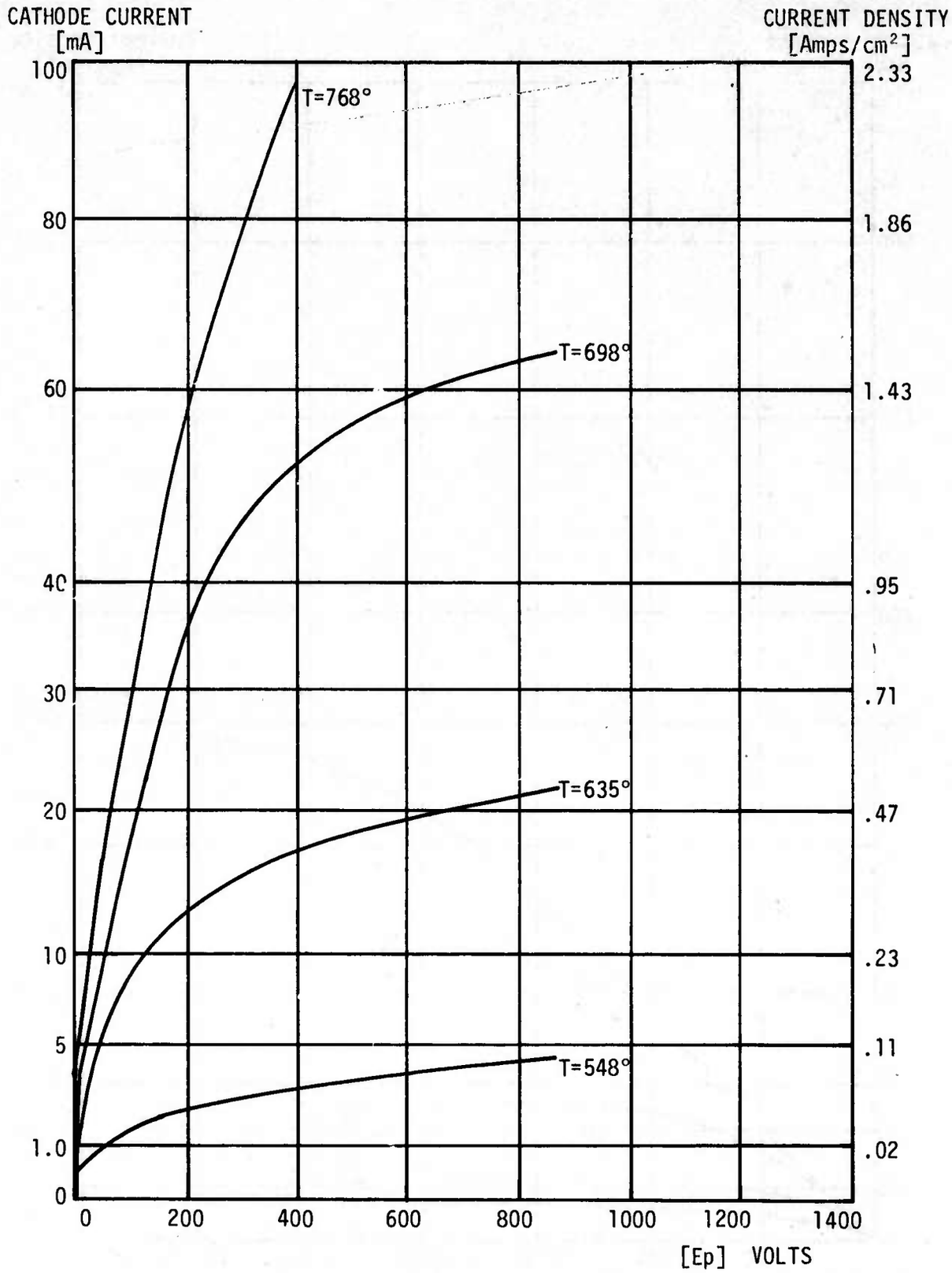


Figure 27. $I^{2/3}$-V Characteristics of Spectra-Mat Cathode in Pulse Condition at Different Temperatures.

- Two cathodes (Figures 26 and 27) delivered by Spectra-Mat. Data at higher cathode temperatures could not be taken due to heater limitations.

In general, the maximum current densities measured in cw-operation are lower than those measured in pulse operation. Although these observations may be due to poor environmental conditions (anode degassing), Warnecke believes that these observations are factual. In any case, a cw-current density of 12 Amps/cm^2 has been measured with Warnecke's Cathode W-5, and a current density of 13 Amps/cm^2 has been measured in cw-operation with a cathode (134 A-2) fabricated by G. Medicus.

5.2 The Saturation Current

Once the applied voltage is large enough, the current "saturates" and the current voltage characteristic "enters" the saturation region. The saturation current, by no means, is a constant and well determined current, but varies with the applied voltage.

The variation of the current with applied voltage in the saturation region is unreproducible enough so that a definition and a measurement of the saturation current is difficult, especially for oxide cathodes. However, the saturation current is a good measure for the quality of the cathode, since it determines the maximum current which can be emitted by a given cathode under "normal" conditions.

Because of the difficulties arising in the physical definition and in the measurement of a saturation current, Huber and Freytag[5] defined the emission quality factor of a cathode through sparking current, which they compare to a reference cathode.

In spite of these facts, an attempt will be made in the following to define a saturation current and, therefore, to calculate the Richardson work function, and the effective work function of the Medicus Matrix cathode. The question whether or not the work functions determined in this fashion have a physical basis and a physical meaning has still to be determined. We will use three different function plots, namely:

5.2.1 The Schottky Plot.

In Sommerfeld's model of a metal, the work function of the metal is reduced by the applied electric field E between anode and cathode. By the superposition of the field, and the image force, the increase in saturation current, ΔI_S, can be calculated as a function of the applied electric field as follows:

$$\Delta I_S = I_S \exp\left(\frac{4.39}{T}\sqrt{E}\right)$$

where T is given in degrees Kelvin, and E in V/cm. Therefore, if the logarithm of the current is plotted as a function of the square root of the applied voltage, a straight line should be obtained for high applied voltages. Theoretically, the saturation current I_S can be determined by extrapolating the straight line obtained (Schottky-plot) to zero voltages (intersection with the y-axis). Furthermore, the slope of the straight line obtained determines, at least theoretically, the temperature T of the cathode.

For pure tungsten cathodes, this theory is verified by the experiment. However, for oxide cathodes[12], the anticipated straight line in the Schottky-plot is generally not obtained, and the calculated temperatures are generally too low (a few hundreds of °K) when compared to the real operational temperature of the cathode (above 1000°K). Therefore, a difference must exist between pure metallic cathodes and "semi-conducting" cathodes. Figure 28 shows the Schottky-plots obtained with the Warnecke cathode W-8, the operating temperature being the variable parameter. As shown, a fairly good agreement exists between the operating temperature measured with the thermocouple and the temperature calculated from these Schottky-plots. At least, the difference between the two temperatures is much less as observed with "semi-conducting" cathodes (oxide cathodes).

Figure 29 shows some of the Schottky-plots obtained with different cathodes. The upper curve, related to cathode W-7, exhibited a relatively large discrepancy between real and Schottky temperatures: the emitted current density of this cathode was measured to be above 20 Amps/cm^2. The lower curve related to cathode W-7 exhibits a fairly good agreement between real and Schottky temperatures. The current density was measured to be only 10 Amps/cm^2. The lower curve was measured 24 hours after the measurement of the upper curve.

The upper curve related to the cathode W-8 was measured at relatively high temperature and under pulse conditions: the Schottky-plot corresponds fairly well to a straight line. However, at lower temperature, the Schottky-plot is no more linear (lower curve related to cathode W-8).

The results obtained so far indicate that the Medicus Matrix cathode behaves as a cathode which exhibits neither the Schottky characteristics of a metal nor those of a "semi-conducting" (oxide) cathode. The characteristics are located "in between", sometimes exhibiting the characteristic of a metal, sometimes those of a semiconductor, depending on the test conditions and fabrication processes. In general, "good" emitting cathodes exhibit the semiconductive characteristics, i.e., the real temperature and the Schottky temperature do not correspond. The higher the emitted current density is, the lower the Schottky temperature is calculated. Fairly good emitting cathodes exhibit the metallic characteristic, and their real operating temperature corresponds to the calculated Schottky temperature.

5.2.2 The $I^{2/3}V$ Plot.

Another method to determine a saturation current is shown in Figure 30. On the $I^{2/3}V$ plot of the current voltage characteristic, the saturation current voltage characteristic at high voltage is extrapolated to zero voltages (intersection with the y or $I^{2/3}$ axis).

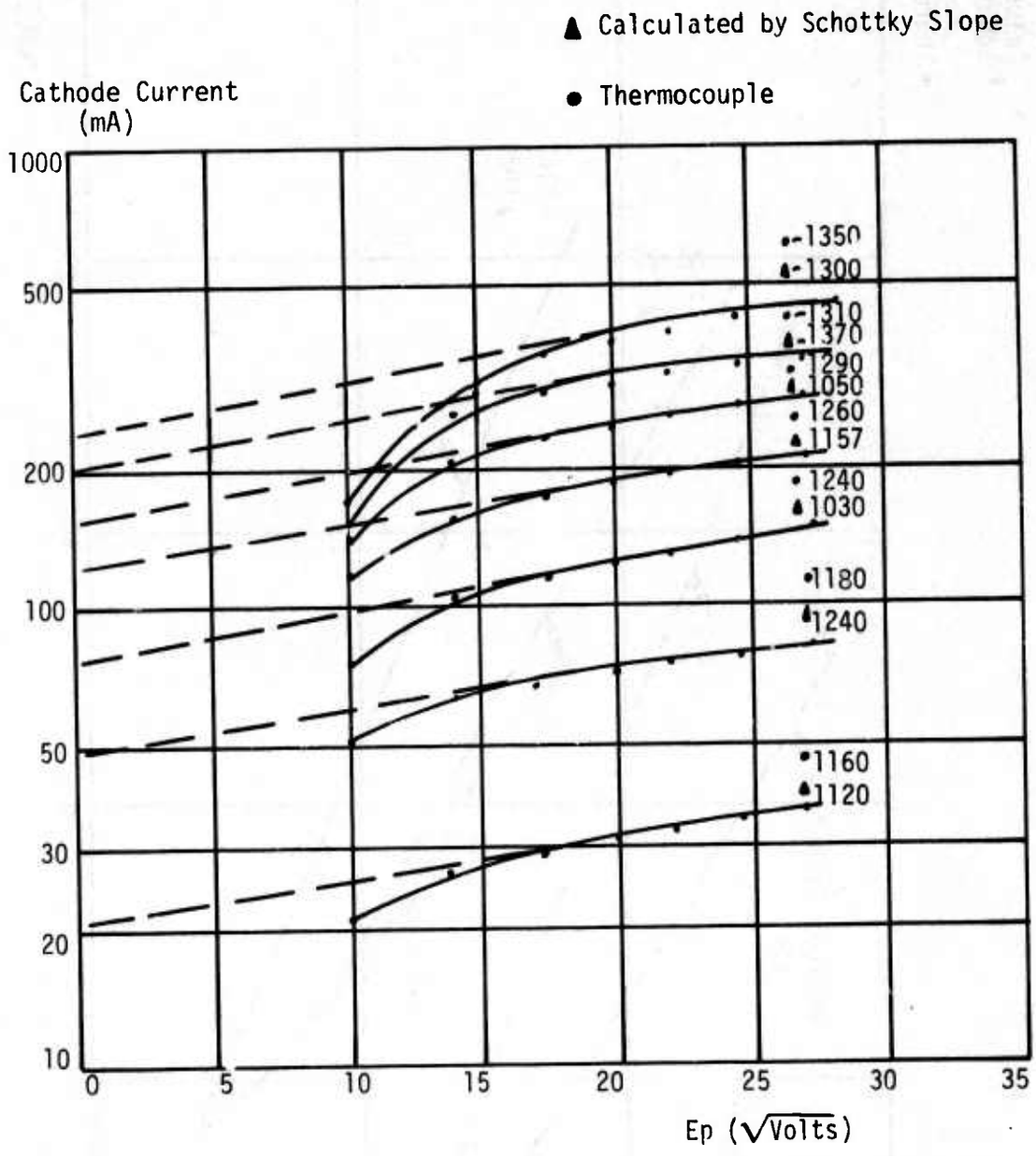


Figure 28. Schottky-Plot of Warnecke's W-8 Cathode.

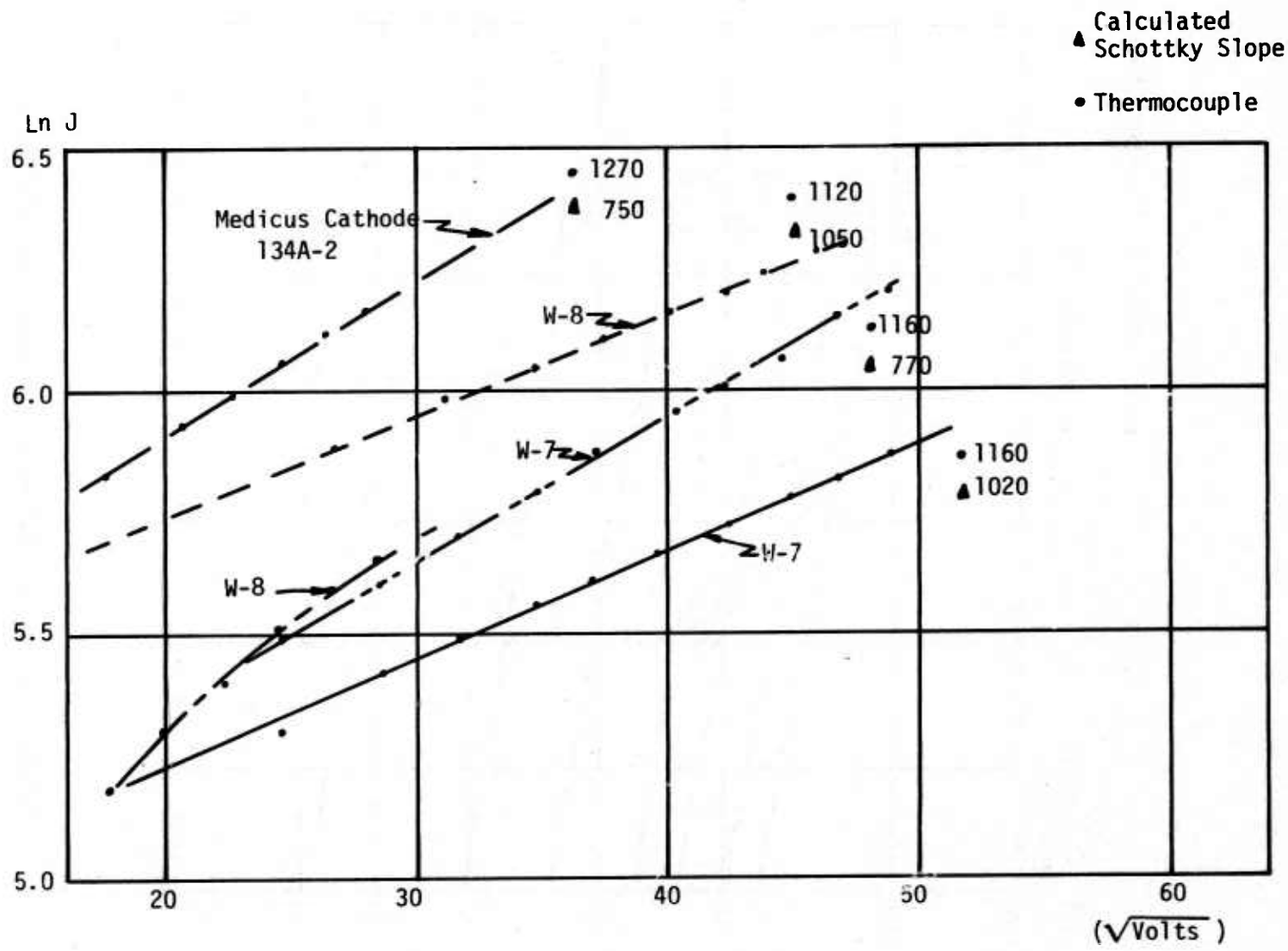


Figure 29. Schottky Plots for Various Cathodes.

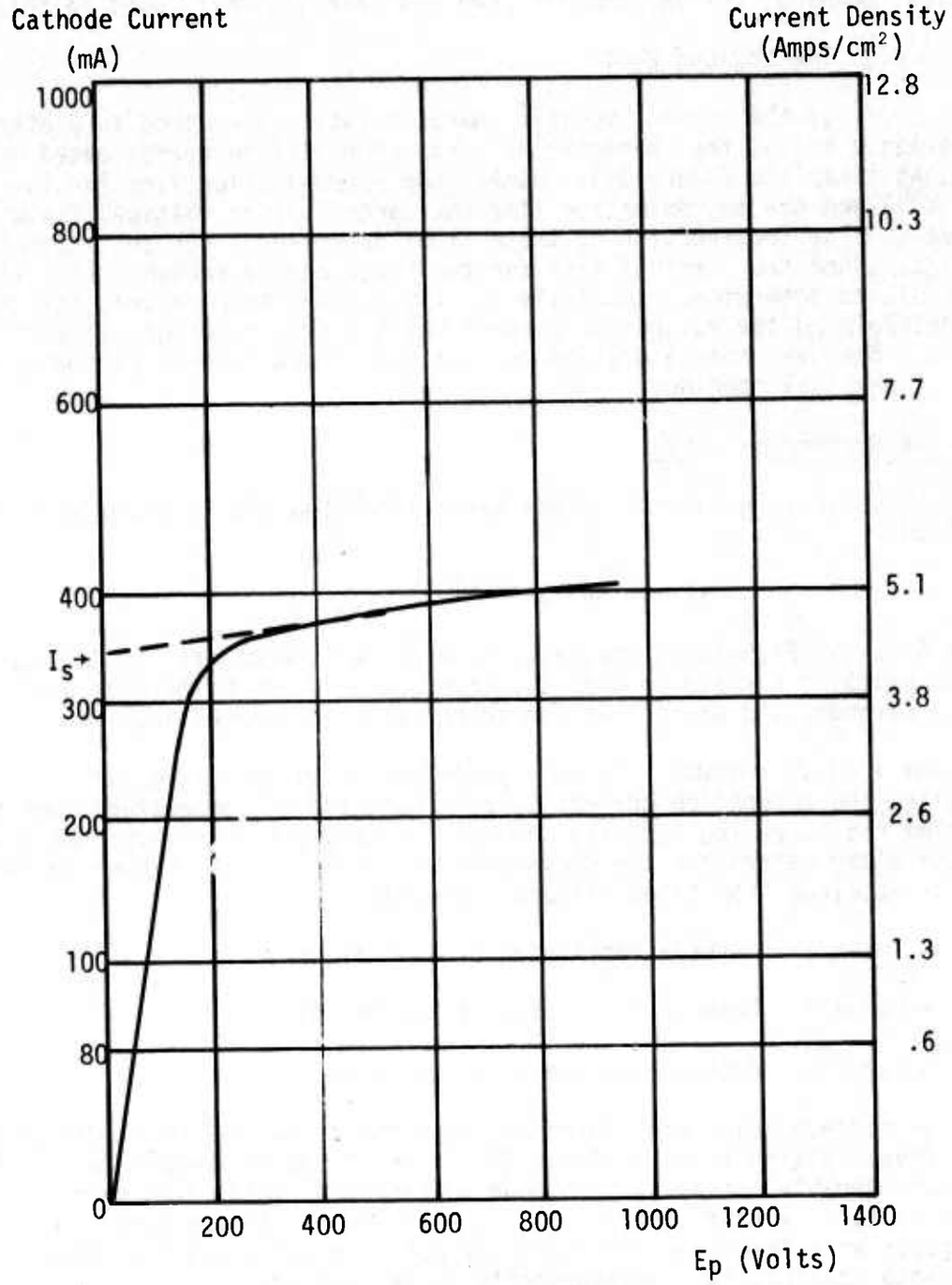


Figure 30. Voltage-Current Characteristics for Warnecke Cathode in CW Operation (W-8).

The saturation current determined by this method has no real physical meaning, but is commonly used and been generally used in this report.

5.2.3 The Log-Log Plot.

If the current voltage characteristic of a diode is plotted on a log I-log V scale, the characteristic can generally be approximated by two straight lines (see Figure 31): namely the approximation line for low voltages ($I \sim V^{3/2}$) and the approximation line for large applied voltages (saturation current). The intersection of these lines determine a current saturation. However, since the straight line for the space charge region ($I \sim V^{3/2}$) is difficult to determine, especially for low cathode temperature, this method for determining the saturation current has not been used throughout this report. Besides, the saturation current determined through this method has no real physical meaning.

5.3 The Richardson Curve

The saturation current I_S has been calculated and is given by Richardson's equation:

$$I_S = SAT^2 e^{-e\phi/kT}$$

where A is the Richardson constant, theoretically equal to 120 Amps/cm^2, S is the emitting surface area of the cathode, ϕ is the Richardson work function of the cathode, and where T is the temperature in degrees Kelvin.

For a given cathode, the work function can be determined by measuring the saturation current I_S as a function of temperature, and by plotting the curve log I_S/T^2 vs. 5034/T. A straight line should be obtained, and the slope determines the Richardson work function ϕ. Figure 32 shows the results obtained from three different cathodes.

- Curve 1: Cathode fabricated by G. Medicus.
- Curve 2: Cathode fabricated at Spectra-Mat.
- Curve 3: Cathode fabricated at Warnecke.

The corresponding work functions were the lowest values achieved by the three investigating laboratories. The value of the work function ϕ varies with considerable spread from cathode to cathode: variations from 1.17 eV (Medicus) to 2 eV have been observed. Furthermore, it was observed that the Richardson work functions determined by pulse measurements are generally lower than those obtained by cw-measurements (same cathode).

5.4 The Effective Work Function

The Richardson equation above requires 120 Amps/cm^2 for the constant A. However, the Richardson work function determined from the Richardson plot does not require the knowledge of the value for A, which, normally, can deviate by several orders of magnitude from the theoretical value.

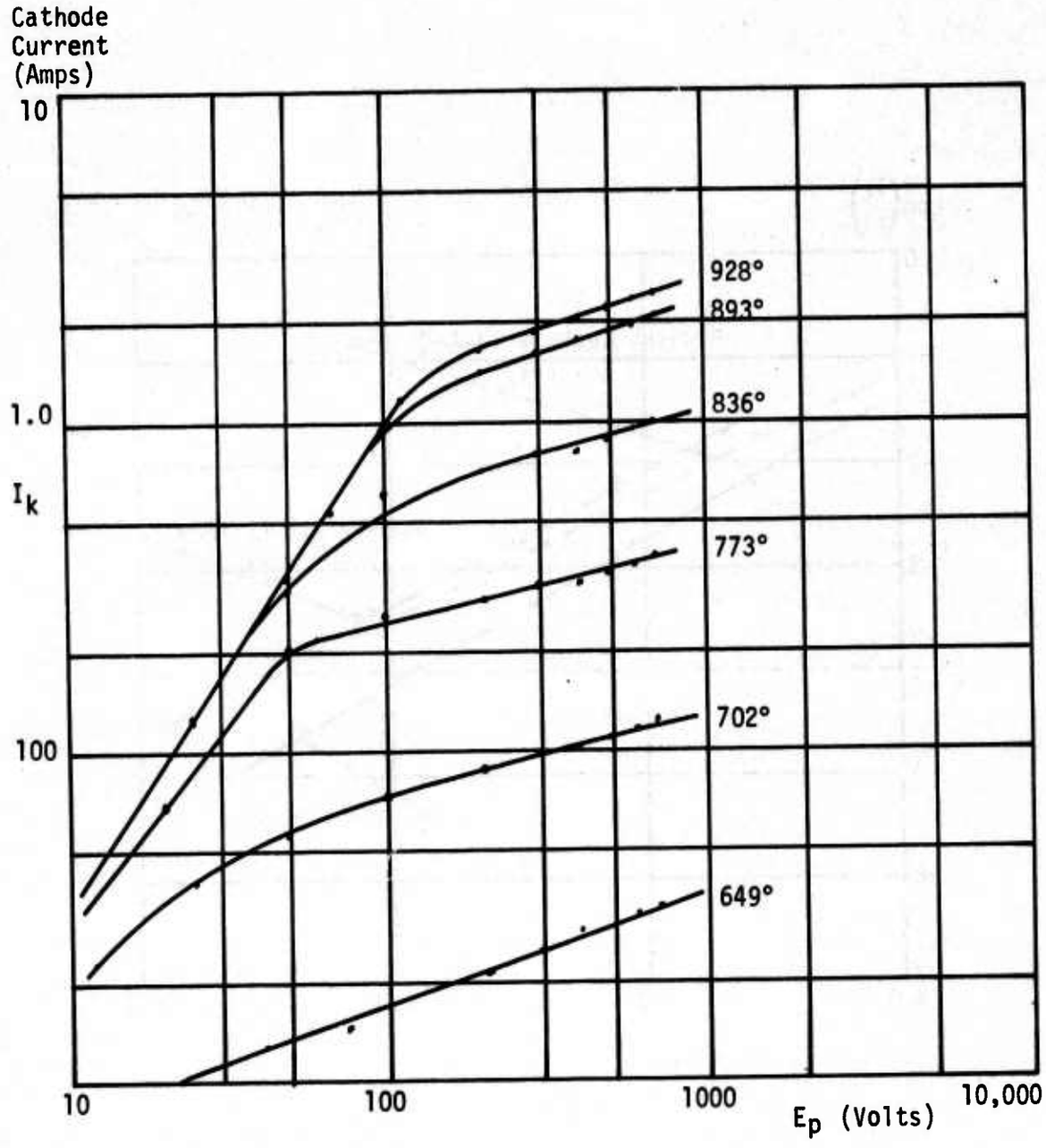


Figure 31. Log-Log Plot of Current Voltage Characteristics for W-11 #2.

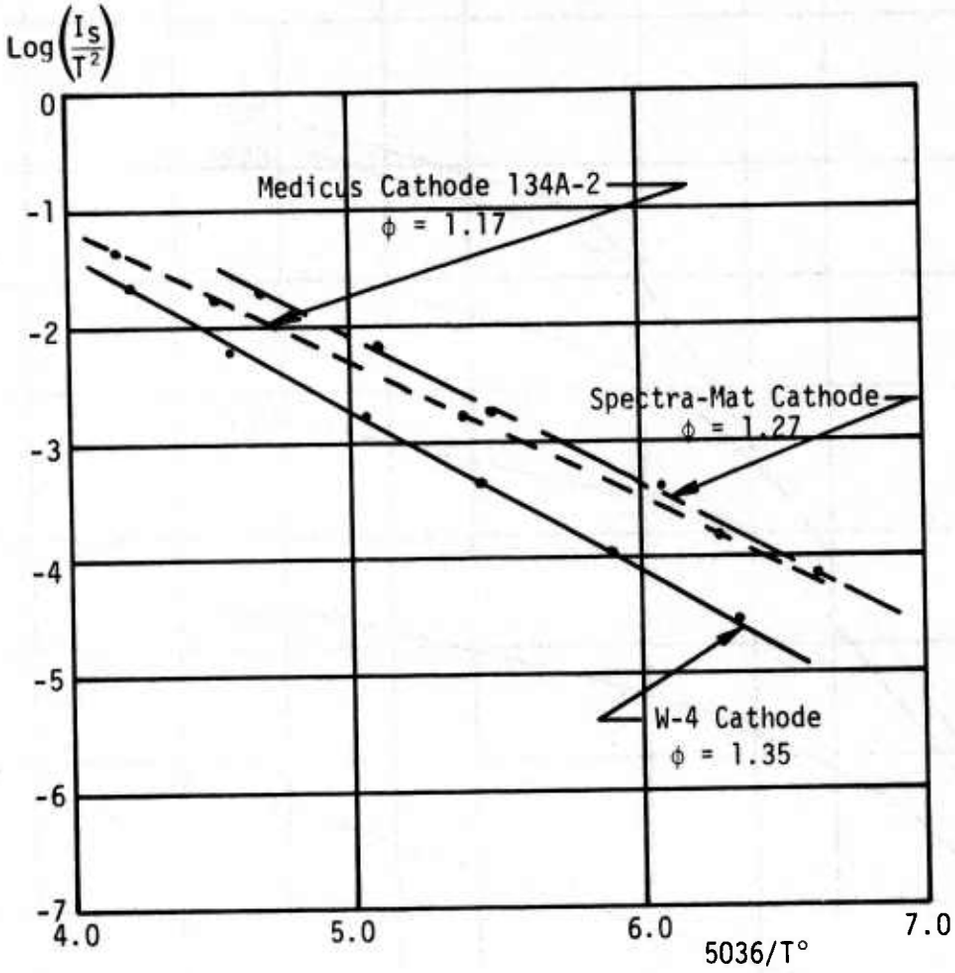


Figure 32. Richardson Curves for Cathodes Made by Medicus, Spectra-Mat and Warnecke.

If the value of A is assumed to be 120 Amps/cm^2, and if the emitting surface area S is known, then, by determining the saturation current and the temperature, an effective work function ϕ' can be determined from the relation:

$$I_S = 120\ ST^2 \exp -(e\phi'/kT)$$

The effective work function determined by using the theoretical value of A is, in fact, a measure of the quality of the cathode: a cathode with relatively low Richardson work functions may emit a lower saturation current than a cathode with higher Richardson work function if the coefficient A for this cathode is small.

Figure 33 shows the lowest effective work functions measured on cathodes fabricated by the three investigating laboratories. The effective work function was measured under pulse and cw-conditions. The effective work functions measured under pulse conditions (10-100 μs, .1-3% duty) is also much lower than the effective work functions measured under cw conditions. It is surprising to find the effective work function of the Spectra-Mat cathode (cw-condition) to decrease with temperature (see Figure 33). Furthermore, a comparison with section 5.3 shows that the effective work function of the Spectra-Mat cathode is even lower than the Richardson work function. The cathode-anode distance of the diode was calculated by using Langmuir-Child's Law, and it was found that the calculated value was about two times larger than the measured value (measurement made prior to assembly). The diameter of the cathode supplied by Spectra-Mat was only 2.3 mm, and diffusion of barium onto the nickel sleeve surrounding the emitting cathode may have been the cause of the anomalies observed with the Spectra-Mat cathode.

The Richardson constant A can be calculated:

$$A = 120 \exp -e\ (\phi' - \phi)/kT$$

where ϕ' and ϕ are the effective and the Richardson work functions, respectively. Table VI shows the A-constant calculated from data compiled over a wide range of temperatures.

Table VI. Calculated Richardson Constant A Over Wide Temperature Range.

	ϕ(RICHARDSON) [eV]	ϕ(EFFECTIVE) [eV]	A [Amps/cm^2]
W-8 PULSE	1.65	1.69-1.81	22-75
W-8 CW	1.47	1.85-1.92	2.2-2.7
W-5 PULSE	1.38	1.45-1.5	34-55

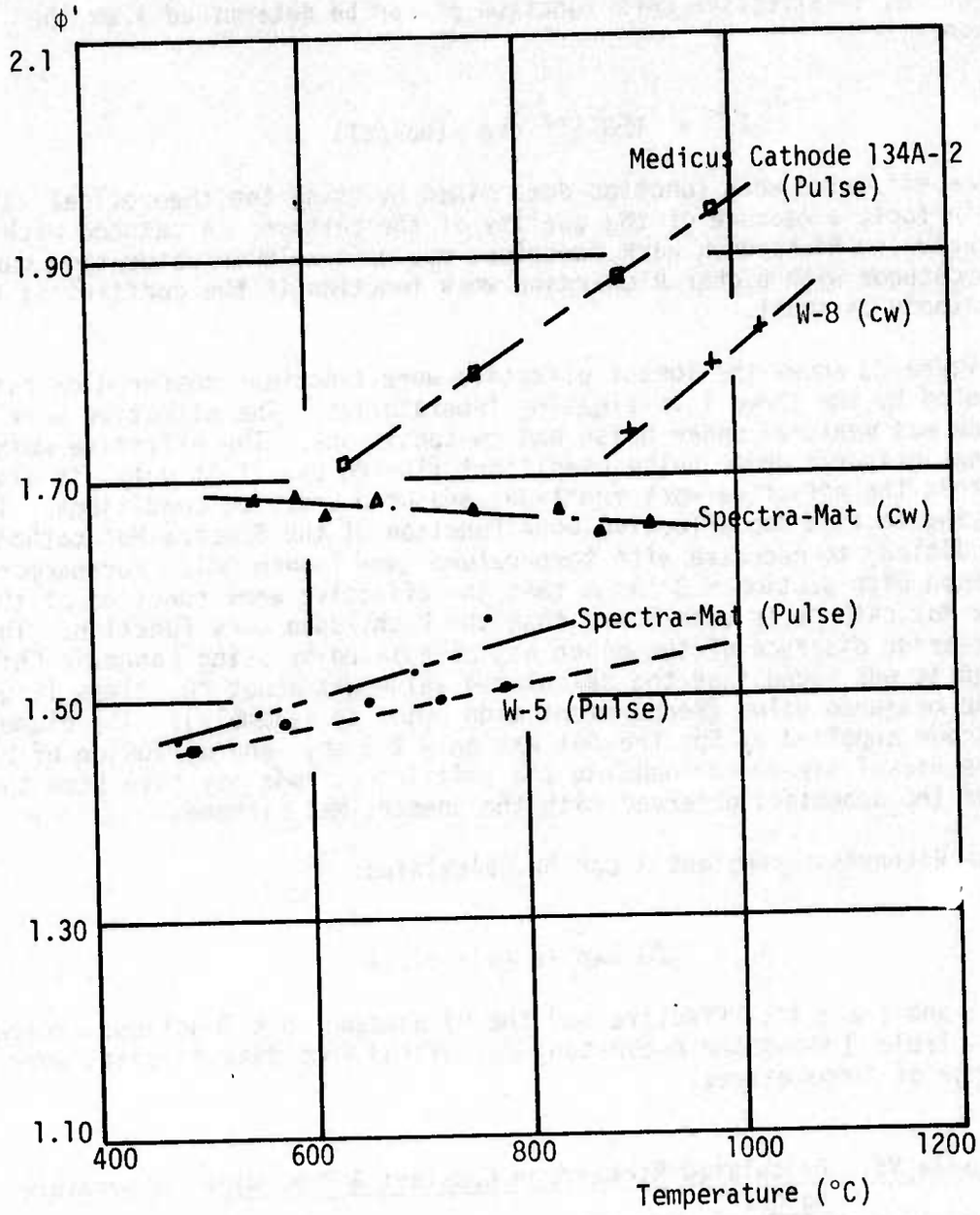


Figure 33. Effective Work Functions φ' for Different Medicus Cathodes versus Temperature.

Many cathodes exhibit a much smaller Richardson constant than the values calculated for the Medicus cathode. The fact that the Richardson constant is close to the theoretical value shows the metallic behavior of the cathode. It should be pointed out that the cathodes W-5 and W-8 exhibited the highest emission current density and the most homogeneous emission pattern.

5.5 Discussion on the Current Voltage Characteristics

There are different reasons for the deviations of the measured Richardson constant from the theoretical value of 120 Amps/cm^2 to occur.

5.5.1 Electron Reflection.

The reflection of electrons crossing the potential barrier at the surface of the metal leads to a factor (1-r) in front of the Richardson constant.

$$A^* = A(1-r) = 120\ (1-r)\ A/cm^2T^2$$

For metals, the reflection coefficient is of the order of .05, and depends slightly on the applied electric field and a periodic variation of the Schottky line can be observed under certain conditions. This periodicity can be attributed to the variation of the reflection coefficient with the applied electric field. Since the deviations observed are much larger than those predicated by the theory, we will neglect the coefficient r in the following.

Similar to the reflection of electrons at the barrier potential, the tunneling through the barrier can affect the Richardson constant seriously, especially at high applied fields. The measurements discussed above, however, exclude tunneling of the electrons through the barrier as the reason for the observations made.

5.5.2 The Temperature Dependence of the Work Function.

The work function is defined as the energy difference between the potential energy of the exterior (vacuum) and the Fermi-energy. The potential wall existing between the inside of the cathode and the outside appears because the energy of the electron in the periodic crystal field is considerably lower than outside. This provides the principal contribution to the work function. On the other hand, at the surface of the crystal, the periodicity of the crystal is deeply disturbed, so that the work function is determined by an internal contribution and a pure surface effect. It can be shown that the internal contribution plays the most important role for alkali and most of the metals[18]. However, dipole moments at the surface may be arranged regularly and form a so-called double layer with a relatively strong potential jump. In general, for metals, it can be shown that the changes in the work function with temperature will be of the order of 10^{-4} eV/degree.[18] If we assume this order of magnitude to apply to the Medicus cathode, then the temperature dependence of the work function cannot explain the experimental results presented above.

5.5.3 The Surface Condition.

There exists no ideally smooth surface as is normally assumed in theoretical models. Furthermore, the surface can be of polycrystallic structure so that the surface intersects the individual crystallites completely differently. As a result, the current emission is very non-uniform: Herring and Nichols (1969), present a detailed discussion on this and other related problems.

From the experimental results related to the emission homogeneity, it can be concluded that the surface is made of "mini" areas presenting different emission capabilities: some areas will appear dark (current saturation) while others appear white (see Section 5.8). As a model, let us consider Figure 34, which schematically represents a "mini" area of low work function

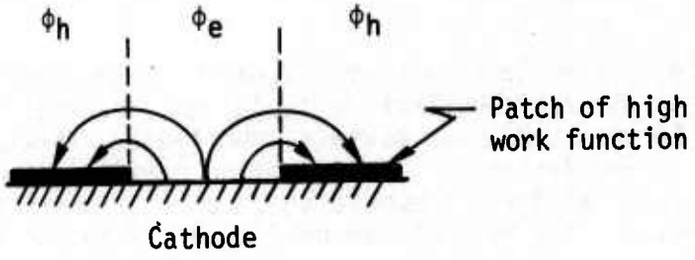


Figure 34. Schematic of a "Patched" Cathode (Work ϕ_e < Work Function ϕ_h).

ϕ_e surrounded by "mini" areas of high work function ϕ_h. The origin of these mini-areas shall not be discussed here, since they can be due to a polycrystalline structure of the surface, to a partial cover of the surface by Barium or by strontium oxide, etc. The local electrical fields between two adjacent patches (or mini-areas) will essentially be the same as that produced by replacing the patches with conductors that have a potential difference $\phi_h - \phi_e$. At low applied voltage, electrons emitted from areas of low work function may be captured by the areas with high work function.

A surface with repetitive patches of different work functions ϕ_i will produce a local "patched" electric field which will decrease exponentially as exp $-X/\overline{D}$, where $\overline{D}$ is the mean diameter of the patches. At distances large compared to $\overline{D}$, the potential assumes a value:

$$\overline{\phi} = \Sigma f_i \phi_i$$

where f_i is the fraction of the area with work function ϕ_i.

As a result, at low applied voltages ($|E| \ll (\phi_h - \phi_e)/\bar{D}$), the emission current will be given by[19].

$$j_e = f_e A T^2 \exp -\left(\frac{\bar{\phi}e - e\sqrt{e/\varepsilon E}}{kT}\right)$$

and corresponds thus to the Schottky line with the Richardson constant multiplied by fraction of area whose work function is ϕe. If the applied field E is large compared to $(\phi_h - \phi_e)/D$, then one may proceed as though there were no patch fields and the emission from each patch is independent of its neighbor. Hence, the emission current is given by:

$$j \simeq A T^2 \left[\sum_i f_i \exp -\left(e\phi_i/kT\right)\right] \exp -\left(\frac{e\sqrt{e/\varepsilon E}}{kT}\right)$$

As a result, a variation of emission current as schematically represented in Figure 35 can be expected. In the region where:

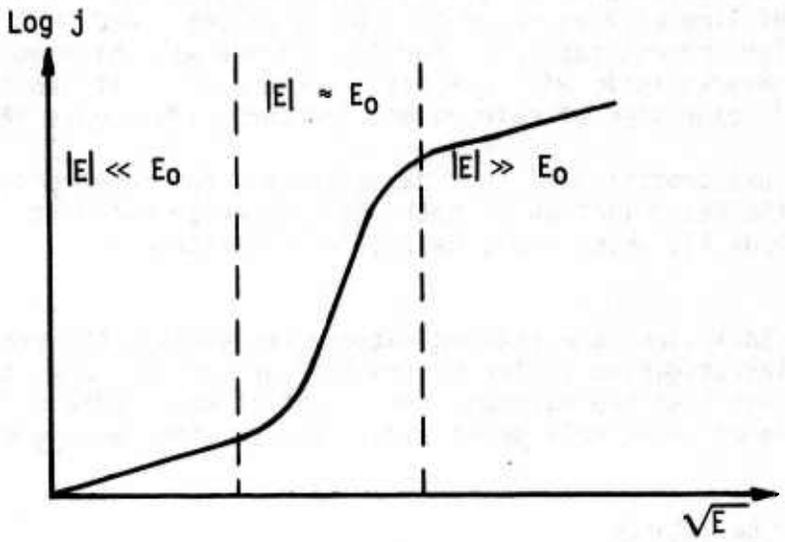


Figure 35. Expected Emission Current (Saturation Current) for a "Patched" Cathode ($E_0 = (\phi_h - \phi_e)/\bar{D}$.)

the applied field E is approximately equal to the patch field $E_0 \simeq (\phi_h - \phi_e)/\bar{D}$, the applied field neutralizes the patch field, and the effective work function will be decreased in this region.

Furthermore, this theory can be complicated if one considers the coefficients f_i corresponding to the fraction of area of work function f_i to vary with temperature. It has been observed that areas of high emission currents may vary in size and in time as a function of temperature and even as a function of the applied electric field: if the applied electric field is increased suddenly, areas of high current density can appear, which may or may not disappear after a certain amount of time (of the order of minutes). An

increase of temperature will result, if at all, to an increase of the sum over the areas of low work function, since an increased diffusion of Barium to the surface may occur. Thus, a reduction of measured effective work function with increased temperature can be explained. On the other hand, if, with increasing temperature, the Barium evaporates faster than it is furnished from the interior of the cathode, an increase in work function can be observed (high temperature).

From these discussions, it follows that the anomalies observed previously can be explained. However, the parameters f_j, ϕ_j, $\bar{D}$, etc. can always be chosen in order to fit some experimental results.

One point should be mentioned here. It has been frequently observed that the $I^{2/3}$ V characteristic obtained from the Medicus cathode exhibits a slope α_1 at low applied voltages, and a slope α_3 at higher voltages before saturation occurs. This may be explained rather easily by assuming the patch field E_0 to be very low. A low applied voltage (and with constant f_1 and f_2), the current is the sum over two currents: the currents from two cathodes in parallel, with surfaces f_1 and f_2, work function ϕ_1 and $\phi_2(\phi_1 < \phi_2)$ and at the same temperature. A straight line will be observed (sum of curves 1 and 2 in Figure 36) until the emission current saturates for the cathode with high work function ϕ_2. Then the characteristic will exhibit a slope $\alpha_3(= \alpha_2$ if Schottky effect is neglected) until saturation of cathode No. 1 occurs (see Figure 36).

The extrapolation of the characteristic for intermediate currents should lead to the determination of both the saturation currents I_{S_2} (cathode 2) and I_{S_1} (cathode 1), which could be tracked separately.

In conclusion, the patched cathode can explain the preliminary data observed. The investigation so far on the Medicus cathode shows that a patched cathode exists, but that the patches, the origin of which have not been determined as yet, are of relatively small sizes (see emission homogeneity, Section 5.8).

5.6 The Barrier Resistance

All semiconductive cathodes have a "barrier" resistance which is the sum over the following resistances:

- Base to semiconductor interface resistance.
- Semiconductor layer resistance.
- Dipole—surface resistance.

It is quite clear that the barrier resistance with the barrier capacitance is a limiting factor of the cathode for high duty pulse or cw-operation. A power loss will result due to joule's heating of this barrier resistance. This will result in an increase of the temperature of the cathode. However, due to the emission of electrons, the cathode will be cooled due to the potential barrier the electrons have to surmount when leaving the cathode. The power dissipated within the cathode layer is thus given by:

$$P = I^2 R - I (\phi + \bar{V})$$

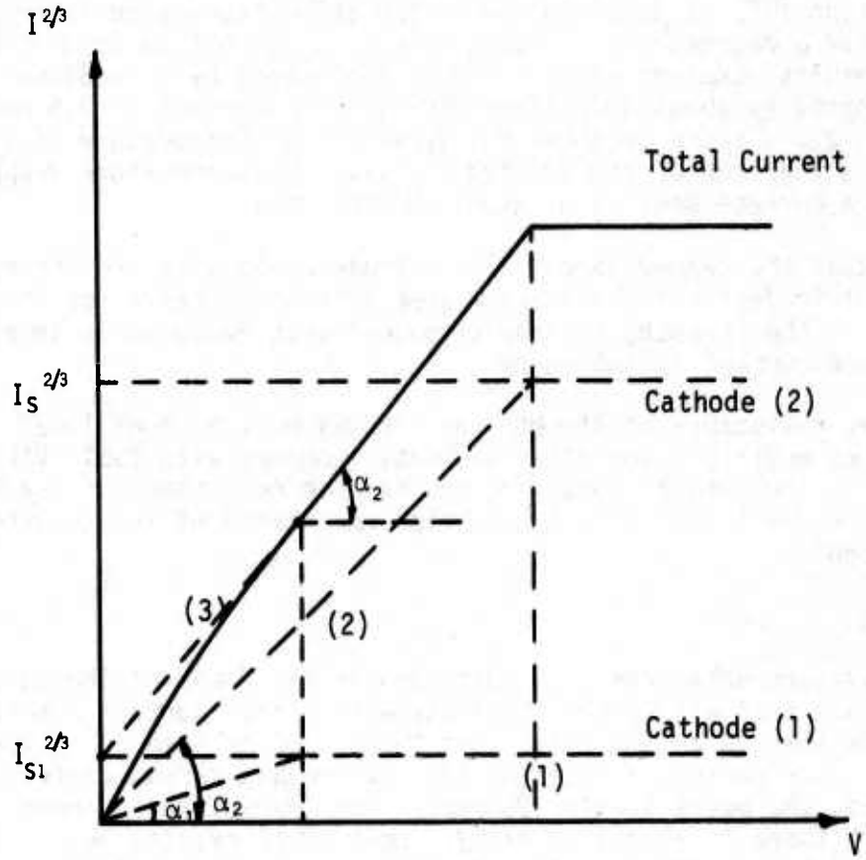


Figure 36. Explanation for Observed Characteristic in the Apparent Space Charge Region.

where R is the barrier resistance, ϕ the work function, $\bar{V}$ the equivalent voltage with which the electrons are emitted ($\simeq$ 2kT/e) and where I is the emitted current. The barrier resistance has been determined for many cathodes, and some results are presented in Table VII[13]. The barrier resistance for BN-cathodes is of the order of 2-10 Ω/cm^2, which leads to a power dissipation of 20-100 watts at a cw current of 3 Amps/cm^2.

The first Medicus cathodes fabricated showed a cathode temperature increase with increased emitted current (about 5°C for a current density of 1 Amp/cm^2 under 1% duty in pulse condition, cathode No. 134A). However, the cathodes with high current densities in cw-operation fabricated later in the program exhibited a decrease in temperature when a current is drawn. Figure 37 shows the results obtained with a cathode fabricated by G. Medicus: the temperature dropped by about 30°C (from 980°C) for a current of 7.5 Amps/cm^2 (Cathode 134A 1-2). Figure 38 shows the variation of temperature of a Spectra-Mat cathode as a function of the emitted current: the temperature dropped by about 10°C for a current density of about .6 Amps/cm^2.

The fact that the temperature of the cathode drops with increasing emission current is distinctly different from most other matrix cathodes. The BN-cathodes[14] and the (French) fritted cathodes[5] both increase in temperature when the emission current is increased.

The barrier resistance of the Medicus cathode must be much lower than those values published for other cathodes (compare with Table VII). Furthermore, from the results obtained, the barrier resistance of the Medicus cathode should not be larger than the barrier resistance of the tungsten impregnated cathode.

5.7 Decay Time

Not many measurements have been performed on the decay of the pulse current. The fact that all cathodes operate with higher current density under pulse conditions than in cw indicates that there must be some decay phenomena. Figure 39 shows some current pulses for the cathode W-5 versus plate voltage, the duty was .5%, the pulse length 100 µsec. For low voltages, there is some decay, for 600 V there is almost no decay. Equivalent results were obtained by Ahmed and Beck[14] who explained the reduction of the decay at high current by an instantaneous rise in temperature during the pulse by the power loss in the barrier resistance. At least for the Medicus cathode this explanation is doubtful because for the W-5 cathode, the temperature decreased with cathode current.

Figure 40 shows the decay of the cathode W-11. In this case, the decay seems to correspond to an R-C circuit with a time constant of a few tens of µsec.

5.8 Homogeneity

One of the attractive characteristics of the Medicus cathode is the homogeneity of the emission. The first Medicus cathode was tested when Warnecke had problems with instabilities of the production CFA. At this time

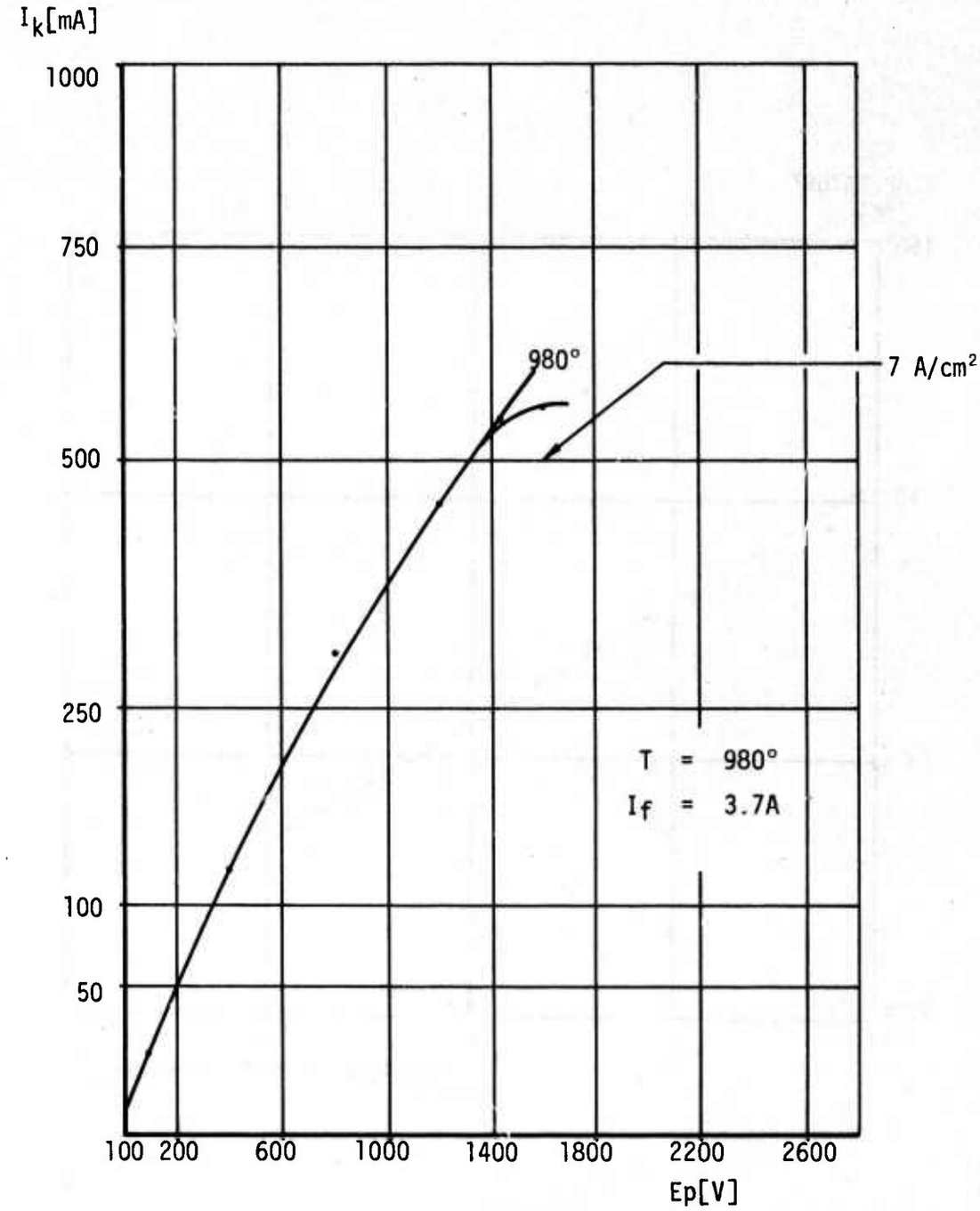


Figure 37. $I^{2/3}$ Voltage Characteristics of Medicus Cathode 134 A 1 Sample #2.

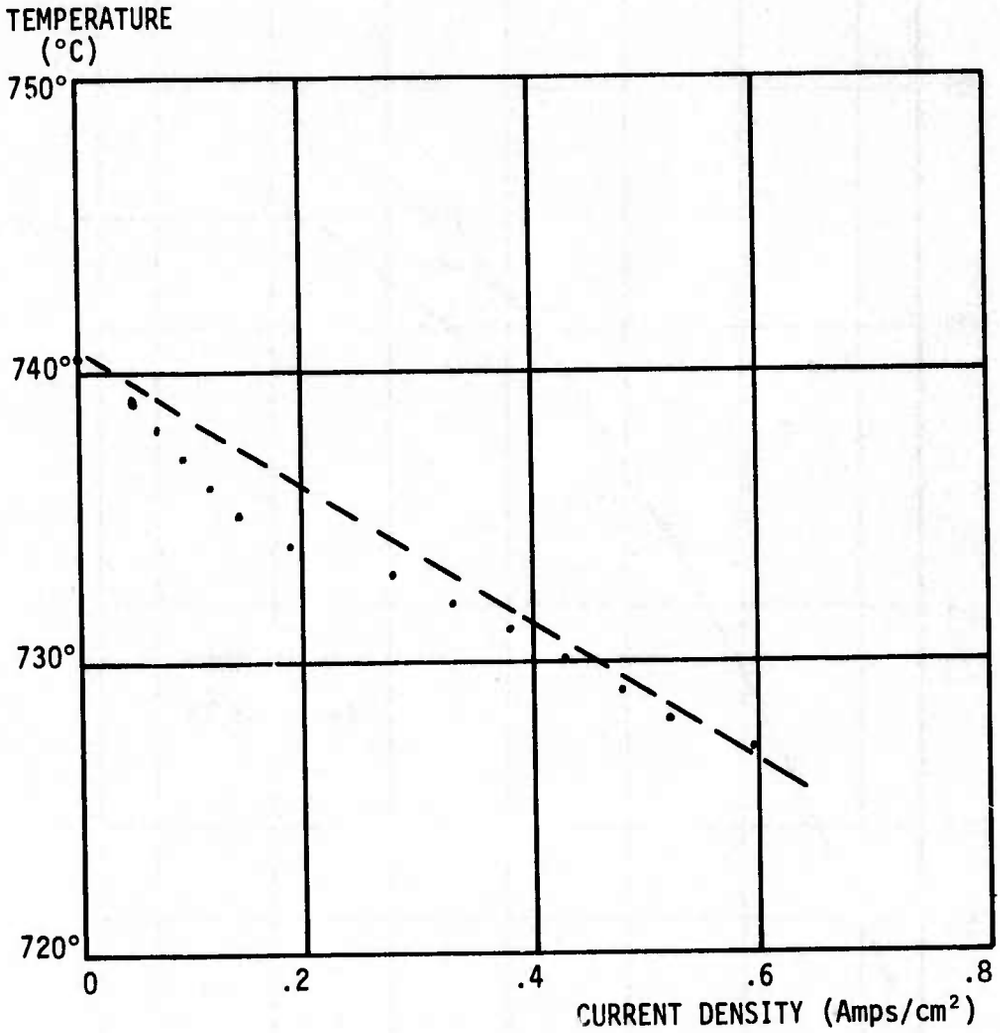
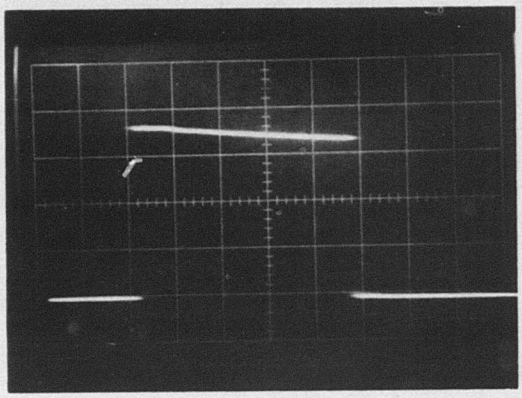


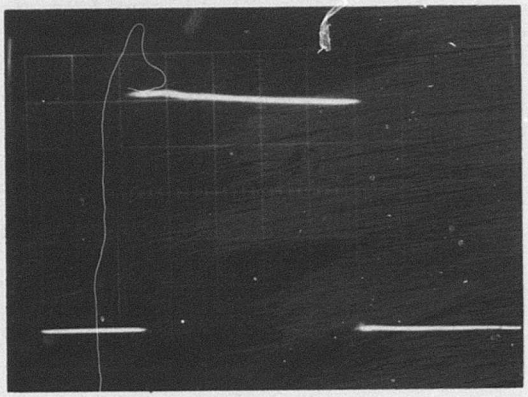
Figure 38. Cathode Temperature Versus Emitted Current Density.

Table VII. Series Resistance of Dispenser Cathodes.

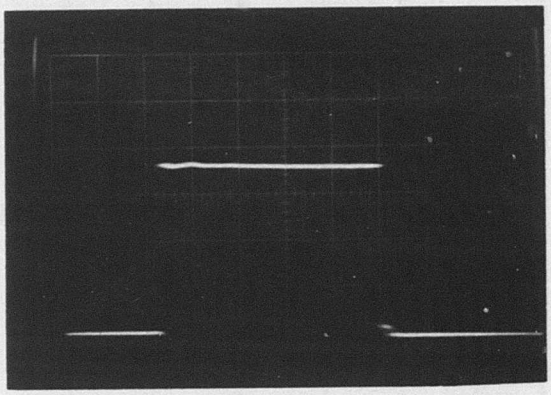
CATHODE	RESISTANCE AT NORMAL OPERATING TEMPERATURE	RESISTANCE CHANGE WITH TEMPERATURE	TEMPERATURE RANGE °B
B. N. CATHODE 1	$3\Omega/cm^2$	$2 - 6\Omega/cm^2$	1200 - 800
B. N. CATHODE 2	$15\Omega/cm^2$	$10 - 30\Omega/cm^2$	1155 - 800
W-ALUMINATE IMPREGNATED CATHODE	$8\Omega/cm^2$	$7 - 13\Omega/cm^2$	1250 - 900
KATZ CAPILLARY CATHODE	$6\Omega/cm^2$	$5 - 10\Omega/cm^2$	1260 - 950
OXIDE CATHODE	$30\Omega/cm^2$	$30 - 100\Omega/cm^2$	800 - 560



E_p = 400 V .5 A/Div.

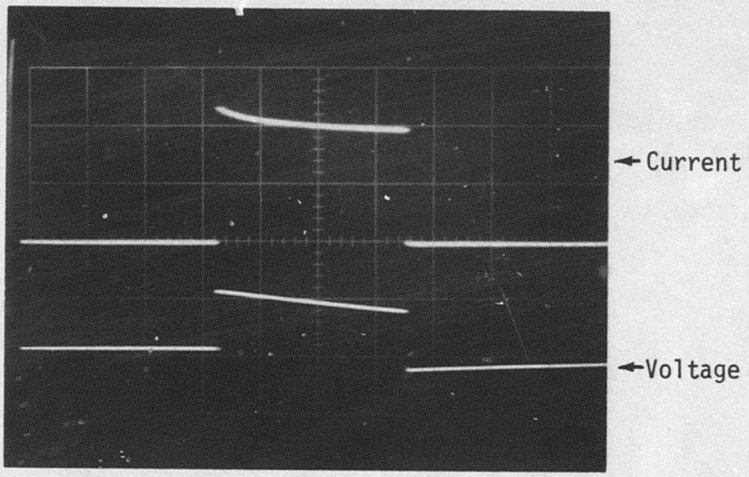


E_p = 500 V .5 A/Div.



E_p = 600 V 1 A/Div.

Figure 39. Pulse Decay of W-5 at 858°C.



T = 885°C

PW = 100 μsec/div.

I = 1 Amp/div.

E = 500 V/div.

Figure 40. Pulse Decay of W-11 at 885°C.

impregnated cathodes were tested for homogeneity and in many cathodes large inhomogeneities were found. Figure 41 shows the emission pattern obtained with a tungsten impregnated cathode.

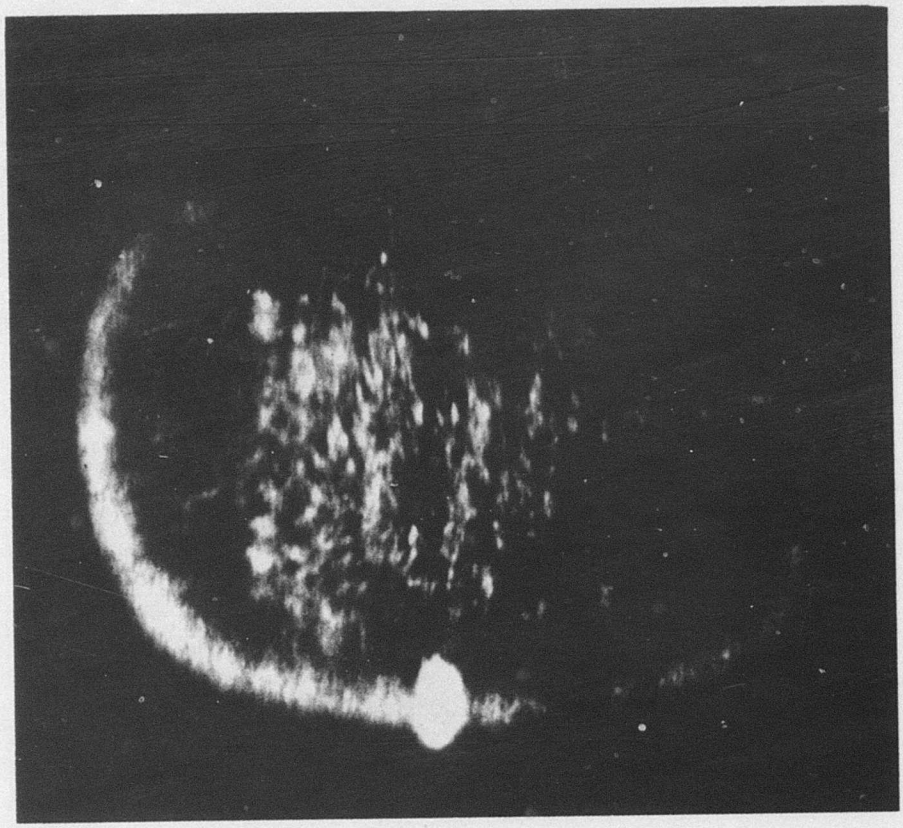


Figure 41. Emission Pattern of Impregnated Cathode. Emission Focussed on Fluorescent Screen by Electron Lens.

A large number of Medicus cathodes have been tested for homogeneity and when the optical view showed cracks, cauliflower, etc., inhomogeneous emission was observed as shown in Figure 42.

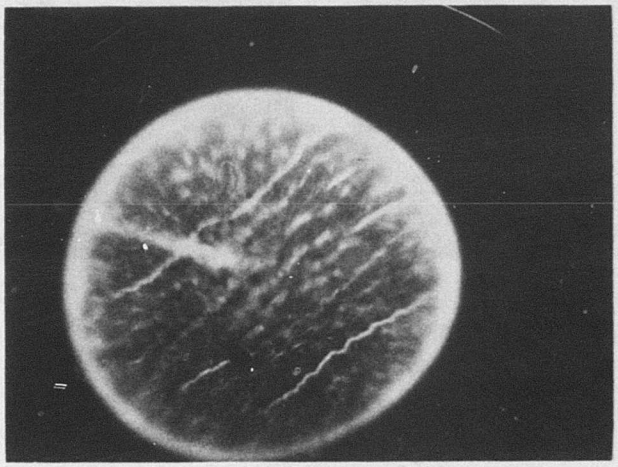


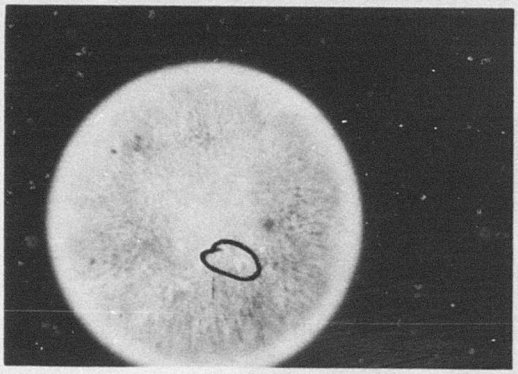
Figure 42. Homogeneity of W-9 with Severe Cracking Apparent.

Figure 43 shows homogeneity tests obtained from cathodes developed by the three investigator groups (Figure 43a cathode fabricated by Warnecke, Figure 43b fabricated by Medicus, Figure 43c fabricated by Spectra-Mat).

There may be some doubt on the usefulness of these tests because the current emitted for homogeneity tests is low compared to the cathode current in a power tube. However, the comparison of Figure 41 with Figure 43 shows that at least qualitatively the homogeneity can be evaluated.

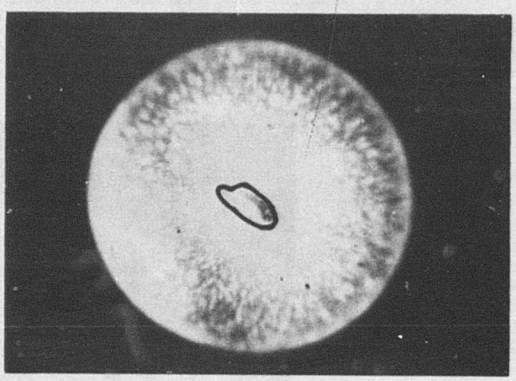
A much better method is a beam tester with high resolution which is actually in construction at Warnecke under another program.

It should be mentioned that Beck[15] tested the homogeneity with a scanning microscope. The homogeneity can then be evaluated if it is assumed that emission and secondary emission are proportional. Haas et al.[1] used scanning low energy electron probe (sleep) to determine directly the work function over the surface of the cathode with high precision of 5 μ and resolution of 30 mV. However, not only the work function is required but also the Richardson constant A to determine the homogeneity of the current. Therefore, the actual emission pattern under operating conditions, namely high temperatures and hign emission currents, is still a problem which should be resolved as soon as possible.



43a. Warnecke

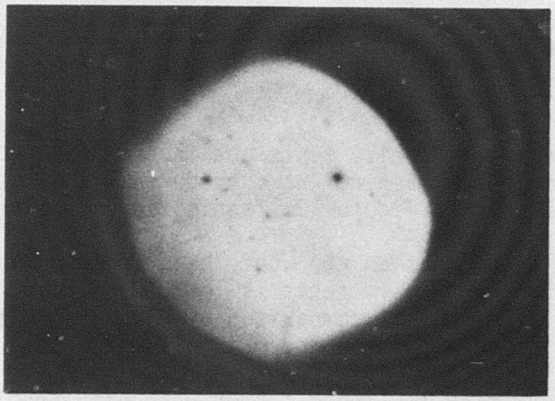
Homogeneity of W-5 at 870°C.



43b. G. Medicus

Homogeneity of Medicus #202 at 890°C.

Blemish of the screen.



43c. Spectra-Mat

Homogeneity of Spectra-Mat Tricarbonate at 780°C.

Figure 43

SECTION VI

LIFE AND EVAPORATION RATE

In order to determine the life and evaporation rate of the Medicus Matrix cathode, a certain number of experiments have been made. The evaporation of the cathode material has been made by measuring the loss of weight as a function of operating time.

Figure 44 for example, shows the evaporation rate of the tungstate and the barium calcium aluminate cathodesas presented by Bondley et al[16] as a function of temperature. The points inserted on this figure are measurements made during this program with the Medicus Cathode. These evaporation rates correspond approximately to those observed with the tungstate cathode and the nickel matrix cathode. The evaporation rate of Ni is approximately the same as the rate of the tungstate cathode[17], i.e., mainly the nickel is evaporated.

For one Medicus cathode, the weight per square cm of surface of the matrix material was measured to be 13 mg/cm^2. If one assumes that:

- The evaporation rate of Ni and earth alkalis is the same (which is unlikely, since BaO has a higher melting temperature than Ni).
- The evaporation rate is independent on the emitted current density, then the maximum attainable life can be calculated as shown in Table VIII.

Table VIII. Expected Life of the Medicus Cathode.

Temperature [°C]	Life [10^{3}h]
750	300
850	25
950	1.2

Thus, an increase of the operation temperature by 100°C will reduce the life by more than a factor of 10.

A life test with a cathode fabricated by G. Medicus (Cathode 134A-2) has been made at a current density of .5 A/cm^2 in cw operation. After 1100 hours of operation, the cathode was subjected to air, and reinserted into the test tube after 24 hours. After 3300 hours, the current density emitted was still

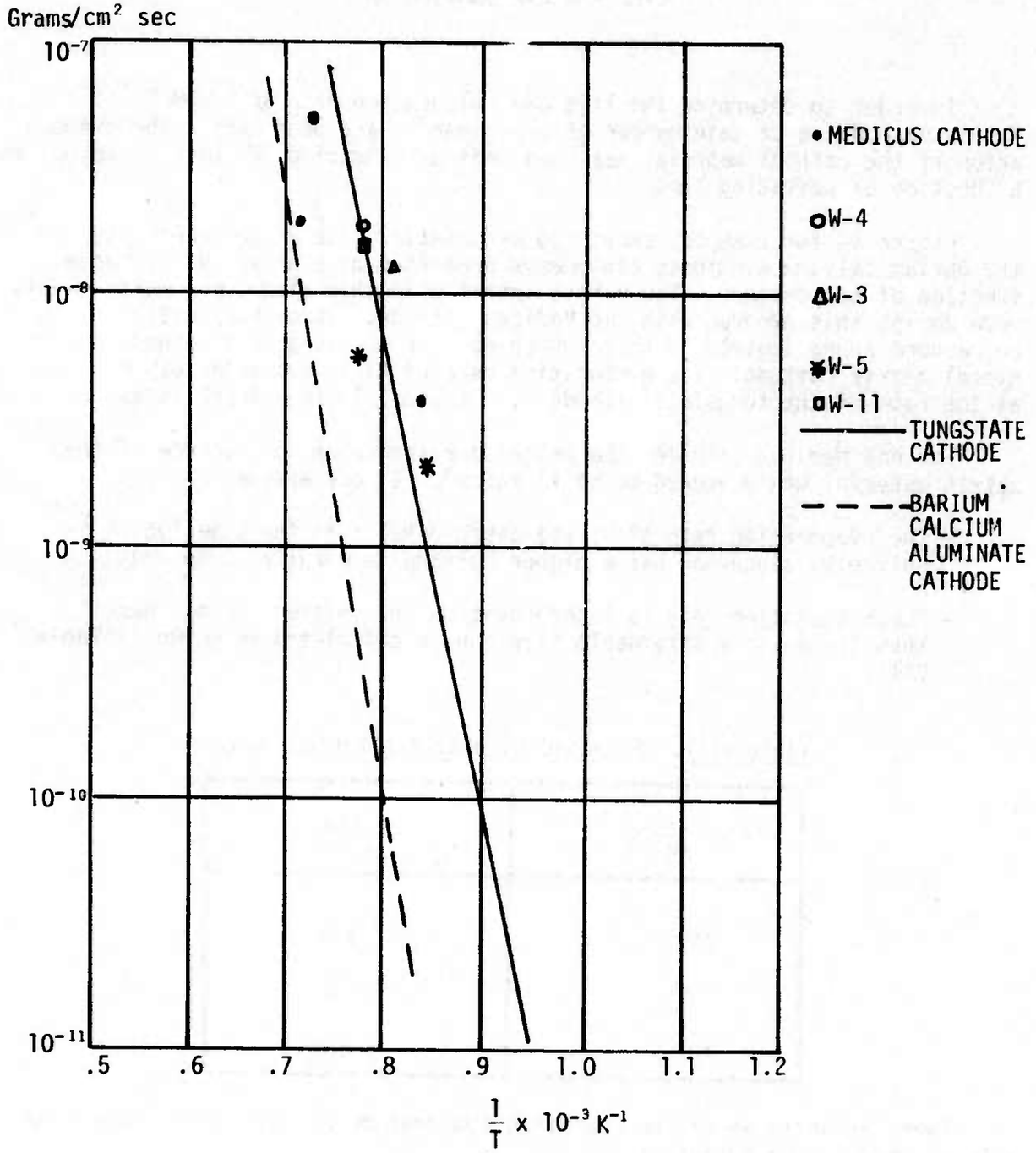


Figure 44. Evaporation Rate Versus Temperature

the same. However, the Richardson work function did change from 1.18 eV to 1.10 eV during this test (see Figure 45).

Furthermore, the cathode W-5 was tested for 53 hours (heater failure) at a minimum current density of 2.5 Amps/cm^2. Figure 46 shows the current density as a function of time. It is believed that the cathode was not fully activated at the beginning of the tests.

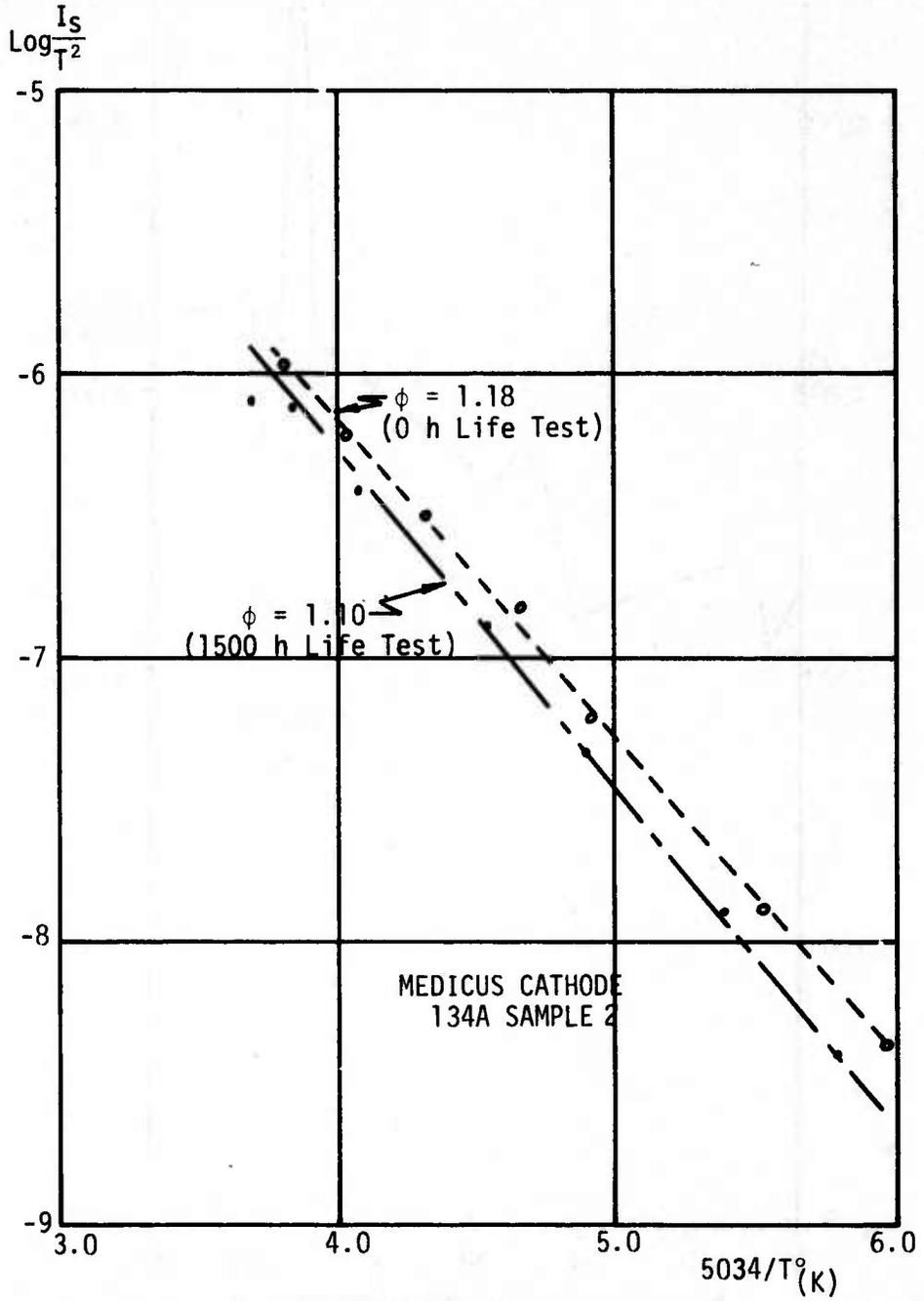


Figure 45. Richardson's Curve for G. Medicus Cathode 134A Sample #2 from 0 Hours Life Test to 1500 Hours.

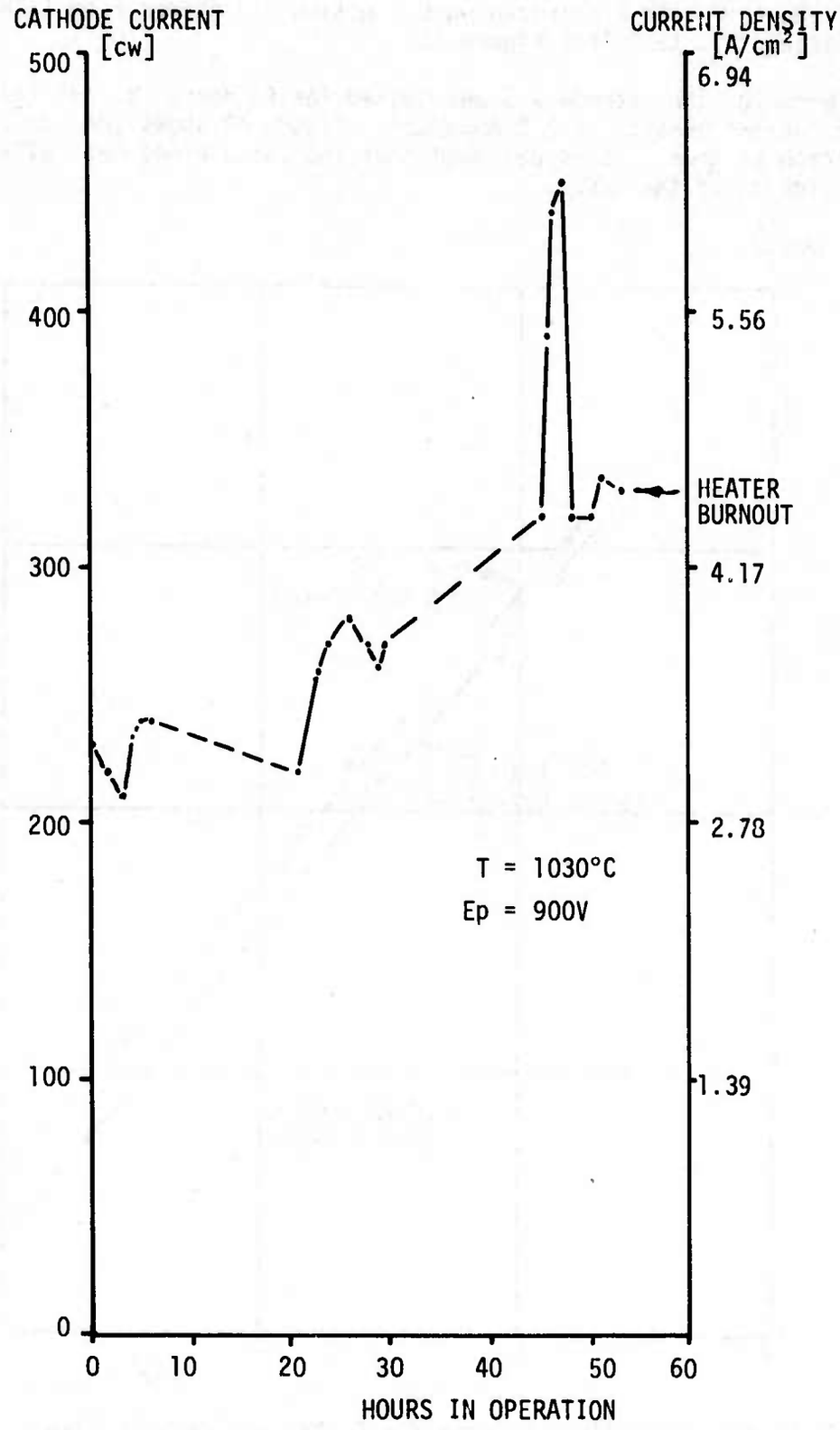


Figure 46. W-5 Operation in C.W.

SECTION VII

POISONING

No real systematic measurement on poisoning of the Medicus cathode has been made. Only some observations are reported here, which are related to poisoning of the cathode. The Medicus cathode 134A1-2 test vehicle was opened to air as reported in Section VI, and resealed and reevaluated after 24 hours of exposure to air. The current density measured was relatively low but did not change (.5 Amps/cm^2).

During the outbaking cycle of the test vehicle, traces of HCl were detected with a mass-spectrograph (probably due to improper cleaning of the vac-ion pump, see Figure 47). Also, the cathode mounted in this test vehicle was activated without the voltage on a vac-ion pump. In spite of these recordings, a current density of 10 Amps/cm^2 at a temperature of 910°C was obtained. However, for a cathode outbaked in an atmosphere of relatively high amounts of HCl (Figure 48), the emission current was only of the order of 1.5 Amps/cm^2. These observations and others have shown that the Medicus cathode is relatively insensitive to environmental conditions.

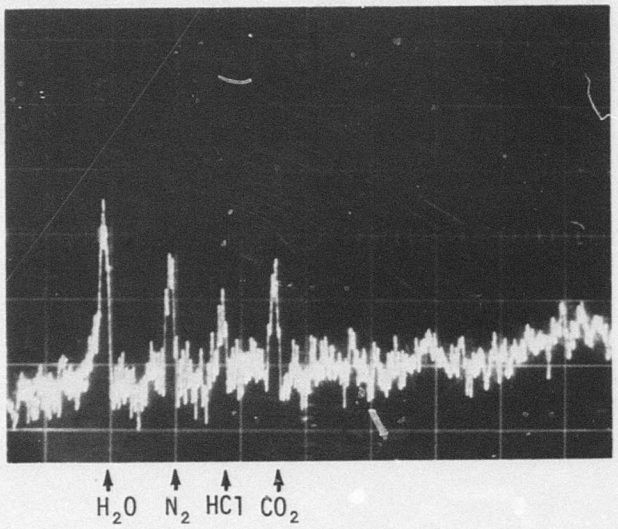


Figure 47. Mass Spectrograph with Small Traces of HCl/ (Good Emission).

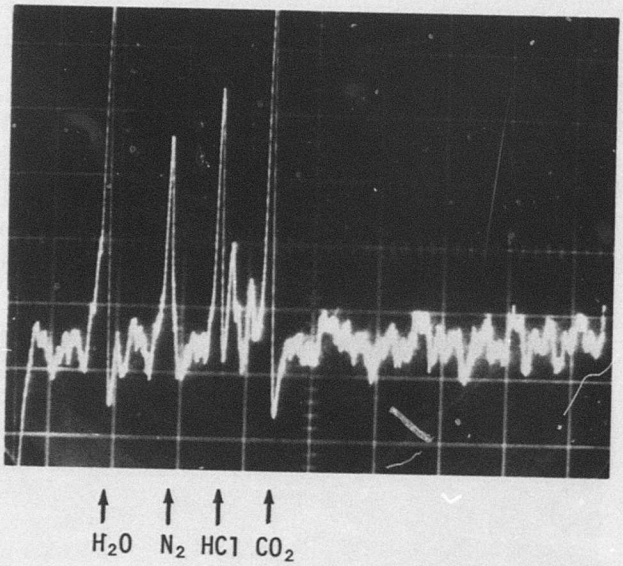


Figure 48. Mass Spectrograph of Warnecke Cathode with Large Traces of HCl (Poor Homogeneity).

SECTION VIII

REMAINING PROBLEMS

During this program, a certain number of problems have been resolved, especially related to the fabrication of the cathode material. It is believed that the problems related to "cauliflowers", "asparagus", etc., have been resolved and that the cathode, when fabricated and handled under well controlled processes and conditions, can emit with high current emission densities in cw operation, and do exhibit the advantages expected, such as emission homogeneity, decay, etc. However, two main technical problems which are directly related to the application of the cathode material are still unresolved, namely:

8.1 The Activation

The activation of the cathode has been found to be difficult and unpredictable. A large number of different activation cycles have been used, starting from the "classical" activation cycle for oxide cathodes and finishing with argon discharges (sputtering) at a few mm of pressure. The results have been more or less successful, sometimes frustrating. However, this problem is not unique to the Medicus Matrix cathode, since the same problem has been known to exist with other nickel matrix cathodes. The use of activators, as generally used, should resolve this problem and should be a subject of study in the future.

8.2 The Reliability

Although the reproducibility of the cathode material has been shown to be possible, the reliability of the cathode remains still one of the major problems to be resolved. For example, Figure 46 shows that, during a life test of more than 50 hours, the emission current density can vary between 2.5 Amps/cm^2 and 5.5 Amps/cm^2. However, it should be pointed out that such observations have also been made with other cathodes, especially during their development phase.

Other problems related to the cathode are more of a physical nature. These are:

8.3 Work Function Variations:

As mentioned above, a relatively high spread and variation of the work function has been observed from cathode to cathode. The conclusion drawn from the measurements and observations still leads to questions which remain unanswered. The variation of the Schottky plots are not yet understood. Why do some cathodes exhibit a metallic cathode behavior and why do some (or the same cathodes under different conditions) exhibit a more semiconductor-like cathode behavior?

8.4 The Hardening (of the Cathode)

The high ductility of the Medicus cathode material is one of the expected advantages. While some cathodes do exhibit the relatively high softness expected, other cathodes did exhibit a hardness which was not expected, and some did show an increase in hardness with time (aging). It is believed that this problem is related to the annealing and rolling cycles, and that a more careful control of these cycles may result in more reproducible results.

It should be understood here that these problems (discussed above) are typical of a cathode under development, and it was not surprising to find some signs of irreproducibility in the fabrication of the Medicus Matrix cathode. Other cathodes have shown to exhibit the same problems during their development, and these same problems have been solved before the take on of a production of the cathode.

The results obtained so far have shown the potentials of the Medicus Matrix cathode material, and have demonstrated the possibilities of a newly developed cathode. The remaining problems can be resolved without any doubt.

SECTION IX

THE MEDICUS MATRIX CATHODES AND CONVENTIONAL CATHODES

The high ductility of the Medicus Matrix cathode is one of its main advantages which leads directly to an inexpensive cathode fabrication in high production quantities: the plasticity of the cathode can be exploited especially when highly complex geometric cathodes have to be fabricated.

A comparison of the Medicus Matrix cathode material to other existing and commercially available cathode is difficult because of the following reasons:

- The Medicus cathode is still in the development phase, while other existing cathodes have completed their development cycle and are in a production phase. The existing cathodes meet well defined specifications, which depend strongly on the cathode in question. For example, the "normal" oxide cathode operates at 750-850°C with a relatively low emission current density in cw operation (<.5 Amps/cm^2). The oxide cathode is also fragile and generally do not exhibit the ruggedness under environmental conditions as required by certain applications. The Tungsten impregnated cathode, however, is more rugged, operates at higher temperatures (1050°-1200°C), is more expensive and less homogeneous in its emission pattern.

- No real quality factor of a cathode exists, since the applications and the use of the cathodes are so different.

- Published data on existing cathodes are incomplete; thus, a full comparison is difficult, sometimes impossible. For example: Cathode temperatures are mostly not specified in the literature with respect to the measurement technique. The real (true) temperature and the emissive (brilliance) temperature may differ as much as 100°C at around 1000°C, depending on the surface condition of the cathode (roughness, emissivity, etc.). Another example is given by the words "pulse conditions". The emission of the cathode is generally a function of the pulse width and the duty. Both values are not always given in the literature.

In the following, an attempt is made to compare the existing cathode with the Medicus cathode, and this comparison may lead to heavy discussions between cathode manufacturers.

9.1 Cathodes Under Pulse Conditions

Peak pulse current densities of the order of 100 Amps/cm^2 have not been observed as yet with the Medicus cathode: it is believed that those current densities, as observed with oxide cathodes, will not be obtainable with the Medicus cathode material. The maximum current density observed is of the

order of 25 Amps/cm^2. However, this value does not depend as drastically on the pulse width (1 μs to 500 μs) as it does for other cathodes, especially the BN-cathodes. The decay of the current during the pulse is much less than observed with BN or regular oxide cathodes. Figure 49 shows the characteristics of different cathodes operated with about 100 μs pulse width.

- Figure 49a. Impregnated cathode, after W. Kohl[2].
- Figure 49b. Medicus Matrix cathode, made by Warnecke.
- Figure 49c. Commercially available Tungsten impregnated cathode (Spectra-Mat).
- Figure 49d. BN-cathode, Beck[4].

A current density of 10 Amps/cm^2 in the space charge limited region can be obtained at 850°C with the Medicus Matrix cathode, at 1000°C with the BN-cathode (Beck[4]), at around 1100°C with the Spectra-Mat cathode (tungsten-impregnated), and at 1130°C (or higher) with the Phillips impregnated cathode (W. Kohl[2]).

Figure 50 shows the current density observed for different cathodes as a function of cathode temperature. The point representative for the French Matrix cathode corresponds to the sparking current measured on this cathode.

9.2 Cathodes Under CW-Conditions

Dudley and Hick[20] have reported the observation of a current density of 30 Amps/cm^2 on an impregnated cathode (Aluminate or Tungstate) in cw-operation, a value which corresponds to those observed on tungstate cathodes by Bondley[16]. Such a high current density has not been observed with the Medicus Matrix cathode, with which a cw-current density of 12 Amps/cm^2 has been observed. The following temperatures have been measured to be necessary for obtaining 10 Amps/cm^2 in cw-operation:

- 1000°C (true) for the Medicus cathode.
- 1100°C (true) for the impregnated cathode.
- 970°C (emissive, brilliance) for the tungstate cathode[16]

Figure 51 shows some current densities achieved as a function of temperature (cw-operation). Notice that some remarks have been made above concerning the current density measured on a Medicus cathode fabricated by Spectra-Mat (see Section 5.4).

9.3 The Barrier Resistance

The barrier resistance of the Medicus Matrix cathode has been found to be much smaller than the barrier resistance of nickel-matrix-cathodes: the temperature of the Medicus cathode has been found to decrease with increasing emitted current. Such a behavior, however, has also been found with tungstate cathodes

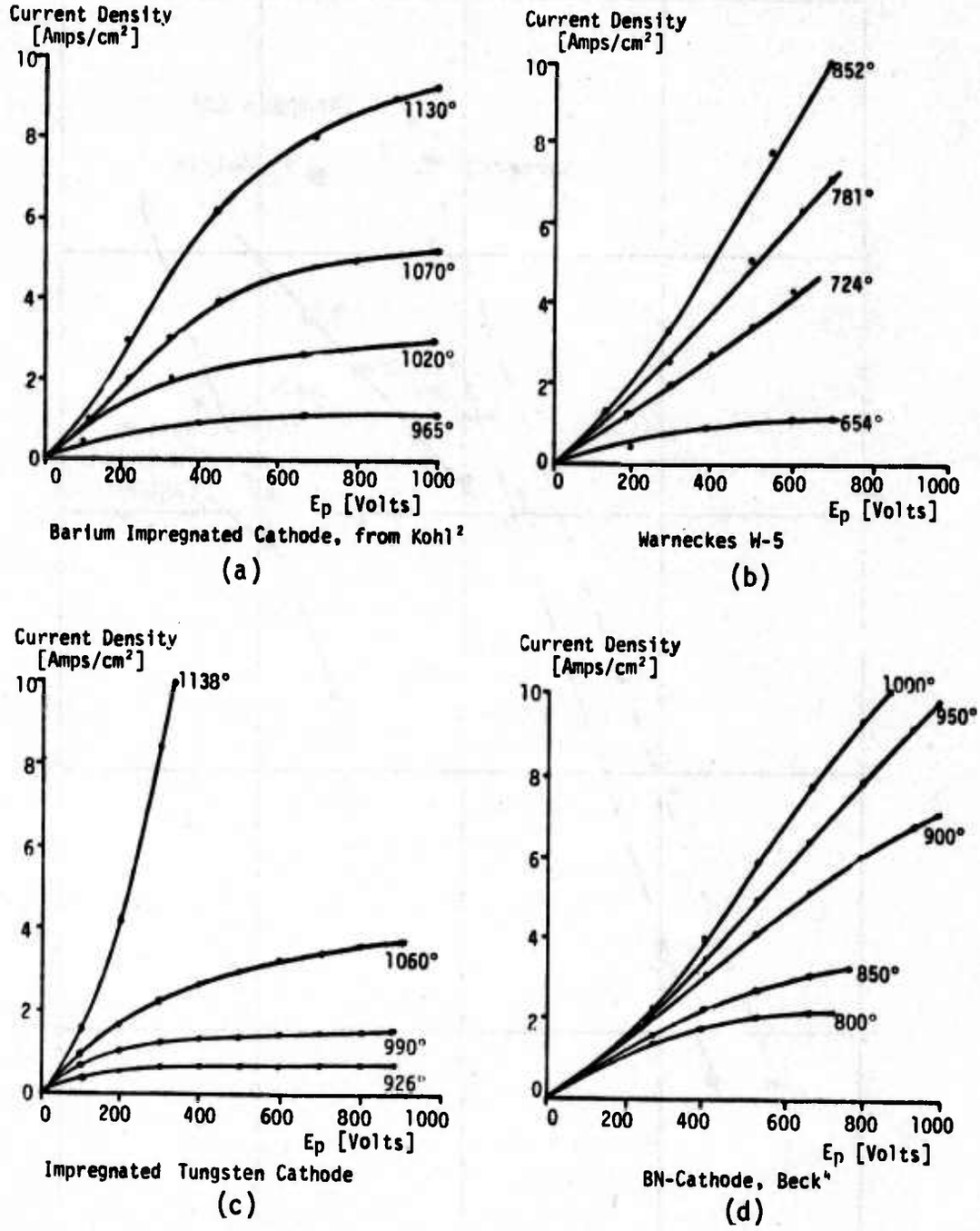


Figure 49. Current and Voltage Characteristics of Different Temperatures for Different Cathodes.

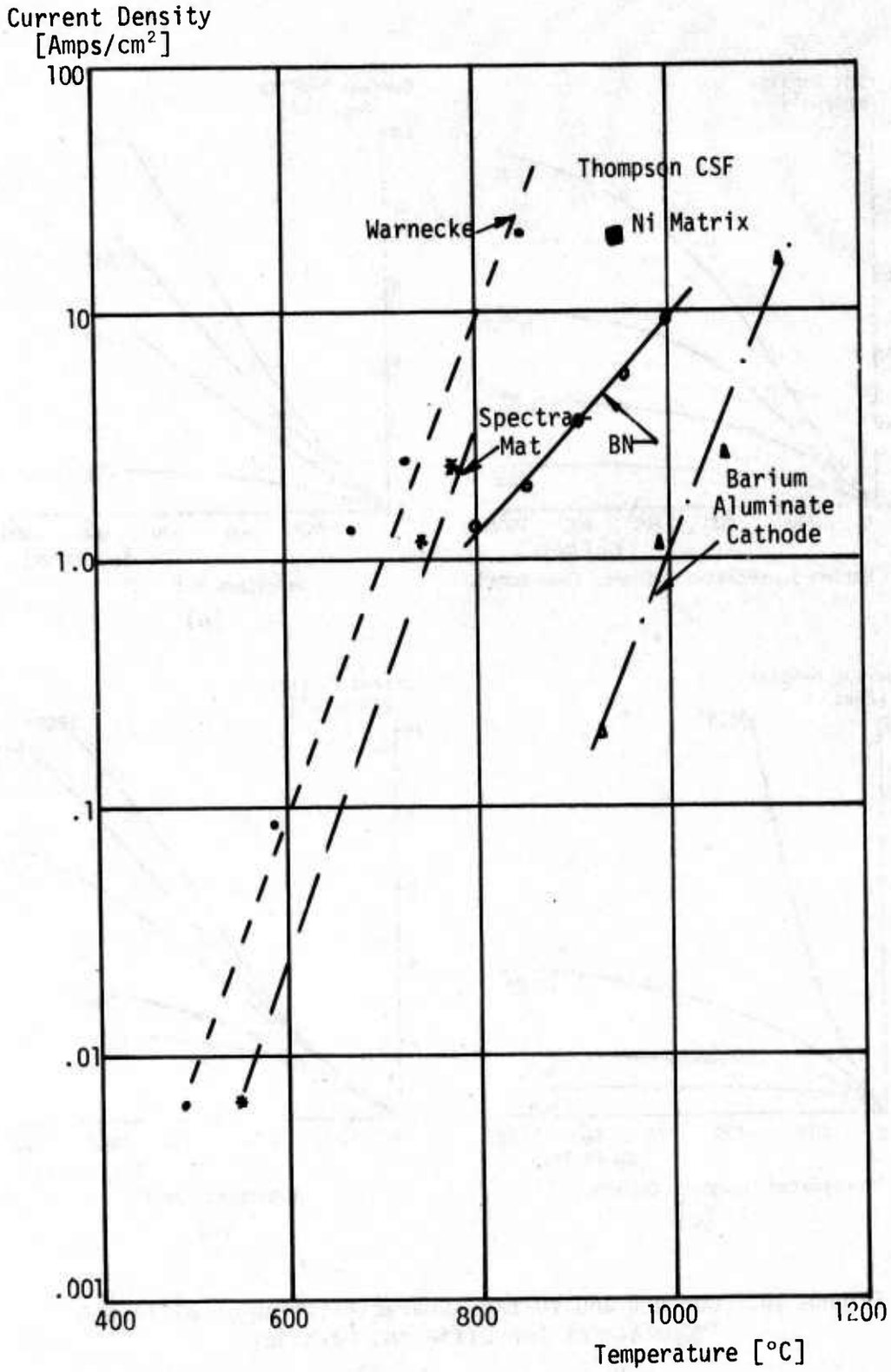


Figure 50. Saturated Current Density versus Temperature for Different Cathodes (Pulsed Conditions $\tau \simeq 100$ μsec).

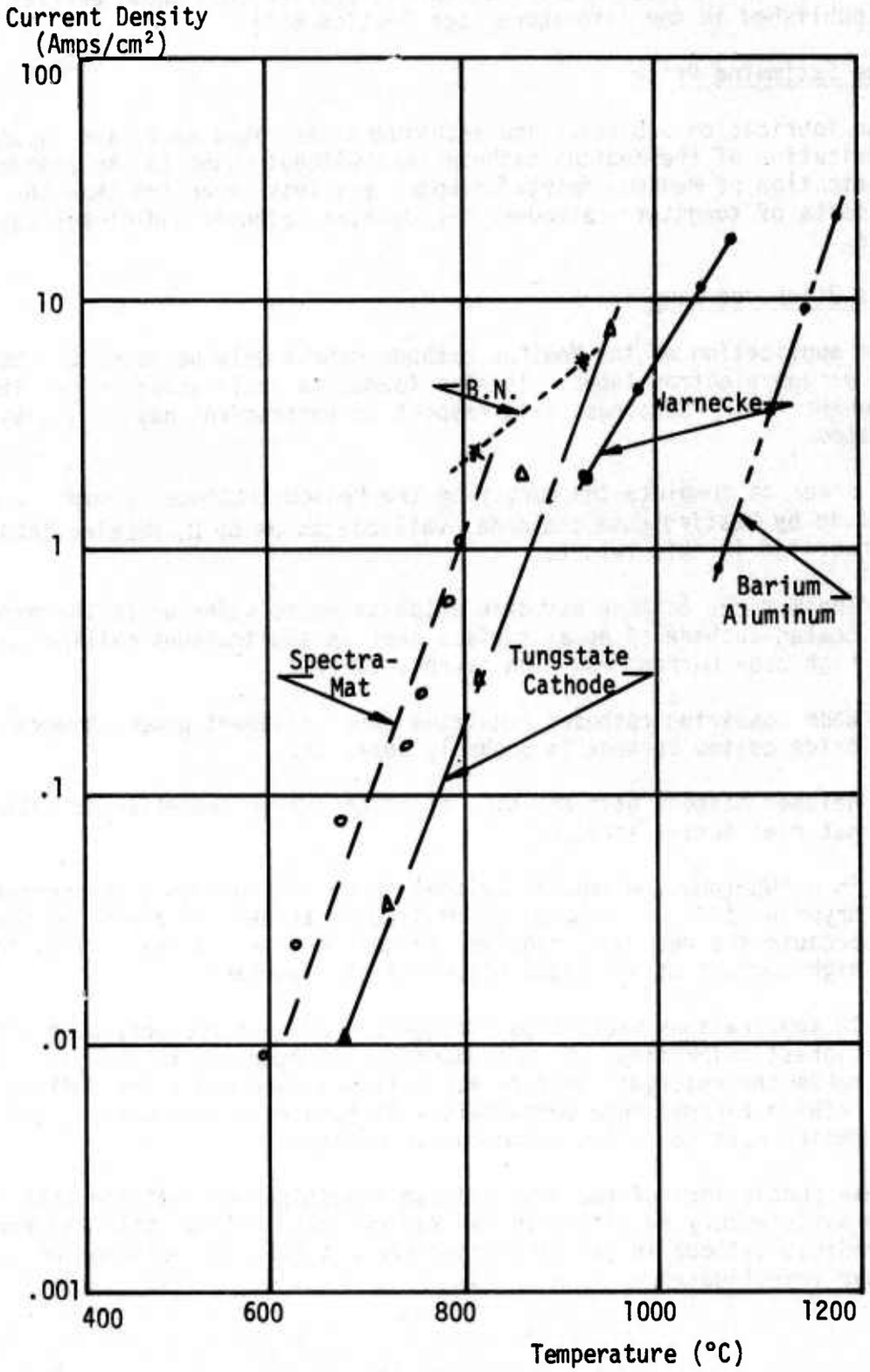


Figure 51. Saturated Current Density versus Temperature for Different Cathodes in CW Operation.

and with impregnated cathodes. Furthermore, it is believed that the barrier resistance of the Medicus Matrix cathode is smaller than those barrier resistances published in the literature (see Section 5.6).

9.4 The Estimated Price

The fabrication processes and techniques described above and necessary for the fabrication of the Medicus cathode lead without doubt to the statement that the fabrication of Medicus Matrix cathodes are less expensive than the fabrication costs of tungstate cathodes, impregnated cathodes and nickel matrix cathodes.

9.5 Gas Discharge Lamp

The application of the Medicus cathode cannot only be found in the domain of high vacuum electron tubes. It also found its application in gas discharge lamps, where their ruggedness with respect to environment has been greatly appreciated.

In order to complete the survey on the Medicus cathode, a summary of a report made by Westinghouse and made available to us by D. McLaine (AFAL) will be incorporated in this report.

- "The Medicus cathode has been established as superior to the oxide coated cathode of equal surface area in applications calling for high peak current and high average current.

- When comparing cathodes requiring equal filament power, however, the oxide coated cathode is probably superior.

- Neither cathode gave any sign of poisoning or depletion of cathode material during service.

- In a PWS (power waveguide switch) to be filled with high-pressure Krypton (100 mm or more) the Medicus cathode will always be used because the reservoir problems do not pertain and the ability to give high current at low anode potential is important.

- In applications where high voltage and/or fast recovery time are the highest priorities, the preponderance of hydrogen in the gas fill makes the reservoir performance critical, and until the Medicus cathode becomes more compatible with good reservoir action, the choice must go to the oxide-coated cathode."

These conclusions of the Westinghouse investigators indicate that there are some satisfactory results with the Medicus cathode, but that the phenomena of the Medicus cathode in gas discharges are not fully understood and should be further investigated.

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ACKNOWLEDGEMENTS

The authors would like to acknowledge and extend sincere thanks to Mr. W. Friz of AFAL, to Dr. G. Medicus of AFAL for the discussions with him, and to Dr. O. Doehler for major contributions and fruitful discussions throughout the program.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1976 — 657-630/617