

A study of a sodium photocell with sensitivity dependent on the potential difference across the collecting anode
by Otto B Van Horn Jr

A THESIS Submitted to the Graduate Committee in partial fulfillment of the requirements for the Degree of Master of Science in Engineering Physics at Montana State College
Montana State University
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A STUDY OF A SODIUM PHOTOCELL WITH SENSITIVITY DEPENDENT ON THE POTENTIAL DIFFERENCE ACROSS THE COLLECTING ANODE

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OTTO B. VAN HORN JR.

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In Charge of Major Work

Chairman Examining Committee

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INTRODUCTION

In May of 1933 an unexpectedly large variation in the sensitivity of a photocell constructed from an ordinary light bulb was observed. The photocell was insensitive to the radiation from a carbon arc unless the anode (tungsten filament) was heated by a minimum potential drop of thirty volts. At higher filament potential drops large currents (plus or minus) flowed from the cathode to the anode; the only illumination of the surface being from the hot filament. Illumination of the cell by the carbon arc at these higher filament potential drops increased the current flowing from the cathode to the anode by amounts that were much larger than the current due to illumination by the carbon arc at the minimum potential.

Investigation of this phenomenon was undertaken as a project for a Masters' Thesis in Engineering Physics at Montana State College.

DESCRIPTION OF PHOTOCELL

Construction

The photocell was constructed from a 60 watt, inside frosted, gas filled, second grade, G.E. light bulb. A platinum wire was sealed through the wall of the cell to make contact with the photoelectric surface. An approximate cross section of the cell is shown in Fig. 1. The glass was partially cleared for about 0.75 centimeter around the platinum wire due to the sealing process.

Atmospheric gases were admitted to the cell during the insertion of the platinum lead. Although 0.32 gram of magnesium ribbon was introduced into the cell for use as a getter of residual gases it was not found feasible to flash the magnesium.

The vacuum assembly consisted of a glass condensation pump using butyl pthallate, backed by a motor driven Cenco oil pump. The cell was connected to the pumps for twenty four hours. During this time the walls of the cell were heated to just below the melting point by the direct application of the blue flame of a Bunsen burner for 4 fifteen minute intervals, in an attempt to free the walls of the cell of occluded gasses.

Both before and after sealing off, the application of a 75,000 volt potential from a Cenco spark coil failed to produce a visible discharge through the cell. This indicated the pressure within the cell to be not higher than the order of 10^{-4}

millimeters of mercury.7

The introduction of the metallic surface into the cell was accomplished by electrolysis through the glass walls. A molten mixture of half sodium and half potassium nitrates was used as the electrolyte. The metallic layer deposited around the platinum contact wire was quite transparent to daylight.

Visual spectroscopic inspection of the flame spectrum of the deposited metal showed it to be sodium. The spectroscope used had sufficient power to show clearly the red lines of calcium in a flame spectrum produced from a 1% calcium nitrate solution. It was not felt that this was entirely satisfactory but served to give one reason to feel that very little potassium or magnesium was present in the metal of the cathode.

Treatment After Completion

As mentioned under "Construction" the pressure in the newly evacuated cell was estimated to be not higher than 10^{-4} millimeters of mercury. After about 50 hours of experimental use the application of a 50,000 volt potential from the spark coil caused a dim blue discharge through the cell thus indicating a pressure in the cell estimated to be of the order of 10^{-3} millimeters of mercury.7

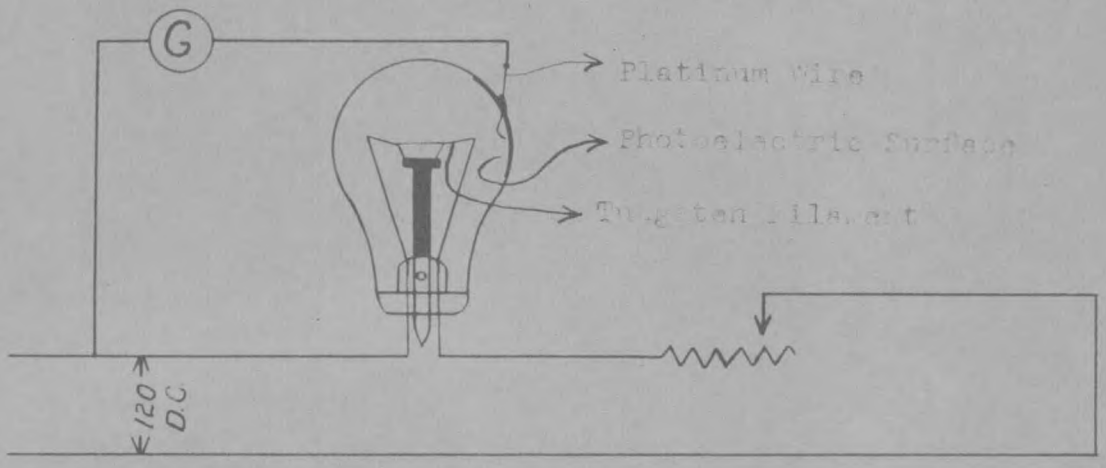


Figure 1. Electrical connections used in the original study of the phenomenon.

EXPERIMENTAL METHODS

Early in the course of the experimental work it became apparent that the photoelectric sensitivity of the cell was somewhat dependent on the immediate usage of the cell prior to the taking of data. Apparently the passage of a thermionic current (electrons from filament to sensitive surface) decreased the sensitivity of the cell, the passage of photoelectric current produced the opposite effect. This effect was small compared with the effect of filament potential drop upon the sensitivity.

In order to check these minor variations in the sensitivity and if possible to connect the cause of them with the major dependence of the sensitivity on the filament potential drop, attempts were made to regulate the sensitivity of the cell by varying the conditions of cell operation before and during the taking of data. This was done by arranging the passage of small thermionic or large photoelectric currents through the cell before starting to take a set of data and maintaining these conditions of operation between the taking of successive data.

A study was also made of the variation of the current through the cell with potentials of varying sign applied to the cathode. The electrical connections used in obtaining current data are shown in Figure 2.

The arc used was formed between the tips of plain, $\frac{1}{2}$ inch,

carbon sticks, and drew a current of 12 amperes. A tungsten filament lamp operating at 110 volts, burning magnesium, and a flashlight were all tried as light sources for illuminating the cell but proved to be ineffective.

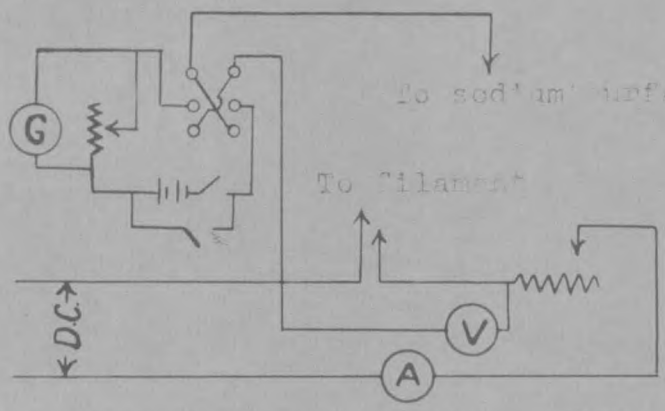


Figure 3. Electrical connections used for cell current measurements.

EXPERIMENTAL DATA

A study of the photoelectric sensitivity of the photocell as a function of the filament potential drop is shown by the data plotted in Fig. 3. In obtaining the data for Fig. 3 an attempt was made to determine the effect of passing small currents of the order of 10^{-9} ampere through the cell between the taking of successive data. Experimental data taken in this manner were obtained in the interval between taking the data for curve 2 and later the data for curve 1.

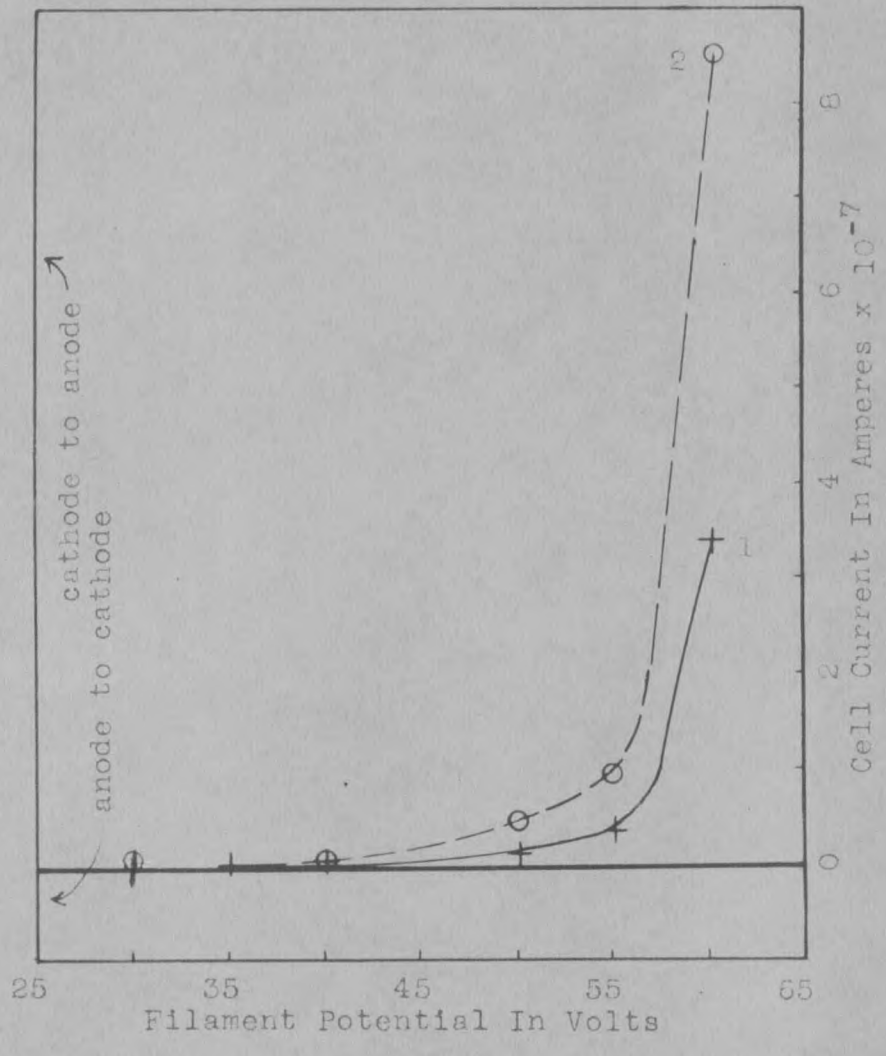
For a given filament potential drop the sensitivity of the cell was less in the set of data shown in curve 1 than for curve 2. At a 60 volt filament potential drop the ratio of the currents I_2/I_1 was 2.5/1.

A study of the photoelectric sensitivity of the cell as a function of the filament potential drop with different potentials applied to the cathode is shown by the data plotted in Fig. 4. In obtaining the data for Fig. 4 an attempt was made to determine the effect of passing large currents averaging 5×10^{-7} ampere through the cell between the taking of successive data.

The data for curves 1 and 2 were obtained in this manner at the beginning of the run, then after several sets of data were taken in a similar manner the data for curves 3 and 4 were obtained. Finally the cell was again operated under conditions corresponding to those for curve 1.

The effect of applying plus 6.25 volts to the cathode in obtaining the data for curves 3 and 4 was to cause the passage of current from anode to cathode until a filament potential drop of 59 volts was reached. The current reversed at this value of the filament potential drop and at the maximum filament potential drop of 65 volts the current values for curves, 3 and 4 were about half the values for curves 1 and 2. Curve 5 was not of the same shape as curve 1 but the current values for corresponding filament potential drops were closely the same indicating that the sensitivity of the cell had been maintained.

In obtaining the data for Figure 4' potentials of opposite sign were applied to the cathode while running the cell as before in an attempt to determine the effect of an electrostatic field on the passage of current through the cell. Curve 1 shows data taken with -48.3 volts applied to the cathode. The current was small until a filament potential drop of 59 volts was reached then it very rapidly rose to values that were nearly 50 times the current through the cell without any applied electrostatic field. (See curve 2,Fig. 3 and curve 1, Fig. 4). Reversing the applied electrostatic field also had the effect of reversing the current at all values of the filament potential drop used. The current flow from anode to cathode in this case did not rise abruptly as in curve 1 but more nearly approached a



1,———,0 volts to cathode,arc off.10:40-10:50
2,— —,0 volts to cathode,arc off. 9:18-9:25

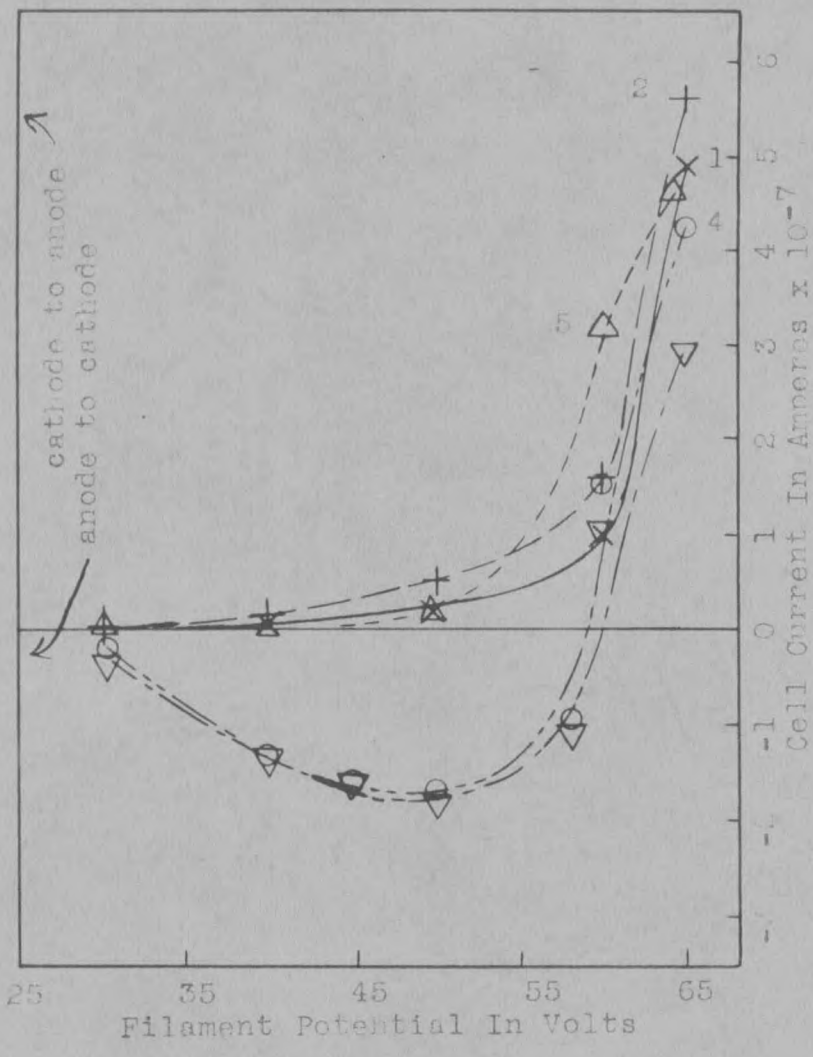
Figure 3. Decrease of photoelectric sensitivity with the passage of small currents.

TABLE I

January 28, 1934

Cell Current - Filament Potential Data for Fig. 3.

Filament Potential In Volts	Cell Current In Amperes x 10^{-7}
0	0.00
30	0.00
40	0.06
50	0.45
55	0.96
60	8.50
0 volts to cathode. Arc off. 9:18-9:25	
0	0.00
30	- 0.06
35	- 0.06
40	0.00
50	0.12
55	0.32
60	3.40
0 volts to cathode. Arc off. 10:40-10:50	



1, ×, ———, 0volts to cathode, arc off. 3:30-3:37
2, +, — —, 0volts to cathode, arc on. 3:37-3:50
3, ▽, — - —, +[illegible].25 volts to cathode, arc off. 4:50-5:25
4, ○, — - - —, +[illegible].25 volts to cathode, arc on. 4:50-5:25
5, △, - - - - -, 0volts to cathode, arc off. 5:25-5:45

Figure 4. Variation of cell current with filament [illegible] applied cathode potentials.

Table II.
February 4, 1934
Cell Current - Filament Potential Data For Fig. 4.

Filament Potential In Volts	In Amperes x 10^{-7} Cell Current
65	4.85
60	0.94
50	0.27
40	0.07
35	- 0.07
30	- 0.02
0	0.00
0 volts to cathode.	Arc off. 3:30-3:37
65	5.60
60	1.55
50	0.47
40	0.10
30	0.03
0	0.00
0 volts to cathode.	Arc on. 3:37-3:50
65	2.94
60	1.01
58	- 1.08
50	- 1.69
45	- 1.55
40	- 1.35
30	- 0.27
0	0.00
+ 6.250 volts to cathode.	Arc off. 4:50-5:25
65	4.19
60	1.55
58	- 0.94
50	- 1.62
45	- 1.55
40	- 1.35
30	- 0.20
0	- 0.00
+ 6.250 volts to cathode.	Arc on . 4:50-5:25

Table II Continued

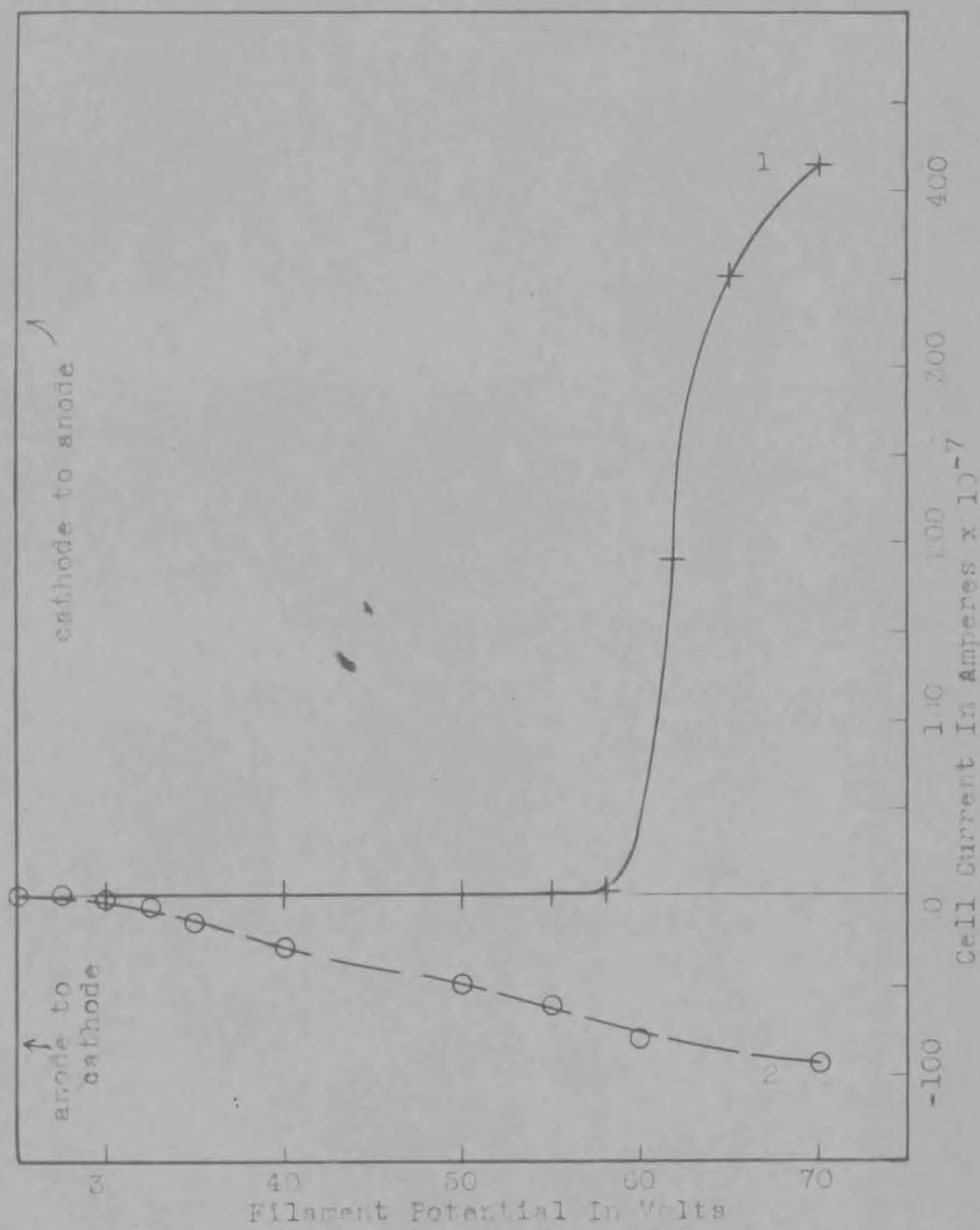
Filament Potential I In Volts	Cell Current In Amperes x 10^{-7}
65	4.72
60	3.17
50	0.20
40	0.07
30	0.07
0	0.00
0 volts to cathode	Arc off. 5:25-5:45

linear dependence on the filament potential drop. The maximum current value reached was slightly less than $\frac{1}{4}$ the corresponding current value for curve 1.

The resistances of the lamp filament at various filament potential drops were utilized to calculate the temperature of the filament for any given voltage drop in the range used.[6] The plotted curve of filament potential drop against filament temperature may be found in the appendix. The temperatures corresponding to the working range of voltage (30-60 volts) ran from 1350°K to 1880°K.

The sodium in the photocell had at room temperature a vapor pressure of 6.8×10^{-8} millimeters of mercury.[4] By use of Langmuirs modification of the Saha equation, the temperature at which the tungsten filament would ionize every sodium atom that fell upon it was calculated to be 940°K.[2] This meant that any enhancement of the electron emission due to a thin layer of sodium on the tungsten surface would occur only at temperatures which were at least 400°C below the minimum working temperature.[1] Accordingly the thermionic emission from the filament throughout the working range of temperatures was that characteristic of tungsten.

It should be noted here that even with minus 90 volts applied to the cathode, there was no detectable current (with the instrument used) passing from the cathode to the anode, when



1, ————,-48.3 volts to cathode, arc off.4:15-4:30
2, — — —,-48.3 volts to cathode, arc off.4:35-4:47

Figure 4'. Variation of cell current with filament and applied cathode potentials.

Table III

Cell Current - Filament Potential Data For Fig. 4'

	Filament Potential In Volts	Cell Current In Amperes x 10^{-7}
	30.0	0.00
	40.0	0.03
	50.0	0.13
	55.0	0.26
1	58.0	0.42
	61.8	189.10
	65.0	349.50
	70.0	414.00

- 48.3 volts to cathode. Arc. off. 4:15-4:30

	25.0	- 0.25
	27.5	- 0.83
	30.0	- 2.69
	32.5	- 7.05
2	35.0	- 16.67
	40.0	- 30.10
	50.0	- 51.30
	55.0	- 64.10
	60.0	- 83.30
	70.0	- 96.10

+ 48.3 volts to cathode. Arc off. 4:33-4:47

the cell was illuminated by the carbon arc and with 0 volts impressed across the filament.

The presence in the cell of the active photoelectric desensitizing agent, oxygen at pressures far greater than permissible when working with comparatively clean alkali metal surfaces is certain. 5 (See "Treatment After Completion", page 5)

DISCUSSION

Two physical hypotheses are here offered to explain the phenomenon described in the "INTRODUCTION".

1. The phenomenon may be explained by a change in the photoelectric sensitivity of the sodium surface which is due to;

   A. The occluded oxygen which is a known photoelectric desensitizer being partially driven off of the surface by heat energy transmitted from the hot filament by gas conduction and convection.[5]

   B. The occluded oxygen being partially driven off of the surface by the absorption of the energy of a current of electrons from the hot filament.

2. The photoelectric sensitivity of the surface remains constant and the phenomenon may be explained in terms of the ionization of the gas caused by photoelectrons being attracted to the positive end of the filament.

A more extended statement of the first hypothesis is as follows. At the minimum working temperature of 1350°K the gaseous transmission of heat from the filament becomes large enough to drive off sufficient of the occluded oxygen to allow the sodium surface to respond photoelectrically to the light sources used; i.e. the carbon arc and the heated filament. As the filament temperature rises the sodium surface experien-

ces a corresponding rise in temperature and increase in photoelectric sensitivity. This process continues until at a filament potential drop of 59 volts (where the curves of Figures 3 and 4 turn sharply upward) the sodium surface which is comparatively well freed of oxygen begins a copious emission of electrons, resulting in a large increase in the current from cathode to anode.

The B part of the first hypothesis substitutes the electron current from the hot filament for gas conduction and convection as the method of transmitting the heat which drives off the occluded oxygen.

Under the second hypothesis, that of constant photoelectric sensitivity, the number of photoelectrons reaching the filament is negligible until the filament potential drop (which is equal to the electrostatic field across the cell) reaches the minimum working potential of 30 volts. From the 30 volt minimum up to 59 volts the electron current from the cathode to the anode gradually rises with the electrostatic field between the sodium surface and the plus end of the filament. At 59 volts filament potential drop the electrons begin to be attracted to the filament with velocities sufficient to ionize the gas molecules with which they collide. This ionization process amplifies the photoelectric current to an extent that accounts for the sharp upturn of the curves at 59 volts.

The supposition that the photoelectric sensitivity is con-

stant is refuted by the following data. As mentioned under "EXPERIMENTAL DATA" on page 17 no detectable current was observed upon illumination of the cell by the carbon arc with 0 volts impressed filament potential, even though a minus 90 volts was applied to the cathode. If the photoelectric sensitivity were constant the response to illumination with an applied potential of this magnitude should be greater than the difference between the currents of curves 1 and 2 of Figure 4 at the maximum working potential of 65 volts. This does not prove to be the case.

The supposition that a sudden increase in the photoelectric sensitivity of the sodium surface occurs at a filament potential drop of 59 volts (see curve 1 Figures 3 and 4) is highly improbable. This improbability is perhaps best shown by inspecting curve 1 of Figure 4'. With a potential of 48.3 volts applied so as to make the total electrostatic field pulling electrons from the cathode to the plus end of the anode equal to 107.3 volts, the current very rapidly increases. The increase is so rapid, in fact, that at 60 volts filament potential drop, the current from the cathode to the anode has increased to 238 times the current at 58 volts. An increase in the cell current of this magnitude with such a small increase in the filament potential drop is explainable only on a basis of ionization.[3]

Perhaps a combination of the two hypotheses will explain the phenomenon and still be backed by the experimental evidence.

At 0 volts filament potential drop the cell is photoelectrically insensitive to the light from the carbon arc regardless of applied fields of the magnitude used. At the minimum working potential of 30 volts the heat energy of the filament is by one of the means mentioned under A and B transferred to the sodium surface at a rate fast enough to drive off the occluded oxygen in an amount sufficient to permit the sodium surface to respond photoelectrically to either the carbon arc or the light from the filament. This last statement is apparently in accordance with the data of curves 1 and 2 of Figure 4 at the minimum working potential. As the filament potential drop increases the photoelectric sensitivity of the cell increases by small amounts. The increase in the electrostatic field between the cathode and the plus end of the filament permits a greater proportion of the increased number of photoelectrons emitted from the surface to flow to the filament. This statement is apparently in accordance with the gradual increase of current through the cell as shown by the data plotted in curves 1 and 2 of Fig. 4, between the minimum potential of thirty volts and the point of sharp current upturn at 59 volts filament potential difference. At the point of sharp upturn the photoelectrons begin to attain speeds aided by the electrostatic field across the cell that enable them to ionize the gases in the cell and so account for the amplification of the current.

There are still other experimental facts to be explained

by the combination hypothesis. Can the variation in the sensitivity of the cell for a given filament potential drop (see curves 1 and 2 of Figure 3 and curves 1 and 5 of Figure 4) be properly explained? When small currents pass through the cell between the taking of successive sets of data as in the case of the curves of Figure 3, perhaps the oxygen redeposits each time. After an initial rapid change at the higher filament potential drop the removal of the occluded oxygen slows up to the extent that the galvanometer gives the impression of a constant reading which is considerably less than the true reading which might be obtained by waiting a few minutes. This might give reduced sensitivity in comparison with a surface which is kept comparatively clean of oxygen between the taking of successive sets of data by the maintenance of high filament potential drops between readings. The downturn of curves 3 and 4 of Figure 4 and curve 2 of Figure 4' indicates that the very considerable electronic emission of the hot filament will, if given a chance, flow as a current to the sodium surface. [6]

If therefore seems fairly safe to say that a combination hypothesis of gas ionization due to photoelectrons moving across the cell under the influence of the electrostatic field, and a change of sensitivity of the sodium surface due to a loss of occluded oxygen from gas conduction and convection of the heat from the filament does satisfactorily explain the phenomenon.

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1. Compton and Langmuir. Reviews of Modern Physics. April 1930, page 138

2. Ibid 1. Page 135

3. Hughes and DuBridge. Photoelectric Phenomena. McGraw-Hill. Page 161

4. Ibid 3. Page 250

5. Ibid 4. Page 435

6. Jones and Langmuir. General Electric Review. June 1927, pp 310-319.

7. Newson, H.W. of the Montana State College Department of Chemistry. Unpublished work of.

APPENDIX

GALVANOMETER CALIBRATION FOR TABLE 1, FIG. 3.

January 28, 1934

1.54427 volts applied through 20,000 ohms and 0.01 shunt gives an average deflection of 12.025 centimeters.

Sensitivity is 6.415×10^{-9} amperes per millimeter.

Galvanometer calibration for Table 2, Fig. 4.

February 4, 1934

1.54427 volts through 20,000 ohms and 0.01 shunt gives an average deflection of 11.45 centimeters.

Sensitivity is 6.74×10^{-9} amperes per millimeter.

Galvanometer calibration for Table 3, Fig. 4.

Same as Table 1.

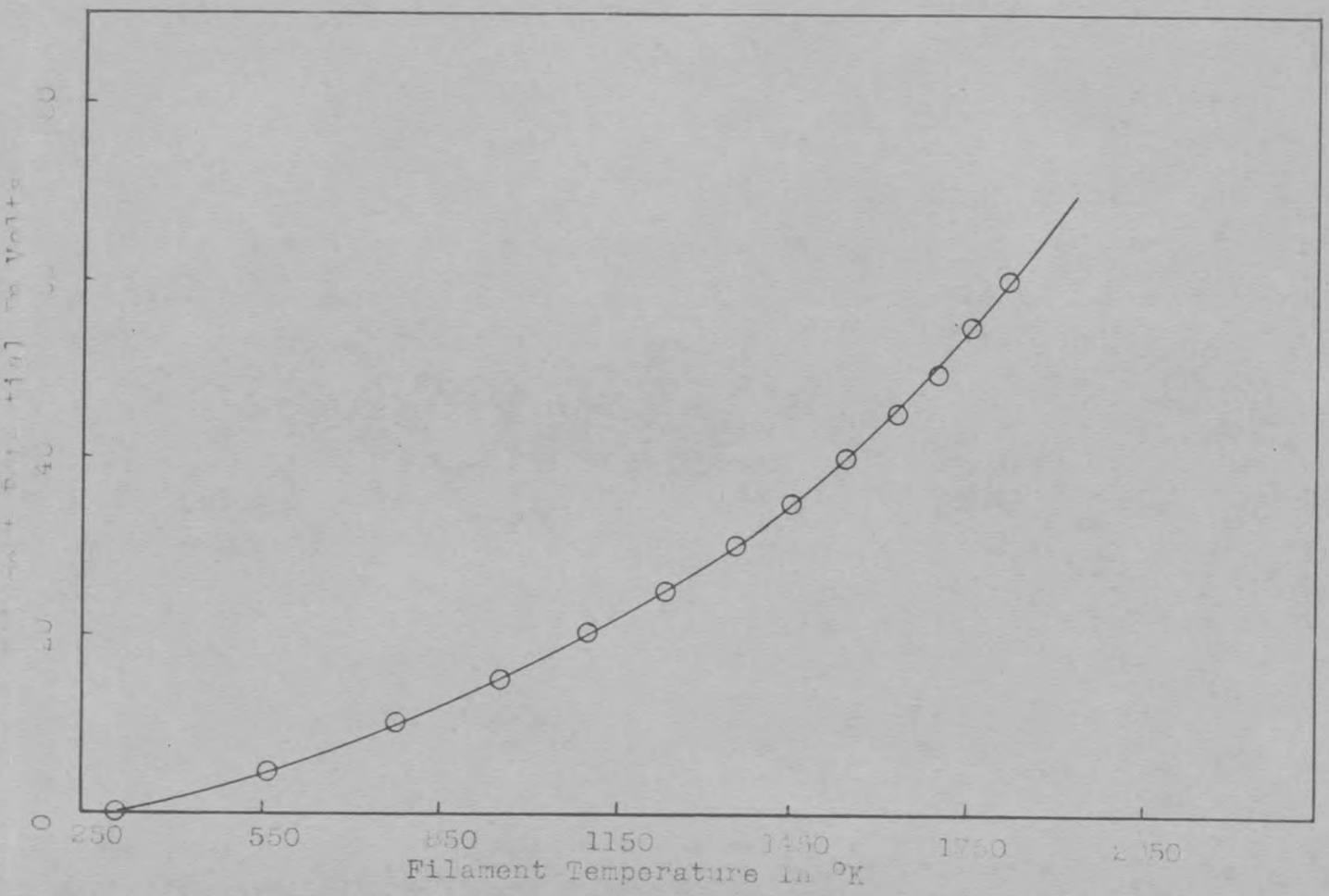


Figure 5. Filament temperature-voltage characteristic of the filament used.

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