CESIUM EMISSION IN DISPENSER PHOTOCATHODES

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Abstract

Photocathodes are a promising electron source for future high average current FELs, with ps response, kA/cm^2 peak and A/cm^2 average current, but will require delicate cesium-based coatings to achieve requisite quantum efficiency (QE). The University of Maryland (UMD) dispenser photocathode replenishes cesium from a subsurface reservoir, extending lifetime [1]. Recesiation has been shown to reverse oxidizer-induced QE loss [2]. Optimization of pore size and spacing will enable uniform recesiation without emitting excess cesium into the cavity. We here quantify for the first time cesium emission from an active dispenser photocathode and summarize status of experimental and modeling efforts.

BACKGROUND

The cesium dispenser photocathode, a candidate long-life high-QE photocathode under development at UMD, is based on existing thermionic dispenser cathode technology. The latter, specifically the M-type thermionic dispensers, have been tested in photoinjectors [3]: M-type will photoemit, though their QE is not high. In contrast the cesium dispenser photocathode has not yet been gun-tested. Prior to gun testing, cesium emission is of concern and must be quantified. High cesium emission depletes the cesium reservoir prematurely. More critically, it contaminates cathode-facing cavity surfaces with cesium, lowering work function and increasing risks of dark current and arcing. But because photocathode emission is decoupled from temperature, the cesium dispenser need not be heated continuously and may be rejuvenated periodically if needed, even to the extent of cathode retraction from the cavity during rejuvenation. The cesium dispenser therefore operates at temperatures well below thermionic cathodes: near room temperature (NCRF) or LN2 temperature (SRF) without rejuvenation and near 200ºC during rejuvenation, versus 1000ºC or more for barium dispensers like the M-type. We here investigate whether this lower temperature regime results in lower cesium emission rates. This is not evident *a priori*, for cesium diffuses and evaporates more readily than barium with a lower melting point and higher vapor pressures.

The following experiments conducted at the Naval Postgraduate School (NPS) describe first tests of cesium emission from the 2nd generation UMD dispenser [4] and quantify cesium emission rates, with a comparison to Knudsen theory and typical thermionic cathode barium emission, looking towards future in-gun tests.

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EXPERIMENT

Cathode Design

The cathode tested here and shown in Fig. 1 follows the standard 2nd generation UMD-type cesium dispenser design. A 0.5" dia. stainless steel reservoir cathode with a 0.040" thick, 70% dense sintered tungsten cap encloses a reservoir volume containing a Cs:Bi intermetallic alloy. This alloy sublimates Cs at 1 mTorr at 450ºC; release of Cs from the alloy into the reservoir requires this high activation temperature. At elevated temperature Cs also diffuses through the porous tungsten cap onto the cathode's photoemissive surface. Excess Cs will evaporate: this is the Cs emission of interest in this work.

Following a complete activation, the reservoir has been filled with free Cs and now only a gentle heating of about 200ºC is required to cause additional cesium to slowly and controllably diffuse to the surface and rejuvenate the coating. Cs emission (or lack thereof) at operating temperatures is also of interest.

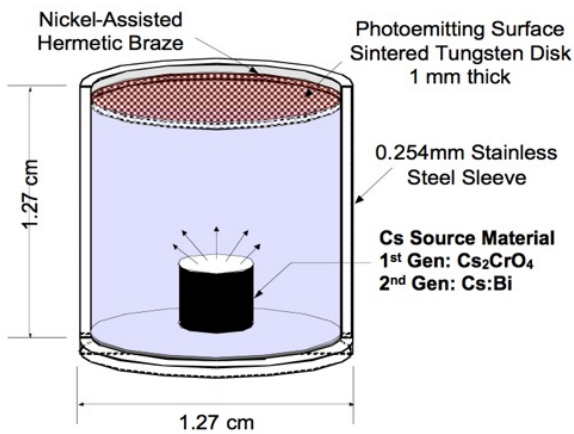

Figure 1: UMD Cs dispenser photocathode.

Apparatus

The experimental apparatus in Figure 2 consists of a UHV chamber under ion pumping with a central 6-way cross. The chamber achieves ~10^{-8} Torr without cathode heating. The cathode stalk with heater is mounted on one side of the cross. Facing the cathode is the residual gas

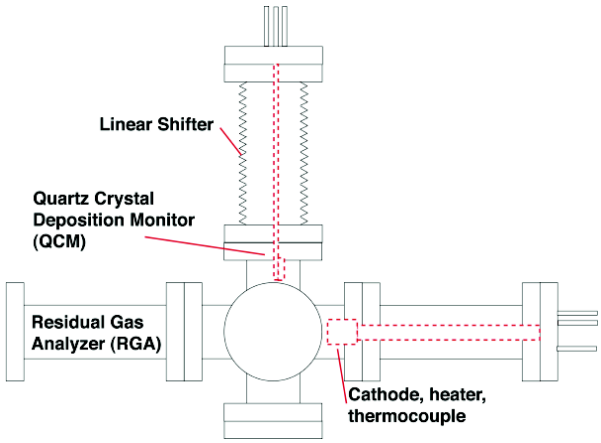

Figure 2: Experimental apparatus.

analyzer, or RGA. Also facing the cathode, but mounted on one side of the cross with a linear shifter so it may be shifted out of the RGA line of sight, is a quartz crystal deposition monitor (QCM). With the QCM's 0.8 cm^2 area facing the cathode 12 cm distant, the QCM intercepts approximately 4% of the total emission (assuming a cosine flux distribution). And with the QCM shifted away, the RGA-100 sees the 66.5 amu secondary ionization peak confirming Cs.

Temperature Calibration

The cathode under test, consisting of the steel cylindrical reservoir design shown in Fig. 1, is mounted on the molybdenum face of the heater body. The thermocouple used to measure temperature during cathode tests is mounted within the heater body and only approximates the hotter heater face temperature (taken to be the dispenser reservoir temperature). A thermocouple was therefore mounted to the heater face under separate test and the calibration was $T_f=1.94T_b+1.24$, where T_f is the face temperature and T_b is the heater body temperature. All data reported herein uses the heater face (cathode reservoir) temperature. A similar calibration was not performed for the cathode face itself, but poor thermal conductivity of the stainless steel walls and tungsten face of the cathode would imply the actual cathode surface temperature is lower.

Deposition Rate vs. Evaporation Rate

Evaporation rate is typically given for thermionic dispensers in units of flux: $\mu g/cm^2/hr$. However, measured rates of deposition at the QCM in this apparatus are in Å/min. Assume all cesium incident on the QCM sticks, a good assumption in this case. Then the total evaporation rate from the cathode can be calculated from the deposition rate on the QCM using the bulk density of Cs, 1.85 g/cm^3, the fact that the QCM intercepts just 4% of the emission, the cathode diameter of 1.1 cm, and the QCM crystal diameter of 0.8 cm. The result is that 0.1 Å/min on the QCM is equivalent to 1.5 $\mu g/cm^2/hr$ from the cathode. The smallest deposition rate measureable by the QCM is 0.1 Å/min, so the resolution limit of the evaporation rate measurement is taken to be 1.5 $\mu g/cm^2/hr$.

For comparison, a monolayer cesium coating on a tungsten cathode is approximately 0.096 $\mu g/cm^2$ of cesium (using the bulk density of cesium and the Cs covalent radius of 5.2 Å as the monolayer thickness). The hypothetical 0.1 Å/min on the QCM in this example is then equivalent to 15 monolayers per hour evaporating from the cathode. But of course, were this rate seen in a real system, the cathode would be evaporating cesium into a cavity with perhaps four orders of magnitude larger surface area and would deposit perhaps a thousandth of a monolayer per hour. It is clear that to avoid long-term buildup of cesium on the cavity walls, the evaporation rate should be minimized, but rates of less than 1 $\mu g/cm^2/hr$ may be acceptable. As will be noted later, even thermionic cathodes accepted as safe for use in injectors do not in general perform this well.

CESIUM EMISSION RESULTS

Initial activation of the dispenser was performed at 485ºC until Cs deposition was seen on the QCM for about 20 minutes. The dispenser was rapidly cooled. For thermal cycles 2 and 3, the temperature of the cathode was increased rapidly from room temperature to the highest target temperature and held there for about 25 minutes. The temperature was then reduced stepwise by 20-50 degrees per step, holding each temperature constant for about 25 minutes. For the last thermal cycle the temperature was ramped to 475ºC and held constant for four hours, with a constant evaporation rate measured.

Results of all thermal cycles appear in Figure 3. The apparatus resolution limit and typical UMD-type Cs dispenser rejuvenation temperatures are shown.

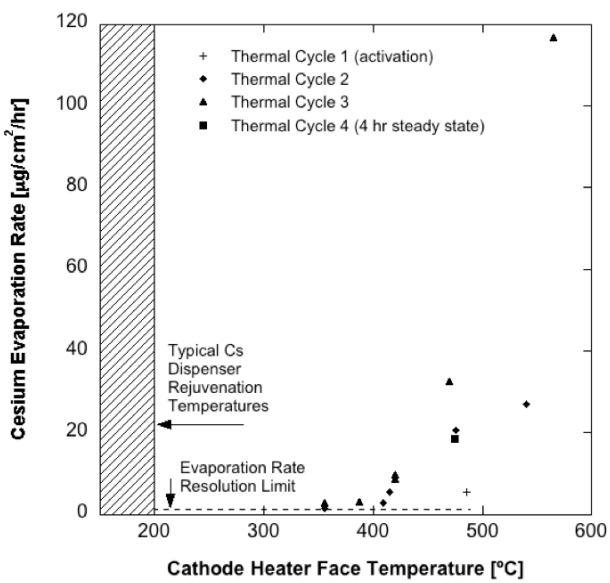

Figure 3: Dispenser evaporation rate.

ANALYSIS

A basic Knudsen analysis [5] for molecular flow through long thin tubes may be applied to the dispenser cathode with two simplifying assumptions: straight pores and no grain boundary cesium diffusion. The former overstates and the latter understates the predicted flow rate.

The evaporation rate (mass flux) Q from a dispenser cathode of area A with N long, thin, straight pores of radius R and length L, with zero Cs vapor pressure on the outside and P on the reservoir side, for a temperature T, is given by:

$$Q = \frac{4}{3}\sqrt{\frac{2\pi M}{N_A kT}}\frac{R^3}{L}\frac{N}{A}P(T) \qquad (1)$$

where M is the molecular mass of Cs, N_A is Avogadro's number, and k is Boltzmann's constant. The vapor pressure of Cs as a function of temperature is approximated by the empirical fit

$$P(T)[\mathrm{Pa}] = 1.04\times10^{9}e^{-(8660/T[\mathrm{K}])} \qquad (2)$$

and for the UMD cathode with T measured and M, L, and A known (132.91 g/mole, 1.016 mm, and 0.933 cm^2, respectively), Q depends only on two unknowns: pore number N and pore radius R. Pore number is estimated from an average pore surface density of 0.030 um^{-2}, obtained via electron microscopy from a sample area of the 70% dense sintered tungsten cathode surface containing 50 pores [6]. Pore radius is found by fitting Q(T) to the data as shown in Fig. 4, where the fit is to the best value of R, here determined to be 230 nm.

The above electron microscopy of the cathode surface had estimated R at 175 nm, but given the approximations made in using the Knudsen formula, the agreement is noteworthy. However, if instead one imposes smaller pores of 175 nm and a longer pore length of 2 mm due to convolutions in the path between grains, the Knudsen prediction is reduced by 2.25 and 2, respectively, for a total reduction in predicted evaporation rate of 4.5. To bring the prediction back in line with experiment one must conclude the total grain boundary diffusion at the surface is several times higher than the total pore diffusion at the surface, as has been postulated in previous work [7]. This likely contributes to the high uniformity of cesium coverage observed [8].

To place cesium evaporation rates in context, barium dispenser cathodes can emit 1-20 μg/cm^2/hr in operation [9]. Here, such low rates are measured for the UMD-type cesium dispenser well *above* continuous rejuvenation temperatures and are below the resolution limit at 200ºC: when room temperature or cold, cesium emission should be practically negligible.

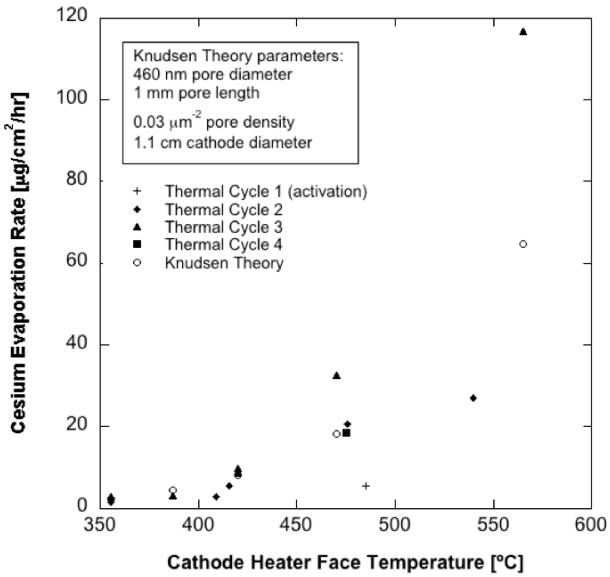

Figure 4: Knudsen theory and pore diameter.

SUMMARY

Cesium evaporation rate from the UMD-type dispenser photocathode is measurable above 350ºC. A rate of 1-20 μg/cm^2/hr, comparable to barium thermionic dispensers, is found from 350º to 475ºC. Typical cesium dispenser operation near 200ºC exhibits an evaporation rate below the apparatus resolution limit. Such results are well-supported by a simple Knudsen analysis and imply grain boundary diffusion may dominate over pore diffusion. One may consider further minimizing cesium emission by activating the reservoir with a retracted photocathode and operating in a periodic rejuvenation mode during future in-gun testing.

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