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EXPERIMENTAL INVESTIGATION OF
LOW-PRESSURE ALKALI-METAL THERMIONIC
CONVERTERS FOR DC AND RF POWER

by

Hans K. Richards

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Printed in the United States of America

Available from

Clearinghouse for Federal Scientific and Technical Information

National Bureau of Standards, U. S. Department of Commerce

Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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Reactor Physics Division

September 1967

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NOMENCLATURE

I	$\equiv$ total current
I_0	$\equiv$ observed current without oscillations
J	$\equiv$ current density = current/cm ² = $J_e + J_i$
J^+	$\equiv$ current density of particles moving from emitter to collector
J^-	$\equiv$ current density of particles moving from collector to emitter
J_C	$\equiv$ calculated current density, mA/cm ²
J_e	$\equiv$ calculated electron current density, mA/cm ²
J_i	$\equiv$ current density in plasma, mA/cm ²
J_M	$\equiv$ measured electron current density
J_s	$\equiv$ saturation current density
K	$\equiv$ Boltzman's constant
m	$\equiv$ mass
n	$\equiv$ density in plasma
n^+	$\equiv$ density of particles moving from emitter to collector
n^-	$\equiv$ density of particles moving from collector to emitter
n_0	$\equiv$ atomic density of alkali-metal vapor in reservoir
n_T	$\equiv$ total number of particles between emitter and collector
p	$\equiv$ alkali-metal vapor pressure, mm Hg
T	$\equiv$ absolute reservoir temperature, °K
T_C	$\equiv$ collector temperature, °K
T_e	$\equiv$ emitter temperature, °K
T_0	$\equiv$ trap temperature, °K
v	$\equiv$ time- and space-dependent velocity
v^+	$\equiv$ velocity of particles moving from emitter to collector
V_i	$\equiv$ ionization potential
V_0	$\equiv$ negative voltage from zero to knee of characteristic curve
α	$\equiv$ fraction of atoms ionized
ϵ	$\equiv$ electronic charge
σ	$\equiv$ microscopic scattering cross section, cm ²
Σ	$\equiv$ macroscopic scattering cross section, cm ⁻¹
ϕ_C	$\equiv$ collector work function
ϕ_e	$\equiv$ emitter work function

Subscripts

a	refers to atoms
e	refers to electrons
i	refers to ions

Other expressions will be defined as used.

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ABSTRACT

Experiments with a low-pressure thermionic converter have been conducted with cesium, potassium, and sodium-metal vapors. These metals provided for the neutralization of the electron space charge and the reduction of the collector work function. A tantalum emitter was brought to the desired temperature by electron bombardment. A molybdenum collector and guard ring were situated opposite the collector. The emitter-collector distance could be varied several millimeters by means of a micrometer control.

The investigation included the dc electron current, output voltage, and power as a function of emitter temperature, vapor pressure, emitter-collector distance, and effect of the different alkali metals. Covered in the investigation was the production of high-frequency oscillations (rf). The frequency, rms voltage, and power output were reported in detail as functions of the dc collector voltage, emitter temperature, emitter-collector distance, vapor pressure, and alkali metal. In addition, a dc-rf interaction was observed and analyzed. For this purpose, the rf and dc sections were separated by capacitance-inductance networks. Photos from an oscilloscope showed the amplitudes and wave shapes of the rf output.

The results were also discussed as to their application for the design of thermionic reactor fuel elements. Special consideration was given to the relative merits of different alkali metals for neutralization of the space charge and reduction of the collector work function.

I. INTRODUCTION

This report describes a series of experiments conducted to evaluate the performance of low-pressure thermionic converters.

The results of the investigation should help in the selection of favorable conditions for the design of thermionic reactor fuel elements, including rf output, if desired for special applications.

Since the emitter work functions for reactor operations will probably be limited at present to 3 eV or less, while the work function of the experimental emitter was slightly above 4 eV, the results for practical reactor application will need to be modified.

Although cesium is usually used as an ion producer, the results for potassium were surprisingly good. Even sodium vapor produced a relatively high power output but less than cesium and potassium. Since the work functions of potassium and sodium are higher than that of cesium, they would permit a higher collector temperature without excessive electron back emission, a factor of importance for space application, where heat rejection becomes a major problem.

For the experiments, a tantalum emitter was used instead of uranium-zirconium carbide, since it was desirable that the physical properties of the emitter remain unchanged during the experiments. Since the work function of tantalum is higher than that of the carbide, higher temperatures were required for power densities of 10 W/cm^2 or more. At present, these temperatures cannot be produced in reactor operations. However, conclusions for emitters with lower work functions can be obtained by reasonable extrapolations. Although most experiments were limited to low pressures of 10^{-5} to 10^{-2} mm Hg, some results were obtained at pressures up to 1 mm Hg. The high-pressure data included ignited modes.

The following features were the principal objects of investigation:

1. Voltage-current characteristics as a function of emitter-collector distance (EM-C.D.), alkali vapor pressure or density, and emitter temperature.
2. Production of dc and rf power as a function of vapor pressure, geometry, and temperature.
3. Interaction of dc and rf voltage and power.
4. Comparison of cesium, potassium, and sodium for (a) space-charge neutralization, (b) work-function reduction of the collector, and (c) dc and rf power.
5. An explanation of rf-dc interaction.
6. A generalized theory of rf generation.

This report presents the experimental results; however, some theoretical aspects will be included. The analysis of ion plasma oscillations will be reported in ANL-7378, Theoretical Investigation of Low-pressure Alkali-metal Thermionic Converters for Dc and Rf Power.

II. EXPERIMENTAL EQUIPMENT AND PROCEDURES

Figure 1 shows the design of the cell used for this experiment. The electron source for the cell is a heated tantalum button (labeled emitter in Fig. 1), set in a tantalum diaphragm. Above the tantalum button is an electron gun, consisting of a tungsten filament which produces electrons that are accelerated by a high voltage and pass through the button. As Fig. 1 shows, the diaphragm separates the evaluated electron gun from the cell region which contains the alkali-metal vapor. Opposite the tantalum emitter are a molybdenum collector and a molybdenum guard ring, also shown in Fig. 1. The collector is cooled by silicone oil flowing through copper tubing. The guard ring is also cooled by oil. For experimentation, the cell and the electron gun sections are evacuated separately, and then the alkali metal is introduced into the cell region. The emitter-collector distance can be varied using the bellows-sealed micrometer head. The entire cell and electron gun assembly is placed in a container filled with silicone oil.

An alkali-metal reservoir (not shown in Fig. 1), connected to the cell, is also located inside the oil. The oil bath maintains a constant temperature environment, which can be maintained as high as 350°C to regulate the alkali-metal vapor pressure inside the reservoir and the cell. Considerable time is required (about one-half hour) to equalize the pressure inside the reservoir and the cell.

The temperature of the tantalum emitter is observed through a sapphire window, shown in Fig. 1. The emitter contains a hole, with a length five times its diameter, which is used as a blackbody source for optical temperature measurements. A bellows connects the frame of the sapphire window to the opening in the cell to compensate for the different expansion coefficients of the container and the cell material. A schematic diagram of the experimental setup is shown in Fig. 2. The cell, the housing of the electron gun, and the diaphragm containing the emitter button are electrically grounded; the tungsten filament is at a variable negative high voltage. Figure 3 is a view of the assembled apparatus. The collector and the guard ring are shown in Fig. 4.

The collector and the guard ring are connected separately through rf chokes to a transistorized voltage regulator called the dc reversing circuit. This circuit, shown in Fig. 5, supplies voltages varying from -12 to $+12$ V and compensated cell current up to 20 A.

The collector is connected through rf choke II to an X-Y recorder (as shown in the lower right-hand portion Fig. 2). Resistor R_1 provides a voltage drop, proportional to the dc output, which is recorded on the Y axis. Figure 6 is a schematic diagram showing the X-Y recorder connections with the cell and the reversing circuit.

112-8649

Fig. 1. Direct-conversion Cell with Variable Emitter-collector Distance

Fig. 2
Connections for Dc and Rf Power Conversion

112-8650

112-2357

Fig. 3. Experimental Assembly

112-3040

Fig. 4. Collector and Guard Ring

112-8651 Rev. 1

Fig. 5. Dc Transistorized Reversing Circuit

112-8652

Fig. 6. Schematic Diagram of Cell-reversing Circuit and X-Y Recorder Connections

The rf choke and the two capacitances C (also shown in Fig. 2) separate the dc output from the rf output of the cell. The rf outputs from the guard ring and the collector are each connected to a three-position switch, which can be opened, attached to a load consisting of inductance-free resistances, or short-circuited to ground. The rms voltage is measured with a vacuum-tube voltmeter, and the frequency and wave shape are observed on an oscilloscope.

For a demonstration of dc output power, the dc circuit could be disconnected from the regulator, and R_1 could be replaced by 2-V incandescent lamps in parallel. Similarly, the rf power output can be measured by replacing the rf load with lamps and making photometric comparisons against an identical lamp load powered by a known dc source. This procedure is preferable for determining rf power output, since the rf voltages are not sinusoidal, frequently being even pulses, and vacuum-tube voltmeter readings are only correct for a sinusoidal wave shape.

As can be seen in Fig. 2, the guard ring and the collector can be connected to measure the total output produced by the emitter.

To facilitate comparisons, experiments with different alkali metals were conducted in the same sequence and under conditions as nearly identical as possible.

First, a low vapor pressure of about 10^{-5} mm Hg was obtained by adjusting the oil temperature. This pressure was maintained by holding constant the oil bath temperature. The emitter-collector distance was adjusted with the micrometer, and the emitter was heated to produce an electron current.

With a suitable value of R_1 and the rf section switch open, a dc voltage-current characteristic curve was traced on the X-Y recorder,[†] as shown in the portion of the curve labeled O in Fig. 7. The plot was

112-8653 Rev. 1

Fig. 7. Dc Voltage-Current Characteristic Curves for Rf Open and Short-circuited

then repeated with the rf section shorted to ground, the result being shown in the portion of the curve labeled S in Fig. 7. Differences between the two curves show the interaction of dc and rf outputs. Simultaneously with the dc measurements, rf output was studied. Frequency, peak-to-peak voltage, and amplitude of the emitter rf output were observed on the oscilloscope. In addition, guard-ring rf output was also checked with the oscilloscope. The rms voltage and rf power were measured by both the vacuum-tube-voltmeter method and the photometric method. Since power is fed into the cell at positive voltages, heat is converted into electricity only at negative collector voltages. However, the positive voltage range provides useful information, such as saturation current values and evidence of ignited modes.

The theory of the converter operation is discussed in detail in ANL-7378. However, for convenience, some points will be reviewed briefly here. The negative voltage from zero to the "knee" of the dc output voltage-current characteristic curve, V_0 , is approximately given by

$$V_0 = \phi_e - \phi_c$$

and represents the maximum voltage obtainable from the device, except for a small contribution arising from the finite temperature distribution of the electrons. (For example, see Fig. 7.)

[†]In addition, ion current was measured outside the range of the characteristic curve at -5 to -6 V.

Extraction of power from the cell is limited by the space charge of electrons traveling from the emitter to the collector. Figure 8A shows

Fig. 8. Potential Minimum Neutralization of Space Charge and Typical Cell Characteristic Curve

the voltage relationships for an emitter with work function ϕ_e connected directly (short circuit) to a collector with work function ϕ_c . In this case, both electrodes have the same Fermi level, FL. Because of the electronic space charge between emitter and collector, an electron traveling from the emitter to the collector must pass through a potential minimum PM, which is a voltage δ below ϕ_e . The current density J_e is thus only $J_s \exp[-e(\phi_e + \delta)/KT_e]$.

Addition of a load changes the voltage relationships, as shown in Fig. 8B. The voltage drop across the load, V_0 , separates the Fermi levels of the emitter and the collector. The current density has been reduced below that of Fig. 8A. Useful power

output is given by the product of J_e and V_0 . To obtain practical amounts of power, we must remove the exponential factor by eliminating the space charge. Reduction of the emitter-collector distance to the order of 10^{-3} cm would prevent the buildup of a space charge, but is impracticable for reactor applications.[†] Fortunately, the space charge can be neutralized by the introduction of positive ions. Figure 8C indicates neutralization by cesium ions. Any other vapor of low ionization voltage could be used as well. The ionization can occur either by contact with a hot surface or directly by electron collisions between the electrodes. Figure 8D shows a typical current-voltage characteristic curve from a cesium cell in the nonignited mode.

Peak-to-peak voltage, amplitude, and frequency of the rf output were measured at collector voltages of +3, +1, 0, -1, -2, and, if possible, -2.5 V. As Figs. 2 and 6 show, the applied voltages at the collector and the guard ring differ only by the small voltage drop across R_1 .

The same procedure was repeated for different emitter temperatures, emitter-collector distances, vapor pressures, and alkali metals.

The ion current over the negative portion of the characteristic was also measured. The open-circuit voltage was obtained directly from the characteristic graph, since it is the voltage at the point where the curve crosses the X axis.

[†]Swelling and other effects would produce short circuits between emitter and collector.

Experimental results are presented and discussed in terms of the following quantities:

1. Emitter temperature; and collector temperature, if significantly different from the alkali-metal reservoir temperature.
2. The atomic density, n_0 , of the alkali-metal vapor in the reservoir.
3. The emitter-collector distance, EM-C.D., in mm.
4. The ratio of measured current density, J_M , to the calculated one, J_C ,[†] J_M/J_C , in mA/cm², if not stated otherwise.
5. The dc voltages applied to the collector.
6. The rf output frequencies and rms values measured at the given dc voltages and, in some instances, the peak-to-peak voltages and voltage amplitudes.
7. The dc and rf power maxima in mW.
8. The ion current density, J_i in mA/cm².

Other quantities of interest, such as the measured output voltage, V_0 , measured from zero applied voltage to the knee of the characteristic, are shown as required.

Since the area of the collector was 0.5 cm², the numerical values of the current densities given in the tables are twice those of the currents traced on the graphs.

The densities, n_0 , were calculated from pressure tables for alkali metals considering the vapor as an ideal gas; i.e., $n_0 = p/KT$, where T is the absolute reservoir temperature and p is the alkali-metal vapor pressure at T .

The density in the emitter-collector space will be different from n_0 . Exact calculations are difficult. The appendix shows a calculation under assumptions that have been used for theoretical computations.

For higher emission currents, the trap temperature and cell temperature could not be kept quite constant, a fact that might frequently have made the estimate of n_0 too low.

[†] Calculated for a vacuum using the Richardson equation.

III. CESIUM CELL

A. Experimental Current-Voltage Characteristics

1. Results for $10^{11} < n_0 < 10^{12}$

Figures 9-12 are current-voltage characteristic curves obtained with a cesium cell operated at low vapor densities n_0 , in the range 10^{11} - 10^{12} atoms/cc. Emitter-collector distances (EM-C.D.) were varied from 0.25 to 2 mm, and T_e from 1950 to above 2500°K.

Figure 9 presents the results from measurements spanning the density range $1.8\text{--}7.0 \times 10^{11}$, T_e range 1979 to 2237°K, and EM-C.D. range 0.5-2 mm. Table I lists the experimental conditions for Fig. 9.

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Fig. 9. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of $1.8\text{--}7.0 \times 10^{11}$, T_e of $1979\text{--}2237^\circ\text{K}$, and EM-C.D. of $0.5\text{--}2.0$ mm. (Experimental conditions for cases A-F are listed in Table I.)

TABLE 1. Experimental Conditions and Results for Fig. 9 (Cesium Cell)

[illegible]

For completeness, the table (as well as subsequent, similar tables) includes rf frequencies, rms voltages, and rf power data. The output voltage $V_0 \sim \phi_e - \phi_c$ cannot be determined precisely from Figs. 9A-E, but values in the range 2.5-2.7 V are consistent with the curves. For Fig. 9F, V_0 is approximately 2.65 V.

The O curve is lower than the S curve in Figs. 9A-E, being particularly pronounced for the 2-mm EM-C.D. of Figs. 9A and D. This indicates a significant interaction between the dc and rf output, since the rf output is suppressed by the S rf-section switch position which short-circuits the rf output.¹⁻³ (See Fig. 2.) Figs. 9A and D also have pronounced negative slopes over much of the characteristic curves.

The J_i 's were measured at collector voltages of -5 to -6 V in these and following runs.

Table I includes the ratio of J_M to the calculated electron current, J_C , computed for saturation current in a vacuum. If the alkali-metal vapor density is sufficient for space-charge neutralization, and ϕ_e is not significantly reduced by vapor deposition on the emitter, the ratio should be of the order of unity.

For the runs recorded in Fig. 10, the EM-C.D. was held fixed at 2.0 mm, and the values of n_0 ranged only from 1.4×10^{11} to 3.0×10^{11} . Table II presents experimental conditions and data for Fig. 10. In cases A-C, the ratios of measured current to calculated current are of the order of unity; the ratio for D is low, indicating poor neutralization of the space charge. Values of V_0 obtained from the curves are in the range 2.7-2.9 V, in reasonable agreement with results from the runs of Fig. 9. The values

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Fig. 10. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 1.4 - 3.0×10^{11} , T_e of 2024-2558°K, and EM-C.D. of 2.0 mm. (Experimental conditions for cases A-D are listed in Table II.)

TABLE II. Experimental Conditions and Results for Fig. 10 (Cesium Cell)

Case	T _e , °K	n ₀	EM-C.D., mm	J _M /J _C	Collector Voltage, V								Maximum Power, mW		J _i , mA/cm ²	V ₀ , V
					+1		0		-1		-2					
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Dc	Rf		
A	2024	1.4 x 10 ¹¹	2.0	0.56	330	-	340	-	500	-	300	-	-	-	0.06	2.8
B	2190	1.4 x 10 ¹¹	2.0	0.65	220	0.5	210	1.6	190	1.0	-	0.1	-	-	0.2	2.5
C	2380	1.7 x 10 ¹¹	2.0	0.61	-	0.9	-	1.1	-	1.0	-	0.6	300	7.2	0.4	2.7
D	2558	3.0 x 10 ¹¹	2.0	0.18	-	-	-	1.6	-	1.2	-	0.6	560	18	1.0	2.9

of maximum rf power measured for cases C and D were about 2-3% of the dc maxima. The two maxima did not occur at the same points in the characteristic curves: maximum dc power was registered at the knees of the characteristic curves; maximum rf power values were measured in the range -0.5 to 0 V. The differences between power maxima for dc and rf were studied by removing the applied voltage and placing lamp loads of matched impedances in the rf and dc sections of the circuitry (shown in Fig. 2). When the maximum dc output occurred, the rf lamps remained dark; the rf lamps lit up when the dc was short-circuited by connecting the collector and the emitter directly. Maximum dc outputs measured photometrically were generally in the range 2-2.5 V; maximum rf outputs measured this way occurred at dc potential differences of 1.5-2.5 V less than the dc maxima.

The experimental runs shown in Fig. 11 cover essentially the same range of conditions as those for Fig. 10, except that the EM-C.D. was reduced to 1.0 mm. Table III gives the data for Fig. 11. The results are

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Fig. 11. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 2.7×10^{11} , T_e of 1983-2589°K, and EM-C.D. of 1.0 mm. (Experimental conditions for cases A-E are listed in Table III.)

TABLE III Experimental Conditions and Results for Fig 11 (Cesium Cell)

Case	T_e , °K	n_0	EM-C D, mm	J_M/J_C	Collector Voltage, V								J_1 , mA/cm ²
					+1		0		-1		-2		
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	
A	1983	2.7×10^{11}	1.0	0.73	450	-	440	-	430	-	400	-	0.06
B	2180	2.7×10^{11}	1.0	0.80	340	0.8	200	0.8	200	0.9	170	0.6	0.25
C	2319	2.7×10^{11}	1.0	0.96	1500	0.7	-	0.8	-	0.9	-	0.5	0.40
D	2445	2.7×10^{11}	1.0	0.96	-	0.7	-	1.0	-	0.9	-	-	1.2
E	2589	2.7×10^{11}	1.0	0.50	-	-	-	-	-	-	-	-	2.0

similar to those of Fig. 10. Ratios of J_M to J_C are close to unity, except for case E. However, for this EM-C.D., the current ratio of case E is significantly higher than the corresponding case of Fig. 10. As shown in Figs. 11A-D, V_0 is in the range 2.6-2.8 V. Case E is anomalous. Rf frequencies for the same T_e tend to be higher than those for the larger EM-C.D. of Fig. 10.

Figure 12 shows characteristic curves for experiments extending those of Fig. 10 up to $n_0 = 5.5 \times 10^{11}$. Table IV presents the experimental conditions for Fig. 10. The ratios of J_M to J_C are low, and pronounced

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Fig. 12. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 2.8 - 5.5×10^{11} , T_e of 2238 - 2643°K , and EM-C.D. of 2.0 mm. (Experimental conditions for cases A-C are listed in Table IV.)

TABLE IV Experimental Conditions and Results for Fig 12 (Cesium Cell)

Case	T_e , °K	n_0	EM-C D, mm	J_M/J_C	Collector Voltage, V								Maximum Power, mW		J_1 , mA/cm ²
					+1		0		-1		-2				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Dc	Rf	
A	2238	3.2×10^{11}	2.0	0.48	400	0.8	360	0.7	220	1.0	170	0.4	81	8	0.4
B	2423	2.8×10^{11}	2.0	0.46	500	1.1	300	1.2	260	1.2	200	0.7	372	20	0.5
C	2643	5.5×10^{11}	2.0	0.13	-	2.0	-	1.8	320	1.4	200	0.8	733	33	2.0

negative slopes occur in the curves (cf, cases C and D of Fig. 10). These ratios indicate an electron-rich plasma.

2. Results for $10^{12} < n_0 < 10^{13}$

Results of measurements made with cesium vapor densities between 10^{12} and 10^{13} are shown in Figs. 13-15.

Figures 13A-D present results from runs made with $n_0 = 2.7 \times 10^{12}$, $T_e = 2116^\circ\text{K}$, and EM-C.D. ranging from 0.25 to 2 mm. Despite the variation in EM-C.D., the curves of Figs. 13A-D are essentially identical. The EM-C.D. was held constant at 1.1 mm over the runs graphed in Figs. 13E-H, for which $n_0 = 1.7 \times 10^{12}$. However, T_e was increased from 1896°K in Fig. 13E to 2243°K in Fig. 13H, which produced a corresponding increase in current. Data for Fig. 13 are given in Table V. All eight cases have ratios of J_M to J_C of the order of unity. In many cases of Table V, the rf did not have a true sine-wave form, and frequency could not be determined.

Higher vapor densities were used in the runs reported in Fig. 14, for which $n_0 = 5.8$ and 7.0×10^{12} . The EM-C.D. was fixed at 1 mm, and T_e was varied from 1958 to 2498°K . Data for Fig. 14 are given in Table VI. Again the ratio of J_M to J_C was of the order of unity. The magnitude of the

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Fig. 13. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 1.7 and 2.7×10^{12} , T_e of 1896 - 2243°K , and EM-C.D. of 0.25 - 2.0 mm. (Experimental conditions for cases A-H are listed in Table V.)

TABLE V Experimental Conditions and Results for Fig. 13 (Cesium Cell)

Case	T_e °K	n_0	EM C D mm	J_M/J_C	Collector Voltage V								J_1 mA/cm ²
					+1		0		-1		-2		
					Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	
A	2116	2.7×10^{12}	2.0	1.2	150	1.5	140	0.8	130	1.0	-	0.4	0.22
B	2116	2.7×10^{12}	1.0	1.2	200	0.6	180	0.5	150	0.5	-	-	0.17
C	2116	2.7×10^{12}	0.5	1.2	200	0.5	160	0.3	150	-	-	-	0.10
D	2116	2.7×10^{12}	0.25	1.2	210	0.4	190	0.25	190	0.1	-	-	0.07
E	1896	1.7×10^{12}	1.1	1.4	-	-	-	-	-	-	-	-	0.02
F	2036	1.7×10^{12}	1.1	1.0	-	0.37	140	0.5	-	0.1	-	0.2	0.04
G	2103	1.7×10^{12}	1.1	1.5	180	1.0	170	0.8	400	0.1	-	0.1	0.08
H	2243	1.7×10^{12}	1.1	1.2	-	0.6	-	0.6	-	0.7	270	0.5	0.15

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Fig. 14. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 5.8 and 7.0×10^{12} , T_e of 1958-2498°K, and EM-C.D. of 1.0 mm. (Experimental conditions for cases A-E are listed in Table VI.)

TABLE VI Experimental Conditions and Results for Fig. 14 (Cesium Cell)

Case	T_e °K	n_0	EM C D mm	J_M/J_C	Collector Voltage V								Maximum Power mW		J_1 mA/cm ²
					+1		0		1		-2				
					Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	Dc	Rf	
A	1958	5.8×10^{12}	1.0	1.0	350	-	350	-	500	-	320	0.3	-	0.06	
B	2155	5.8×10^{12}	1.0	1.0	220	2	200	1.7	180	1.2	-	0.6	-	0.6	
C	2294	5.8×10^{12}	1.0	1.6	160	2.5	150	2.0	90	1.4	-	-	375	16	
D	2416	7.0×10^{12}	1.0	0.81	-	-	-	-	-	-	-	-	450	50	
E	2498	7.0×10^{12}	1.0	1.1	-	-	-	-	-	-	-	-	1440	160	

Collector Temperature 400°K

current increased considerably as T_e was increased. In many instances, frequencies could not be measured. However, as T_e became higher, the maximum rf power became relatively high, exceeding 10% of the maximum dc power in cases 14D and E.

Figure 15 presents results from runs with relatively high T_e values of 2445 and 2571°K. Densities were 6.8 and 8.2×10^{12} . The EM-C.D. was varied over 0.5 to 2 mm. Data for Fig. 15 are tabulated in Table VII. Variation of the EM-C.D. did not make a large change in the ratios of J_M to J_C but did change the rf frequencies considerably. Cases A-C had J_M approximately equal to J_C ; cases D-F showed J_M only about half of J_C .

112-8660

Fig. 15. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 6.8 and 8.2×10^{12} , T_e of 2445 and 2571°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table VII.)

TABLE VII. Experimental Conditions and Results for Fig. 15 (Cesium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	Collector Voltage, V								Maximum Power, mW		J_i , mA/cm ²
					+1		0		-1		-2				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Dc	Rf	
A	2445	6.8×10^{12}	2.0	0.74	280	2.5	-	2.1	80	1.0	80	1.0	500	55	4.4
B	2445	6.8×10^{12}	1.0	0.76	220	2.4	200	2.6	200	1.4	180	0.5	550	40	5.0
C	2445	6.8×10^{12}	0.5	0.99	-	-	-	1.0	-	-	-	-	640	-	5.0
D	2571	8.2×10^{12}	2.0	0.44	1300	1.2	1300	1.8	1200	1.1	1100	0.5	960	60	8.0
E	2571	8.2×10^{12}	1.0	0.52	220	2.5	220	2.0	-	1.2	-	-	1150	40	8.0
F	2571	8.2×10^{12}	0.5	0.52	350	2.0	350	1.3	310	0.8	-	-	1150	-	6.0

Collector Temperature, 364°K.

3. Results for $10^{13} < n_0 < 10^{14}$

Graphical data from runs made with cesium vapor densities, n_0 , in the range 10^{13} to 10^{14} are given in Figs. 16 and 17. Data for the two figures are tabulated in Tables VIII and IX, respectively.

Figure 16 is for runs with $n_0 = 2 \times 10^{13}$. The EM-C.D. was varied over 0.5-2.0 mm. However, for a given T_e , the EM-C.D. had little effect on current. The current variations for the higher T_e (2498°K) may have been due to changes in T_e , since at high emitter temperatures it was difficult to keep T_e constant over the time required to measure several characteristic curves. For all six cases, the knees of the curves are quite sharp, and the currents are nearly constant for voltages greater than the knee voltages. In many runs (see Table VIII) the rf output could not be characterized by a frequency, but an rms voltage and power output could be measured.

Figure 17 presents curves for a constant EM-C.D. of 1.5 mm and T_e increasing from 2160 to 2743°K. Currents increase rapidly as T_e

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Fig. 16. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 2.0×10^{13} , T_e of 2257 and 2498°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table VIII.)

TABLE VIII Experimental Conditions and Results for Fig. 16 (Cesium Cell)

Case	T_e , °K	n_0	EM-C D, mm	J_M/J_C	Collector Voltage V								Maximum Power, mW		J_1 , mA/cm ²
					+1		0		-1		-2				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V			
					Dc	Rf									
A	2257	2.0×10^{13}	2.0	1.0	200	2.8	220	1.9	90	1.2	40	0.5	190	16	0.7
B	2257	2.0×10^{13}	1.0	0.94	150	1.9	140	1.4	110	1.0	40	0.5	190	5	1.0
C	2257	2.0×10^{13}	0.5	0.88	140	1.0	110	0.7	80	0.6	70	0.4	150	-	0.8
D	2498	2.0×10^{13}	2.0	0.67	-	1.9	-	1.8	-	1.4	-	0.7	1080	70	2.0
E	2498	2.0×10^{13}	1.0	0.67	-	2.1	-	2.0	-	1.3	-	0.7	700	20	2.0
F	2498	2.0×10^{13}	0.5	0.67	-	0.8	-	0.6	-	0.5	-	0.4	520	-	-

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Fig. 17. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 8.0×10^{13} , T_e of 2160-2743°K, and EM-C.D. of 1.5 mm. (Experimental conditions for cases A-F are listed in Table IX.)

TABLE IX Experimental Conditions and Results for Fig. 17 (Cesium Cell)

Case	T_e , °K	n_0	EM-C D, mm	J_M/J_C	Collector Voltage, V								Maximum Power, mW		J_i , mA/cm ²
					+1		0		-1		-2				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V			
					Dc	Rf									
A	2160	8.0×10^{13}	1.5	0.96	250	1.5	220	1.5	180	1.0	-	0.5	43	-	0.6
B	2310	8.0×10^{13}	1.5	1.0	100	3.0	90	2.5	80	1.7	72	1.0	260	25	2.6
C	2371	8.0×10^{13}	1.5	0.93	100	4.6	85	3.0	80	2.0	70	1.2	450	50	2.8
D	2528	8.0×10^{13}	1.5	0.81	-	3.0	40	2.3	50	1.5	-	-	1275	160	3.0
E	2613	8.0×10^{13}	1.5	0.81	-	-	-	-	-	-	-	-	3012	400	2.0
F	2743	8.0×10^{13}	1.5	0.69	-	-	-	-	-	-	-	-	5200	250	4.0

is raised. The ratio of J_M to J_C decreases as T_e increases. (Note a similar effect in Fig. 16). Rf power maxima become larger than 10% of the dc power maxima as T_e increases, up to case F, for which J_M/J_C is relatively low.

4. Results for $n_0 > 10^{14}$

Characteristic curves for n_0 between 10^{14} and 10^{15} are shown in Figs. 18 and 19. Corresponding data are in Tables X and XI, respectively.

Figure 18 was obtained with a constant n_0 of 2×10^{14} ; T_e covered the range from 2010 to 2380°K. Emitter-collector distances of 1 and 2 mm were used. Some relatively high values of rf power were measured. In addition, J_M/J_C ratios of approximately 2 were realized. The characteristic curves have round knees and pronounced slopes below the knees.

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Fig. 18. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 2.0×10^{14} , T_e of 2010-2380°K, and EM-C.D. of 1.0 and 2.0 mm. (Experimental conditions for cases A-E are listed in Table X.)

TABLE X Experimental Conditions and Results for Fig. 18 (Cesium Cell)

Case	T_e , °K	n_0	EM-C D , mm	J_M/J_C	Collector Voltage, V								Maximum Power mW	
					+1		0		-1		-2			
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Dc	Rf
A	2010	2.0×10^{14}	2.0	2.25	375	1.6	350	1.5	360	0.9	200	0.5	27	1
B	2060	2.0×10^{14}	1.0	2.0	360	1.5	320	1.1	260	-	-	-	-	-
C	2284	2.0×10^{14}	2.0	1.7	-	3.0	-	2.8	80	2.0	70	1.1	310	44
D	2268	2.0×10^{14}	1.0	2.4	120	2.5	-	2.5	100	1.2	70	0.8	500	25
E	2380	2.0×10^{14}	2.0	2.2	-	2.0	-	-	-	-	-	-	900	97

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Fig. 19. Current-Voltage Characteristic Curves for Cesium Cell at Vapor Density of 3.5×10^{14} , T_e of 2371-2730°K, and EM-C.D. of 0.6 mm. (Experimental conditions for cases A-E are listed in Table XI.)

TABLE XI. Experimental Conditions and Results
for Fig. 19 (Cesium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	$J_M/J_C^{(a)}$	Maximum Power (dc), mW	J_i , mA/cm ²
A	2371	3.5×10^{14}	0.6	0.95	425	7
B	2496	3.5×10^{14}	0.6	0.93	1130	45
C	2560	3.5×10^{14}	0.6	0.86	1560	50
D	2603	3.5×10^{14}	0.6	1.52	3400	90
E	2730	3.5×10^{14}	0.6	1.21	5000	-

(a) J_M measured at zero collector voltage.

Figure 19 presents results from runs with higher T_e , the EM-C.D. fixed at 0.6 mm, and $n_0 = 3.5 \times 10^{14}$. Large increases in current are shown for positive voltages. The rf output became very weak, disappearing completely over certain operating ranges. In cases B-E, dc power in excess of 1 W was measured, reaching 5 W for an emitter temperature of 2730°K.[†]

5. Results for High-pressure Cesium Cell

Figures 20-22 are graphs of characteristic curves obtained with high cesium pressures.

Figure 20 and Table XII are for runs with $n_0 = 10^{15}$. Cases A-C were from experiments at $T_e = 2103^\circ\text{K}$ and a collector temperature of 793°K. Case D had $T_e = 2196^\circ\text{K}$ and collector at 793°K; and cases E and F had emitter and collector temperatures of 2196 and 502°K, respectively. In all instances, the ratio J_M/J_C was well over unity. Figures 20A, D, and E show reversals in the curves. Current increases with increasing positive voltages are pronounced. Figure 21 shows the effects of higher pressures for $n_0 = 2.3 \times 10^{15}$. Data for this figure are given in Table XIII. The reversals have disappeared from the characteristic curves. Emitter temperatures were varied from 2195 to 2523°K. The EM-C.D. was held fixed at 0.5 mm (cf, Figs. 20A and D). Figures 21A, B, and C show significant negative currents at emitter voltages below -3 V as do the remaining three curves of Fig. 21, but to a lesser extent.

Figure 22 shows results from runs with a very high n_0 of 1.6×10^{16} . Values of T_e ranged from 2036 to 2586°K. (See Table XIV.) Reversals are again appearing, this time for the two runs with $T_e = 2286^\circ\text{K}$. Larger negative currents occur, and in case C, current becomes negative at only -2.3 V. Note the high ratios of J_M to J_C .

[†]The emitter temperatures for these power densities are too high for present reactor applications, but they show the capabilities of these direct-conversion cells.

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Fig. 20. Current-Voltage Characteristic Curves for High-pressure Cesium Cell at Vapor Density of 10^{15} , T_e of 2103 and 2196°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table XII.)

TABLE XII. Experimental Conditions and Results for Fig. 20 (High-pressure Cesium Cell)

Case	T_e , °K	Collector Temperature, °K	n_0	EM-C.D., mm	J_M/J_C	Maximum Power (dc), mW
A	2103	793	10^{15}	0.5	2.23	67
B	2103	793	10^{15}	1.0	2.39	55
C	2103	793	10^{15}	2.0	1.84	40
D	2196	793	10^{15}	0.5	2.40	170
E	2196	502	10^{15}	1.0	1.73	110
F	2196	502	10^{15}	2.0	1.73	90

Fig. 21

Current-Voltage Characteristic Curves for High-pressure Cesium Cell at Vapor Density of 2.3×10^{15} , T_e of 2195-2523°K, and EM-C.D. of 0.5 mm. (Experimental conditions for cases A-F are listed in Table XIII.)

112-8666

TABLE XIII. Experimental Conditions and Results for Fig. 21
(High-pressure Cesium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	Maximum Power (dc), mW	J_i , mA/cm ²
A	2195	2.3×10^{15}	0.5	0.83	34	8
B	2288	2.3×10^{15}	0.5	1.28	180	20
C	2307	2.3×10^{15}	0.5	1.39	305	30
D	2413	2.3×10^{15}	0.5	1.33	800	50
E	2460	2.3×10^{15}	0.5	1.45	1300	80
F	2523	2.3×10^{15}	0.5	1.53	2600	200

112-8667

Fig. 22. Current-Voltage Characteristic Curves for High-pressure Cesium Cell at Vapor Density of 1.6×10^{16} , T_e of 2036-2586°K, and EM-C.D. of 0.5 and 1.0 mm. (Experimental conditions for cases A-F are listed in Table XIV.)

TABLE XIV. Experimental Conditions and Results for Fig. 22
(High-pressure Cesium Cell)

Case	T_e , °K	Collector Temperature, °K	n_0	EM-C.D., mm	J_M/J_C
A	2036	562	1.6×10^{16}	0.5	4.33
B	2036	562	1.6×10^{16}	1.0	4.33
C	2286	562	1.6×10^{16}	0.5	3.38
D	2286	562	1.6×10^{16}	1.0	3.38
E	2570	562	1.6×10^{16}	0.5	2.08
F	2586	562	1.6×10^{16}	1.0	2.00

B. Discussion of Current Characteristic Curves for Experimental Cesium Cell

We will now discuss the experimental data of Section A above. For completeness, reference will be made to the rf data where relevant. Additional data and discussion on rf voltage output wave forms and amplitudes of the cesium cell will be presented in Section C.

For low-pressure cells, that is, $n_0 < 10^{15}$, values of V_0 in the range 2.5-2.7 V are typical of the neutral or ion-rich cells in which pronounced characteristic-curve knees appear. Assuming that $\phi_e = 4.2$ V, this results in an effective $\phi_c = 1.5$ -1.7 V.

Negative characteristic curves are frequently observed if the ionization is not quite sufficient for neutralization and the plasma is electron rich. Negative characteristics were first shown in Figs. 9A and D. Although the cesium density should be adequate for the relatively low currents, the comparatively large EM-C.D. for these cases produces additional potential minima between the emitter and the collector. Similar results occur for the 2-mm EM-C.D. runs presented in Fig. 10. Figures 10C and D show currents far below saturation. Figures 10D and 12C have V_0 increased from the typical value of about 2.6 to 3 V, indicating an increase in the effective work function (see Fig. 8) by about 0.4 V. This reduces the cell current to values given by $J_s \exp(-e\Delta\phi/KT)$, where $\Delta\phi = (\phi_e + \delta)$, T is T_e , and J_s is the saturation current.

Two experimental indications of saturation are the shapes of the characteristic curves and the ratio of J_i to J_C . In the absence of a negative characteristic (or the "ignited modes" to be discussed briefly for high-pressure cell runs), saturation is shown by a current that remains constant or increases only slightly as the collector voltage becomes more positive. Since J_i 's were measured at relatively large negative collector voltages, they may not be identical with the ion currents at more positive voltages. However, the ratios of J_i to J_C indicate whether space-charge neutralization would be possible. For cesium, the ratio should be $1/493$ or higher.[†] Ratios of J_i/J_C for the 2-mm EM-C.D. of cases 9A and D are low, in agreement with the other data.

Knechtli and Wada⁴ have attributed the negative characteristics to a decrease in plasma density at points away from the emitter. Qualitatively, this explanation accounts for the negative characteristics. For sufficiently large load resistances, the negative slopes of the characteristics can produce oscillations. In addition, oscillations have also been observed for very ion-rich plasmas without observable negative slopes (cf, cases 9B and C). The theory of these oscillations will be treated in ANL-7378.

[†]That is, the ratio of electron current to ion current should equal $\sqrt{m_i/m_e}$.

Interactions between the rf and dc outputs are shown by the differences between the characteristic curves marked S and O. In cases 9A and D, the O curves are lower; in other cases, such as Figs. 10B-D and Figs. 12A-C, the O curves are higher.

These interactions may be explained by the following tentative theory:

Assume first (as in Fig. 9) that a sufficiently ion-rich plasma exists. If oscillations are suppressed by a short circuit of the rf section, the dc current will depend only on the electron emission and on the ion concentration in the plasma. If oscillations are produced by an open current due to a negative characteristic, instabilities, or other means, a potential minimum will be produced during the negative half-periods of the oscillations. If the amplitude is sufficiently large to cause a minimum $\Delta\phi$, the instantaneous current will be reduced to $I = I_0 \exp(-e\Delta\phi/KT)$, where I_0 is the observed current without oscillations. If I_0 is already the saturation current or very close to it, the positive half-period will produce at most only a very small current increase. The observed average dc current will therefore be lower for the O curves than for the S curves, as for Figs. 9A and B, for example.

Next consider an electron-rich plasma or a cell with a potential minimum that reduces J_M/J_C well below unity, as in cases 10B-D. Let J_M be the current density of the S curve. Then

$$J_M = J_s \exp\left(-\frac{e\phi_M}{KT}\right),$$

where

J_s = saturation density, and

ϕ_M = potential minimum. (1)

If the rf short circuit is removed, oscillations will start. These oscillations will increase the potential minimum, i.e., make it more negative by $\Delta\phi$ during the negative half-cycle, and decrease the minimum by $\Delta\phi$ during the positive half-cycle. Thus, $\Delta\phi = f(t)$, where $f(t)$ is a periodic function. As a simple example, assume equal rectangular positive and negative pulses of duration $\tau/2$, where τ is the period of $f(t)$.

For the negative half-cycle, the current density, J , is given by Eq. 1 with ϕ_M increased by $\Delta\phi$. That is,

$$J = J_s \exp \frac{-e(\phi_M + \Delta\phi)}{KT_e} = J_M \exp \frac{-e\Delta\phi}{KT}. \quad (2)$$

Setting

$$\frac{\epsilon \Delta \phi}{KT_e} = a,$$

we obtain

$$J = J_M e^{-a}. \quad (3)$$

Thus, during the negative half-period, J differs from J_M by ΔJ , which is given by

$$\Delta J_1 = J_M(e^{-a} - 1). \quad (4)$$

Similarly, during the positive half-period, $\Delta \phi < 0$, and J differs from J_M by ΔJ_2 , or

$$\Delta J_2 = J_M(e^a - 1). \quad (5)$$

The average of ΔJ , $\overline{\Delta J}$, is $\frac{\Delta J_1 + \Delta J_2}{2}$ or

$$\overline{\Delta J} = J_M \left(\frac{e^a + e^{-a}}{2} - 1 \right) = J_M \left(\cosh \frac{\epsilon \Delta \phi}{KT_e} - 1 \right) > 0. \quad (6)$$

Thus, for an electron-rich plasma, the measured dc currents of the O curves are higher than the currents of the S curves. The rf-dc interaction is much more pronounced for the large EM-C.D. of 2 mm in Figs. 10 and 12 than for 1 or 0.5 mm, since the amplitudes of the rf increase with the EM-C.D.

Both the rf and characteristic-curve data show dependence upon the EM-C.D.

In most instances, the frequency of the rf output increases as the EM-C.D. is decreased. As an example, see the data for $V_0 = -2$, for cases 9A-B, 9B-C, and 9D-E. (This behavior is not followed for V_0 in the range -1 to +1.)

The increase of the rf frequency with increasing applied dc collector voltage has been observed quite generally not only for cesium but also for potassium and sodium plasmas. Exceptions occurred, particularly when there was a change of mode. Occasionally the frequency doubled or decreased to a fraction of its original value.

Tables I-X show the details, including some exceptions.

The dependence of the rms voltage and the rf power output on EM-C.D. is very important. The maximum output is observed at EM-C.D. of 2 mm or more. The voltage and power decrease with decreasing EM-C.D. (See Tables VII, VIII, and X.) This result is observed as long as the density of the cesium is so low that the EM-C.D. is less than the mean free path (mfp).

At densities above $1-2 \times 10^{13}$, effects attributable to electron scattering become apparent, first for EM-C.D. of 2 mm. As n_0 is increased, scattering becomes important at smaller EM-C.D. Fractions of electrons scattered for distances comparable to the EM-C.D. will be calculated. These calculations will be done for electron energies of both 0.05-0.06 and 0.8-1.2 eV. Although electron thermal energies are typically fractions of an electron volt, the plasma sheath may increase electron energies to several electron volts.

Table XV gives electron scattering cross sections for cesium. Microscopic scattering cross sections for 0.8-1.2 eV are from Brode;⁵ cross sections for 0.05-0.06 eV are from Flavin and Meyerand.⁶ Cross sections for other alkali metals are slightly less. Also in Table XV are the macroscopic scattering cross sections, Σ , for several values of cesium density.

TABLE XV. Electron Scattering Cross Sections for Cesium

Electron Energy Range, eV	Microscopic Scattering Cross Section, σ , cm^2	Macroscopic Scattering Cross Sections, Σ , cm^{-1} , for Some Values of n_0					
		$n_0 = 10^{13}$	$n_0 = 5 \times 10^{13}$	$n_0 = 10^{14}$	$n_0 = 2 \times 10^{14}$	$n_0 = 5 \times 10^{14}$	$n_0 = 10^{15}$
0.8-1.2	5.0×10^{-14}	0.5	2.5	5.0	10	25	50
0.05-0.06	0.483×10^{-14}	0.0483	0.241	0.483	0.966	2.41	4.83

We can assume that the electrons leave the emitter isotropically. The acceleration due to the sheath potential, however, will be essentially along the shortest distance from the emitter to the collector, except at the fringes of the emitter. At energies of 1 eV and more, the velocity due to the plasma sheath far exceeds the thermal velocity in magnitude, and the electrons will travel the shortest EM-C.D. before scattering. In this case, for $n_0 = 10^{13}$ and 2 mm EM-C.D., only about 6% will be scattered, and even less will be scattered at 1 and 0.5 EM-C.D. For $n_0 = 5 \times 10^{13}$, 39 and 22% would be scattered at EM-C.D. of 2 and 1 mm, respectively.

For $n_0 = 10^{14}$, the scattered percentages are 63 and 39% for 2 and 1 mm, respectively. The scattered electrons would not lose any appreciable energy (except for inelastic scattering), but the kinetic energy would no longer be in the forward direction. If the potentials of the emitter and the collector are essentially the same at the knee of the characteristic curve, the scattered electrons may not have sufficient kinetic energy in the forward direction to penetrate the negative potential of the collector relative

to the plasma. After several collisions, the energy of the electrons will be randomized and partially⁷ attain a Maxwellian distribution. In this case, collisions of electrons with neutral atoms will produce additional ionization, if the plasma sheath is at several volts. For cesium atoms, 3.87 V will be sufficient for direct ionization. Ionization in stages will take place for lower voltages by means of the formation of metastable states. (Nottingham⁷ has described these conditions in detail.) In addition, ionization of the dimer, Cs_2 , will occur at lower energies than that of the monomer, cesium.

These calculations explain progressive rounding-off at the knees of the characteristic curves in Figs. 16-19. Figures 16 and 17 show curves for n_0 in the range 10^{13} to 10^{14} . For this range, electron scattering would occur but not dominate. The curves of Figs. 16 and 17 all have J_M/J_C of about unity, relatively independent of EM-C.D. The knees of the curves are sharp, and the currents remain constant even for positive collector voltages.

Figures 18 and 19 show the graphs for densities between $n_0 = 10^{14}$ and 10^{15} . There will be scattering even for low energies (0.05-0.06 eV) as indicated in Table XV. As a result, the knees of the characteristic curves are more rounded. The slopes at the left sides of the knees indicate higher electron temperatures.

At high emitter temperatures (cf, Figs. 19D and E, the sharp increase of current to the right indicates volume ionization.

The currents exceed the saturation values expected in vacuum or with contact ionization only. Oscillations become weak or disappear completely, except for a limited range. This is probably due to collisions between ions and atoms. These collisions will scatter the particles participating in ion oscillations out of phase.

In Figs. 19C, D, and E, the dc power reaches several watts. However, the T_e 's are at present too high for practical applications in a reactor

Figures 20-22 show graphs for high-pressure cells. Volume ionization becomes more important. The reversals of curve directions of Figs. 20A, D, and E indicate slips of the recording pin due to sudden transitions to ignited modes. More detailed information has been reported elsewhere for high-pressure cells.⁸⁻¹⁰

C. Measurements of Rf Voltage Wave Forms and Amplitudes with an Oscilloscope

Figure 23 shows typical oscilloscope pictures of the rf plasma oscillations. The EM-C.D. is shown above the columns; the emitter temperature settings and oscilloscope Y-axis scales are below the columns. The dc voltage at the collector is given at the left side for each row. The n_0 is 5×10^{13} ,

112-3660

Fig. 23. Cesium Plasma Oscillations

corresponding to a cesium pressure of 5×10^{-3} mm Hg. The first column shows the variation of the frequency and amplitude with applied dc voltage for an EM-C.D. of 2 mm. At -2 V, the oscillations are washed out. The oscillations in this column are close to sinusoidal. The voltage amplitudes are on the order of volts.

The middle column, at higher T_e but the same EM-C.D. as the first column, shows amplitudes in the order of 2.5 V and more irregular shapes. The third column shows more irregular wave forms than those in the middle column at an EM-C.D. of 1 mm.

Comparing the last two columns shows that the average voltages are larger at 2 mm than at 1 mm, while the peak voltages are about equal.

MEASURED AT 2 V-dc: $n(\text{Cs}) = 2 \times 10^{14}$
Y-DIRECTION: 5 V/cm;
X-DIRECTION: 10^{-5} sec/cm;
rms = 1.1V

112-8668

Fig. 24. Oscillations in Cesium Cell with $T_e = 2280^\circ\text{K}$, $n_0 = 2 \times 10^{14}$, and $V_0 = 2$ V

In Fig. 24, the similarity to sinusoidal oscillations has disappeared, and the wave form consists of a sequence of triple pulses. As pointed out before, an rms voltmeter does not give valid data for this shape.

The data for Fig. 24 are as follows: emitter temperature, 2280°K ; n_0 , 2×10^{14} ; V_0 , -2 V. The short pulses indicate that the positive amplitude is close to the peak-to-peak voltage of about 6-7 V, although the rms meter showed

only 1.1 V. This high amplitude was observed at -2 V dc, i.e., close to the end of the range of oscillations where the amplitudes are usually much less than at zero or short-circuit dc, as can be seen from Fig. 23.

Tables XVI-XVIII show measurements of rf peak-to-peak voltage, voltage amplitude, and maximum power, as well as maximum dc power.

TABLE XVI. Rf Data for Cesium Cell with $n_0 \sim 1.1 \times 10^{12}$

Case	T_e , °K	T_c , °K	n_0	Rf at 0 V dc				Maximum Power, mW		J_M/J_C	J_i , mA/cm ²
				Frequency, kc	Rms Voltage, V	Peak-to-peak Voltage, V	Amplitude, V	Dc	Rf		
A	2128	380	1.1×10^{12}	200	1.7	6	3	40	1.9	0.94	0.1
B	2195	380	1.1×10^{12}	200	2.1	9	5-6	95	6.25	1.11	0.25
C	2248	393	1.1×10^{12}	190	2.2	10	6-7	150	14	0.83	0.5
D	2308	405	1.1×10^{12}	180	2.0	10	6-7	260	26	1.00	1.4
E	2373	405	1.1×10^{12}	?	2.2	16	10	440	45	1.05	40
F	2518	405	1.1×10^{12}	?	2.2	15?	?	1250	100	0.71	8.0

TABLE XVII. Rf Data for Cesium Cell with $n_0 \sim 1.8 \times 10^{14}$

Case	T_e , °K	T_c , °K	n_0	Rf at 0 V dc				Maximum Power, mW		J_M/J_C	J_i , mA/cm ²
				Frequency, kc	Rms Voltage, V	Peak-to-peak Voltage, V	Amplitude, V	Dc	Rf		
A	2141	442	1.8×10^{14}	220	2.4	8.8	6-7	43	5	1.02	-
B	2180	462	1.8×10^{14}	200	2.4	12	~8	103	11	1.27	0.4
C	2232	470	1.8×10^{14}	190	2.1	15	~9	162	20	1.33	0.4
D	2380	485	1.8×10^{14}	?	2.3	14	~10	490	45	0.82	2.0
E	2415	485	1.8×10^{14}	?	2.6	~16	?	640	72	0.66	2.1
F	2475	509	1.8×10^{14}	?	2.8	20	8-10	1350	110	?	?

TABLE XVIII. Rf Data for Cesium Cell with $n_0 \sim 4 \times 10^{14}$

Case	T_e , °K	T_c , °K	n_0	Rf at 0 V dc				Maximum Power, mW		J_M/J_C	J_i , mA/cm ²
				Frequency, kc	Rms Voltage, V	Peak-to-peak Voltage, V	Amplitude, V	Dc	Rf		
A	2030	475	2.8×10^{14}	350	1.25	4.5	?	14	1	1.33	0.2
B	2113	455	5.0×10^{14}	190	2.0	8	6	48	5	-	-
C	2155	455	5.0×10^{14}	170	2.5	9	6	85	10	1.49	0.6
D	2216	460	5.0×10^{14}	?	2.8	9	6	125	20	1.45	-
E	2310	460	5.0×10^{14}	100	?	12	8	350	50	1.36	2.0
F	2370	460	5.0×10^{14}	70	2.8	15	10?	574	100	1.28	4.0
G	2500	460	5.0×10^{14}	?	3.4	18	10?	1500	200	0.92	3.0
H	2595	460	5.0×10^{14}	?	3.5	20	?	3500	200	1.13	4.0

The rf data were taken at an emitter-collector distance of 2 mm and at zero V_0 (i.e., dc short circuit), except where stated otherwise. Lamp loads were used to obtain accurate rf power output photometrically, as explained before. The dc power maxima, included for completeness, were recorded at the knee of the characteristic curve. The rf voltage amplitudes were estimated, since only the peak-to-peak voltages can be measured accurately for pulses of short duration which are separated by large time intervals. In these cases, the amplitudes are close to the peak-to-peak voltages.

Table XVI shows results for $n_0 \sim 1.1 \times 10^{12}$ as a function of T_e and T_c . Actually, n_0 will vary somewhat at higher T_e , since the entire structure is heated with increasing T_c .

For $T_e = 2128^\circ\text{K}$ in Table XVI, the amplitude is half the peak-to-peak voltage, and the oscillations are close to sinusoidal.

At larger T_e 's, the pulse shape becomes more pronounced, as shown in Fig. 24; however, the shapes are usually single, not triple ones.

As seen in Table XVI, the rms voltages do not exceed 2V for T_e over the range 2128-2518°K. However, the amplitudes are above 4 V from

B to F, usually increasing with T_e . Since the ionization voltage of cesium is 3.89 eV, rf oscillations could contribute to volume ionization in such cases, where the contact ionization becomes insufficient because of a low emitter work function.

The ratio of the rf to dc power maxima first increases with T_e , up to case E, and then decreases somewhat for F. Ratios of J_M/J_C are all close to unity.

Table XVII presents rf data for an appreciably higher n_0 , 1.8×10^{14} . Results follow the same pattern as those of Table XVI.

Table XVIII presents results for $n_0 \sim 4.0 \times 10^{14}$. Ratios of J_M to J_C are higher than those in the other two tables. In general, the data were similar to those of the other two tables, except that much higher current densities resulted from the use of higher n_0 .

D. Summary of Results for Cesium Cell

1. The dc currents in an ion-rich cell have the order of magnitude expected from the Richardson equation for vacuum.
2. The voltage output V_0 is about 2.5-2.7 V. Assuming a ϕ_e of about 4.1-4.2, the effective ϕ_c of the cesium-covered molybdenum collector is about 1.5-1.6 V.
3. The rf oscillations are observed over a range extending from positive collector voltages to the knee of the characteristic curve. At higher cesium densities, oscillations occur also at -6 V.
4. As a rule, the rf frequencies decrease with decreasing collector voltage; however, the wave forms frequently depart quite far from sinusoidal, and at high dc currents the rf becomes noise-like.
5. The rms voltages increase with increasing emitter-collector distance up to 2 mm. The dc currents remain nearly constant, as long as the emitter-collector distances remain small compared with the mfp. Since higher current outputs, 1-10 A, require higher cesium densities with lower mfp, the dc currents decrease with EM-C.D. (cf, Shavit and Hatsopoulos¹¹).
6. The rf power output usually has a maximum rf/dc power ratio in the range -0.5-0 V dc (i.e., zero voltage or short circuit). The rf power increases with emitter-collector distance.
7. The rms voltages at low dc currents frequently have a nearly sinusoidal shape, but at higher dc currents the shape is either noise or single pulses separated by large time intervals. The peak-to-peak voltages attained the range of 10-20 V.

8. In some instances, the dc-current characteristic curve is higher with the rf "open" than with the rf "shorted." In other cases, the S current curves are higher than the O curves.

9. At higher densities, $n_0 = 5 \times 10^{14} - 10^{16}$, the ignited modes appear and the rf oscillations decrease and disappear, except within a limited voltage range. An ignited mode appears also for -6 V and more at the collector.

10. The rf power output can become as high as 15% of the dc power. Usually the rf percentage is low at low dc current, then increases to a maximum, and decreases again as the dc current increases.

IV. POTASSIUM CELL

A. General Considerations

The substitution of potassium for cesium with a tantalum emitter and molybdenum collector affects the conditions for contact ionization at the emitter and the reduction of the work function at the collector.

Table XIX¹² presents data for work function, excitation levels, and ionization levels of alkali metals.

TABLE XIX. Alkali-metal Work Functions, Ionization Levels, and Excitation Levels

Element	First Ionization Voltage, eV	Excitation Levels, eV	Method of Measurement		
			Thermionic	Photoelectric	Contact
			Work Function, eV		
Cesium	3.87	1.4	1.81	1.9-1.96	-
Potassium	4.318	1.6	-	2.24 ^a	1.60
Sodium	5.12	2.1	-	2.28 ^a	1.60-2.26
Barium	5.19	1.56	2.11	2.48	1.73-2.39

^aThe most probable value of work function.

The value of the tantalum work function is about 4.1-4.2 eV. The calculation of contact ionization with the Saha-Langmuir¹³ equation would require a correct knowledge of the tantalum work function. However, the work functions of metals are only averages due to the patch effect, except for single crystals with a given atomic plane and no impurities. In addition, the work functions for electron emission and contact ionization are not necessarily identical. Therefore, the Saha-Langmuir equation can be used only as an order-of-magnitude check, and exact measurements have to be made to obtain correct values.

If the currents at voltages near the knees of the current-voltage characteristic curves for close emitter-collector distances are of the order of the saturation currents calculated by the Richardson equation, we can assume that the effective contact ionization is adequate. Volume ionization gives much higher currents, but the output voltages are usually less. Because of the difference in mass of cesium and potassium, the ratio of electron current to ion current should be only 267 for potassium, rather than the 493 needed for cesium.

The reduction in the work function of the collector will depend on the alkali metal, the work function of the collector material, and the thickness of the alkali-metal layer on the collector surface. From the data in Table XIX, we would expect that the work function reduction of potassium is less than that of cesium for the same substrate.

The following results do not confirm this conclusion, but indicate that the effective collector work functions of potassium and cesium are very close, at least for an emitter with a high work function like that of tantalum or molybdenum.

B. Experimental Results

Figure 25 and Table XX show the graphs and data at a low potassium-vapor concentration of about 10^{12} . As stated previously, the actual concentrations might be higher than the values calculated for vapor in equilibrium at the temperature of the alkali-metal reservoir.

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Fig. 25. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 0.9 and 1.0×10^{12} , T_e of 1968 and 2174°K , and EM-C.D. of 0.5 - 2.0 mm. (Experimental conditions for cases A-F are listed in Table XX.)

In any case, from the J_M/J_C ratio and the nearly constant current characteristics, it appears that saturation current was attained over a voltage range extending from the knee of the characteristic curve to positive collector voltages. This indicates that the tantalum electrode produced sufficient ions by contact ionization.

From the characteristic curves in Fig. 25, a V_0 of 2.6 - 2.7 V can be estimated as the useful output voltage in cases A, B, and C, and a somewhat lower V_0 in D, E, and F. Comparison with corresponding characteristic

curves obtained with cesium vapor shows no appreciable difference. Figure 25D indicates a slightly negative characteristic for 2-mm EM-C.D., suggesting that the ion density is somewhat low.

TABLE XX Experimental Conditions and Results for Fig 25 (Potassium Cell)

Case	$T_e, ^\circ K$	n_0	EM-C D , mm	J_M/J_C	Collector Voltage, V								J_1 , mA/cm ²
					+1		0		-1		-2		
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	
A	1968	0.9×10^{12}	2.0	1.19	400	0.65	650	0.56	380	0.15	350	0.40	0.1
B	1968	0.9×10^{12}	1.0	1.19	450	0.56	430	0.35	380	0.25	320	0.22	0.08
C	1968	0.9×10^{12}	0.5	1.21	510	0.50	470	0.42	450	0.30	380	0.16	0.08
D	2174	1.0×10^{12}	2.0	0.88	600	1.5	550	1.2	500	0.80	-	0.40	0.3
E	2174	1.0×10^{12}	1.0	0.88	1450	0.8	1400	0.5	1250	0.40	-	0.30	0.3
F	2174	1.0×10^{12}	0.5	0.88	380	0.3	380	0.2	350	0.20	120	0.18	0.3

Figure 26 shows the cell operating at higher T_e 's and n_0 about 70% higher than in Fig. 25. The characteristic curves at 2-mm EM-C.D. have negative slopes for the S curves, particularly at the knees, while the O curves have only a slightly less negative slope. This effect is less at 1-mm EM-C.D. in B and E. The higher values of the O characteristics are apparently connected with the rf oscillations, as was discussed for the cesium cell. (See Table XXI.)

112-8670

Fig. 26. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 1.6 and 1.8×10^{12} , T_e of 2285 and 2581°K , and EM-C.D. of 0.5 - 2.0 mm. (Experimental conditions for cases A-E are listed in Table XXI.)

TABLE XXI Experimental Conditions and Results for Fig. 26 (Potassium Cell)

Case	Te, °K	n ₀	EM-C D, mm	J _M /J _C	Collector Voltage, V								Maximum Power, mW		J _i , mA/cm ²
					+1		0		-1		-2				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V			
					Dc	Rf									
A	2285	1.6 x 10 ¹²	2.0	1.11	-	1.8	-	1.5	-	1.1	-	0.6	240	22	0.8
B	2285	1.6 x 10 ¹²	1.0	1.11	1350	1.2	-	0.9	-	0.9	-	0.5	240	4	0.6
C	2285	1.6 x 10 ¹²	0.5	1.11	4500/380	0.2	-	0.2	-	0.2	-	0.1	300	-	0.6
D	2581	1.8 x 10 ¹²	2.0	0.50	-	2.5	-	2.3	-	1.7	-	0.7	1700	110	6.0
E	2581	1.8 x 10 ¹²	1.0	0.50	-	-	-	-	-	-	-	-	1870	-	5.0

In Fig. 26, the rf power output is again a function of the emitter-collector distance. In Fig. 26C at +1 V, two frequencies (4500 and 380 kc) are recorded, the lower frequency modulating the higher one. Similar conditions have frequently been observed. In Figs. 26D and E, saturation currents were not reached.

The ion currents are measured at -6 V, rather than at the voltages over which the characteristics are measured. No electron current exists at -6 V. However, the ion-current measurements show whether neutralization is possible. Actually, the ionization required for neutralization might be higher than the theoretical value, particularly at large EM-C.D.

In Figs. 26D and E, J_e/J_i and J_M/J_C are somewhat low. Thus, the cell operates with an electron-rich plasma, indicating that ionization must be higher than the theoretical value for complete neutralization. The negative slopes are characteristic for these operations, and the slopes may contribute to plasma instabilities favoring plasma oscillations.

In Fig. 27, n_0 is higher than in Fig. 26 and the J_e/J_i ratio appears sufficient for an ion-rich plasma. In addition, J_M/J_C indicates saturation current, and the dc power output varies only slightly with EM-C.D. (See Table XXII.)

A comparison of the O and S curves shows the O curves to be higher than the S curves in Figs. 26A, B, D, and E. In Fig. 27A, and, to a certain extent, in Fig. 27B, the S curves are higher.

As for cesium, the ratio of rf power to dc power is highest for 2-mm EM-C.D. The ratio exceeds 20% for Fig. 27A. Differences between the S and O characteristics are frequently very pronounced for a high rf power output.

Figure 28 shows the characteristic curves for densities of 0.6 and 1.1×10^{13} , at temperatures in the range 2400-2560°K. Data for Fig. 28 are given in Table XXIII. As is seen from the J_M/J_C , electron currents are higher than expected. The output voltages, V_0 , are low, being much less

than 2.5 eV for D, E, and F. In Figs. 26 and 27, V_0 was usually 2.5-2.7 V. At high currents, the voltage drop through resistance R_1 (see Fig. 6) becomes significant and should be added to V_0 . Since R_1 is about 0.1Ω , this amounts to 0.25 V in 28 E and F. This correction is too small to account for the difference in V_0 .

112-8671

Fig. 27. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 5.2×10^{12} , T_e of 2174 and 2237°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table XXII.)

TABLE XXII Experimental Conditions and Results for Fig. 27 (Potassium Cell)

Case	$T_e, ^\circ K$	n_0	EM-C D, mm	J_M/J_C	Collector Voltage, V								Maximum Power, mW		J_1 mA/cm ²
					+1		0		-1		-2				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V			
					Dc	Rf									
A	2174	5.2×10^{12}	2.0	1.05	266	4.1	220	3.4	180	2.6	-	1.0	75	16	1.0
B	2174	5.2×10^{12}	1.0	1.05	280	3.4	220	2.4	210	1.4	120	1.0	81	5	1.2
C	2174	5.2×10^{12}	0.5	1.05	310	2.2	280	2.1	-	1.2	-	0.6	73	-	1.2
D	2237	5.2×10^{12}	2.0	1.45	-	3.8	-	3.0	-	2.0	-	1.0	204	30	1.4
E	2237	5.2×10^{12}	1.0	1.45	180	3.2	120	2.5	-	1.8	-	0.8	180	-	1.8
F	2237	5.2×10^{12}	0.5	1.45	450	0.6	450	0.6	-	1.3	-	0.7	174	-	1.6

112-8672

Fig. 28. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 0.6 and 1.1×10^{13} , T_e of 2400 - 2560°K , and EM-C.D. of 0.5 - 2.0 mm. (Experimental conditions for cases A-F are listed in Table XXIII)

TABLE XXIII. Experimental Conditions and Results for Fig. 28 (Potassium Cell)

Case	$T_e, ^\circ K$	n_0	EM-C.D., mm	J_M/J_C	Collector Voltage, V								Maximum Power, mW		J_j , mA/cm ²
					+1		0		-1		-2				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V			
					Dc	Rf									
A	2400	0.6×10^{13}	2.0	1.98	550	3.8	-	2.6	-	1.4	-	0.6	1000	225	8
B	2453	0.6×10^{13}	1.0	2.00	2000	1.8	2000	1.9	1800	1.8	1700	1.0	1550	40	10
C	2453	0.6×10^{13}	0.5	2.00	-	-	-	-	-	-	-	-	1550	-	12
D	2560	1.1×10^{13}	2.0	1.62	-	-	-	-	-	-	-	-	2600	120	26
E	2560	1.1×10^{13}	1.0	1.92	-	-	-	-	-	-	-	-	3450	-	26
F	2560	1.1×10^{13}	0.5	1.85	-	-	-	-	-	-	-	-	3500	-	20

However, there might be a greater work-function reduction at the emitter than previously, as indicated by the large J_M/J_C values. The saturation currents have been increased significantly above the theoretical values, and in cases 28E and F, the dc power reaches about 3.5 W. Since the collector area is 0.5 cm^2 , the power density is about 7 W/cm^2 .†

† Since a current density of 10 - 20 W/cm^2 is desired for reactor applications, a comparatively low K density would satisfy ionization requirements.

In case 28A, the rf power output reaches 22.5% of the dc power. This indicates that potassium is more favorable than cesium for plasma oscillations.

Figures 29 and 30 (Tables XXIV and XXV, respectively) show characteristic curves obtained at increasingly higher potassium densities. V_0 again falls in the range of 2.5-2.7 V. For Fig. 30, oscillations are observed at -6 V on the collector, i.e., at a condition with $J_e = 0$. Apparently the voltage is high enough to produce plasma instabilities. For this collector voltage, two frequencies are observed (cf, Fig 27C).

112-8673

Fig. 29. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 3×10^{13} , T_e of 2206 and 2310°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table XXIV.)

TABLE XXIV Experimental Conditions and Results for Fig 29 (Potassium Cell)

Case	Te, °K	n ₀	EM-C D mm	J _M /J _C	Collector Voltage V								Maximum Power, mW		J ₁ mA/cm ²
					0		-1		-2		-6				
					Rf Frequency, kc	Rms Voltage V	Rf Frequency, kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V	Rf Frequency kc	Rms Voltage V			
					Dc	Rf									
A	2206	3 0 x 10 ¹³	2 0	2 25	-	3 0	110	2 2	-	1 0	-	-	237	36	3 0
B	2206	3 0 x 10 ¹³	1 0	2 00	125	2 6	110	2 0	100	1 0	480 30	0 06	212	20	3 0
C	2206	3 0 x 10 ¹³	0 5	2 13	130	2 3	120	1 7	50	0 7	470 35	0 04	221	1	3 0
D	2310	3 0 x 10 ¹³	2 0	2 09	100	3 8	90	2 2	-	1 4	500 30	0 05	550	100	5 0
E	2310	3 0 x 10 ¹³	1 0	2 35	100	3 0	50	2 0	2 0	-	450 30	0 03	680	110	8 0
F	2310	3 0 x 10 ¹³	0 5	2 44	300	0 8	100	0 6	0 6	7 0	410 40	-	750	-	8 0

112-8674

Fig. 30. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 2×10^{13} , T_e of 2365 and 2391°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table XXV.)

TABLE XXV Experimental Conditions and Results for Fig. 30 (Potassium Cell)

Case	$T_e, ^\circ K$	n_0	EM-C D , mm	J_M/J_C	Collector Voltage V								Maxi- mum Power mW		J_1 , mA/cm ²
					0		-1		-2		-6				
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage V	Rf Frequency kc	Rms Voltage, V	Rf Frequency kc	Rms Voltage, V			
					Dc	Rf									
A	2365	2.0×10^{13}	2.0	1.11	-	3.8	-	2.0	-	1.0	500	0.18	400	80	3.0
B	2365	2.0×10^{13}	1.0	1.08	-	2.6	1200	1.2	1200	0.6	-	-	468	38	4.4
C	2365	2.0×10^{13}	0.5	0.95	3500	2.3	3500	1.3	3200	0.8	480	0.02	450	5	5.0
D	2391	2.0×10^{13}	2.0	1.22	500	3.5	-	1.8	-	0.7	500	-	500	100	6.0
E	2391	2.0×10^{13}	1.0	1.34	1800	3.0	1200	1.1	1200	0.6	-	-	625	38	6.0
F	2391	2.0×10^{13}	0.5	1.34	3500	2.2	3500	1.6	3500	0.8	500	-	700	-	6.0

Cases 29D and 30A produce relatively high rf power. A comparison of the ratios of rf to dc power for cases 29A and D, and 30A and D, shows that this power ratio increases slowly and reaches a maximum as T_e is increased at a constant potassium vapor density. This sequence is similar to the behavior observed for a cesium cell. Figure 31 and Table XXVI show less rf power than that in Fig. 30 and Table XXV. J_M/J_C is approximately 2, while V_0 is somewhat less than 2.5 V. Since $n_0 = 1.1 \times 10^{14}$, there is probably a reduction of the emitter work function due to a certain coverage with potassium. This would explain the increase of J_e and reduction of V_0 .

Figure 32 and Table XXVII give results, for n_0 of 1.3×10^{14} , at 2404 and 2539°K. In each case, the measured current is approximately twice the calculated value. For densities above 10^{14} , the rf power decreases

relative to dc power, and no rf data are given in Table XXVII. The V_0 is about 2.2 V in Figs. 33A-C. The high ratios of J_M to J_C may be due to an emitter-work-function reduction by potassium that increases J_e and reduces V_0 . The effect of emitter-collector distance is pronounced in Figs. 32A-D.

112-8675

Fig. 31. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 1.1×10^{14} , T_e of 2181 and 2280°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table XXVI.)

TABLE XXVI Experimental Conditions and Results for Fig. 31 (Potassium Cell)

Case	$T_e, ^\circ K$	n_0	EM-C D , mm	J_M/J_C	Collector Voltage, V				Maximum Power, mW		J_e , mA/cm ²	V_0 , V
					0		-1		Dc	Rf		
					Rf	Rms	Rf	Rms				
					Frequency, kc	Voltage, V	Frequency, kc	Voltage, V				
A	2181	1.1×10^{14}	2.0	1.93	440	2.2	440	17.0	120	10	3.0	2.3
B	2181	1.1×10^{14}	1.0	1.93	570	1.2	320	1.2	125	-	3.0	2.3
C	2181	1.1×10^{14}	0.5	1.93	500	0.72	350	0.9	145	-	5.0	2.4
D	2280	1.1×10^{14}	2.0	2.22	800	1.7	580	1.6	360	10	6.0	2.5
E	2280	1.1×10^{14}	1.0	2.22	1400	0.7	1000	0.6	480	-	8.0	2.4
F	2280	1.1×10^{14}	0.5	2.22	-	-	-	-	440	-	-	2.5

112-8676

Fig. 32. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 1.3×10^{14} , T_e of 2404 and 2539°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-E are listed in Table XXVII.)

TABLE XXVII. Experimental Conditions and Results for Fig. 32 (Potassium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	Maximum Power (dc), mW	J_i , mA/cm ²
A	2404	1.3×10^{14}	2.0	1.67	1030	14
B	2404	1.3×10^{14}	1.0	2.04	1210	26
C	2404	1.3×10^{14}	0.5	2.22	1265	36
D	2539	1.3×10^{14}	2.0	1.55	2800	60
E	2539	1.3×10^{14}	1.0	2.25	4080	60

The arrows in Fig. 32 show the functional dependence of J_e on the direction of the voltage variation.

Starting at a collector voltage of -4 V, the current reaches a higher value close to the knee of the characteristic curve than is observed if the voltage is reduced from a positive collector voltage. The high value is due to a discharge and an ignited mode at negative voltages. The power at the high vapor densities depends very much more on the emitter-collector distance than it did at the lower densities of Fig. 28. At 2-mm EM-C.D., the sharp knee of the characteristic curve disappears and the J_e 's are reduced very much at -2 V. This is probably due to electron scattering, since the electron mfp has become comparable to the EM-C.D.

Figures 33A-C compare the power output at EM-C.D. of 2.0, 1.0, and 0.5 mm, respectively. Data are given in Table XXVIII. Again the rf output is negligible. The vapor density, n_0 , is probably one order of magnitude higher than 1.6×10^{13} , since the temperature of the storage tank and trap could not be held constant at the necessary high power of the cell. (See Table XXVIII.) However, the differences in power for different EM-C.D. are small in this case of potassium vapor density sufficient for very large currents and power densities.

112-8677

Fig. 33. Current-Voltage Characteristic Curves for Potassium Cell at Vapor Density of 1.6×10^{13} , T_e of 2560-2710°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-E are listed in Table XXVIII.)

TABLE XXVIII. Experimental Conditions and Results for Fig. 33 (Potassium Cell)

Case	T_e , °K	$n_0^{(a)}$	EM-C.D., mm	J_M/J_C	Maximum Power (dc),	J_i , mA/cm ²
A	2560	1.6×10^{13}	2.0	1.59	2970	-
B	2560	1.6×10^{13}	1.0	1.82	3480	20
C	2560	1.6×10^{13}	0.5	1.77	3760	-
D	2690	1.6×10^{13}	2.0	1.52	5880	-
E	2710	1.6×10^{13}	1.0	2.17	9000	20

(a) Calculated for alkali-metal reservoir temperature. The true value may have been much larger. See paragraph above.

The runs shown in Figs. 33D and E evidently produced ignited modes with very high currents and power but low output voltages.

C. Performance of the Potassium Cell Compared with That of the Cesium Cell

The experimental results for the potassium cell are similar to those observed for cesium. Particularly interesting is the fact that the output voltages, V_0 , for cesium and potassium are practically identical, except where volume ionization increases the currents and reduces the output voltages. At moderate emission currents, V_0 is between 2.6 and 2.7 V, and for high currents it is about 2.4 to 2.5 V. The power density with K reaches $\sim 10 \text{ W/cm}^2$, at emitter temperatures of 2600-2700°K, even when the vapor densities are not high. The potassium rf power appears to be somewhat higher than for cesium.

From the unignited-mode results, the vapor densities required for space-charge neutralization by cesium and potassium can be estimated. As was pointed out earlier, an exact calculation is not possible, since the work function of the tantalum emitter is a variable. A value of 4.15 eV shall be assumed for contact ionization.[†] This will be discussed in Section V below.

[†]At high emitter temperatures and currents, some additional ionization will occur due to photoionization, and, for a sufficiently high sheath potential, ionization will be produced by electron impact.

V. ANALYSES OF POTASSIUM AND CESIUM CELL OPERATION WITH A NEUTRAL OR ION-RICH PLASMA BY MEANS OF CONTACT IONIZATION

For the unignited mode, the ion production depends primarily on contact ionization. Other modes might become important as are discussed in Section VI below. The Saha-Langmuir equation, as was pointed out earlier, gives only approximate values, since the work function of the emitter is not constant. However, an order-of-magnitude estimate will be made for the vapor densities required to produce sufficient ionization with cesium and potassium.

The Saha-Langmuir equation is given by

$$\alpha = \frac{n_i}{n} = \left\{ 1 + 2 \exp \left[- \frac{\epsilon}{KT_e} (\phi_e - V_i) \right] \right\}^{-1}, \quad (7)$$

where V_i = ionization potential.

The arrival rate of neutral particles at the emitter is in equilibrium with those leaving it.

Under conditions stated in the appendix, the density of the particles leaving the emitter is given by

$$n^+ = n_i + n_a^+ = \frac{n_0}{2} \sqrt{\frac{T_0}{T_e}}. \quad (8)$$

For a Maxwellian distribution in equilibrium at T_e , the average velocity, v^+ , in the direction from emitter to collector is

$$v^+ = \sqrt{\frac{2KT_e}{m_a \pi}}.$$

But,

$$m = m_a \sim m_i.$$

Therefore, the particle current density, J^+ , is

$$J^+ = v^+ n^+ = \frac{n_0}{2} \sqrt{\frac{2KT_0}{m \pi}}, \quad (9)$$

or the ion particle current density is

$$J_i = \alpha \frac{n_0}{2} \sqrt{\frac{2KT_0}{m\pi}}. \quad (10)$$

For alkali metals, one electron charge of 1.6×10^{-19} coulomb is attached to each ion. If we introduce the values for cesium and potassium, the ion current densities are

$$J_i(\text{Cs}^+) = \alpha(\text{Cs}) \times 5.14 \times 10^{-14} \sqrt{T_0} \times n_0(\text{Cs}) \text{ mA/cm}^2; \quad (11a)$$

$$J_i(\text{K}^+) = \alpha(\text{K}) \times 9.32 \times 10^{-14} \sqrt{T_0} \times n_0(\text{K}) \text{ mA/cm}^2. \quad (11b)$$

Using $\phi_e = 4.15$ eV and the ionization voltages for cesium and potassium (see Table XIX), we can obtain α from Eq. 7. Table XXIX gives values of α for cesium and potassium, at 100°K intervals from 2000 to 2600°K.

TABLE XXIX. Calculated Values of α for Cesium and Potassium with a Tantalum Emitter

T_e	$\alpha(\text{Cs})$	$\alpha(\text{K})$	T_e	$\alpha(\text{Cs})$	$\alpha(\text{K})$
2000°K	0.720	0.147	2400°K	0.659	0.181
2100°K	0.702	0.164	2500°K	0.647	0.185
2200°K	0.685	0.169	2600°K	0.636	0.190
2300°K	0.673	0.175			

For space-charge neutralizations, J_e/J_i should equal $\sqrt{m_i/m_e}$. For cesium, the ratio of J_e to J_i required is 492, and for potassium it is 267. For practical purposes, it is advisable to use lower ratios, i.e., to work with an ion-rich plasma. Given in Table XXIX and the preceding equations together with the electron emission for T_a , the ion current densities, J_i , and saturation current densities, J_s , can be calculated for each emitter temperature.

Table XXX shows for cesium and potassium the α values, saturation current densities, and the ion current densities required for space-charge neutralization for emitter temperatures from 2000 to 2700°K. Also listed are the alkali-metal vapor densities required and the alkali-metal reservoir temperatures necessary to produce the vapor densities shown.

TABLE XXX. Alkali-metal Vapor Temperatures and Densities for Neutralization of Space Charge Using Ion Production by Contact Ionization at Tantalum Emitter

T_e , °K	α	J_s , mA/cm ²	J_i , mA/cm ²	T_c , °K ^a	n_0
<u>Cesium Cell</u>					
2000	0.72	7.2	0.014	295	3.4×10^{10}
2200	0.685	75	0.152	318	2.8×10^{11}
2400	0.659	520	1.06	342	1.85×10^{12}
2600	0.636	2900	5.86	366	8.8×10^{12}
2700	0.624	6100	12.4	381	2.1×10^{13}
<u>Potassium Cell</u>					
2000	0.147	7.2	0.027	353	1.2×10^{11}
2200	0.169	75	0.280	383	10^{12}
2400	0.181	520	1.99	411	5.8×10^{12}
2600	0.190	2900	10.9	440	3.0×10^{13}
2700	0.20	6100	23.0	455	6.2×10^{13}

^a T_c is assumed to be the vapor temperature of the trap and collector.

Since the J_s and J_i values are quite uncertain, it is advisable to operate at a somewhat higher trap temperature than the ones listed. Over the range of interest, a temperature rise of 10 to 15°C will increase n_0 by a factor of two or three.

Doubling the n_0 to obtain an ion-rich plasma will leave the electron mfp large enough to keep losses due to electron scattering small for emitter-collector distances of 1 and possibly 2 mm. For potassium, the densities required for 10 W/cm² or more are $1.5 - 3 \times 10^{14}$. The experimental results indicate that for 1 mm the losses even at these densities are limited.

The comparisons of cesium and potassium show that the output voltages with a tantalum emitter are very similar. Evidently the work-function reduction of a molybdenum collector are practically identical for both gases. The potassium cell trap has to be operated at a higher temperature than that of the cesium cell, since not only is the temperature for a given saturated vapor density higher for potassium than for cesium, but also a higher pressure is required for neutralization by potassium than by cesium.

Houston specifies that for optimum conditions the ratio ϕ_e/ϕ_c should equal T_e/T_c . Thus, T_c has to be relatively high. In space applications, heat rejection from the collector is limited to radiation, so that the collector might be at temperatures high enough for its cesium layer to produce considerable electron emission. This emission could probably be kept lower with potassium.

The high work function of tantalum requires temperatures for efficient operation of a low-pressure cell that cannot be realized in a reactor at present. Thus, it would be advisable to repeat the potassium measurements reported here with an emitter like UC-ZrC having a work function of 3 eV or less. Although results with cesium are very well known, the ionization conditions for lower work-function emitters are more complicated, volume ionization becoming important. Hence, no firm predictions can be made from the results shown in this report.

Also, a combination of cesium and potassium should be investigated with lower work-function emitters. The principle behind this is that the cesium density be only high enough to produce approximate neutralization, and potassium would be the principal material deposited at the collector, thus producing less back emission than a pure cesium layer.

VI. SODIUM CELL

A. Ionization Process

In cesium and potassium low-pressure cells, ionization of the vapor atoms can be produced primarily by surface ionization on the hot surface of the tantalum emitter. Other processes such as photoionization, volume ionization, and step ionization from excited states may be of secondary importance as long as the thermal ionization described by the Saha-Langmuir equation is sufficient to supply the minimum ion density required for $J_e = J_s$.

Table XIX (p. 29) compares data for excitation and ionization levels and work functions for cesium, potassium, sodium, and barium.

For an emitter work function of 4.1-4.2 eV (tantalum), previous calculations showed that cesium and potassium can provide adequate ionization by contact. However, other ionization modes might also be important.

Work functions of UC, UC-ZrC, and other carbides probably have values of about 2.9-3 eV. These values are uncertain, not only because of the patch effect mentioned earlier, but also because of carbide decomposition and formation of different compounds during heating. Therefore, emitter surface regions having work functions considerably higher than the measured averages might account for sufficient contact ionization for neutralization.

The experiments with sodium vapor to be described (cf, also experiments with barium vapor at low pressures¹⁴) may have excited other ionization modes for the current neutralization.

Optical radiation from the emitter at wavelengths of 8943 and 8521 Å can produce excited states in cesium close to 1.45 eV by resonance absorption.¹⁵

Another possibility¹⁵ is formation of the dimer in an excited state, Cs_2^* , from excited atoms, Cs^* , according to the reaction $2Cs^* \rightarrow Cs_2^* + e$. The ionization energy of Cs_2^* is only 3.2 eV.

Similar reactions of step ionization might occur for potassium and sodium since the excitation energies are 1.6 eV for potassium and 2.2 eV for sodium.

Excitation and step ionization might also be affected by the high-energy tail of the electron distribution in equilibrium with the higher vapor densities.

B. Experimental Results

The sodium cell showed an unexpectedly good performance in the unignited mode of operation.

Consider first ionization from contact ionization. For this case, ion currents can be calculated by Eq. 10, yielding

$$J_i^+(\text{Na}) = \alpha(\text{Na}) \times 1.251 \times 10^{-13} \sqrt{T_0} \times n_0(\text{Na}) \text{ mA/cm}^2. \quad (11c)$$

The α 's are calculated from the Saha-Langmuir equation using $\phi(\text{Ta}) = 4.2 \text{ eV}$. The $n_0(\text{Na})$ values have been calculated from published data on saturated vapor pressure, assuming the vapor as an ideal gas.

Table XXXI shows the $\alpha(\text{Na})$ values calculated as a function of temperature for a tantalum emitter. Because of uncertainties, the figures in Table XXXI can only be considered as order-of-magnitude values. For sodium, the ratio of J_e/J_i required for neutralization is 204.

TABLE XXXI. Calculated Values of α for Sodium with a Tantalum Emitter

$T_e, ^\circ\text{K}$	α	$T_e, ^\circ\text{K}$	α
2000	0.00243	2400	0.00586
2100	0.00302	2500	0.00695
2200	0.0082	2600	0.00827
2300	0.00488	2700	0.00952

Figure 34 has been plotted from Eq. 11c for sodium vapor densities from 2×10^{11} to 10^{15} . The currents represent the saturation values expected for the conditions stated in the appendix.

Figure 35 shows the observed current characteristic curves for two values of emitter temperature and a vapor density of 2.2×10^{11} . The emitter temperature is 1860°K for cases A-C and 1963°K for D and E. The first column shows the ratio of measured-to-calculated electron-current densities; the second column, the ratio of measured-to-calculated ion-current densities, J_i ; and the following column, the J_e/J_i . Power maxima are given only for dc. Rf frequencies, (in kc) appear only for case D. These data show that the measured J_e 's are somewhat low, but the values of J_e/J_i indicate a neutral or ion-rich plasma for A-C. However, leakage currents across the insulators might have introduced significant errors into the measurements of the very low ion currents. The output voltage, V_0 , at the knee is close to 2.2 eV in these curves. This value is in agreement with most of the other graphs for sodium cells. Assuming $\phi(\text{Ta})$ as 4.1-4.2 V, this gives 1.9-2 eV for the effective ϕ_c , a value close to those in Table XIX

Fig. 34

Sodium Ion Density and Saturation Ion Current Densities

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Na: Ta-EM: Mo-COLL. J(COLL) $T_c = 433^\circ\text{K}$: $p(\text{Na}) = 10^{-5}\text{mm}$: $n_{\text{Na}} = 2.2 \times 10^{11}$

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Fig 35. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 2.2×10^{11} , T_e of 1860 and 1963°K, and EM-C.D. of 0.5-2.0 mm

Results for higher T_e are recorded in Fig. 36 and Table XXXII. The measured and calculated J_e 's are relatively close in cases 36A-D. Except for D, the currents do not increase with increasing voltage above zero, indicating that J_s has been reached. However, D and E show negative characteristics, as is frequently observed for electron-rich plasmas; this agrees with $J_e < J_s$ and $J_e/J_i \gg 204$ for these two cases. The large difference between the currents in cases E and F is evidently due to the difference in emitter-collector distances. This is probably a result of the potential minimum being more pronounced for larger distances.

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Fig. 36. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 5×10^{12} , T_e of 1984-2258°K, and EM-C.D. of 1.0 and 2.0 mm. (Experimental conditions for cases A-F are listed in Table XXXII.)

TABLE XXXII. Experimental Conditions and Results for Fig. 36 (Sodium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	J_i (meas), mA/cm ²	J_i (calc), mA/cm ²	$\frac{J_M}{J_i \text{ (meas)}}$
A	1984	5.0×10^{12}	2.0	1.19	0.03	0.029	190
B	1984	5.0×10^{12}	1.0	1.19	0.04	0.029	190
C	2056	5.0×10^{12}	2.0	0.66	0.05	0.035	210
D	2056	5.0×10^{12}	1.0	0.69	0.07	0.035	158
E	2258	5.0×10^{12}	2.0	0.36	0.12	0.056	424
F	2258	5.0×10^{12}	1.0	0.71	0.16	0.056	664

The vapor density and the T_e 's are higher in Fig. 37 than in Fig. 36. The solid lines of the characteristic curves refer to the S circuits, and the dashed lines to the O circuits. The frequencies measured for the rf output are shown next to the current curves in Figs. 37A and B. The rms voltages for various collector voltages are shown for cases A-C. The high J_e/J_i ratios indicate that the plasma is electron rich. The J_e 's measured in A and B are higher than expected for this condition. However, the negative characteristics, particularly for 2-mm EM-C.D., are as expected. In agreement with Eq. 6, the O characteristics are higher than the S ones. Values of rf power were not recorded.

Figures 38 and 39 show characteristic curves obtained with higher vapor densities, approximately 2×10^{14} . Figure 38 has T_e 's of 2145 and 2269°K. Figure 39 has curves for somewhat higher T_e values.

Tables XXXIII and XXXIV give data for Figs. 38 and 39, respectively. Both tables show the power maxima for dc and rf outputs. Cell currents are somewhat higher than calculated values, indicating that the plasma is neutral or ion rich.

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Fig. 37. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 4×10^{13} , T_e of 2351 and 2472°K, and EM-C.D. of 1.0 and 2.0 mm

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Fig. 38. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 2×10^{14} , T_e of 2145 and 2269°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table XXXIII.)

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Fig. 39. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 1.6×10^{14} , T_e of 2265-2341°K, and EM-C.D. of 0.6-2.0 mm. (Experimental conditions for cases A-E are listed in Table XXXIV.)

TABLE XXXIII. Experimental Conditions and Results for Fig. 38 (Sodium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	Collector Voltages, V						Maximum Power, mW			
					0		-1		-2		Dc	Rf	J_i (meas) J_i (calc)	J_M J_i (meas)
					Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V	Rf Frequency, kc	Rms Voltage, V				
A	2145	2.0×10^{14}	2.0	1.25	250 ^a	1.1	b	0.8	-	0.15	48	5	0.40	62
B	2145	2.0×10^{14}	1.0	1.45	300	1.0	b	0.6	-	0.20	61	-	0.50	58
C	2145	2.0×10^{14}	0.5	1.60	350	1.1	220	0.4	b	0.16	70	-	0.60	53
D	2269	2.0×10^{14}	2.0	1.38	b	0.9	b	0.9	b	0.30	246	16	0.74	117
E	2269	2.0×10^{14}	1.0	1.41	b	1.2	b	1.1	b	0.25	276	5	0.82	108
F	2269	2.0×10^{14}	0.5	1.47	-	1.1	b	1.0	b	-	287	-	-	-

^aModulated by higher frequency.^bNoise-type wave form.

TABLE XXXIV. Experimental Conditions and Results for Fig. 39 (Sodium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	Maximum Power, mW		J_i , mA/cm ²	J_i (meas) J_i (calc)
					Dc	Rf		
A	2275	1.6×10^{14}	1.0	1.47	210	-	8.0	3.63
B	2265	1.6×10^{14}	2.0	1.28	180	20	2.4	1.09
C	2265	1.6×10^{14}	0.6	1.35	190	-	6.0	2.73
D	2341	1.6×10^{14}	2.0	1.42	420	40	7.0	2.69
E	2341	1.6×10^{14}	1.0	1.48	460	-	7.0	2.69

High current and power densities are recorded in Fig. 40. The J_e/J_i ratios indicate insufficient neutralization, as do the negative slopes of the characteristics, but the J_e 's are higher than would be expected for an electron-rich plasma. In case D, the dc power reaches 4 W, corresponding to a power density of 8 W/cm². An ignited mode is shown in case F at 0 V. The ratios of J_M to J_i (meas) are all higher than 204. Data for Fig. 40 are given in Table XXXV.

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Fig 40. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 2×10^{14} , T_e of 2424 and 2624°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-F are listed in Table XXXV.)

TABLE XXXV. Experimental Conditions and Results for Fig. 40 (Sodium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	Maximum Power, mW		$\frac{J_i \text{ (meas)}}{J_i \text{ (calc)}}$	$\frac{J_M}{J_i \text{ (calc)}}$
					Dc	Rf		
A	2424	2.0×10^{14}	2.0	1.25	880	50	1.05	212
B	2424	2.0×10^{14}	1.0	1.69	1200	-	1.05	287
C	2424	2.0×10^{14}	0.5	2.21	1575	-	1.21	326
D	2624	2.0×10^{14}	0.5	1.14	4000	-	1.32	570
E	2624	2.0×10^{14}	1.0	1.13	3800	-	1.89	395
F	2624	2.0×10^{14}	2.0	0.97	2850	-	2.27	283

The parts of Fig. 41 are similar to each other. Experimental conditions for the figure are given in Table XXXVI. The negative characteristic slopes indicate electron-rich plasmas; the high values of J_M indicate saturation currents. The ratio of J_M to J_i (meas) is ~204 for cases D and E;

for the other cases, it is about half of 204. From the calculated values of J_i , the plasma should be ion rich, but the calculational model assumes a mean free path larger than the EM-C.D. (see appendix), a condition that is not correct for these sodium vapor densities. The loop in case D between 0 and 1 V indicates a change of mode. An ignited mode apparently exists, even if the currents are not as large as would be expected.

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Fig. 41. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 9.5×10^{14} , T_e of 2217-2435°K, and EM-C.D. of 0.5-2.0 mm. (Experimental conditions for cases A-E are listed in Table XXXVI.)

TABLE XXXVI. Experimental Conditions and Results for Fig. 41 (Sodium Cell)

Case	T_e , °K	n_0	EM-C.D., mm	J_M/J_C	Maximum Power (dc), mW	$\frac{J_i \text{ (meas)}}{J_i \text{ (calc)}}$	$\frac{J_M}{J_i \text{ (meas)}}$
A	2269	9.5×10^{14}	2.0	1.75	280	0.19	117
B	2269	9.5×10^{14}	1.0	1.94	310	0.22	111
C	2217	9.5×10^{14}	0.5	2.92	280	0.25	87
D	2435	9.5×10^{14}	2.0	1.49	1010	0.33	183
E	2435	9.5×10^{14}	1.0	2.02	1500	0.33	250

Figure 42 shows characteristic curves obtained under conditions for which ignited modes prevail. Table XXXVII lists the experimental conditions for Fig. 42. As can be seen, the dc currents depend on the direction of the applied collector voltage. The O and S curves traced from negative to positive collector voltages have higher current densities than those taken from positive to negative. The O curves are higher than the S curves.

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Fig. 42. Current-Voltage Characteristic Curves for Sodium Cell at Vapor Density of 3.4 and 5.6×10^{13} , T_e of 2413 - 2630°K , and EM-C.D. of 0.5 - 2.0 mm. (Experimental conditions for cases A-F are listed in Table XXXVII.)

TABLE XXXVII. Experimental Conditions and Results for Fig. 42 (Sodium Cell)

Case	T_e , $^\circ\text{K}$	n_0	EM-C.D., mm	J_M/J_C	Maximum Power, mW		J_i (meas), mA/cm ²	J_i (calc), mA/cm ²	$\frac{J_M}{J_i \text{ (meas)}}$
					Dc	Rf			
A	2413	3.4×10^{13}	2.0	0.58	380	50	4.0	0.6	87
B	2413	3.4×10^{13}	1.0	1.10	720	40	2.0	0.6	330
C	2413	3.4×10^{13}	0.5	0.60	440	1	?	?	?
D	2600	5.6×10^{13}	2.0	0.63	2000	200	20.6	1.1	92
E	2600	5.6×10^{13}	1.0	0.77	2480	140	10.0	1.1	230
F	2630	5.6×10^{13}	0.5	0.78	2640	100	8.8	1.1	284

APPENDIX

Particle Density of Atoms and Ions
in Emitter-Collector Space

Assume an alkali vapor density of n_0 , equal to the saturated vapor density at the trap temperature of T_0 (in °K). This is the vapor density outside the emitter-collector space. The total density in the plasma region between the emitter and collector shall be n . The mfp is assumed to be large enough so that no appreciable scattering occurs for ions and atoms.

If positive sheaths exist at the emitter and the collector, the sheath density of the ions will be considerably higher than the average over the EM-C.D.; but the sheath thickness will usually be negligible, compared with the thickness of the neutral plasma region for n_0 above 10^{11} and emitter-collector distances larger than 0.5 mm. As an approximation, only the density in the plasma region will be calculated as n . At the knee of the characteristic curve, potentials of the collector and emitter sheath are the same.

At the emitter, a portion of the arriving particles, ions, and atoms will be ionized, the rest remaining neutral. Ions and atoms will again be evaporated from the emitter at temperature T_e .

All the neutral particles will arrive at the collector, and so will that portion of the ions with momentum in the emitter-collector direction large enough to overcome the sheath voltage. Ions with insufficient momentum in the forward direction will be reflected back to the emitter. At the comparatively cold collector, the ions will lose their charge and will return as atoms at the collector temperature T_c . At equilibrium, the particle current in the positive direction (i.e., from emitter to collector), $J_i^+ + J_a^+$, must be equal to the current in the negative direction, J_a^- . Therefore

$$n = n_i^+ + n_a^+ + n_a^-. \quad (A-1)$$

Denoting

$$n^+ = n_i^+ + n_a^+, \quad n^- = n_a^-, \quad (A-2)$$

we can write n as

$$n = n^+ + n^-. \quad (A-3)$$

Assuming that the average atom velocity is that for a Maxwellian distribution, and multiplying average velocity by atom density, we obtain, for $m_a \sim m_i = m$,

$$J_a^+ = \frac{1}{2} \sqrt{\frac{2KT_e}{m\pi}} n^+. \quad (A-4)$$

Similarly,

$$J_a^- = \frac{1}{2} \sqrt{\frac{2KT_c}{m\pi}} n^-. \quad (A-5)$$

Since, at equilibrium, the two currents are equal,

$$n^+ \sqrt{T_e} = n^- \sqrt{T_c}. \quad (A-6)$$

Eliminating n^- from Eq. A-6 by use of Eq. A-3 results in

$$n^+ = n \frac{\sqrt{T_c}}{\sqrt{T_c} + \sqrt{T_e}}. \quad (A-7)$$

Similarly,

$$n^- = n \frac{\sqrt{T_e}}{\sqrt{T_e} + \sqrt{T_c}}. \quad (A-8)$$

Particles will flow in both directions across the boundary[†] of the emitter-collector space. At equilibrium, the number of particles entering the space from the outside at T_0 will be equal to the particles leaving at T_e and T_c . Assuming, as in Eqs. A-4 and A-5, that the average velocity of the particles from outside is given by the average over a Maxwellian distribution, we can write this equality as

$$n^+ \sqrt{T_e} + n^- \sqrt{T_c} = n_0 \sqrt{T_0}. \quad (A-9)$$

From Eqs. A-7 and A-8, it follows that Eq. A-9 can be rewritten as

$$n_0 \sqrt{T_0} = 2n \frac{\sqrt{T_c T_e}}{\sqrt{T_c} + \sqrt{T_e}}. \quad (A-10)$$

[†] This boundary is perpendicular to the emitter and collector surfaces.

Thus,

$$n = \frac{n_0}{2} \sqrt{T_0} \left(\frac{1}{\sqrt{T_e}} + \frac{1}{\sqrt{T_c}} \right). \quad (\text{A-11})$$

Substituting Eq. A-11 into Eq. A-7 and simplifying results in

$$n^+ = \frac{n_0}{2} \sqrt{\frac{T_0}{T_e}}. \quad (\text{A-12})$$

Similarly, substituting Eq. A-11 into Eq. A-8, we obtain

$$n^- = \frac{n_0}{2} \sqrt{\frac{T_0}{T_c}}. \quad (\text{A-13})$$

Let

$$n_i = \alpha n^+. \quad (\text{A-14})$$

Then, from Eq. A-12,

$$n_i = \alpha \frac{n_0}{2} \sqrt{\frac{T_0}{T_e}}. \quad (\text{A-15})$$

ACKNOWLEDGMENTS

I am obliged to many members of the staff and the technicians of the Reactor Physics Division, Central Shops, and Shop 17 for their help and assistance.

E. S. Sowa did the mechanical design of the experimental equipment. K. J. Schmidt, G. T. Goldfuss, and G. G. Dewey helped to prepare the experiments, constructed auxiliary equipment, and assisted in the completion of the experiments.

A. J. Ulrich discussed the results and their significance, as did R. O. Brittan. C. E. Dickerman reviewed the report and suggested many improvements. L. D. Borders and Sigmund V. Smith and his group completed difficult designs with refractory metals for electron emission. Also to many other persons who contributed directly or indirectly, I want to express my sincere appreciation and thanks.

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