

# Modern dispenser cathodes

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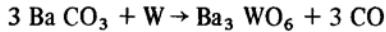
**Abstract:** The paper is a review of tungsten-base dispenser cathodes. Particular emphasis is placed on the many factors that contribute to the performance of a dispenser cathode. The review includes a history of the evolution of the modern dispenser cathode, fabrication techniques and their influence on cathode performance, state-of-the-art performance characteristics for various types of dispenser cathodes and possible future developments for dispenser cathodes.

## 1 Definition and scope

The modern dispenser cathode consists, essentially, of a strongly-bonded, continuous metallic phase of a refractory metal or metals, interspersed uniformly with the emitting material. The porous metal matrix acts as a reservoir from which the emitting material can diffuse to the surface, maintain an active layer and, consequently, provide a low work-function surface for the thermionic emission of electrons. This definition excludes oxide-coated cathodes, pure metal emitters and thoriated tungsten. Cathodes covered extensively in the review are Philips 'B' and 'M', barium scandate, barium tungstate and iridium matrix cathodes.

## 2 Evolution of the modern dispenser cathode

The family of modern tungsten dispenser cathodes traces its roots back to the early oxide cathode which was  $(\text{Ba Sr}) \text{CO}_3$  sprayed onto a nickel base. The oxide cathode history, manufacture and characteristics are treated extensively in the two volume work by Hermann and Wagener [1]. The first stage in the development of the modern dispenser cathode was the transition from an oxide coating on nickel to  $(\text{Ba Sr}) \text{CO}_3$  in a cavity behind a porous tungsten plug. The new cathode was termed the 'L' cathode and its development was attributed to Philips Research Laboratories in Holland around 1950 [2]. The L provided good emission-current capability and long life but had several disadvantages. It proved difficult to make a barium vapour leak-tight seal between the porous tungsten emitter and the molybdenum support body. Obtaining uniform cathode temperatures was difficult because there is little heat transfer through the cavity containing the emissive mix to the porous tungsten plug. Further, it was found that outgassing and activation processing had to be carried out in a narrow temperature range for good emission. Attempts to impregnate porous tungsten with  $(\text{Ba Sr}) \text{CO}_3$  failed because of the reaction



$\text{Ba}_3 \text{WO}_6$  is a nonemitting compound and no free barium is produced [3]. The base metal for dispenser cathodes became exclusively tungsten as these cathodes showed markedly superior dimensional stability compared to nickel cathodes.

Hughes, Coppola and Rittner [4], working at the North American Philips Company in New York, found that a pressed cathode made from barium aluminate and tungsten powder was vastly superior to the L. The barium aluminate was approximately 70% BaO to 30%  $\text{Al}_2\text{O}_3$ , prepared by mixing barium carbonate with aluminium oxide and firing the mixture at about 2000°C to form the aluminate and free the mixture of the carbonate. This arrangement solved the problems associated with critical processing and activation temperatures.

Levi and Hughes [5], in New York at the North American Philips Company, found that further improvements could be made if the cathode was first formed from porous tungsten and then impregnated with barium aluminate. This type of cathode could be easily machined to close mechanical tolerances, had better dimensional stability than pressed cathodes, and the emitter could be made much smoother than pressed emitters. This cathode became known as the Philips 'A' cathode and is attributed to Levi and Hughes in about 1952 [6].

Levi then discovered that additions of calcium oxide to the impregnant reduced the barium sublimation rate and greatly enhanced the emission properties [7]. The cathode was termed the Philips 'B', developed in about 1955, and is still the most widely used cathode today. The impregnant is 5 BaO: 3 CaO: 2  $\text{Al}_2\text{O}_3$  and is sometimes referred to as simply 5-3-2. The 5-3-2 is the most common mix but other variations are in widespread use (i.e. 3 BaO: CaO:  $\text{Al}_2\text{O}_3$  and 4 BaO: CaO:  $\text{Al}_2\text{O}_3$ ).

Scientists in Holland, in around 1964, discovered that overcoating the B cathode with a thin layer of osmium, iridium, ruthenium or rhenium greatly enhanced the emission properties [8]. The effect was verified by scientists in the United States [9]. As is well known, the emission level from a cathode is a function of the work function of the emitting surface: the lower the work function, the higher the emission level. It was found that a substantial reduction in the work function of the emitting surface of a tungsten-based dispenser cathode could be obtained by the addition of a porous coating of certain refractory metals. These metals have work functions which are actually higher than that of tungsten but, nevertheless, the overall work function is lower than that of a tungsten base alone. Surprisingly, it turns out that the overall work function of the emitting surface, containing a barium and oxygen layer on the refractory metal as a substrate, is inversely related to the work function of the pure substrate itself. In other words, by employing a material for the refractory matrix surface having a higher work function than that of tungsten, the overall work function of that surface with the barium monolayer is less than that of the comparable tungsten surface. The results of this effect are very impressive giving a choice of either a reduction in operating temperature of up to 100°C for the same emission density as an uncoated cathode or an increase in emission of well over 300% for the same operating temperature.

Platinum and palladium are not used because they eventually poison the basic cathode. The work functions of osmium and ruthenium are in the region of 5.5–5.6 eV which makes them preferable to rhenium and iridium (5.1 eV and 5.4 eV, respectively) [8].

Later results, around 1968, describe an improvement over the use of a single refractory-metal layer [10]. It developed that a coating of osmium definitely increased emission levels but also had certain drawbacks. For instance, although cathode life was reasonable, it was not of the order of 100 000 hours as predicted [11]. Also, osmium tetroxide is very poisonous

and consequently difficult to work with. The method of osmium deposition (by sputtering) resulted in contamination of the equipment by osmium tetroxide particles. This fact ruled out the method for reasonable manufacture by semi-skilled operators. It was found that by using a coating comprising an alloy of either osmium-ruthenium or osmium-iridium the difficulties were overcome. The layer is applied by sputtering the alloy to a thickness of a few thousand Ångströms. The B cathode over-sputtered with 2000–5000 Å of osmium-ruthenium is called the 'M' cathode.

Between 1964 and 1968, the General Electric Company of Schenectady, New York, under the direction of R.J. Bondley and M.J. Slivka, developed techniques to produce a tungsten matrix dispenser cathode capable of  $8 \text{ A/cm}^2$  while operating at  $1000^\circ\text{C}$  in a close-spaced diode [12–14]. This event represented an advance in the state of the art for high current-density emitters. The emissive compound had the formula  $\text{Ba}_5 \text{ Sr } (\text{WO}_6)_2$  resulting in the term 'tungstate' which will be referred to throughout this review. The barium tungstate cathode in various forms (barium calcium tungstate, barium strontium tungstate etc.) has been known since at least 1955 [15, 16]. The early versions promised to provide high emission current at low operating temperatures. However, due to the very high evaporation rate, the cathode has not found wide acceptance in industry. Workers in the United States have improved the tungstate cathode by using impregnation techniques instead of pressing techniques [17]. The advantages of the impregnated version appear to be its significantly reduced evaporation rate and consequently longer life while maintaining the high emission-current capability.

The barium scandate cathode in various forms (pressed, impregnated etc.) has been studied by various workers since 1967 [18]. It is essentially a porous tungsten matrix containing barium scandate ( $3 \text{ BaO} : 2\text{Sc}_2\text{O}_3$ ) or barium calcium aluminium scandate [19]. The early scandate cathode was  $3\text{BaO} : 2\text{Sc}_2\text{O}_3$  with tungsten powder impressed to form the cathode. Impregnation is impractical due to the very high melting point of barium scandate. The early impregnated scandate was a mixture of  $\text{BaO}$ ,  $\text{CaO}$ ,  $\text{Sc}_2\text{O}_3$  and  $\text{Y}_2\text{O}_3$  melted into porous tungsten. This version worked well but is very expensive to manufacture due to the large quantities of rare-earth metal oxides (5.5%  $\text{Sc}_2\text{O}_3$  and 18%  $\text{Y}_2\text{O}_3$  by weight). The most recent impregnated scandate cathode is a mixture of  $\text{BaO}$ ,  $\text{CaO}$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Sc}_2\text{O}_3$  melted into porous tungsten. The  $\text{Sc}_2\text{O}_3$  is 2–7% by weight and the mixture melts at reasonably low temperatures. The scandate cathode should provide high emission current at low operating temperatures and reduced evaporation rates. Some of the most exciting results obtained from recent cathode research were based on the 'mixed-metal' matrix dispenser cathode. These cathodes are basically a porous metal matrix made of tungsten and either iridium or osmium and impregnated with barium calcium aluminate. During 1975, work in England at EMI-Varien, EMI's Central Research Laboratory, and also at Cambridge University, indicated that the same benefits which are obtained from a sputtered film of osmium or iridium on the surface of the cathode could be obtained by incorporating the enhancing material into the matrix [42]. This improvement assured the permanency of the emission enhancement by avoiding removal of the osmium or iridium by arcing or ion bombardment. Due to the known hazard of osmium tetroxide, which forms quite readily when finely divided particles of osmium are exposed to air, subsequent research concentrated on the tungsten-iridium matrix.

Experiments at the US Naval Research Laboratories have shown encouraging results with cathodes consisting of a matrix of pure iridium containing barium oxide in the pores [20]. Tungsten and iridium have been mixed successfully to lower cost. The matrix is infiltrated with water-soluble alkaline earth

salts such as Ba, Ca and Sr acetate mixtures, and is then dried and fired at high temperature to break down the acetates to oxides. These cathodes have the disadvantage that the decomposition products of the soluble organic compounds dispersed in the pores of the matrix exude as gases for long periods of time.

In summary, modern dispenser cathodes in current use in practical vacuum devices include the B, M, and scandate cathodes. The tungstate and mixed-metal-matrix cathodes are in the advanced development stage and are used in limited applications.

### 3 Fabrication techniques and their effects on cathode performance

Currently, the majority of dispenser cathodes go into devices such as cross-field amplifiers, klystrons, magnetrons, travelling-wave tubes, backward-wave oscillators, cathode-ray tubes and gas-ion lasers. Other applications include electron-bombarded semiconductor (EBS) devices and X-ray tubes. The choice of the cathode fabrication technique to be used for a particular vacuum device is determined by such factors as the environment in which the cathode is to be operated, the required emission current density, the temperature at which the cathode must be operated to obtain that emission density, and device life requirements. The emission current capability of a tungsten dispenser cathode is dependent on several variables:

- (i) emitter temperature
- (ii) work function of emitting surface
- (iii) tungsten-matrix pore size
- (iv) pore density (pores per unit surface area)
- (v) uniformity of pores.

Reliable electron current over a long period of time is a function of the equilibrium established between the rate of arrival of barium at the emitting surface and the rate of evaporation of barium from the emitting surface. The barium is produced in the pores of the tungsten matrix by the reaction of the impregnant and the tungsten. The equilibrium established at the cathode surface supports only a monolayer or less of barium on the surface. As the pores near the surface are depleted of barium, barium migration decreases with time and the monolayer becomes a partial monolayer. At the end of cathode life, when the rate of barium arrival gives a partial monolayer whose work function is too high to sustain the required emission, the cathode fails.

The arrival rate of barium can be controlled by the pore characteristic of the tungsten matrix. Numerous small pores contribute to long life by limiting the arrival rate of barium. However, high-temperature structural stability may decrease when there are excessive numbers of small pores.

#### 3.1 Raw materials

Techniques for fabricating porous tungsten with controlled pore characteristics require close control of powder particle size, particle-size distribution, particle shape and purity of the powder, sintering temperature and compaction pressure.

Interparticle friction, which controls the extent of packing of powder particles, is a function of the particle shape and surface. These variables determine the initial packing and consequently are more important parameters than sintering time, temperature and atmosphere. High interparticle friction, and hence poor packing, is found to result from oxidised particle surfaces and protuberances, such as sharp corners, characteristic of angular powder. Such poor packing results in bridging and irregularly-large pores. Table 1 lists the important characteristics of tungsten powder used for dispenser cathode fabrication. Fig. 1 is a 5000 $\times$  SEM of typical tungsten powder. Table 2 lists the important parameters of porous tungsten made from the powder characterised in Table 1.

**Table 1: Tungsten-powder characteristics**

Type	hydrogen-reduced tungstic acid		
Particle size	Fisher subsieve — average between 6.0 $\mu\text{m}$ and 8.0 $\mu\text{m}$ photometer — average between 7.0 $\mu\text{m}$ and 9.0 $\mu\text{m}$ minimum 90% between 2.0 $\mu\text{m}$ and 14.0 $\mu\text{m}$		
Shape	angular		
	Typical impurities		
Element	Maximum impurities	Element	Maximum impurities
	ppm		ppm
Al	10	Mn	10
C	10	Mo	200
Ca	10	Ni	40
Co	10	O <sub>2</sub>	1000
Cr	30	Pb	10
Cu	10	Si	10
Fe	50	Sn	10
Mg	10	Ti	20

There are two common cathode fabrication techniques; the pressing technique and the impregnating technique. Most cathodes can be made by either technique but the impregnating technique is more common.

### 3.2 Pressed-cathod fabrication

Fig. 2 summarises the pressed-cathode fabrication process. Pressed-dispenser-cathode fabrication starts by blending high-purity base powder, such as tungsten or tungsten-iridium, with an emissive mix and an activator. The emissive mix generally contains two or three alkaline earth metals, such as barium, calcium or strontium, as either oxides or carbonates. The activator most commonly used is zirconium hydride and serves to produce free barium by the reduction of barium oxide. The powders must be thoroughly mixed by ball milling and may require additional operations such as grinding, sieving or hydrogen firing before use. The cathode mix is thus ready for pressing.

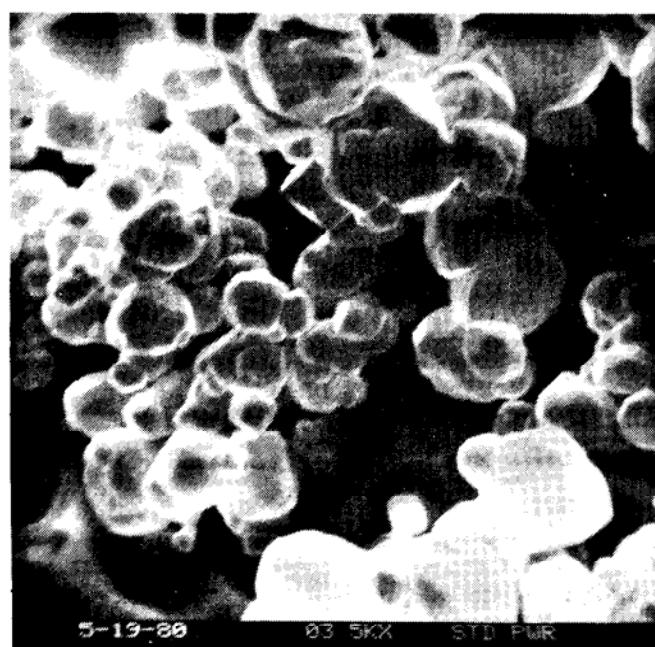


Fig 1 Tungsten powder, 5 000 magnification

The powders making up the cathode mix may be pressed directly into a molybdenum sleeve or pressed into pellets and then crimped into molybdenum cylinders. The compaction pressures for these types of cathodes may vary from  $140-1400 \times 10^6 \text{ N/m}^2$  ( $10-100 \text{ ton/in}^2$ ) depending on the cathode type.

**Table 2: Hydrogen sintered tungsten: typical characteristics**

Density	$(15.44 \pm 0.39) \text{ g/cm}^3$ (or $80\% \pm 2\%$ of the theoretical density of tungsten)
Average pore diameter	3 $\mu\text{m}$ (maximum)
Pore diameter range	1-7 $\mu\text{m}$
Mean pore area	$(16 \pm 8) \mu\text{m}^2$
Pore density	8 000-36 000 pores per $\text{mm}^2$

The cathode is next sintered for 5-60 min in hydrogen to raise the density. This step may also be used to convert any carbonates to oxides by choosing a sufficiently high sintering temperature. Typical densities of cathodes at this state of fabrication are within 50-70% of the theoretical range.

The final step in the fabrication is finishing, generally accomplished by lathe turning, which may have the advantageous side effect of helping to close the ends of the pores at the cathode surface, thereby reducing the barium evaporation rate.

base powder + emissive mix + activator

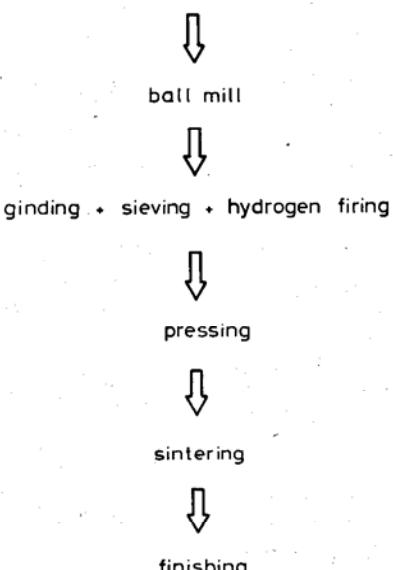


Fig. 2 Pressed dispenser-cathode fabrication process

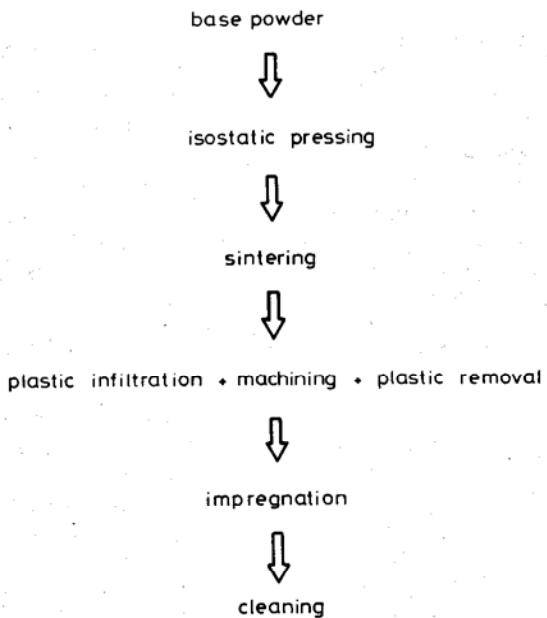
### 3.3 Impregnated-cathode fabrication

Impregnated-dispenser-cathode fabrication starts by blending high-purity tungsten or tungsten-iridium powders with particle sizes in the 2-14  $\mu\text{m}$  range. Exact particle size and distribution is important to maintain a final interconnecting, open-pore structure while optimising physical strength within 80% of the theoretical density range. The blended powder is then sealed in rubber moulds and isostatically pressed at  $140 \times 10^6 \text{ N/m}^2$  (20 000 p.s.i.). The resulting billets will possess a density of approximately 60% of the theoretical level and subsequent sintering in a hydrogen atmosphere at  $2500^\circ\text{C}$  for 30 min will raise the density to the desired 80%.

The next step in the cathode fabrication process is machining the sintered billet to the desired cathode shape. The sintered billet must first be infiltrated with an inert plastic filler or pure copper. This is done to act as a lubricant during machining and to maintain an open-pore structure. Ordinary lathe turning and milling operations may then be performed with relative ease.

With the tungsten machined to the correct shape, final fabrication of the cathode may be effected following complete removal of the plastic filler. This is accomplished by an air firing at approximately  $250^\circ\text{C}$  or the copper is removed by a vacuum firing at  $1700^\circ\text{C}$ . The cathode is then ready for the impregnation process.

The impregnant is melted into the porous tungsten in a hydrogen or inert atmosphere. The cathodes must be weighed before and after impregnation as a quality-control measure to insure adequate impregnation. A final cleaning process to remove excess surface impregnant is accomplished by grit blasting with 220 mesh alumina in a stream of nitrogen, or by polishing with 500 grit alumina paper. This process completes the impregnated-cathode fabrication process. The procedure is summarised in Fig. 3.

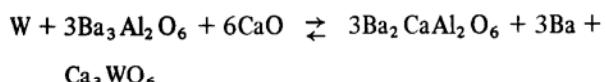


**Fig. 3 Impregnated dispenser-cathode fabrication process**

#### 3.4 Impregnant

There are many factors which influence the performance of dispenser cathodes. One of the most important influences on evaporation and emission properties is the emissive mix or impregnant composition. Over the years, various emissive mixes have been proposed to achieve high emission current densities, low sublimation rates and long life. Barium oxide ( $\text{BaO}$ ) has been the principally preferred emission material for many cathodes. However, barium oxide is very hygroscopic and in normal atmosphere readily converts to barium hydroxide and eventually to barium carbonate. Consequently, many cathodes include barium oxide in combination with other materials whereby the barium oxide is stabilised. Materials that have been suggested are alkaline earth-metal silicates, aluminates, thorates, berylliates, borates, tungstates and scandates. Of these materials, barium aluminates have been used most extensively with recent attention to the scandates and tungstates.

When it became known [21] that enhanced cathode performance could be achieved by the substitution of calcium oxide for part of the barium oxide, barium calcium aluminate dispenser cathodes were used. In the barium calcium aluminate, which is found to consist of three phases ( $\text{Ba}_3\text{Al}_2\text{O}_6$ ,  $\text{Ba}_2\text{CaAl}_2\text{O}_6$  and  $\text{CaO}$ ), a chemical reaction takes place at the operating temperature of the cathode, probably in accordance with the equation



which ensures an adequate supply of barium to the emitter surface.

Barium calcium aluminate may be fabricated by converting a mixture of barium carbonate, calcium carbonate and aluminium oxide to the aluminate. This is accomplished by air

firing at  $1100-1200^\circ\text{C}$  for a time sufficient to drive off all  $\text{CO}_2$ . The resulting impregnant is thoroughly ground in a mortar before use. The same impregnant may be formed by using ammonium carbonate to coprecipitate barium carbonate, calcium carbonate and aluminium oxide from barium nitrate, calcium nitrate and aluminium nitrate. The carbonates are usually reduced to oxides before use to avoid severe oxidation of the porous tungsten body during  $\text{CO}_2$  outgassing. Three common barium calcium aluminate impregnant compositions are described in Table 3. These types of impregnant can be

**Table 3: Barium-calcium-aluminate impregnant composition**

	$\text{BaO}$	:	$\text{CaO}$	:	$\text{Al}_2\text{O}_3$
Molar ratio	4	:	1	:	1
Molar weight %	79.5		7.3		13.2
Molar ratio	3	:	1	:	1
Molar weight %	74.4		9.1		16.5
Molar ratio	5	:	3	:	2
Molar weight %	67.3		14.8		17.9

used in tungsten-iridium matrix cathodes, pure tungsten matrix cathodes and M type cathodes.

Various barium tungstate compounds are reduced by tungsten, under cathode operating temperatures, and thereby dispense barium to the emissive surface of the cathode. The preferred emissive mix from this family is  $\text{Ba}_5\text{Sr}(\text{WO}_6)_2$  or, alternatively,  $5\text{BaO}: \text{SrO}: 2\text{WO}_3$ .  $\text{Ba}_2\text{CaWO}_6$  is also a good emissive mix. Barium strontium tungstate is prepared from stoichiometric quantities of reagent-grade barium carbonate, strontium carbonate and tungsten trioxide. The powders are ball-milled wet with methanol, the resulting slurry is filtered and the filter cake is fired in a platinum crucible, in air, at  $1400-1500^\circ\text{C}$ . After cooling to room temperature, the powder is ground in an alundum mortar and refired as before. The refired powder is then ground and screened through a fine sieve before use. X-ray analysis of this emissive mix indicates a solid solution of  $\text{Ba}_3\text{WO}_6$  and  $\text{Ba}_2\text{SrWO}_6$  at a composition of 50 atomic percent. This emissive mix may be used directly as an impregnant or used in the fabrication of pressed cathodes. For pressed cathodes, the emissive mix is ball-milled with an activator such as the hydrides of zirconium or hafnium and tungsten powder. The mixture is then pressed, sintered and finally machined in the normal manner. Table 4 compares the impregnation and pressed fabrication techniques for the barium strontium tungstate cathode. It should be noted that the proportions, purity, particle sizes, mixing times, compression pressures and firing or sintering temperatures are all very critical for good emission and life properties in the finished cathode.

Another family of emissive mixes that provides high emission-current capability, low sublimation rate and long life is the barium scandate family. Barium scandate has the advantage of being less hygroscopic than barium aluminate or barium tungstate. Further, barium scandate is reduced by tungsten so that there is no need for the addition of activators like aluminum, zirconium hydride or hafnium hydride. Barium scandate is formed by air firing stoichiometric quantities of barium carbonate and scandium oxide to drive off the  $\text{CO}_2$ . Cathodes are fabricated using 5–30% by weight of barium scandate and the balance of tungsten powder. The mixed powders are pressed, sintered and finally machined in the normal manner. Barium calcium aluminium scandate can be formed by air firing barium carbonate, calcium carbonate, aluminium oxide and scandium oxide for a time sufficient to drive off the  $\text{CO}_2$ . The resulting solid solution consists mainly of barium scandium aluminate and calcium scandium aluminate. In a similar fashion, an impregnant or emissive mix can be fabricated from barium carbonate, calcium carbonate, scandium oxide and yttrium oxide. The melting points of

Table 4: Fabrication methods for the tungstate cathode

Pressed version	Impregnated version
<b>Cathode mix</b>	
a Ba <sub>5</sub> Sr(WO <sub>6</sub> ) <sub>2</sub> 325 mesh	9.14 wt.%
b ZrH <sub>2</sub> 325 mesh	1.22 wt.%
c tungsten 5 µm average	89.64 wt.%
<b>Compaction/Impregnation</b>	
60 tonf/in <sup>2</sup> by hydraulic press	melt into machined 80% dense tungsten in inert atmosphere
<b>Sinter</b>	
1500°C for 5 min, then 1840°C for 5 min in H <sub>2</sub>	1500°C for 5 min, then 1840°C for 5 min in H <sub>2</sub>
<b>Finish</b>	
machine emitting surface	final polish to clean
<b>Storage</b>	
short-term in dessicator, long-term in evacuated glass vials	short-term in dessicator, long-term in evacuated glass vials

barium calcium aluminium scandate and barium calcium yttrium scandate are below 1700°C making them very suitable for impregnants.

### 3.5 M-type cathodes

Dispenser cathodes of the M family are fabricated from porous tungsten impregnated with barium calcium aluminate. The cathode thus impregnated is coated with a thin layer of osmium-ruthenium or osmium-iridium. Coating is usually done by sputtering, although vapor deposition and ion plating have been used with success. The coating process is carried out to produce a thickness of 2000–10 000 Å and, after coating, the cathodes are fired in a hydrogen atmosphere for several minutes to further sinter the coating to the tungsten substrate. There does not appear to be any critical limit to the thickness of the sputtered layer, however, it must have a minimum thickness to prevent loss by diffusion and evaporation, and the coating must not be so thick that barium cannot be continuously supplied to the emitting surface. These limits are in the range 500–25 000 Å thick.

### 3.6 Mixed-metal matrix cathodes

A natural extension of the M type cathode was to put the metal comprising the sputtered layer into the matrix itself. This would improve the resistance of the cathode to ion-bombardment and other desputtering effects. It would further enhance the mechanical properties of the cathode by removing the fragile thin film that is sometimes susceptible to peeling. This outgrowth of the M cathode has become known as the mixed-metal matrix cathode.

Mixed-metal matrix cathodes have been made from tungsten-osmium [22], tungsten-rhenium [23], and tungsten-iridium [24]. The most suitable of these appears to be the tungsten-iridium, again due to the toxicity of osmium.

Iridium is one of the most corrosion-resistant metals known. It is also one of the hardest and most difficult to machine and has been used as an alloying ingredient to harden platinum and palladium. Cathodes may be manufactured by either pressing or impregnating techniques. However, due to the extreme hardness of billets made from tungsten-iridium or tungsten-osmium, the cathode is usually more porous, thus allowing greater infiltration by the copper or plastic machining lubricant. Unfortunately, the evaporation rate of the impregnant constituents appears to be greater, owing to the increased porosity. In general, tungsten and iridium or osmium tetroxide are mixed in about 4:1 weight ratio. This blend is then either pressed, sintered, machined and impregnated, or mixed with an emissive mix, pressed, sintered and finally machined. The optimum addition of iridium or osmium is not accurately

known nor is the mechanism by which the addition of the platinum-group metals to tungsten lowers the overall cathode work function. The particle size, distribution and purity of the osmium and iridium powders follow those of the tungsten powder discussed previously.

### 3.7 Cathodes for space

The cathode fabrication techniques discussed this far apply to general-purpose cathodes. The cathode designer may extract the best of these fabrication techniques and design a special-purpose cathode for a specific application. There are currently three major trends in these special-purpose cathodes: high emission current (4–10 A/cm<sup>2</sup> space-charge current densities), fast warm-up (3–5 s) and long life for space applications.

Cathodes for today's spaceborne microwave tube must meet stringent requirements (Table 5 shows a few of those most important). Does the cathode industry have a cathode that meets all these requirements simultaneously? Probably not. Fig. 4 shows a typical space dispenser cathode. The emitter is impregnated with 5:3:2-type barium calcium aluminate and is 20% porous tungsten. The dotted line in the Figure indicates

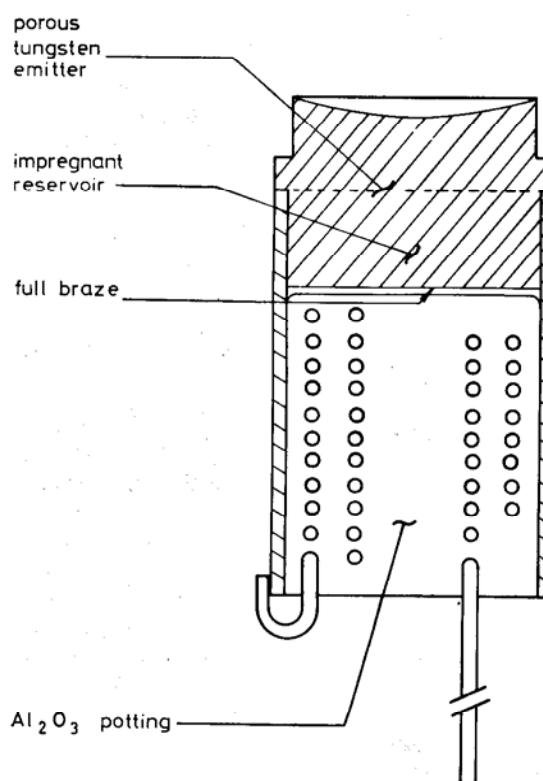
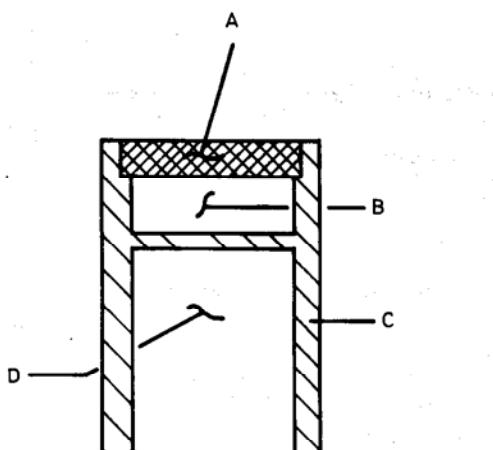


Fig. 4 Space dispenser cathode

where the emitter would end for a nonspace design. The full braze prevents the impregnant from evaporating from the rear of the emitter and reacting with the heater potting. Practical life expectancy of this cathode is 40 000 to 50 000 h with some decrease in emission current over the life of the cathode.

The ideal cathode for long-life applications may look like the cathode shown in Fig. 5. The emitter is porous tungsten



**Fig. 5 Advanced space dispenser cathode**

A: porous tungsten  
B: cavity for emission mix  
C: molybdenum body  
D: heater cavity

#### Operating mechanism:

- (i) evaporation of BaO as oxide within cavity
- (ii) streaming of BaO vapor into pores of tungsten emitter
- (iii) reaction of BaO with tungsten to produce Ba
- (iv) Knudsen flow/surface migration of Ba atoms along pores and over emitting surface
- (v) evaporation of active material from emitting surface
- (vi) electron emission from a layer of Ba-ON-O-ON-W

#### Advantages:

- (a) constant path length for Ba migration
- (b) no reaction products to impede Ba migration
- (c) substantial reservoir of emissive mix for long life
- (d) constant cathode current with life

backed by a cavity containing a source of barium oxide. The barium oxide streams into the pores of the tungsten emitter where it reacts with the tungsten to produce free barium. The barium travels along the pores and spreads over the emitter surface and electron emission results from a layer of barium and oxygen on tungsten. The advantages of this system over the impregnated cathode are: constant path length for barium migration; no reaction products clogging the pores and impeding the barium migration; a substantial reservoir of emissive mix for longer life; and an emission current that is constant with life. Some possible disadvantages to this type of cathode are that it is not as structurally simple as an impregnated cathode and it usually proves difficult to obtain a tight seal between the porous tungsten emitter and the molybdenum body.

### 3.8 Fast-warmup cathodes

In many modern electronic systems for missile applications, there is a need for electron tubes with quick turn-on capability. The heart of these electron tubes is the cathode on which these missile systems impose severe demands. System power-supply requirements dictate high thermal efficiency, launch conditions impose severe environmental requirements as well as fast warmup capability, and mission requirements demand very high reliability.

The design and fabrication of a fast-warmup-cathode assembly to meet these requirements is based on two principles of heat transfer, as shown in Table 6. The first states that the heat required to raise a mass to a given temperature is propor-

**Table 5: Requirements for space dispenser cathodes**

- 1-2 A/cm<sup>2</sup> continuous space-charge limited emission current
- 7 year life (> 61 000 h)
- no degradation of emission current during life
- minimal evaporation rate
- resistance to shock and vibration
- minimum input power requirements
- high reliability
- predictability

tional to the mass, the specific heat of the mass and the required change in temperature. The second principle states that the rate of heat transfer through a material is proportional to the thermal conductivity of the material, cross-sectional area, required temperature difference and is inversely proportional to path length. These two principles lead to the fabrication guidelines shown in Table 6.

Fig. 6 is an example of an actual fast-warmup, impregnated dispenser cathode. The support struts are pure rhenium located in three places 120° apart.

**Table 6: Fast-warmup cathode design guidelines**

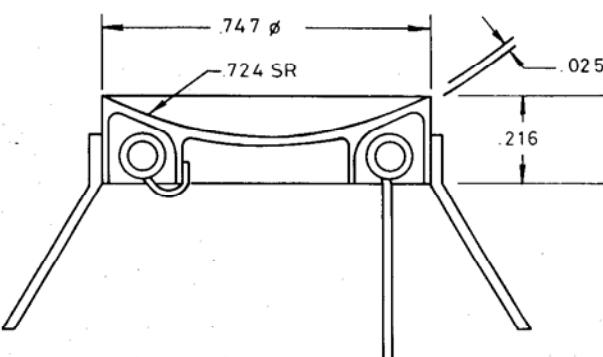
Principles	$\Delta Q = mC_p \Delta T = \rho V C_p \Delta T$
	$Q/t = KA\Delta T/L$
Guidelines	<ul style="list-style-type: none"> <li>minimise cathode mass</li> <li>minimise conduction losses</li> <li>minimise radiation losses</li> <li>maximise heat transfer between cathode and heater</li> <li>use materials of low density, low specific heat and high thermal conductivity</li> </ul>

### 4 Performance characteristics and influencing variables

Many factors contribute to the overall performance of a dispenser cathode. Some factors are internal to the cathode, such as impregnant composition, matrix porosity, material impurities and sublimation rate. Some factors external to the cathode also have considerable influence on cathode performance. Possibilities include adsorbed gases, contamination, ion sputtering of the cathode surface by arcing or electron bombardment. It is, therefore, important to consider the cathode as part of the overall vacuum device in which it must operate and not as a discrete component. Performance measured in the laboratory will certainly not be the same as performance observed in real vacuum devices. This review will discuss performance characteristics in the context of the conditions under which the measurements were made.

#### 4.1 Impregnant composition

One of the major factors governing the performance of a dispenser cathode is the composition of the impregnant. In a



**Fig. 6 Fast-warmup dispenser cathode**

Dimensions in cm

Table 7: Work functions of various cathode systems

System	$\phi = \phi_0 + \alpha T$	$\phi$ at 1450 K
	eV	eV
502	$1.53 + 5.73 \times 10^{-4}T$	2.36
532	$1.67 + 3.17 \times 10^{-4}T$	2.13
311	$1.67 + 3.07 \times 10^{-4}T$	2.12
411	$1.67 + 2.82 \times 10^{-4}T$	2.08
532 M	$1.43 + 4.35 \times 10^{-4}T$	2.06
532 scandate	$1.43 + 4.36 \times 10^{-4}T$	2.06
311 M	$1.43 + 4.25 \times 10^{-4}T$	2.05
311 scandate	$1.43 + 4.25 \times 10^{-4}T$	2.05
411 M	$1.43 + 3.99 \times 10^{-4}T$	2.01
411 scandate	$1.43 + 4.01 \times 10^{-4}T$	2.01
Tungstate	$1.14 + 5.52 \times 10^{-4}T$	1.94

xxx indicates the molar ratio of  $x\text{BaO}:x\text{CaO}:x\text{Al}_2\text{O}_3$

series of classic experiments, Dudley demonstrated the emission and evaporation properties of barium calcium aluminate impregnated cathodes as a function of the impregnant composition [25]. Fig. 7 shows how cathode emission current varies as the barium and calcium content is varied. The lower curves shows how emission varies as the BaO content is varied from 1.0 to 4.0 moles while holding the calcium oxide and aluminium oxide content constant. The curve shows that, as the barium oxide content is reduced from 4 moles to 2 moles, the emission dropped 30%, whereas below 1.5 moles the emission drops very rapidly. It appears that at least 1.5–2.0 moles of BaO are required for good emission. The upper curve shows the change in emission due to changes in the CaO content: a large increase in emission as the CaO content is increased from 0 to 1 mole, but there is little additional increase when the CaO is increased above 1 mole. Fig. 8 shows how the evaporation rate varies as the BaO content is varied: as the BaO content is reduced from 4 to 2 moles, the evaporation rate is reduced by a factor of 6. It is apparent that calcium and at least 2.0 moles of BaO are required for good emission.

#### 4.2 Matrix porosity

Fig. 9, also from Dudley's work, shows the variation of evaporation rate with tungsten matrix porosity. Increasing the

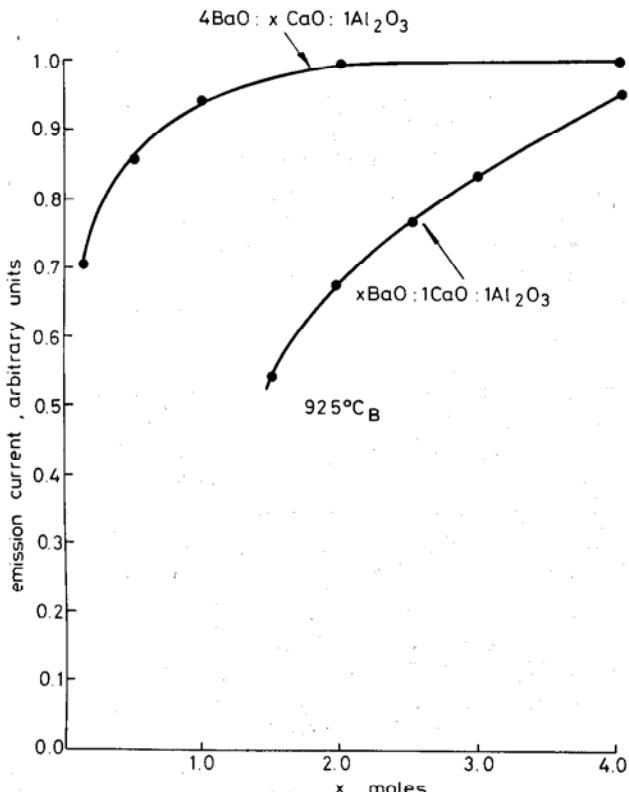


Fig. 7 Emission current against impregnant composition

porosity from 20% to 24% causes a 50% increase in evaporation rate and, conversely, decreasing the porosity from 20% to 16% causes a 50% drop in evaporation rate. Emission is relatively insensitive to matrix porosity in the  $80 \pm 2\%$  density range.

#### 4.3 Determination of thermionic properties

Before embarking on a discussion of the thermionic properties of modern dispenser cathodes, it will be necessary to define the procedures and methods used to obtain the work function and zero-field emission current.

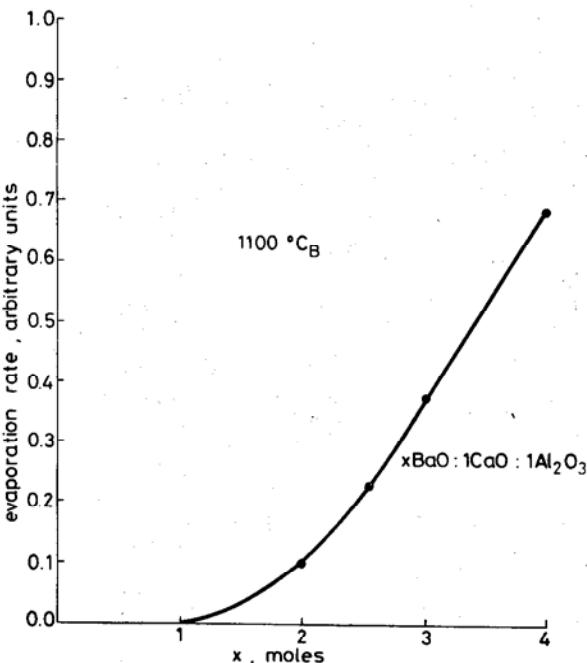


Fig. 8 Evaporation rate against impregnant composition

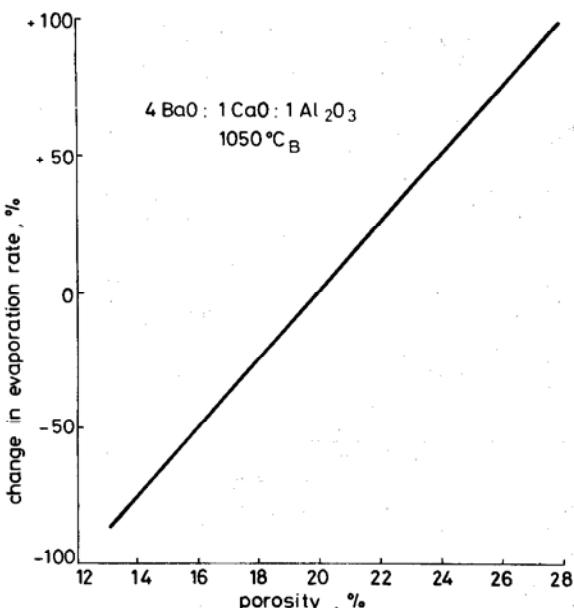


Fig. 9 Evaporation rate as a function of porosity

It is a well-established experimental fact that the thermionic emission current from nearly all surfaces can be represented by an equation proposed by Richardson [26]. The equation is of the form:

$$I = SA_0 T^2 e^{-\phi/kT}$$

Here,  $I$  is electron current,  $S$  is emitting area,  $T$  is cathode temperature,  $\phi$  is work function,  $k$  is Boltzmann's constant and  $A_0$  is a constant. A more complete statement of the Richardson

equation includes work-function variations with temperature and the Schottky effect. The equation takes the form:

$$I = SA_0 T^2 e^{-(\phi_R + \alpha T)/kT}$$

where  $\phi_R$  is the Richardson work function and  $\alpha$  is its temperature coefficient.  $e^{\phi E/kT}$  is the Schottky-effect term and accounts for the reduction of work function due to an external electric field at the cathode surface.

Ideally, one would like to measure the thermionic emission from a cathode which has a zero electric field at its surface. However, this is not possible since the presence of space charge will increase the potential in front of the cathode surface. The existence of the Schottky effect gives rise to the term  $J_0$ , the 'zero-field current density'. It is of interest to know the emission capability of a cathode without the effects of external electric fields at the cathode surface. The experimental procedure involves measuring the saturated emission current at several temperatures and plotting the measured current against the square root of the anode voltage. These plots are then extrapolated back to zero applied voltage to give the value of

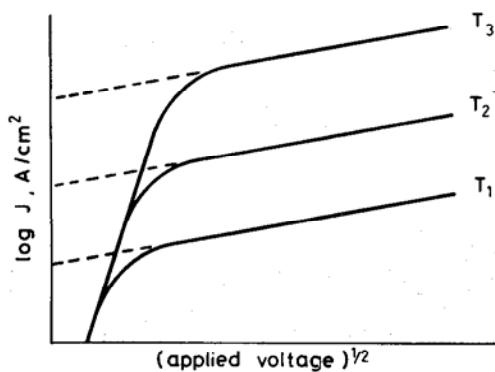


Fig. 10A Schottky plot

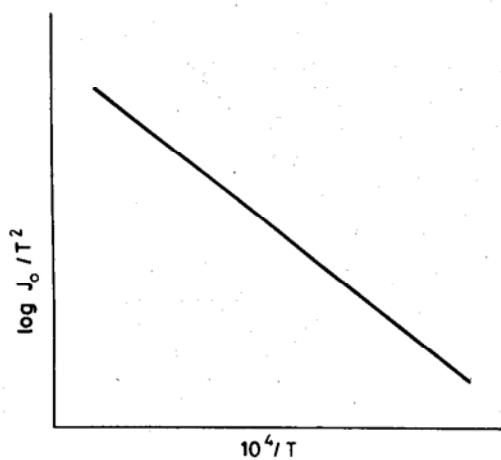


Fig. 10B Richardson plot

$J_0$ , the current density at zero electric field. Fig. 10A is an example of a Schottky plot.

A factor which is frequently of comparable importance in accounting for an increase in emission current with increasing anode voltage is the modification brought about in the non-uniform true work function by the electric field. Since the effects of a nonuniform or patchy work function usually outweigh the Schottky effect, the use of a Schottky plot to extrapolate the effective work function to zero electric field will lead to some error in  $J_0$ . On the other hand, there is no simple direct method for analysing the effect of the electric field on the patchy work function.

The work function may also be determined from the

experimental data. Richardson's equation may be written as

$$I = A_0 ST^2 e^{-(\phi_R + \alpha T)/kT} = A_0 ST^2 e^{-\alpha/k} e^{-\phi_R/kT}$$

$$\frac{I}{S} = J = A_0 e^{-\alpha/k} T^2 e^{-\phi_R/kT}$$

Taking the logarithm of both sides of the equation

$$\begin{aligned} \log \frac{J}{T^2} &= \log (A_0 e^{-\alpha/k}) + \log (e^{-11605 \phi_R/T}) \\ &= \log A_0 - \frac{\alpha}{2.3k} - \frac{11605 \phi_R}{2.3T} \\ &= \log A_0 - 5040\alpha - \frac{5040 \phi_R}{T} \end{aligned}$$

It can be seen that a plot of  $\log J/T^2$  against  $1/T$  will yield a straight line of slope  $-5040 \phi_R$  and intercept of  $-\log A_0 - 5040\alpha$ . The cathode work function can be determined from the  $T = 0$  intercept. Fig. 10B is an example of a Richardson plot. In this method  $A_0$  is assumed to have the numerical value of  $(4\pi mek^2)/h^3 = 120$ .

Generally, cathodes that behave like oxide-coated cathodes have steep Schottky slopes and cathodes that behave like pure metal cathodes have very small Schottky slopes. Depending on the Schottky slope, the  $J_0$  value may be in the space-charge limited region or the temperature limited region.

Hence, the  $J_0$  value is not a really useful design parameter for a microwave-tube designer but it is a very useful parameter for comparing performances of different cathode types. These experimental methods usually require rather high anode voltages in order to establish saturated emission and zero-field emission. The product of high voltage and high current density leads to power levels that are difficult to handle and can result in a number of phenomena that may influence emission measurements. The determination of  $J_0$  is, therefore, somewhat dependent upon the ability of the anode or electron collector to dissipate power without affecting the cathode and, consequently, the measurements are usually made on a pulse basis.

There are other experimental techniques available for evaluating the thermionic properties of cathodes. One, the retarding-potential method, similarly requires a high potential to establish the saturated emission level at high current densities [43, 44]. By reducing the cathode temperature and emission to the proper level, zero-field measurements may be made by either the retarding-potential method or the Schottky method, and the effective work function can be readily determined. However, the effective work function is measured only in a certain low temperature range and its actual value, under high-current-density operation, is determined by an extrapolation of the effective work function to the higher temperatures and higher current densities.

Some objections may be raised in determining the thermionic properties in this manner since measurements were not made at the temperature of operation nor at a current density in excess of  $1 \text{ A/cm}^2$ . All emission and work function data reported herein were reduced by the Schottky plot and Richardson line methods. A very complete treatment of the theory and practice of emitter evaluation is given in Reference 27.

#### 4.4 Determination of temperature

Since temperature is a very important factor in the thermionic emission of electrons, it is important to determine the temperature of the emitting surface with a high degree of accuracy. The most common method is by optical pyrometry.

Essentially optical pyrometry consists of matching the

brightness of the unknown surface with that of a filament in a standardised lamp. The temperature of the filament of the standardised lamp at different filament currents has been obtained by a previous calibration. Pyrometry is a very accurate method of determining temperature because the increase in brightness of a hot body with increasing temperature is about four times as large as the percentage change in temperature. The pyrometer reading does not give the true temperature directly but rather the brightness temperature (the temperature at which a black body is as bright as the emitter which is being measured). Brightness temperature is always lower than true temperature, and the conversion from brightness temperature to true temperature may be calculated from the formula:

$$\frac{1}{T} - \frac{1}{S\lambda} = \frac{\lambda \times 2.303 \log \epsilon\lambda}{C}$$

where

$T$  = true temperature, K

$S\lambda$  = brightness temperature, K

$C = 1.433 \text{ cm deg} = 14360 \mu \text{deg}$

$\epsilon\lambda$  = spectral emissivity corresponding to wavelength  $\lambda$

Fig. 11 shows a graph of optical-pyrometer temperature conversions to true temperature. All temperatures used in this review are true temperatures.

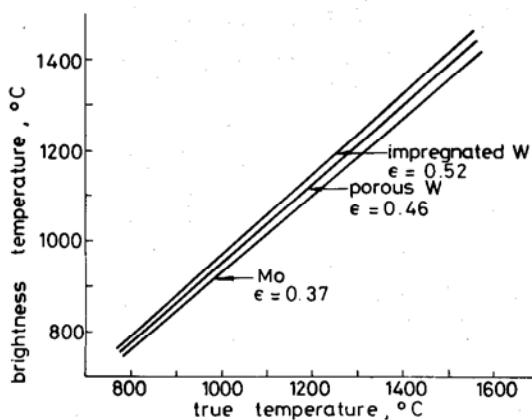


Fig. 11 Optical pyrometer temperature conversions

$\lambda = 0.65 \mu\text{m}$

#### 4.5 Life Characteristics

Emission current at a specified temperature is dependent upon the work function of the cathode surface, which, in turn, is partially dependent upon the fraction of the emitter surface covered by barium. The barium coverage on the emitter surface at a specified temperature is determined by an equilibrium condition such that the rate of evaporation of barium from the surface is equal to the rate of arrival at the surface of barium generated in the cathode pores by the reaction of the impregnant with the tungsten matrix. Early in the life of the cathode, more than enough barium is generated to sustain at least a monolayer of surface coverage because the barium is being generated in pores very close to the surface. As the pores near the surface are depleted of barium, the arrival rate of barium decreases for two reasons: longer path length and pore blockage due to impregnant reaction products. The barium depletion results in a reduced evaporation rate and also reduced surface coverage. The cathode will operate satisfactorily as long as the monolayer surface coverage is sufficient to maintain the work function. Eventually, only partial monolayer surface coverage can be maintained, the work function increases and emission current drops. These facts explain the well-known characteristics of impregnated dispenser cathodes: decreasing

evaporation rate and decreasing emission current as a function of cathode life. The current delivered by a cathode in a fixed voltage electron gun or diode decays slowly with time, the rate of decay increasing with increasing temperature. Longo [28], of Hughes Aircraft Company, has shown that the relationship between the percent of degradation per 1000 h ( $D$ ) and the cathode operating temperature ( $T$ , K) takes the form

$$D = 1.5 \times 10^{11} e^{-\frac{3.62 \times 10^4}{T}}$$

Independent results from TWTs tested by other companies fit reasonably well to the equation.

The M-type cathodes show a gradual increase in emission current at fixed gun voltages [29]. The increase levels-off after a long period of time and then begins to decrease in the same manner as the emission currents of impregnated dispenser cathodes. This somewhat contradictory behaviour can be explained by a simple theory. The osmium and ruthenium in the coating diffuse into the tungsten forming a compound that is a very good emitter. The diffusion is very gradual at low temperatures and hence takes thousands of hours to reach the optimum chemical composition. During this time, the emission current rises as the metallic composition approaches the optimum, after which point, the emission current decreases in the same manner as other dispenser cathodes.

Fig. 12 shows a plot of the expected life of a dispenser

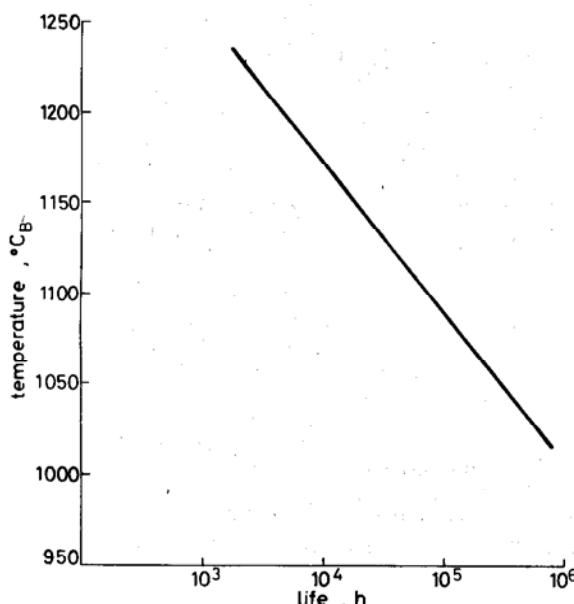


Fig. 12 Life against operating temperature for 41182 dispenser cathode

cathode against operating temperature [30]. A large number of tubes were placed on life test at elevated temperatures. The cathodes were 82% dense tungsten-matrix dispenser cathodes impregnated with 4BaO: 1CaO: 1Al<sub>2</sub>O<sub>3</sub>. Extrapolated results predict a life of 130 000 h at 1035°C<sub>B</sub>.

A series of life-test studies are being conducted by the US National Aeronautics and Space Administration, Lewis Research Center [31]. The objective has been to evaluate the performance of different cathode types by life testing under identical electrical, geometrical and vacuum conditions that realistically duplicate operating conditions in a transmitter tube. The test vehicle was designed to simulate a 12.2 GHz TWT operating at 4 kW CW. The cathode loading is 2.0 A/cm<sup>2</sup>. Cathodes tested included the B and M from Philips Metalonics, the S(411) from Semicon Associates and the tungstate from the General Electric Company. Four B-types were tested. One failed at 27 000 h and the remaining three are still operating

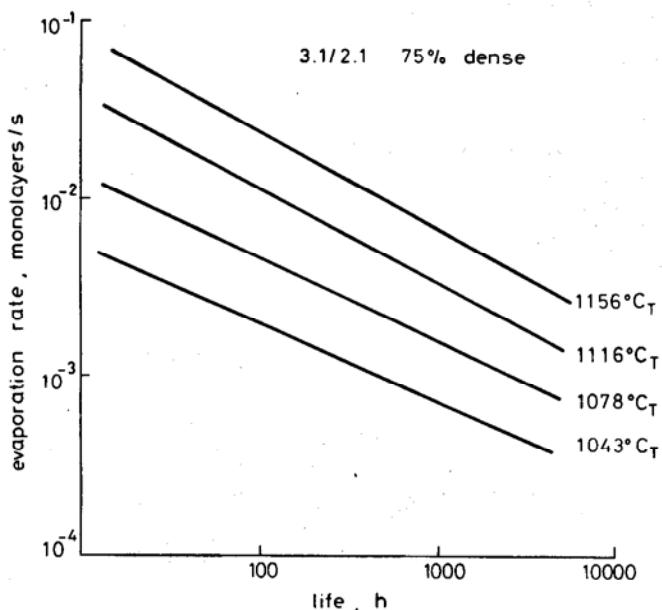
with 40 000–50 000 h life on each. During the life of the cathodes, emission activity has slowly declined. Operating temperature is 1100°C (true temperature).

Four tungstate cathodes were tested at 1000°C true temperature and all four showed severely degraded emission characteristics after less than 7000 h.

Four S-type cathodes showed a slowly decreasing emission characteristic until end of life at approximately 20 000 h. Operating temperature was 1060–1100°C (true temperature).

Four M-types are being tested at an operating temperature of 1010°C true temperature. One has operated for over 34 000 hours, one over 19 000 h and the other two have run for over 12 000 h. There is a gradual increase in emission current at constant anode voltage.

No life data yet exist, to the author's knowledge, that depicts the scandate or mixed-metal matrix cathode life capability against operating temperature.



**Fig. 13** Evaporation rate against life for a  $3\text{BaO} \cdot \frac{1}{2}\text{CaO} \cdot \text{Al}_2\text{O}_3$  cathode

#### 4.6 Evaporation-rate characteristics

Electron tubes and lasers are directly dependent upon the life of the cathode but are indirectly affected by the evaporation rates of materials sublimed from the cathode. The evaporant products can induce grid emission, electrical leakage, secondary emission, RF losses, fogged Brewster windows, and alter other tube characteristics. It is obvious that some evaporation of barium is inherent in the satisfactory operation of all barium dispenser cathodes and that a certain minimum rate is required to maintain an active emitting surface. The ultimate life of the cathode is limited by the amount of barium potentially available but the life of the device in which it is used may be shortened by the evaporant causing changes in operating characteristics or electrical breakdown across ceramic insulators. Consequently it is essential that the sublimation rate of barium dispenser cathodes be determined before the overall performance can be assessed.

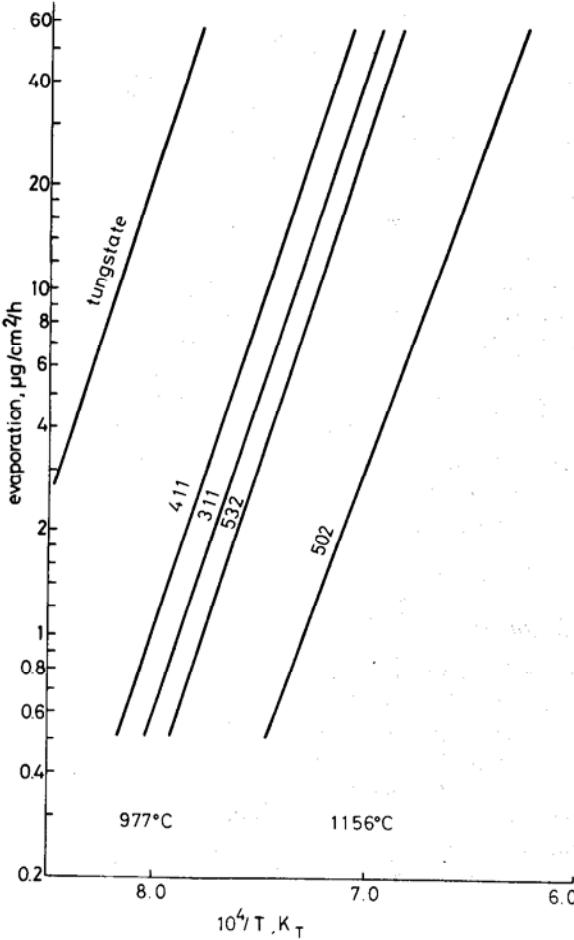
Many techniques have been employed to measure evaporation from cathodes and all have some particular disadvantage or shortcoming. A compromise must be made, based upon the sensitivity of the measurement, the accuracy and reproducibility, the complexity of equipment and procedure, and the need to identify the evaporated species.

Two methods appear to be most widely accepted. One is the quartz crystal oscillator or thin-film deposition monitor

and the other is the Becker-diode method [32–34]. Results reported here have been obtained by both methods.

A fundamental characteristic of dispenser cathodes is the rapid decrease in evaporation rate very early in life. The initial 'burst' of evaporant may be due to residual impregnant on the cathode surface or the fact that barium is produced faster and escapes more readily from pores that have not yet become clogged with impregnant reaction products. Fig. 13 illustrates the point [35]. The evaporation rate is seen to fall rapidly as a function of life and the higher the operating temperature, the more rapid the fall. Because of this characteristic, evaporation data are only meaningful if it is known at what point in the cathode life the data were taken. Consequently, most data are not instantaneous but represent an average taken over the period of time necessary to make the measurement.

Fig. 14 is a summary of various cathode types and their evaporation rates. The 502 is the Philips A plotted to show the effects of no calcium in the impregnant [36]. The tungstate is the pressed version and the data were taken using a crystal oscillator (deposition rate monitor). The barium calcium aluminate impregnated dispenser cathodes were measured using the Becker diode technique and represent an average of the first 24 h of cathode life.



**Fig. 14** Barium evaporation rates

Extensive research was conducted on the evaporation rates of barium calcium aluminate dispenser cathodes by Brodie and Jenkins, at the General Electric Company in Wembley, England in 1956 [39], using, as the evaluation technique, the Becker diode method. The main conclusions from that work and later research by other scientists lead to some fundamental principles regarding the evaporation of barium from dispenser cathodes. The evaporation rate  $E$  is related to the true cathode temperature  $T$  by an equation of the form:

$$\log E = C - \frac{5040\phi}{T}$$

where  $\phi$  is the activation energy for evaporation in electron volts and  $C$  is a constant. The evaporant consists of a mix of pure barium, barium oxide and some calcium. After the very early stages of cathode life, the rate of evaporation is inversely proportional to the square root of cathode thickness [35].

#### 4.7 Secondary electron emission

In some tube applications such as magnetrons, the contribution of secondary electron emission to the total electron emission is very important. In a magnetron many of the emitted electrons are accelerated by the RF field and then driven back against the cathode with appreciable velocity. The resulting secondary electron emission probably accounts for a majority of the total emission from the cathode, although thermionic emission is generally required to keep the tube in operation. On the other hand, secondary emission can adversely affect the characteristics of certain multielectrode vacuum tubes. Grid-controlled tubes have been found to be unstable because of secondary emission from the grid. In many circuits grid bias is developed by means of an external resistor and a small amount of secondary emission from the grid can reduce the bias sufficiently to cause 'run-away' conditions where electrons bombard the grid until it is destroyed. Secondary electron emission from grids can also increase the noise in the device.

Secondary emission takes place primarily near the surface of materials. The secondary electron yield for a given bombarding electron energy is found to be directly proportional to the current of the primary electrons incident upon the surface. For pure metals, this yield is nearly independent of temperature and the secondary electron yield ( $\delta$ ) of a target material is defined as the ratio of the total number of secondary electrons per primary electron. The ratio  $\delta$  is largely dependent upon the energy of the incident electrons.

Fig. 15 shows the ratio  $\delta$  of secondary electrons per primary

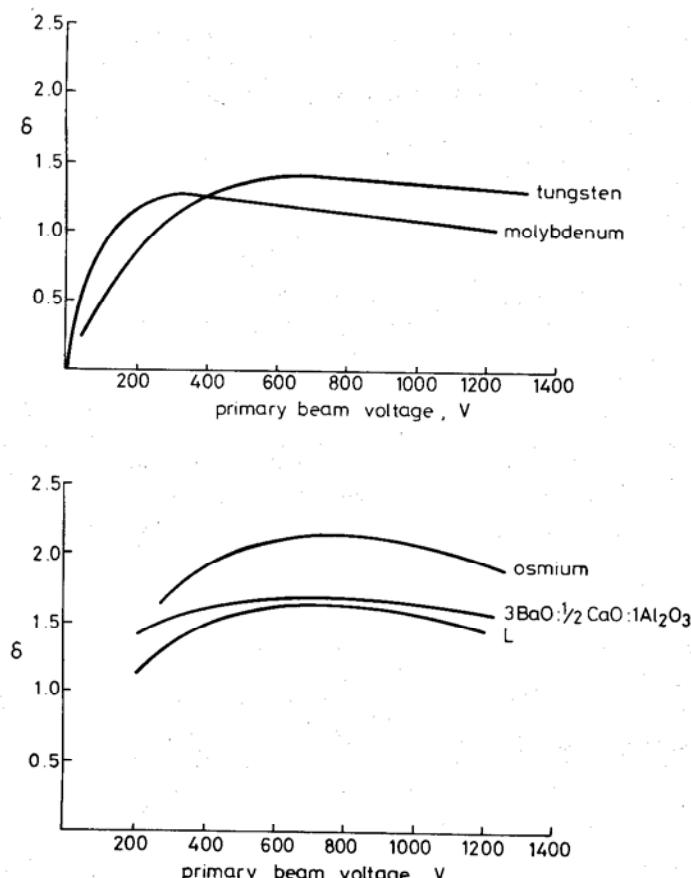


Fig. 15 Secondary emission coefficient  $\delta$  as a function of primary beam voltage

electron against primary beam voltage for tungsten [37], molybdenum [37], a barium calcium aluminate dispenser cathode [38], an osmium coated L [8] and an L cathode [8]. The maximum secondary-electron-emission coefficient of the  $3\text{BaO}\cdot\frac{1}{2}\text{CaO}\cdot 1\text{Al}_2\text{O}_3$  dispenser cathode is about 1.7 occurring at about 750 V. This value is higher than that of pure tungsten alone which is given as 1.4 occurring at 700 V. The osmium coated L shows a coefficient of about 2.1 occurring at about 750 V. The L and osmium coated L each contained a pellet of tungsten and  $5\text{BaO}\cdot 3\text{CaO}\cdot 2\text{Al}_2\text{O}_3$ .

At this time, there are no data available for the secondary-electron-emission characteristics of the tungsten cathode, mixed-metal matrix cathode or scandate cathodes. However, the secondary-electron-emission characteristics are not expected to differ greatly from the characteristics presented here.

#### 4.8 Primary-electron-emission characteristics

In scientific cathode research, comparisons of the emission capability of different cathodes are normally made by measuring their work function. In commercial manufacture, however, a simpler method is to measure the space-charge and saturated emission currents. The resulting data are graphed in Schottky-plot form and reported as the zero-field current density. The values for work function reported in this Section were obtained by the Richardson line method discussed in Section 4.3. The plots of zero-field current density were obtained by pulse measurements (1% duty,  $100\ \mu\text{s}$  pulse width) on cathodes mounted in close-spaced diodes. Temperatures were measured optically and converted to true temperature using Fig. 11. Table 7 lists the effective work functions for various modern dispenser cathode systems. The mixed-metal matrix cathodes are not listed but their work functions are slightly better than the M types for the same impregnant compositions, the actual value depending upon the matrix composition. In general, the more barium in the impregnant the less the work-function temperature coefficient. All of the work-function values reported are for impregnated dispenser cathodes except the tungstate, which is a pressed dispenser cathode. The work functions are averages for the total emitting

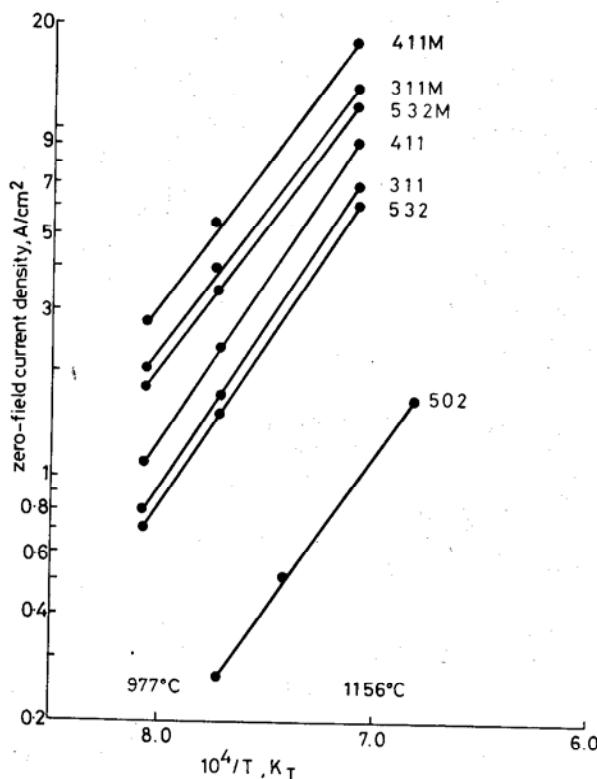


Fig. 16 Emission of various cathode systems

surface so that patch effects and nonuniformities are neglected. This circumstance is a result of the test method.

Fig. 16 compares the zero-field emission of the M family of cathodes to that of the family of barium calcium aluminate impregnated tungsten dispenser cathodes. The 502 contains no calcium and is plotted to show the increase in emission due to the calcium oxide addition. It can be seen that the M coating of 80% Os/20% Ru allows a drop in operating temperature of 70°C over a non-M of the same impregnant composition at the same emission density.

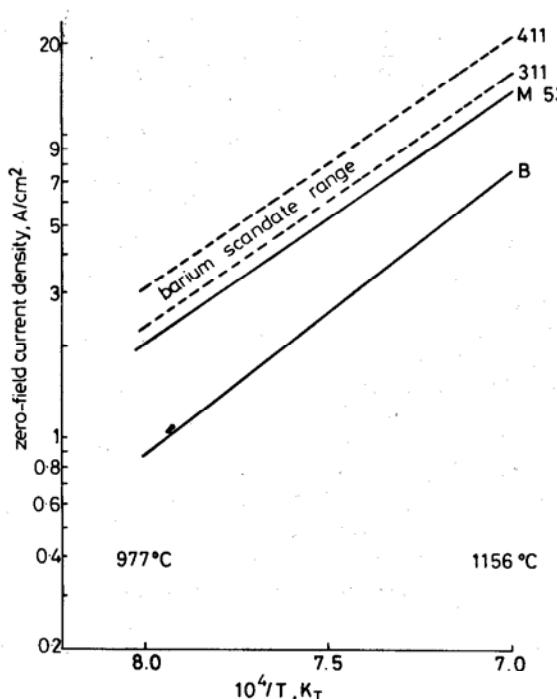


Fig. 17 Emission of various cathode systems

Fig. 17 compares the emission capability of the barium scandate impregnated dispenser cathodes to the 532 and 532 M. A range is given because scandium oxide can be added to the three types of barium calcium aluminate to produce three types of barium scandate. The scandate family of impregnated dispenser cathodes gives emission levels that are approximately equivalent to those of M-type cathodes with the same impregnant composition. Barium scandate cathodes have two advantages over M-type cathodes:

- (i) The scandate cathodes have no thin metallic film on the surface and hence are not as susceptible to ion sputtering.
- (ii) The scandate cathodes appear to be much less sensitive to poisoning effects than the M cathodes.

Fig. 18 compares the emission capability of the pressed barium strontium tungstate cathode to the 532 M and the B. The tungstate cathode is a very good thermionic emitter but suffers from the disadvantage of having a very high barium sublimation rate. The impregnated tungstate cathode is not shown but its emission capability is slightly less than the pressed version, with a correspondingly lower evaporation rate.

Fig. 19 illustrates the zero-field emission capability of the sputtered iridium cathode. It is possible to fabricate at least three types of sputtered iridium cathodes: 532, 311 and 411. The emission from the sputtered iridium types is very similar to the M sputtered osmium/ruthenium types.

## 5 Future directions

Significant improvements have been made in the performance of vacuum devices utilising dispenser cathodes in recent years. Some of the achievements can be attributed to improved cathode performance, such as greater emission current

densities at lower evaporation rates and operating temperatures. Cathode research must keep pace with the increasing demands of the cathode users. Currently available commercial dispenser cathodes will not fill the projected performance requirements for vacuum devices to be manufactured in the next decade. Cathodes will be asked to deliver 2–10 A/cm² for life times in excess of 50 000 h, and preferably in excess of 100 000 h. Additionally, cathodes will have to be more reliable, reproducible and predictable.

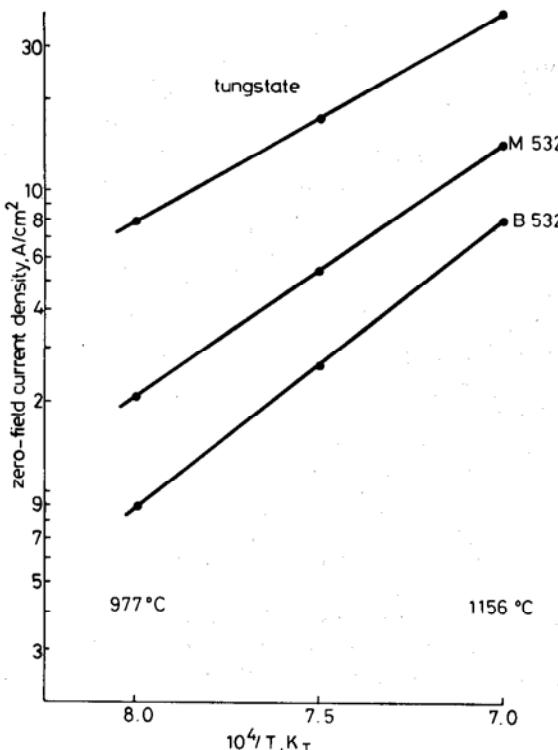


Fig. 18 Emission of various cathode systems

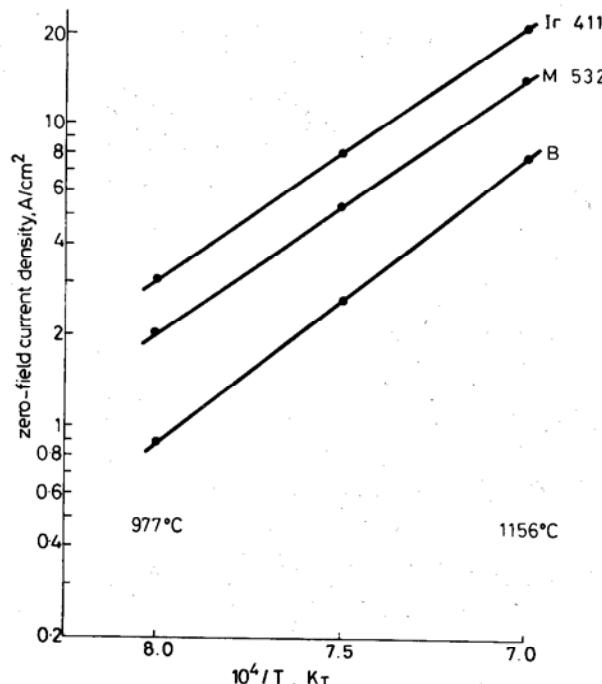


Fig. 19 Emission of various cathode systems

In order for the cathode industry to supply emitters which will be capable of meeting the ever increasing demands of advanced designs, new types of cathodes, or improved versions of existing cathodes, will have to be developed. In order to develop new cathode types and turn them into practical

components for the vacuum-device designer, fundamental research must be done. There are numerous questions that must be answered about the basic physical and chemical mechanism of cathode operation. Emission mechanisms, barium transport processes, surface interactions, poisoning and degradation mechanisms must be thoroughly understood. The continued use of surface analytical instrumentation such as scanning the electron microscope (SEM), the scanning Auger microprobe (SAM), the secondary ion mass spectrometer (SIMS), electron spectroscopy for chemical analysis (ESCA), the scanning low-energy electron probe (SLEEP) and the electron emission microscope will make it possible to more accurately characterise the surface and emission properties of the dispenser cathode.

High-power RF sources for millimetre-wave radars will require 5–10 kW at 90 GHz and above. The gyrotron, a cyclotron-resonance traveling-wave amplifier, has shown the greatest potential for producing large amounts of RF power at millimetre wavelengths. Further, the gyrotron can be designed to provide microwave heating power for nuclear fusion experiments and offers a means of heating fusion plasma not possible with previous technology. The performance requirements for dispenser cathodes to be used in gyrotrons are quite different from the characteristics required in other microwave devices. Electron guns are normally designed to operate in the space-charge limited regime to avoid the need for highly-regulated heater supplies and to minimise emission fluctuations associated with local poisoning. The electron gun for the gyrotron is a magnetron injection-type gun and the cathode is operated in the temperature-limited regime because of space-charge effects in the resultant electron beam. Space charge in the beam greatly affects the transverse velocity spread by preventing the electron beam from being tightly focused while passing through the nonadiabatic region of the gun. Thus, increasing space charge translates directly into increasing velocity spread. Consequently, cathodes for magnetron injection guns for gyrotrons must be operated in a temperature-limited mode to achieve a low spread in the transverse velocity distribution. It has also been demonstrated that the emitter surface roughness has a substantial influence on the spread of the transverse velocities in beams that are generated by magnetron injection guns [40]. Unfortunately, very little is known about the operation of dispenser cathodes in the temperature-limited mode. Little is known about the effects of cathode surface roughness or how to achieve cathode surfaces that are very smooth (height of surface roughness less than 5 µm). Further cathode research must be done before high quality cathodes for magnetron injection guns can be successfully fabricated.

Cathodes users would probably agree that much could be done to improve the reproducibility and predictability of the dispenser cathode. A possible approach for the future may involve a controlled porosity cathode. This approach is based on the concept that a surface with a controlled pattern of openings will emit uniformly and, if the pattern is small enough, the emission should remain constant throughout the life of the cathode. The fabrication may involve photolithography or ion-milling techniques used on thin foils which are backed by a reservoir of a barium dispensing compound. A parallel approach would involve the use of classified tungsten powder of very narrow particle-size distribution (perhaps ± 1.0 µm range). The powder may also be more spherical in shape than the angular powder in current use. It is believed that the tungsten matrix resulting from classified powder will be more structurally stable, reproducible and predictable.

In the future it will be beneficial to define a method of cathode evaluation and test that cathode researchers can use in reporting their findings. The advent of a standardised test

vehicle and test procedure will help eliminate the ambiguities and discrepancies that sometimes arise when different laboratories test the same type of cathode. It will then be possible to determine which cathode types are superior, based on emission capability, evaporation rate, life and susceptibility to poisoning.

In summary, it is the author's opinion that the next generation of dispenser cathodes will be of the mixed-metal matrix type, probably a combination of tungsten or molybdenum and one of the platinum family metals (iridium, rhenium, osmium or ruthenium), in a controlled porosity matrix configuration impregnated with a barium calcium aluminate type mix. Space-charge limited emissions of 4–10 A/cm<sup>2</sup> on a CW basis will be achieved at operating temperatures around 1100°C brightness or less and life times approaching 100 000 h will be demonstrated.

## 6 Conclusions

Substantial progress has been made in cathode research and manufacture since thermionic emitters were surveyed by Beck in 1958 [41]. This survey has shown that large increases in dispenser-cathode emission have been achieved in the years since that survey. Modern dispenser cathodes provide several amperes per square centimetre emission current, at operating temperatures below 1100°C brightness temperature, for tens of thousands of hours. Furthermore, fundamental cathode research will continue to increase the understanding of the basic mechanism of dispenser cathode operation and hopefully lead to improved cathodes which will become necessary for many of the next generation of microwave tubes and lasers now in the early planning stages or actually under development.

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## Errata

MAZZONE, A.M., and REES, H.D.: 'Transferred-electron harmonic generators for millimetre band sources', *IEE Proc. I, Solid-State & Electron Devices*, 1980, 127, (4), pp. 149-160:

The following errors occurred in the printed text:

On page 151, the time axis of Fig. 4 should be in ps

On page 153, three lines above Fig. 8, the reference should be to Fig. 4

On page 154, in the first line of Section 5, swell time should read dwell time; and in Fig. 10 the curves should be labelled (reading down) *g, c, a, e, b, d* and *f*, respectively

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HAUS, H.A.: 'Models of modelocking a laser diode in an external resonator', *IEE Proc. I, Solid-State & Electron Devices*, 1980, 127, (6), pp. 323-329:

The following errors occurred in the printed text:

On page 324, the first term on the RHS of eqn. 7 should be  $-n/\tau_n$ ; and the second term in eqn. 10 should be:

$$\frac{\sqrt{2/\tau_e} a}{1 + \frac{1}{r} e^{j\omega T_R}}$$

On page 325, above eqn. 20, the reference should be to eqn. 18; in the second line of eqn. 22, the term outside the brackets should not appear; and in eqn. 23, the LHS should be  $\omega_n$

On page 326, in Table 1,  $\tau_0$  should equal 3.7 ps

On page 328, in line 9 of the second column,  $\omega_c = 0.38 \times 10^{12} \text{ S}^{-1}$ ; and in line 12, the pulses should be 24% longer

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NIELSEN, O.M.: 'Current mechanism of tunnel m.i.s. solar cells', *IEE Proc. I, Solid-State & Electron Devices*, 1980, 127, (6), pp. 301-307:

On page 306, in line 4 of the second column,  $J_o$  should be  $5 \times 10^{-11} \text{ A cm}^{-2}$

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