NASA TECHNICAL MEMORANDUM

NASA TM X-1099

NASA TM X-1099

GENERATION OF ALTERNATING CURRENT BY A POWER DIODE

by Arthur W. Goldstein, Willis H. Braun, and James R. Rose

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1965

NASA TM X-1099

GENERATION OF ALTERNATING CURRENT BY A POWER DIODE

By Arthur W. Goldstein, Willis H. Braun, and James R. Rose

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $1.00

GENERATION OF ALTERNATING CURRENT BY A POWER DIODE

by Arthur W. Goldstein, Willis H. Braun, and James R. Rose

Lewis Research Center

SUMMARY

23831

A device for producing alternating-current power from a plasma diode is analyzed. Electron current in the diode is controlled by a magnetic field, which constitutes the means of providing for regenerative feedback in an oscillator circuit. With the use of experimentally determined characteristics of a magnetically controlled diode, the differential equations governing the circuit are solved numerically for several selected diode-circuit combinations. It was shown from these calculations that an oscillating current output can be obtained and that the current was fully modulated from nearly zero to nearly the maximum obtainable in steady-state operation. The greatest calculated power output was 36 percent of that obtainable from constant current operation and consisted of 58-percent direct-current power and 42 percent alternating-current power. The frequency of oscillation was nearly equal to that calculated from linear circuit theory, which also yielded a criterion for the onset of oscillations.

AUTHOR

INTRODUCTION

Most devices proposed to generate electricity in space directly from a primary source of power produce direct current only. Among these devices are solar cells, batteries, fuel cells, thermoelectric converters, radioisotope cells, and thermionic converters. Alternating current can be produced by passing the output of these devices through an inverter such as a solid-state device. At present, the operating temperature for solid-state inverters ($\sim 425^{\circ}$ K) is sufficiently low so that the accompanying space radiators may prove to be inconveniently large. With the thermionic converter it is possible to produce alternating current directly by several means, one of which is by modulating the plasma diode current with an imposed alternating magnetic field (ref. 1). The purpose of this study is to show some of the design considerations and estimated operating characteristics of a device using this principle. In the following development, the plasma diode is used as the active element in a self-excited generator circuit that produces both alternating and direct current.

SYMBOLS

All units are mks unless otherwise noted.

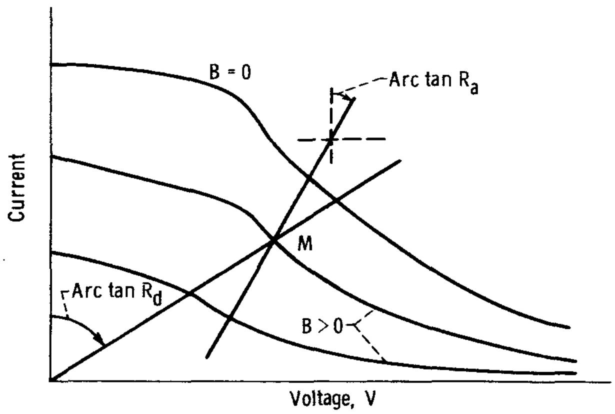
B	magnetic field
C	capacitance
D	emitter diameter
d	thickness of iron shield
e	electron charge
f	iron-shield factor, eq. (13)
H	rate of heat consumption
h	height of diode
I	current (see fig. 3)
i	current (see fig. 3)
j	current density
k	Boltzmann constant
L	inductance
M	center of oscillations (see fig. 1)
n	linear turn density
P	power
Q	radiant and conductive heat loss
q_o	charge on capacitor in steady-state operation
R	resistance of circuit element
R_L	resistance of control coil
r	internal resistance of diode
T	period of oscillation
T_e	emitter temperature
t	time
V	voltage across diode
V_b	barrier voltage in diode (see fig. 5)
V_p	plasma voltage drop (see fig. 5)
w	thickness of control coil
Z	impedance (see fig. 4)
β	feedback coefficient
η	efficiency
θ_e	$2kT_e/e$
μ_o	permeability of free space
ρ	resistivity
φ_c	work function of collector
φ_e	work function of emitter

Subscripts:

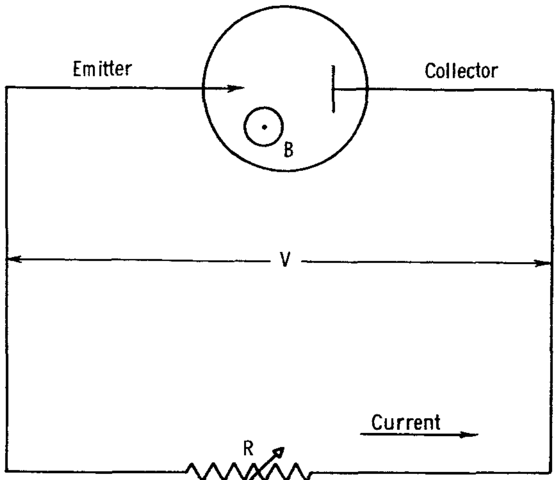
a	alternating-current portion of output or circuit
d	direct-current portion of output or circuit
m	mean value
max	maximum value during cycle
min	minimum value during cycle
o	equilibrium value
s	steady operation (constant current)
u	unsteady operation
1, 2	diode 1, diode 2

DESCRIPTION OF CIRCUITS

The regenerative feature of the oscillator circuits to be described here consists of a



(a) Characteristics.



(b) Typical circuit for measuring characteristics.

Figure 1. - Diode-current response to magnetic field and measuring circuit.

feedback from the output circuit through a magnetic field to control the diode current. The response of a diode current to a magnetic field is shown in figure 1(a), where R_a and R_d are effective alternating- and direct-current load resistances. A set of current - voltage characteristics is illustrated that could be obtained by varying the resistance R and the magnetic field B in the simple circuit shown in figure 1(b). The magnetic field is depicted as perpendicular to the direction of the electron flow in the diode. In the plot of the current - voltage characteristics, only the magnitude, and not the direction, of the magnetic field affects the output voltage and current. The uppermost curve represents the output of the diode when no magnetic field is applied. As the magnetic field is increased, curves such as the two lower characteristics are obtained successively.

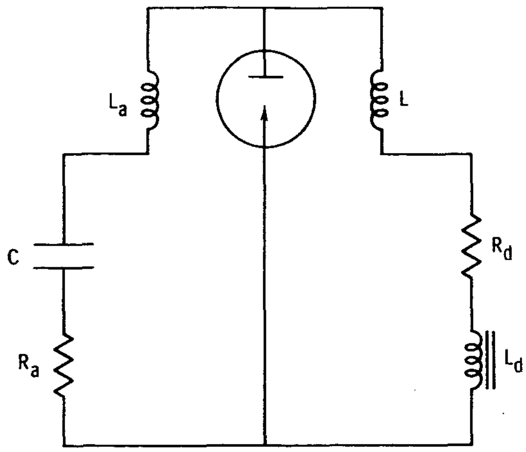


Figure 2. - Single-diode generator circuit.

A simple circuit that generates alternating-current power (and dc power as well) is shown in figure 2, where L and L_a are magnetic field producing coils that are wound around the diode and L_d is a choke coil. Of the current generated in the diode, only a direct-current (average) component can pass through the right leg of the circuit; alternating current is impeded by the choke coil. This leg also contains a load resistance R_d and a coil L that establishes a steady, bias magnetic field in the diode. The bias field causes the diode to operate on a certain characteristic curve (fig. 1(a)) with $|B| > 0$.

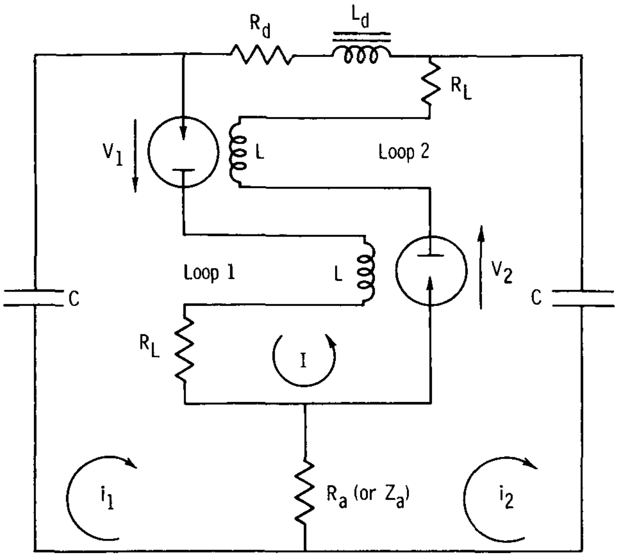


Figure 3. - Tandem-diode generator circuit.

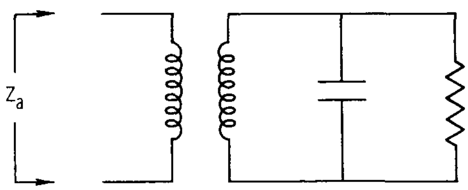


Figure 4. - Alternative load circuit.

For small oscillations, the exact point M along such a curve at which the operation is centered is determined by the intersection of the curve with a straight line through the origin having a slope R_d^{-1}. (When the oscillations are large, the mean operating point does not necessarily lie on the dc load line.) The alternating-current component of the diode current passes through the left leg of the circuit, which contains a load R_a and a series-resonant combination L_aC. The inductance L_a is wound about the diode in such a direction that when an increment in the diode current flows through the diode in the same direction as the direct-current (average) component, the resulting field from the coil L_a opposes that from the coil L.

The generation of alternating current by this circuit may be shown from its instability to small perturbations. One imagines a steady operating condition with the voltage over the capacitor balancing that voltage across R_d. Now suppose a small incremental perturbation in the current occurs; it is blocked from L by L_d and therefore passes through L_a, C, and R_a. This current increment produces a magnetic field in L_a opposed to that generated by L, thus relaxing the constraint on the current flow. If the regenerative coil L_a is sufficiently large, the perturbation is increased until the charge built up on the capacitor provides sufficient voltage to stop and reverse the direction of the perturbation current. This reversed current cannot pass through the diode and, therefore, passes through L_d and maintains a nearly constant current as the voltage changes.

The use of the direct-current bias coil can be avoided by operating two identical diodes in tandem as shown in the circuit diagram (fig. 3). The coil in loop 1, having inductance L and resistance R_L, is taken to be wound about the diode in loop 2; consequently, the current passing through the diode in loop 1 produces a magnetic field that influences the current in the diode of loop 2. Loops 1 and 2 are reciprocally related. The voltages V_1 and V_2 are instantaneous values. The direct-current load is R_d and the choke coil is L_d. The alternating-current load is either a resistance R_a or a transformer-coupled resistance having an effective impedance Z_a (fig. 4). Actual numerical calculations show that if the loading-circuit capacitor and secondary coil are tuned to the natural frequency $\left(1/2\pi\sqrt{LC}\right)$ of the diode loops, then the loading circuit acts as a resistance (R_a).

Again, for small oscillations the coils L and the resistances R_d and R_L determine the bias currents and fields and the mean operating point. The inductances also carry the alternating currents. If the current increases above the mean in diode 1, the magnetic field in diode 2 is increased and the current in diode 2 is reduced. This decrease of current in diode 2 reduces the field on diode 1 and leads to a further increase of current in diode 1. This unstable growth of current in diode 1 is limited by its capacitor, which eventually reverses the alternating current. Again, the frequency of the oscillations will depend on the combination LC.

Basic Equations

To find quantitatively the behavior of the tandum-diode generator, including exact conditions for oscillations, power output, waveforms, and transients, the differential equations for the variation of voltage and current are set up for the combination of diode and circuit on the basis of the current loops shown in figure 3.

$$V_1 = R_L(I + i_1) + L\frac{d}{dt}(I + i_1) + (i_1 - i_2)R_a + \int \frac{i_1}{C}\,dt \tag{1}$$

$$V_2 = R_L(I + i_2) + L\frac{d}{dt}(I + i_2) + (i_2 - i_1)R_a + \int \frac{i_2}{C}\,dt \tag{2}$$

For the s-shaped loop containing the two diodes, the equation is

$$V_1 + V_2 = (2R_L + R_d)I + (2L + L_d)\frac{dI}{dt} + R_L(i_1 + i_2) + L\frac{d}{dt}(i_1 + i_2) \tag{3}$$

The sum and the difference of equations (1) and (2) are

$$V_1 + V_2 = 2\left(L\frac{d}{dt} + R_L\right)I + \left(L\frac{d}{dt} + R_L + \int\frac{dt}{C}\right)(i_1 + i_2) \tag{4}$$

$$V_1 - V_2 = \left(L\frac{d}{dt} + 2R_a + R_L + \int\frac{dt}{C}\right)(i_1 - i_2) \tag{5}$$

The set of equations (3), (4), and (5) is general, and numerical solutions of these for specific current - voltage characteristics will be described later. Because of the complex dependence of the diode voltage on the current and magnetic field, the equations are not suitable for stability analysis of the system without simplification.

Small Oscillation Approximation

The small oscillation approximation is suitable for investigation of the stability of the circuit. It is assumed that there is a steady-state solution for equations (3), (4), and (5) upon which may be superimposed a small amplitude perturbation. The steady state can be established by temporarily removing the resistor R_a (i.e., $R_a = \infty$) so that the currents i_1 and i_2 cannot flow. The voltage V_o and the current I_o of the steady state are related to the charge q_o on each capacitor by equation (3), which now reads

$$V_o = I_o\left(R_L + \frac{R_d}{2}\right)$$

and by the equation for the outer loop in figure 3,

$$\frac{q_o}{C} = \frac{I_o R_d}{2}$$

When the resistor R_a is replaced in the circuit, the currents i_1 and i_2 will begin to flow as well as, possibly, a perturbation ΔI in the s-shaped loop containing the diodes. The voltages generated by the diodes depend on the currents flowing in them and the magnetic fields impressed on them. To a linear approximation the voltage produced by diode 1 is

$$V_1(I_o + \Delta I + i_1, B_1) = V_o + (\Delta I + i_1)\frac{\partial V_o}{\partial I_o} + (\Delta I + i_2)\frac{\partial V_o}{\partial B_o}\frac{\partial B_o}{\partial I_o}$$

The derivative

$$-\left(\frac{\partial V_o}{\partial I_o}\right)_{B_o} \equiv r > 0$$

is the internal resistance of the diode at the steady-state condition. Similarly,

$$-\left(\frac{\partial V_o}{\partial B_o}\right)_{I_o} \frac{\partial B_o}{\partial I_o} \equiv -\frac{\partial V_o}{\partial B_o}\frac{B_o}{I_o} \equiv \beta > 0$$

is the feedback coefficient for the diode. It depends both on the sensitivity of the diode to the magnetic field and the inductance of the coil B_o/I_o. In terms of these parameters the diode voltages are

$$V_1(I_o + \Delta I + i_1, B_1) = V_o - r(\Delta I + i_1) - \beta(\Delta I + i_2) \tag{6}$$

$$V_2(I_o + \Delta I + i_2, B_2) = V_o - r(\Delta I + i_2) - \beta(\Delta I + i_1) \tag{7}$$

Substitution of equations (6) and (7) into equation (5) yields

$$\left(L\frac{d}{dt} - \beta + r + R_L + 2R_a + \int \frac{dt}{C}\right)(i_1 - i_2) = 0$$

or, as a purely differential equation,

$$\left[L\frac{d^2}{dt^2} + (-\beta + r + R_L + 2R_a)\frac{d}{dt} + \frac{1}{C}\right](i_1 - i_2) = 0 \tag{8}$$

The current difference $i_1 - i_2$ is the net current flowing through the alternating-current load R_a; therefore, examination of equation (8) will reveal the growth of alternating-current power in the circuit. The differential operator is that for a harmonic oscillator with a resistive term that is negative, which leads to a growth of the oscillations, provided

$$\beta > r + R_L + 2R_a \tag{9}$$

For the circuit to act as an alternating-current generator, the feedback coefficient must be large enough to overcome the dissipation occurring with the internal resistance of the diode as well as the coil resistance R_L and the alternating-current load R_a.

The period T of the oscillations is given by

$$\frac{2\pi}{T} = \sqrt{\frac{1}{LC} - \left(\frac{-\beta + r + R_L + 2R_a}{2L}\right)^2} \tag{10}$$

and the time in which they grow by a factor e is $2L/(\beta - r - R_L - 2R_a)$. Because the alternating power depends on $i_1 - i_2$, this power generation is greatest when i_1 and i_2, which are equal in magnitude by symmetry, are of opposite phase. The perturbation ΔI, if it appears initially, damps out with time, with a decay rate of $(2R_L + 2r + 2\beta + R_d)/L_d$. The criterion of instability (eq. (9)) applies only to the initial, or small-amplitude, oscillation. The limiting amplitude is determined by the nonlinear characteristics of the system; a large amplitude is obtained by arranging for β to be sufficiently large compared with the resistance terms.

POWER CONSUMPTION AND OUTPUT

A comparison of unsteady diode operation with steady operation (no magnetic field) will show a reduction of power and efficiency that may be compared with the reduction accompanying other methods of conversion of direct to alternating current. Power is reduced because the diode is operating at almost zero power output during part of the cycle, and efficiency is reduced because heat is lost from the emitter by radiation and conduction for all parts of the cycle including times when a negligible amount of power is being produced.

An estimate of the amount of these reductions is made with the following simplifying assumptions:

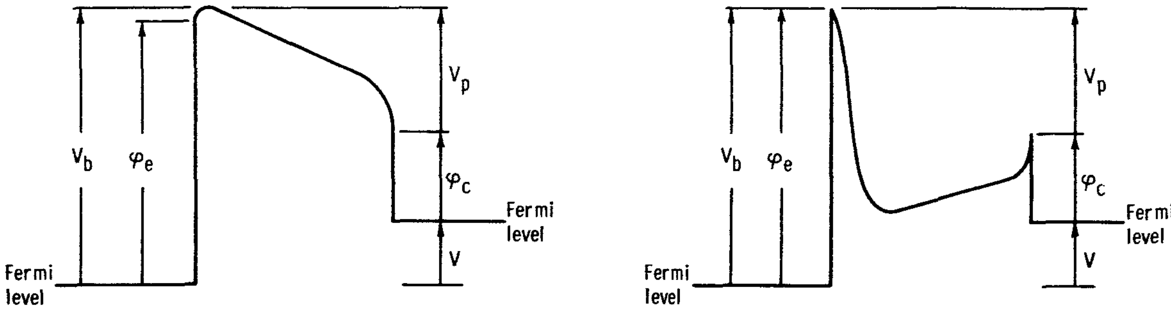
(1) All currents are negligible except those which are composed of electrons emitted from the emitter.

(2) None of the energy of the electrons that reach the collector is returned to the emitter. All the energy of the remaining electrons is returned to the emitter.

It is convenient to think of the losses as being divided into two categories: first, those that depend on the net electron emission current, and second, those that are independent of the current, such as radiation and heat conduction losses.

The electron cooling loss depends on the potential distribution in the interelectrode space. Typical distributions are shown in figure 5. The extinguished mode of operation is characterized by an electron sheath at the emitter and a potential maximum V_b that is higher than the work function of the metal. To reach the collector, each electron must leave the metal with a minimum energy of eV_b. The average electron has an additional kinetic energy of $e\theta_e = 2kT_e$. In this mode of operation, neutralizing ions are supplied by ionization at the emitter surface.

In the arc mode of operation, the ions are supplied in the interelectrode space by the



Extinguished mode Arc mode

Figure 5. - Internal potential distribution.

collision of neutrals with electrons that have first been accelerated through an ion sheath as diagrammed in figure 5, where $V_b = \varphi_e$. In either case, then, the electron cooling loss is equal to $(I + i)(V_b + \theta_e)$, and the electron heat input to the collector is $(I + i)(V_p + \varphi_c + \theta_e)$.

Although the losses are not strongly affected by the mode of operation, the relation between the various types of losses is changed when the operation is changed from conventional direct-current operation to unsteady operation in the oscillator circuit. When subscript s represents diode operation in the conventional steady manner (fig. 1, p. 3 with B = 0) and subscript u designates unsteady (oscillatory) operation in the generator circuit, then the heat-consumption rate H and the current independent loss Q are related to the electron cooling by (arc mode)

$$H_s = I_s(V_{bs} + \theta_e) + Q \approx I_s(\varphi_e + \theta_e) + Q$$

and

$$H_u = (I_u + i)(V_{bu} + \theta_e) + Q \approx (I_u + i)(\varphi_e + \theta_e) + Q$$

In a condition of steady oscillation with full current modulation, $I_u + i$ has a maximum value of approximately I_s and a minimum of zero with an average of approximately $\frac{1}{2} I_s$; therefore, the average energy consumption is

$$H_u \approx \frac{1}{2} I_s(\varphi_e + \theta_e) + Q$$

The power output P_s in steady operation is

$$P_s = I_s V_s$$

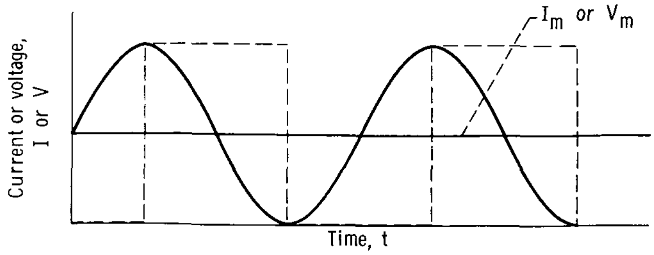


Figure 6. - Current and voltage components for either sinusoidal or square wave output.

In unsteady operation there is a direct-current component of power depending on the mean voltage and current,

$$P_d = I_m V_m \sim \frac{1}{4} I_s V_s = \frac{1}{4} P_s$$

and an alternating-current component P_a, the value of which depends on current and voltage waveform and phase shift and the degree of current modulation by the magnetic field. For fully modulated square wave with no phase lag,

$$P_a = \frac{1}{4} P_s$$

$$P_u = \frac{1}{2} P_s$$

and for a sine wave,

$$P_a = \frac{1}{8} P_s$$

$$P_u = \frac{3}{8} P_s$$

(see fig. 6).

The efficiency is then related to the steady-state value by

$$\eta_s = \frac{P_u}{P_s} \frac{P_s}{\frac{1}{2} I_s(\varphi_e + \theta_e) + Q} = \eta_s \frac{P_u}{P_s} \frac{2H_s}{H_s + Q}$$

This equation indicates that the alternating-current efficiency of a diode will be closer to the direct-current value if the radiation and conduction loss is small compared with the electron cooling loss. If an attainable diode design in which the heat loss by radiation and conduction is one-half the steady-state electron cooling loss is assumed, η_u/η_s = 0.75 for a square wave and 0.56 for a sine wave.

ESTIMATED OPERATION OF A PARTICULAR DIODE WITH SELF-REGENERATIVE CIRCUIT

A specific example will be used to illustrate that a diode design is possible with a spontaneous instability that develops into an almost fully modulated current, with approximately sine-shaped variation, and without prohibitively large energy loss in the coil producing the magnetic field.

Design - Internal Conditions

A diode will operate at somewhat lower efficiency and power output in alternating-current mode than when in steady state; the amount of decrease depends on the diode design and the operating temperatures. The diode utilized for the estimate of the alternating-current generator operation is not optimized for alternating-current operation because there is available only the data from a single set of tests on the effect of an axial magnetic field on operation of a cylindrical diode (obtained by Shock, Eaton, Eisen, and Wolk, ref. 2).

It is possible that alternating-current power of some other diode may compare more favorably with its direct-current power output then these present results indicate. Houston (ref. 3) for some unknown reason obtained somewhat lower current densities than reported in reference 2 for zero magnetic field. The parameters that varied during the tests, and for which specific values were selected for the analysis, were the emitter temperature (1900° K) and the temperature of the cesium vapor source (720° K).

The cesium vapor source temperature is chosen on the basis that at low temperatures the cesium density is too low to eliminate the space charge and thereby permit a large current, while at high temperatures the collision rate is sufficiently high to render the diode current insensitive to the

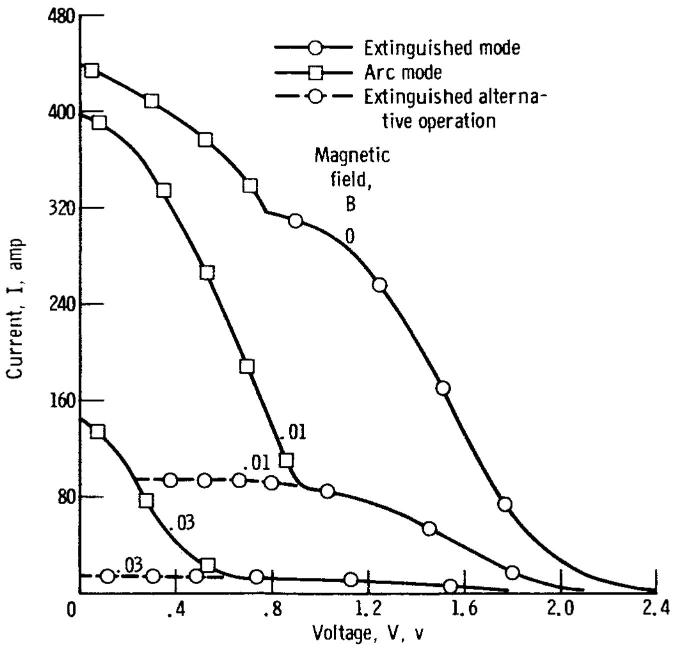


Figure 7. - Voltage - current characteristics of plasma diode with applied magnetic field of 0.01 and 0.03 weber per square meter. Tungsten-emitter temperature, 1900° K; cesium-vapor temperature, 450° K; emitter area, 201 square centimeters.

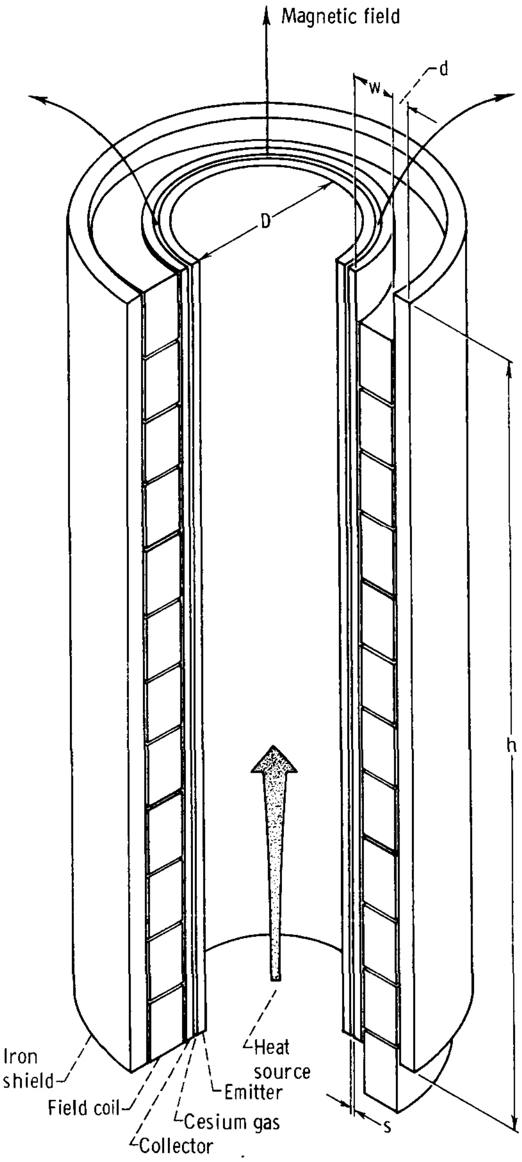


Figure 8. - Diode and field-coil configuration.

magnetic field as a control on the current. The thorium-impregnated tungsten was separated from the cesium-coated molybdenum collector by an electrode spacing of 1 millimeter.

The form of the actual data is shown by the representative curves in figure 7. In contrast to the simple curves of figure 1 (p. 3), the actual characteristic curves for this particular diode are of two types corresponding to the arc mode of operation (high current, low voltage) and the extinguished mode (low current, high voltage). In general, the diode will pass from the extinguished to the arc mode along a path that depends on the external circuit. To obtain the curves for the arc and the extinguished modes, the experimental data were fitted with the following expressions:

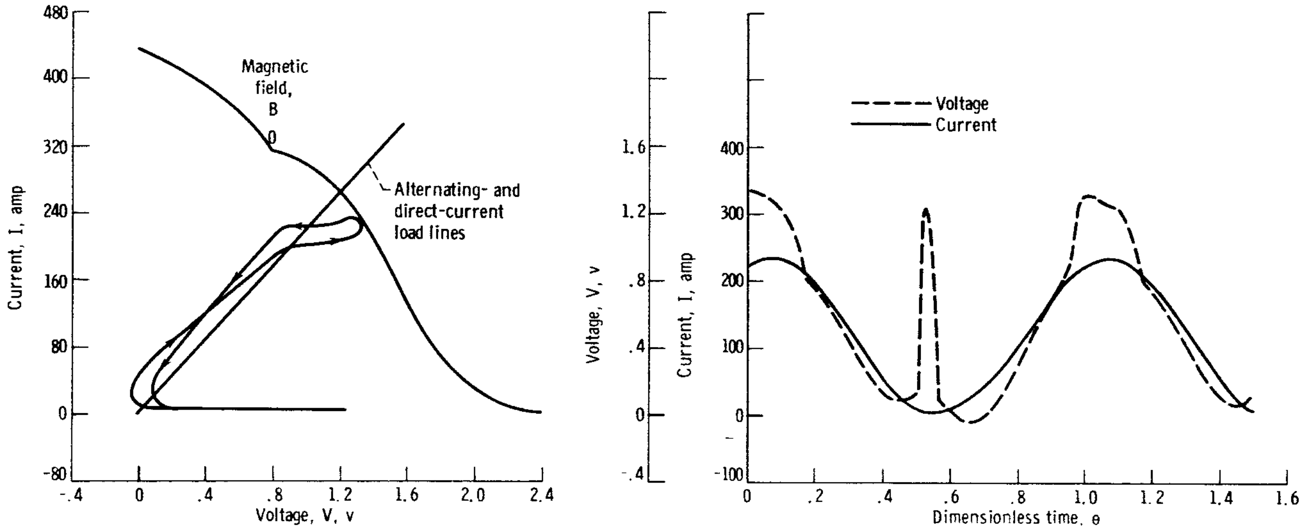
Arc:

$$j = \frac{\left[2.183 - 0.4308(V + 40B)\right]10^4}{1 + \exp\left[5(V + 40B - 1.126)\right]} \tag{11}$$

Extinguished:

$$j = \frac{1.615\times10^4}{\left[1 + (158B)^2\right]\left\{1 + \exp\left[5(V - 1.508)\right]\right\}} \tag{12}$$

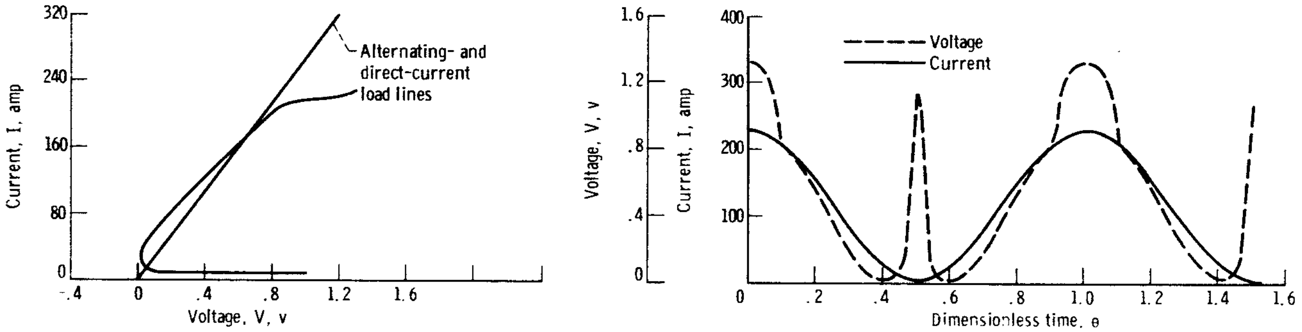
It is not clear in reference 2 whether the low voltage region is one of double-valued currents (whether the dashed portions of the curves in figure 7 are regions of stable operation). For the present purpose the curves may be regarded as single valued, and the larger of the currents from equation (11) or (12) may be used. The calculations were actually programmed to include the possibility of extinguished alternative operation (fig. 7), but no operating points were found in that region. The absence of such states resulted from the extremely small current range of these curves and the size of the current increments that occurred in the course of the calculation.



(a) Voltage - current diagram.

(b) Time variation of voltage and current.

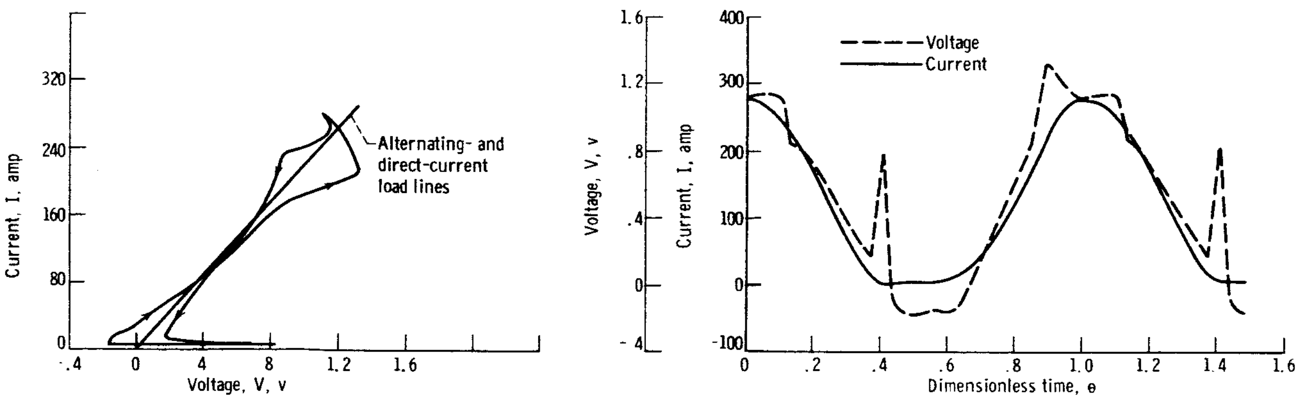
Figure 9. - Generator operation at 1000 cps. Linear turn density, 75 turns per meter; $R + 2R_a = R + R_d/2$, 0.0045 ohm.



(a) Voltage - current diagram.

(b) Time variation of voltage and current.

Figure 10. - Generator operation at 10,000 cps. Linear turn density, 75 turns per meter; $R + 2R_a = R + R_d/2$, 0.0045 ohm.



(a) Voltage - current diagram.

(b) Time variation of voltage and current.

Figure 11. - Generator operation at 120 cps. Linear turn density, 75 turns per meter; $R + 2R_a = R + R_d/2$, 0.0045 ohm.

Design - External Circuit Parameters

In addition to the thermionic cathode - anode pair, the other important element of the diode is the control coil. Its design must provide sufficient magnetic field to regenerate spontaneous oscillations and guarantee a small enough dissipative effect that they are not damped out. The criterion used here is that the maximum magnetic field in a cycle be sufficient to decrease the diode current to a small value compared with the maximum. To actually design the control coil it is necessary to postulate a geometrical configuration for the diode (fig. 8).

The emitter is here taken to be a cylinder of diameter D that contains the primary heat source. The gap between the emitter and the collector is small compared to D so that the measured characteristics of plane diodes can be assumed to apply. The collector is surrounded by the copper control coil of thickness w. The entire assembly is of height h. An outer layer of high-permeability material of thickness d may surround the coil to reduce the reluctance of the magnetic circuit.

For the present case it was assumed that the emitter diameter D is 4 centimeters, the height h is 16 centimeters, and the field-coil thickness w is 1 centimeter. The thickness d of the magnetic material is 0.3 centimeter, which is assumed sufficient to reduce the reluctance of the external magnetic-field path to zero, thereby reducing the required number of turns by one-half. The electrode spacing is 1 millimeter. The external load on each diode consists of a direct-current load of $R_L + R_d/2$ and an alternating-current load of $R_L + 2R_a$; initially, each load was taken to be 4.5×10^{-3} ohm, the value for maximum steady-state power for zero B. Maximum steady-state power is attained at 1.2 volts and 268 amperes. The minimum usable control-coil inductance for this load was found to be 2.36×10^{-6} henry with $n = 75$ turns per meter and $R_L = 0.7\times10^{-3}$ ohm.

At the mean operating point determined by the foregoing load resistance and coil inductance, the feedback factor β and internal diode resistance r are approximately 7.5×10^{-3} and 2.5×10^{-3} ohm, respectively. Frequency of operation was adjusted by means of the capacitors.

The calculations were performed with two types of loading impedance. First, there was used a simple resistance R_a as indicated in figure 3 (p. 4). Secondly, the resistance R_a was replaced with a tuned transformer coupling (fig. 4, p. 4), keeping the effective load equal to R_a, in which the basic frequency of the loading circuit was equal to that in the diode circuit. No difference in performance was detectable.

Waveforms

Numerical solutions of the circuit equations (3), (4), and (5) supplemented by the diode characteristics (eqs. (11) and (12)) are shown in figures 9 to 11 for three different operating frequencies. Paths of operation in the voltage-current plane are shown by curves in figures 9(a), 10(a), and 11(a); arrows indicate succession of operation states. Generally, these curves are open figures with one crossing point. They show the presence of substantial even harmonics by the arching and by the double-loop characteristic. Moreover, the even harmonics, when large, produce an accompanying steady current that shifts the mean operating point from its position on the load line for linear oscillations. Despite the presence of these nonlinear effects, the base frequency is very close to that predicted by linearized theory (eq. (10)).

The corresponding time plots of voltage and current are shown in figures 9(b), 10(b), and 11(b). The current is seen to be more nearly sinusoidal than the voltage curve, which exhibits the appearance of large harmonic components. Particularly noticeable are the voltage spikes near the current minimum where transition from the arc to the extinguished mode occurs. This spike reduces the alternating-current power output because the alternating-current component of current is negative at the same time. At low frequency (fig. 11(b)) the alternating-current power output (47.4 w) is larger than at high frequency (29.5 w, fig. 9(b)) because the form of the current variation is closer to a square wave. Calculated values of the ratio P_a/P_d were 0.70 at low frequency and 0.47 at high frequency (as compared to values of 0.5 for a sine wave and 1.0 for a square wave).

Power Output

Maximum alternating-current power was obtained at approximately the same total load ($2R_a + R_L = 4.5\times10^{-3}$ ohm $= R_L + R_d/2$) as for maximum steady state power. The total power output of the diodes depends on the scale of the device; therefore, the alternating- and direct-current power outputs P_a and P_d for the cases calculated here are given in table I as ratios to the maximum steady-state power output P_s of the diodes. The scale of the device assumed corresponds to $P_s = 322$ watts per diode. These data confirm that an advantage can be achieved in both alternating- and direct-current power if the external circuit is designed to achieve an approximation to a square wave current.

TABLE I. - POWER OUTPUTS

Frequency, cps	Figure	P_a/P_s, percent	P_d/P_s, percent	$(P_a + P_d)/P_s$, percent
120	11	15	21	36
10^3	9	9	19	28
10^4	10	10	19	29

For a given total load resistance the alternating-current power increases rapidly with turn density from zero (at $\beta = r + 2R_a + R_L$) to the power at nearly maximum current amplitude; a further increase in n merely increases the coil loss. For example, of two cases with $2R_a + R_L = 4.5\times10^{-3}$ ohm, one with n equals 72.5 turns per meter develops an alternating-current amplitude of 150 amperes, while the other developed an alternating-current amplitude of 230 amperes when n was increased to 75 turns per meter. The control coil losses are arbitrary in that they depend directly on how much metal one is willing to use; for the dimensions assumed in the present case, the losses were approximately 16 percent of diode output.

Scaling

The results described thus far are limited to a diode of specific size and proportion. The question as to what differences might have been expected if different dimensions were assumed is considered here. Similar operating conditions interior to the diode are expected for the same materials, emitter temperature, cesium temperature, spacing, current density, magnetic field, and voltage. Then since $I = j\pi Dh$, the resistance at the diode terminals is

$$R_L + \frac{R_d}{2} = R_L + 2R_a = \frac{V}{I} = \frac{V}{j\pi hD}$$

Thus larger diodes would require smaller resistances varying as $1/hD$. The required magnetic field B is $nI\mu_o f$ where n is the number of turns per meter, μ_o is the vacuum permeability, and f is the factor resulting from the use of an iron shield. The field coil resistance is then

$$R_L = \frac{\rho\pi(D + w)nh}{w\frac{1}{n}} = \frac{\rho}{\pi}\left(\frac{B}{f\mu_o j}\right)^2 \frac{1}{hD}\left(\frac{1}{D} + \frac{1}{w}\right) \tag{13}$$

where ρ is the specific resistivity. Thus, the ratio of control coil loss to total power $R_L/(R_L + 2R_a)$ varies as $1/D + 1/w$. That is, the control coil is relatively more efficient for larger diodes, although other losses may be larger.

CONCLUDING REMARKS

In view of the simplicity and relatively elevated minimum system temperature of the self-excited alternating-current generating diode and circuit, a complete system analysis might well establish that the inefficiency is tolerable for some space power applications.

The penalty in efficiency that arises from the use of the plasma diode in the proposed alternating-current power-generating circuit is the result of the part-time power production by the diode, while radiation and conduction heat losses continue as in direct-current operation. High efficiency diodes with small conduction and radiation losses would be most suitable for this intermittant use.

Some improvement by reduction in size of the field coil and elimination of the high permeability field coil shield might be achieved by optimization of electrode spacing and cesium vapor density to obtain an increased sensitivity to the magnetic field.

Another feature of alternating-current power generation by magnetic control of a diode output is the continued production of a direct-current component of power, which is at least as great as the alternating-current component. This diode oscillator is, therefore, better suited for application to situations in which the direct-current power can be used.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 18, 1964.

REFERENCES

1. Shock, Alfred: Effect of Magnetic Fields on Thermionic Power Generators. Jour. Appl. Phys., vol. 31, no. 11, Nov. 1960, pp. 1978-1987.
2. Shock, A., Eaton, W. E., Eisen, C. L., and Wolk, B.: Magnetic Field Effects in Thermionic Plasma Diodes. Advanced Energy Conversion, vol. 3, no. 3, July-Sept. 1963, pp. 537-549.
3. Houston, J. M.: Performance Characteristics and Emission Cooling Measurements Taken on a Cs Vapor Thermionic Converter with a Thorium-Tungsten Emitter. Sci. Rep. 1 (AFCRL 63-450), General Electric Co., May 1963.