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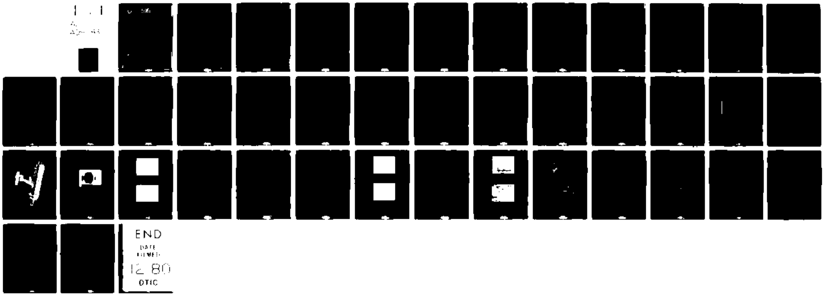

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

DELET-TR-80-13

THE ELECTRON BEAM SEMICONDUCTOR (EBS) AMPLIFIER

Robert M. True
James F. Baxendale
ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

July 1980

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ERADCOM

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The Electron Beam Semiconductor (EBS) concept has existed for three decades; but only within the last decade has an active, well-defined program been underway to develop devices that can operate as high-power radio frequency (RF) amplifiers, fast risetime switches, and current and voltage pulse amplifiers. This report discusses the test procedures, data and results of reliability testing of RF and video pulse EBS amplifiers at Electronics Research and Development Command (ERADCOM), Fort Monmouth, New Jersey. Also, the experimental analysis

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of the series-connected diode EBS device is described in detail. Finally, the report concludes with a discussion of the state-of-the-art of EBS and future trends of the technology.

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THE ELECTRON BEAM SEMICONDUCTOR (EBS) AMPLIFIER

INTRODUCTION

The Electron Beam Semiconductor (EBS) concept, also known as Electron Bombarded Semiconductor has existed for three decades,[1] but only within the last decade has an active, well-defined program been underway to develop devices that can operate as high-power radio frequency (RF) amplifiers, fast risetime switches, and current and voltage pulse amplifiers. This report discusses the test procedures, data and results of reliability testing of RF and video pulse EBS amplifiers at Electronics Research and Development Command (ERADCOM), Fort Monmouth, New Jersey. Also, the experimental analysis of the series-connected diode EBS device is described in detail. Finally, the report concludes with a discussion of the state-of-the-art of EBS and future trends of the technology.

BACKGROUND

The EBS concept, whereby the current through a semiconductor diode is controlled by an incident high energy electron beam, is an intriguing concept since it combines solid state and vacuum tube technologies in a hybrid device. A number of early investigators[2,3] studied the effect, but it was the detailed theoretical and experimental work done by C.A. Norris, Jr.[4,5] at Stanford University under Electronics Command (ECOM) Contract DAAB07-67-C-0320 which provided the impetus for this technology. Spurred on by the impressive results of the applications oriented research of Norris, a number of specialized EBS devices have been developed.

The early days of EBS technology development can be characterized by both skepticism and excessive optimism regarding the potential capabilities of the device. There was no substantive data to back up the claims made by its backers, especially in the areas of actual performance and projected capability. In particular, there was considerable skepticism expressed by

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[1] A.R. Moore, F. Herman, "Semiconductor Signal Translating System," U.S. Patent No. 2,691,076, 1950.

[2] N. Sclar, Y.C. Kim, "The Electron Bombarded Semiconductor as a Circuit Element," IEEE Electron Devices Conference, Washington, D.C., Oct 1957.

[3] A. V. Brown, "Electron Beam Switched PN Junctions," IEEE Transactions on Electron Devices, ED-10, No. 1, pp. 8-12, Jan 1963.

[4] C. B. Norris, Jr., J.F. Gibbons, "Electron Beam-PN Junction Active Devices and Measurements," Stanford Electronics Laboratory Technical Report, SU-SEL-66-118, Mar 1967.

[5] C. B. Norris, Jr., "Electron Beam - Semiconductor Active Devices: Lowpass Amplifiers and Pulse Systems," Stanford Electronics Laboratory SU-SEL-70-019, Final Technical Report RDTR ECOM-0320-F, July 1970.

the scientific community concerning device reliability, since the active semiconductor is bombarded by high energy electrons emitted from a hot cathode within the same vacuum envelope. This hybrid device concept prompted many questions about the long term effects of such diode degradation factors as contamination by emitted cathode materials, electromigration of top contact metal, trapped charges, leakage currents, junction deterioration, thermal dissipation, and bonding voids. This concern over the long term reliability and life of the EBS prompted Defense agencies to initiate a series of life tests at Fort Monmouth, New Jersey and at Watkins-Johnson Company, Palo Alto, California. The life tests conducted at Fort Monmouth are discussed in detail in this report.

In the constant search for improved EBS performance, many unique design concepts and ideas have evolved. One of the most interesting concepts is that of the series-connected diode EBS. This concept involves the use of a multiple diode array of two rows of diodes connected in series to increase the output power capability. Higher operating voltages can be applied to the array than would be possible with a single pair of diodes. Furthermore, connecting the diodes in series in each row has two added benefits. The total diode capacitance is greatly reduced, permitting higher operating frequencies, and the output impedance is raised to a level closer to the optimum line impedance thus simplifying impedance matching circuitry. The experimental results and conclusions are discussed in a later section of this report.

EBS DEVICE CONCEPTS

The EBS device is a hybrid amplifier which uses a high energy electron beam to control the flow of current in a semiconductor diode. A basic device contains a cathode to supply electrons, a control grid to control the electron flow in the beam, and a reverse biased p-n junction diode (or target) mounted in the path of the electron beam. (See Figure 1). This basic configuration can be likened to that of a triode with a semiconductor diode mounted on its plate. Other electrodes may be used for beam deflection, positioning, or for beam shaping. The semiconductor diode is reverse biased so that no diode current flows unless the diode is illuminated by an incident beam of 10 to 15 kilovolt (kV) electrons. These high energy electrons penetrate the thin (1000 angstrom or less) metallic top contact of the diode, where they give up their energy by creating carrier (electron-hole) pairs in the vicinity of the silicon diode p-n junction. The high electric field present in the diode causes immediate separation of the holes and electrons, establishing a current flow within the diode and an external load impedance. One carrier pair is created for each 3.6 electronvolts (eV) of incident energy per electron in silicon. The actual current flow is a function of the incident electron beam energy and density, the amount of diode reverse bias, the load impedance, and the beam energy lost penetrating the top contact. A beam current of several milliamperes (mA) can produce a diode current of many amperes (A). Current gains are typically from 1000 to as high as 3000. Controlling the incident beam current thus controls or modulates the diode current. The diode current can be modulated by either density (grid) modulation or deflection modulation of the beam. This distinction separates the EBS into its two basic type classifications.

The grid (or density) modulated EBS is illustrated in Figure 2. In this type, a voltage pulse or RF signal is applied between the grid and cathode, causing a density modulation of the beam current which results in amplitude modulation of the diode current. This type of EBS is used for nanosecond (ns) switching and fast risetime high voltage modulator and driver applications. It has application as a high peak power pulsed RF amplifier.Its prime disadvantages are that the input signal must be coupled onto the -10 to -15 kV direct current (dc) potential of the grid, and it is difficult to broadband the grid circuit while also performing the input signal coupling function. Recent design advances in this grid circuitry have provided the technology to develop broadband gridded EBS amplifiers.

The deflected beam amplifier is illustrated in Figure 3. In this type of EBS, the electron beam is always on, and is focused onto the neutral space between a pair of diodes at the far end of the tube when no signal is applied to the deflection plates. Upon application of an input RF signal to the deflection plates, the electron beam is deflected sinusoidally in proportion to the input signal such that the beam alternately illuminates first one diode and then the other during each RF cycle. A small signal first deflects the beam a small amount and partially illuminates one diode. At full deflection the diode is fully illuminated and the maximum output signal amplitude occurs. Reversing the input signal polarity causes the beam to deflect in the other direction and illuminate the other diode. With the diodes connected in a Class B configuration, deflection of the beam in one direction produces a current of one polarity in the load while deflection in the opposite direction yields a current of opposite polarity in the load circuit. As a result, a sinusoidal high power RF output signal is developed across the load impedance. The primary application of this type of EBS is as a multioctave high power continuous wave (CW) RF amplifier. Its advantages are very broadband input circuitry which can be referenced to ground, and an output circuit which is also referenced to ground. Its inherent disadvantage is its high sensitivity to external magnetic fields, since the region where the deflection modulation occurs must be over six inches long to provide sufficient deflection sensitivity for input signals. Also, beam alignment is critical to maintain good signal fidelity. The design is complex and the device is much larger than a gridded EBS. As a result, it is more susceptible to damage by shock or vibration and to mechanical misalignment during assembly.

LIFE AND RELIABILITY TESTS

a. Life Test Considerations

Two types of EBS amplifiers were procured and tested by ERADCOM. The first device tested is a deflection modulated Class B RF amplifier known as model W-J 3650-4. This device, shown in the photograph in Figure 4, contains a pair of EBS diodes and a pencil beam electron gun. The electron beam passes through the drift region where RF or other sinusoidal signals applied to a meanderline deflection structure cause the beam to illuminate each diode on alternate half cycles. The resultant diode current generated produces a sinusoidal output waveform across the common output load impedance. These RF amplifiers were fabricated by the Watkins-Johnson Company under contract DAAB07-73-C-0079 and are capable of producing over 50 watts CW output power at frequencies from dc to as high as 250 MHz with over 20 dB gain. The second type of EBS tested at ERADCOM is a grid controlled video pulse amplifier operated as a high current pulse modulator (see Figure 5). This device, known as model W-J 3652, was designed and constructed by the Watkins-Johnson Company under contract DAAB07-73-C-0090. This amplifier provides output pulses of 30 to 40 A peak into a load impedance of 0.5 to 1 ohm with risetimes on the order of 2 ns.

b. RF Amplifier Test Procedures

Life testing of the RF amplifiers commenced in May of 1973. At this time the first two of six devices life tested at ERADCOM were put on test. In October of 1973, the last two devices were placed on life test. The devices were operated continuously except for periodic shutdown to check on the condition of the diodes.

Since the active diode is the heart of the EBS device, these tests were designed to place the diodes under sufficient electrical and thermal stress to simulate the maximum stress levels they would encounter under normal field operation. This was achieved by designing the RF amplifier experiment to maximize the power dissipated in the diode, rather than the output power delivered to the load. The basic power handling limitation for EBS devices is determined by the thermal runaway point of operation of the diode, the diode thermal impedance and its mounting assembly. The RF amplifier experiment was designed to produce a diode thermal stress of at least 20 watts per square millimeter (W/mm^2). This is a substantial stress for these diodes, but the diodes were designed to withstand this power dissipation level. The diodes are mounted on beryllia substrates which are in turn bonded to a copper heat sink. The devices can be water cooled, as the copper heat sink is channeled by machining to maximize heat transfer. In these devices, beryllia is used as an insulating substrate so that the diodes can be biased positive or negative to achieve push-pull operation. Beryllia is an insulator, is transparent to X-rays, and is a very good conductor of heat. X-ray photographs show if there are bonding voids which may cause a poor thermal path for heat transfer from the diode to the heat sink. Bonding voids create localized hot spots in the silicon semiconductor material, leading to thermal runaway and premature diode failure. Any diodes which show substantial void areas are rejected for use in EBS devices.

Aside from a catastrophic failure mode resulting in either an open or shorted diode condition (both of which are easily determined), the best indicator of diode condition is the reverse bias voltage versus leakage current characteristic curve. During the life tests, these curves were periodically checked and photographed for comparison with past and future curve traces. (See Figure 6). A "life history" in the form of diode curve trace photographs were kept for all RF and video pulse EBS amplifiers placed on test, as well as a written record of dc reverse leakage current at the operating diode bias voltage as a function of hours of life. The history we are concerned with is two-fold: one; the diode reverse breakdown voltage, and two; the diode reverse leakage current. (See Figure 6). The higher the reverse breakdown voltage figure is for a given diode, the higher the operating bias voltage can be. Higher bias voltage leads to high device output power capability. Leakage current creates two areas of concern. First, the diode leakage current is wasted power, so device efficiency suffers. Second, the leakage current produces heat in the silicon diodes. Minimizing heat buildup in the diodes is one of the keys to long life EBS devices, therefore the lower the leakage the better. Increased leakage is an indicator of diode degradation. This degradation can be due to sputtering or deposition of cathode or other materials onto the diode surface, resulting in a shunt leakage path which increases the slope of the I-V curve. It can also be due to deterioration of the diode junction itself, in which case the shape of the curve changes, particularly in the breakdown voltage region (the knee or bend) of the reverse characteristic curve.

During 1973 a total of six RF amplifiers were placed on life test at ERADCOM. The objective of these tests was to establish that the EBS diodes could withstand internal heating stresses equivalent to 20 W/mm^2 for a minimum of 10,000 hours of operation. The circuit diagram for the RF amplifier life test is shown in Figure 7. The diode circuitry is referenced to ground, as is the meanderline deflection structure to which the 10 kilohertz (kHz) input signal is applied. Since the purpose of the test was to stress the diodes with a high average heat load, the frequency was not critical, so a low frequency of 10 kHz was used for circuit simplicity. The electron gun portion of the device was referenced to -12 kV. With no signal applied, the potentials on anodes 1 and 2 were adjusted to focus the electron beam to a 1 millimeter (mm) diameter spot size which just filled the neutral area between the two 1 by 2.5 mm rectangular diodes. Applying signals of 10 volts (V) peak-to-peak to the meanderline caused full scale deflection of the beam onto each diode on alternate half-cycles. The diodes were water cooled via machined channels in the copper heat sink mounting assembly of each device. The diodes were operated at up to 80 V of reverse bias. The output signal was developed across a load impedance of approximately 20 ohms. A series cathode resistor limited the beam current to protect the EBS diodes in case of an inadvertent arc or line power surge. Beam currents were on the order of 1 mA. The operating parameters of diode reverse bias voltage, electron beam current and output impedance were set so as to maximize the diode power dissipation. Initially, the diode dissipation was held to low levels of 5 to 10 W/mm^2, but within the first 50 hours it became apparent that the diodes were not deteriorating. The levels were then raised to 20 W/mm^2. The devices performed so well that the levels of dissipation were raised to 30 to 40 W/mm^2 and remained at those levels until the life tests were terminated.

c. Video Pulse Amplifier Test Procedures

In the case of the video pulse amplifier, the stress conditions required for life testing were somewhat different. These devices are used in applications where high peak current or voltage pulses are required as opposed to a continuous power output. These devices typically must provide risetimes on the order of a few ns and narrow pulses of high peak current. The devices tested contained 35 square millimeter (35 mm^2) diodes, since large area diodes are required to produce high current pulses without saturating.

The effect of long term operation at high peak current levels was not known. Accordingly, the tests were performed using 0.5 to 1 ohm load resistors to generate short duration high current pulses of 30 to 40 A peak. The circuit diagram for the video pulse EBS amplifier life test is shown in Figure 8. The diode circuitry is referenced to ground, while the cathode-gril circuitry is all referenced to the -11.3 kV level of the beam high voltage. An isolation transformer is used to float the signal generator at the cathode reference level and the filament power is coupled in a similar fashion. The diode circuitry is shown in simplified form in Figure 9. The 2.2 microfarad capacitor is charged through the 1000 ohm resistor in the time interval between pulses. When the electron beam is pulsed on, the diode conducts, drawing current from the capacitor to develop the output high current pulse across the 1 ohm load resistor.

d. RF Amplifier Life Test Results

The results of the life test of the RF amplifiers are presented in Table 1. All 6 devices were on test for over 21,000 hours without a failure. Tubes Number 5 and Number 9 were on test for 40,000 hours of life each, and no discernible changes occurred in the operating characteristics of these two amplifiers. The 4 other EBS amplifiers were removed from test after operating times ranging from 21,445 to 22,985 hours. No major problems developed with these devices, but the test facilities were needed for other purposes. Also, after 20,000 hours the return on data for the additional hours was considered not to be worth the cost of acquiring it for all six devices. The average time on test was 28,272 hours, almost three times the initial goal. Also, the average dissipation level for the tested diodes was 32.2 W/mm^2 which is also considerably above the projected level of 20 W/mm^2 maximum. The accumulative total for all six devices was 169,630 hours. The mean time to failure (MTTF)[6] is an impressive 183,200 hours at a 60 percent confidence level and 73,800 hours at a 90 percent confidence level. Since no failures were experienced during these tests, the resultant MTTF determinations for these devices are data-limited and not device reliability-limited.

Diode dissipation is determined by considering all of the power components developed in the diode circuitry as follows:

$$P_d = P_b + 1/3\ P_e - 1/2\ P_L$$

$$= I_bV_b + I_eV_e - \frac{1}{2R_L}\left(E_{p-p}/2\sqrt{2}\right)^2$$

where I_b = diode bias current
V_b = diode bias voltage
I_e = incident beam current
V_e = incident beam voltage
P_d = power dissipated by each diode
P_b = power derived from diode bias supply
P_e = incident electron beam power
P_L = output power delivered to load
E_{p-p} = peak-to-peak output signal amplitude
R_L = output load resistance
1/3 = average time per cycle each diode is illuminated
1/2 = amount of output power supplied per diode

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[6] I. Bazovsky, "Reliability Theory and Practice," Prentice-Hall, 1961.

Then the actual power density per diode turns out to be P.D. = Pd/0.785 mm^2, where 0.785 mm^2 is the cross-sectional area of the beam.

The reverse leakage characteristics of the RF amplifier diodes were observed on a curve tracer periodically throughout the duration of the tests. Figure 10 shows the characteristic curves of two diodes which completed the life test. The diode in (a) has operated for 40,000 hours and the curve still looks almost as good as when the tests started. The breakdown voltage has not changed during life, and the diode is still hard (flat slope with sharp knee at breakdown) with low leakage of 60 microamperes (μA). By contrast the diode curve in (b) has a considerably higher leakage and a very soft curve. This diode has the poorest curve of any tested and represents the greatest diode degradation incurred during the tests. Even this diode is still considered satisfactory. Most of the degradation is not due to the life test itself, but rather is the result of accidental damage due to the sudden loss of power during operation and improper tube warm up prior to the reapplication of power. The devices ran smoothly during the tests and the only real problems encountered were those of occasional beam drift which caused non-sinusoidal outputs, and spurious oscillations. The spurious oscillations occurred in the 1 to 5 MHz range and were caused by positive feedback. As several devices were operated in each test rack, the oscillations were due to the close proximity of the devices and associated circuitry and wiring coupled with their high gain characteristics. Whenever these spurious oscillations occurred, considerable effort was required to either eliminate them or reduce them to tolerable levels.

In conjunction with the EBS life tests at ERADCOM, life tests were also conducted at Watkins-Johnson for the Office of Naval Research (ONR) under contract N0014-72-C-0204. Two deflection modulated devices similar in construction to the ERADCOM devices were operated at diode dissipation levels of 20 W/mm^2 for 21,600 and 22,984 hours respectively. A total of 44,984 hours of operation was accumulated during tests without a failure. MTTF figures were 48,150 hours at a 60 percent confidence level and 19,394 hours at a 90 percent confidence level. As with the ERADCOM reliability determinations, these figures are data-limited and not reliability-limited. The combined ERADCOM and ONR tests include data on a total of 8 devices with a total life of 214,214 hours of operation without a failure. The resultant reliability determinations give MTTF figures of 231,350 hours at a 60 percent confidence level and 93,200 hours at a 90 percent confidence level. These figures are also data-limited and not reliability-limited. The combined data is considered valid since both sets of deflection modulated devices were tested under similar CW RF conditions.

It can be concluded from the RF life tests that the EBS is a very reliable device. The major items of concern are cathode life and diode wearout. A Phillips Type B impregnated cathode operating at 900 degrees Celsius or less with a 200 mA/cm^2 current density has an estimated[7] EBS life of over 200,000 hours. The diode wearout for a silicon diffused PN junction operating at a 20 W/mm^2 power dissipation density and a 135 degree Celsius

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[7] D. Bates, B. Bell, Periodic Electron Beam Semiconductor Status Report, Watkins-Johnson Company, Palo Alto, CA, 10 April 1978.

junction temperature is estimated at greater than 1,000,000 hours. Impregnated cathodes operating at low current levels and low temperatures are used in all current EBS devices. This minimizes deposition of cathode material onto the diodes and reduces diode reverse leakage, thereby extending life.

e. Video Pulse Amplifier Life Test Results

The results of the video pulse EBS amplifier tests are presented in Table 2. A total of over 103,000 hours of life without a failure was obtained on 4 devices at peak current pulse levels of up to 40 A. Two devices achieved 35,000 and 33,000 hours of life respectively. The duty cycles were low, but the main purpose of the tests was to determine the effects of peak rather than average current stress levels. MTTF is almost 112,000 hours at a 60 percent confidence level and almost 45,000 hours at a 90 percent confidence level. These figures are data-limited as no failures occurred.

While leakage current has not been a problem in the small (2.5 mm^2) RF amplifier diodes, it is a matter of concern in the large (35 mm^2) diodes in these amplifiers. Leakage currents in the small diodes are typically 50 μA or less at reverse voltages of up to 200 V. For the large area diodes, however, leakage currents are significant. The range in our sample is from 0.5 to 3.0 mA at a reverse bias voltage of only 50 V. It is much more difficult to fabricate a 35 mm^2 diode, since the probability of major defects and faults in the silicon increases with increasing cross-sectional area. The leakage current results in wasted power and reduced efficiency.

Tube Number 19 was removed from test and opened after 15,730 hours for examination. The reverse leakage (Fig. 11) had slowly but steadily increased during life from 2.8 to 8.0 mA. The initial peak is due to burn-in and cathode activation. The tube was still performing properly at this time, and the leakage was not considered excessive since peak pulse currents were over 3 orders of magnitude higher. The tube was opened in order to determine the cause of the increased leakage. Immediately upon opening to air the leakage decreased significantly, and after several hours had levelled off at only 2.6 mA, a level below anything previously measured. It was apparent that a resistive film of barium or other metals from the cathode had been deposited on the diode surfaces, resulting in an additional leakage path. Opening the tube to air oxidized the metal film, causing the shunt resistance path to disappear. The diode characteristic curve was observed to be as good as ever on the curve tracer. To confirm our analysis, the diode surface was examined using microphotography, scanning electron microscopy (SEM), and energy dispersive X-ray (EDX) spectroscopy. The photographs showed fairly heavy deposits of material on the diode top contact active area. A defective braze due to flowing of the brazing material was also observed, but no definite leakage path due to this defect could be determined. The EDX scans confirmed the presence of cathode material on the diode top surface as strong peaks of barium, nickel and silicon were observed, (Fig. 12). The diode top contact material is nickel silicide, which explains the nickel and silicon peaks. The barium is a constituent of the cathode emitting surface. SEM scans also confirmed the presence of surface deposits, (Fig. 13). The surface was covered with deposits of contaminants to a depth of 1.5 to 2.5 micrometers (μm).

Subsequently, a problem occurred with Tube Number 27 after 19,855 hours whereby the leakage suddenly increased from 3 mA at the operating diode bias of 50 V to over 50 mA at only 14 V bias. Leakage had been increasing very slowly in all of the devices on test. The characteristic curve also indicated excessive reverse leakage current and a curve shape similar to that seen during forward conduction. The trouble turned out not to be the tube itself, but rather a defective capacitor in the charging network associated with the diode. In other words, there were no diode failures at all during these tests. Tube Number 27 was opened to the air and examined. The characteristic curve was found to be excellent, having a straight slope which rose to only 70μA at 50 V and 160 μA at 120 V reverse bias. The diode and beam mask were covered with a fairly uniform layer of deposits from the cathode. The grid had 3 small dark spots on it, indicating the possibility of arcing, but there were no major visible defects. The oxide layer of the cathode was smooth but over half of the oxide coating had been stripped off. The coating around the perimeter was completely gone. This was caused by the higher fringe E-fields at the edge due to the high peak current mode of operation. The consensus of opinion was that the cathode was in good condition for a large oxide cathode with 20,000 hours of operation.

SERIES DIODE EBS CONCEPT EVALUATION

a. Device Concept and Description

In the continuing effort to improve the power, bandwidth and high frequency capability of EBS RF amplifiers, several diode arrangements have been considered. For deflection modulated devices, the amount of diode active area must be increased to obtain increased power capability from a device. This is accomplished by using two rows of diodes instead of just two single diodes. Most devices have been made with all of the diodes in each row connected in parallel, and the diodes are bonded directly to the copper substrate. However, the parallel arrangement results in increased capacitance which limits high frequency capability and in an output impedance as low as 1 ohm, making output impedance matching difficult.

The series-connected diode arrangement has several inherent advantages over the parallel approach. By connecting the diodes in each row in series, the total diode capacitance is reduced by a factor of 1/N (N = the number of diodes in a row) instead of increasing by a factor of N, as when parallel connected. This lower capacitance will allow considerably higher operating frequencies to be achieved and a wider operating bandwidth. Also, the individual diode impedances add in series so the output impedance is higher, simplifying impedance matching to line impedances of 50 ohms. The total diode bias voltage which can be applied to the device is higher by a factor of N, leading to the possibility of output power increases on the order of N^2. Six devices were fabricated to our specifications and procured under contract DAAB07-76-C-1345 [8] from the Watkins-Johnson Company. This device concept has the potential for an output power capability of 500 W CW

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[8] B. W. Bell, "Series Connected Electron Bombarded Semiconductor Devices," Final Report, TR ECOM-1345-F, January 1978.

at frequencies up to 3 Gigahertz (GHz). The device is shown schematically in Figure 14. Designated the W-J 3623, it is similar in construction to the deflection modulated W-J 3650 life test devices but differs in that it contains a sheet beam gun assembly, a modified diode target array and a beam rotator. There are 6 each 2.5 mm^2 rectangular diodes arranged in a 2 by 3 array. The static position of the sheet beam is between the two rows of diodes as depicted. All 6 diodes are bonded to a beryllia insulating substrate to allow each diode to be referenced above or below ground potential. Since beryllia substrates were used, the diodes were X-rayed to insure that no severe bonding voids existed. The cathode operates at a negative 12 to 15 kV. Electrons emitted from the cathode are accelerated and focused by 3 anodes in the sheet beam gun to achieve the proper beam dimensions. Once accelerated, they pass through the drift region where rotation and centering dc voltages orient the sheet beam and hence to the beam deflection region where the input RF signals deflect the beam sinusoidally. The electron beam then strikes the target mount, causing the two rows of diodes to conduct on alternate half-cycles. RF output signals are then developed across the 50 ohm load impedance connected to the coaxial output.

The diodes in each row are connected in series electrically within the tube, and the diode interconnection points and end points all have vacuum feed-throughs to allow electrical connections to be made to the individual diodes. This is represented schematically in Figure 15. The common interconnection between the two strings of diodes is connected to a 50 ohm coaxial transmission line, while all other feed-throughs are bias pins. These bias pins allow individual diode biasing, individual diode current monitoring, and individual testing of the condition of each diode with a curve tracer.

The beam rotator consists of a small pair of deflection plates located between the sheet beam gun assembly and the traveling-wave (meanderline) deflection structure. These plates are mechanically displaced about 30 degrees from being parallel to each other. When a dc voltage is applied a non-uniform electrical field is produced. This field exerts more force on one end of the sheet beam than on the other end resulting in a slight twist or rotation of the beam. The rotator was built into the tube to insure that the static position of the sheet beam is exactly parallel to the two rows of diodes. The sheet beam cross-section has dimensions of 0.040 inch by 0.500 inch. When signals are applied, the diodes in each row should be illuminated equally and conduct the same amount. If one diode is illuminated less than the others, it will limit the series current and result in low output power.

b. Series Diode Evaluation Test Procedures

The series-connected diode amplifier operates in a manner similar to other deflection modulated EBS devices. The cathode is operated at -12 to -15 KV, and drive levels of 15 V peak-to-peak produce full scale beam deflection and full diode current modulation. The sheet beam gun accelerating and focusing anodes must be adjusted to obtain the desired sheet beam dimensions, while the grid potential controls the amount of dc beam current. The rotator voltage is adjusted to orient the beam parallel to the diodes, and a dc centering potential is applied to the deflection plates to center the beam on the diode array. Input RF signals are then capacitively coupled onto the deflection plates. Output signals are developed across a 50 ohm resistive load.

Diode biasing is a little more complicated. The ideal biasing arrangement is to have all 3 diodes in each string operate from a single power supply rather than from 3 separate supplies. To this end, the circuit shown in Figure 16 was designed to operate with only one power supply for each diode string. This circuit eliminates the overvoltage problem which can occur if the diodes in a string are not equally illuminated by the sheet beam. The dynamic impedances of the 3 diodes would be different if this happens. The series current must be the same through all 3 diodes, or an unequal voltage distribution would occur. If just one series diode fails, the tube is rendered useless. Each diode in the string is rated nominally at a 200 V reverse breakdown. For tube operation, each diode can be biased at half the breakdown voltage rating or up to 100 V. This places a 300 V differential across each diode string. To prevent damage due to an overvoltage condition caused by signal fluctuations, a 150 V zener diode is placed across each diode, and 1 megohm shunt resistors maintain an even voltage distribution when the diodes are not turned on. RF chokes decouple the RF signal from the bias power supplies. The tests were designed for low frequency operation at 10 to 50 KHz initially to establish feasibility.

In order to evaluate the sheet beam and to align the beam for proper focusing, centering and rotation, individual ammeters were placed in series with each diode to form current loops with no biasing applied. The current readings were used as indicators of the amount of beam flooding each diode. Current probes were used to simultaneously display the individual current waveforms on oscilloscopes.

c. EBS Autocentering Circuit

The deflection modulated EBS device is prone to electron beam drifting. This is due in part to the extremely long drift region between the gun assembly and the diode target mount. This distance is over six inches in most devices and is nearly eight inches in the series diode devices. It is necessary to maintain accurate centering for proper amplification and signal fidelity. The beam can drift from its nominal center position due to temperature variations, mechanical vibrations, or voltage fluctuations to mention a few. To eliminate the effects of drift on the output signal, a circuit was designed to automatically correct the centering voltage whenever the static beam position shifted. This circuit senses any change in the average output levels of the two diode strings. In normal operation, the positive half-cycles produced by one series diode string will have the same amplitude as the negative half-cycles. The average value of the combined output signal developed across the 50 ohm load resistor will then be zero volts, since the output is referenced to ground (Fig 17). If, however, the electron beam drifts, the average value will differ from the zero reference, creating an error signal. This signal is amplified and produces a correction in the centering voltage which returns the beam to center.

As shown in Figure 18, the error signal is applied to the inverting input port of the operational amplifier (OP AMP) and an adjustable centering voltage is applied to the noninverting input port. In "SET" position, the input is grounded to simulate a zero error signal, and the Centering Adjust can be set to center the beam initially. In "NORMAL" position, any error signal will automatically produce an amplified correction signal to return the beam to center position. The circuit corrects for error signals of both polarities, and the static centering voltage can also be of either polarity. The gain of the circuit was varied from 150 to 390 with no loss of beam control. The integrated circuit operational amplifier (IC OP AMP) has a cutoff frequency of 3 kHz for a gain of 330. This is further reduced by the low pass filter network to as low as 100 Hz. This value can be varied by changing the L and C values of the network. The filter network does not reduce or otherwise affect the output signal of 50 kHz developed across the 50 ohm EBS load resistor. An additional low pass filter network is required between the output of the IC and the deflection structure. This network allows the correction signal and dc centering voltage to be applied to the meanderline without affecting the higher frequency EBS input signals. The IC used initially was the 741 OP AMP, which is rated at ± 15 V output signal variation. The IC worked smoothly, and provided a linear output from -16 to +16 V. However, some EBS devices have required centering voltages in excess of 25 V. A model, LM 343 OP AMP rated at ± 35 V was also successfully used in the autocentering circuit. This IC is compatible with the 741 and has similar gain and frequency characteristics.

The series diode tests were conducted at low frequency, and the EBS output signal was monitored to sense any beam drifting. If the devices had been tested at higher frequencies, beam drifting would have been more readily detected by monitoring the average currents of the two diode bias power supplies. A current sensing resistor in the common return line to ground of the positive and negative power supplies senses any differential current and produces an error voltage proportional to the current imbalance. The low frequency series diode tests were conducted with either 6 individual bias supplies or with individual current monitoring loops requiring no external bias.

d. Series Diode Test Results

During testing of the first device at low frequency, several facts became evident. The output waveform contained several types of distortion, including 60 Hz ripple, clipping on both positive and negative peaks, and non-sinusoidal waveforms. Also, the power output had to be limited to several watts to minimize severe distortion and a tendency for very low frequency (motor boating) fluctuations. The 60 Hz ripple was lowered considerably by reducing ground current loop effects but was never completely eliminated. However, the clipping and non-sinusoidal distortions were traced to defects in the tube design. The individual loop average currents were unequal and the current waveforms were likewise of different amplitudes and shapes. All attempts at adjusting operating voltages and external circuit components to equalize currents and improve the waveforms were unsuccessful. Test runs were made using individual bias batteries and current monitoring loops on each diode also, with the same results. Analysis of all of the data gave conclusive evidence that the sheet beam was non-uniform. Four of the devices were tested with the same results; sheet beam non-uniformities. Two of the tubes had sheet beams with a tear drop shape whereby the beam was heavily concentrated at one end. A third device had an "S" shaped beam whereby the center diodes were well illuminated but opposite corner end diodes were very poorly illuminated. A fourth device had a dog-bone beam shape, whereby the end diodes were all well illuminated but the center diodes were poorly illuminated. The presence of beam shape distortion was subsequently confirmed by viewing phosphor screen traces of similar sheet beam guns. Computer studies were conducted at both ERADCOM and Watkins-Johnson with the same results. The sheet beam had a severe crossover directly in front of the cathode. ERADCOM data also indicated that the beam was intercepting the first anode. Mechanical misalignment was detected in several 0.040 inch by 0.700 inch sheet beam guns being produced for use in EBS amplifiers containing parallel-connected diode arrays. Residual magnetic fields as high as 10 gauss were detected on the deflection structures of other devices under development. The electron beam in this device is very susceptible to magnetic fields, due to the 6 to 8 inch drift region between the electron gun and the diode target array.

Another serious problem detected in all of the tubes tested was ionization effects in the gun region. The problem was traced to the heater lead-in wires. The heater wires were partially exposed on the backside of the cathode assembly, and this was causing ionization and a discharge to the anode lead-in wires. This proved to be the source of the motor boating pulsations appearing on the output waveform. The ionization also produced unwanted anode currents and outgassing within the tube. Four of the series diode devices were eventually rendered inoperable by a heavy glow discharge which completely filled the gun region of the tube. This discharge outgassed the tube so severely that the Vacion appendage pump was unable to recover. A fifth device contained a defective diode and therefore was not tested. The sixth device was returned to the manufacturer to be reworked and supplied with a sheet beam gun of improved design and construction. However, due to the cessation of deflection modulated EBS device work by the manufacturer, this device was not modified. This change in technological emphasis is discussed below.

RECENT DEVELOPMENTS IN EBS TECHNOLOGY

The data on the series diode devices showed there was a severe beam optics problem in the deflection modulated EBS devices. At our request, a thorough analysis was made of the failures that had occurred in deflected beam devices, and it was found that poor beam optics was a major cause of failure. The non-uniform beam illumination of the diodes cannot be detected in parallel connected diodes.

Watkins-Johnson made a major effort to correct the problems found in the deflected beam devices and many design improvements have been made to the sheet beam gun assembly since the series diode devices were fabricated and delivered to ERADCOM. These recent improvements include better mechanical rigidity, modifications to reduce end effects on the beam, improved alignment procedures and fixturing, and redesigned first anode and grid-cathode structures to eliminate the electron crossover. Annealing procedures were instituted to eliminate residual fields in the drift region. The diode beam mask has been biased to trap any ionized particles in the vicinity of the diode array. While progress has been made, the deflected beam EBS device still suffers from problems associated with the electron optics. The required sheet beam cross-sectional dimensions are 0.040 inch by 0.750 inch. To obtain sufficient signal interaction and gain using beam deflection the drift region must be over 6 inches long, making the cathode-to-diode distance on the order of 10 inches. An inherent problem of susceptibility to external and residual internal magnetic fields exists because of the long drift region. Due to the large amount of interior surface area, residual gasses and outgassing is also a problem. No true working sheet beam gun exists. The existing sheet beam still contains non-uniformities in beam width, shape, and current density, resulting in non-uniform power dissipation in the diode array which causes individual diode failures. The alignment of the cathode, focus electrode and anodes of the gun assembly remains critical.

In 1976 a density modulated (gridded) EBS amplifier was developed at Watkins-Johnson under ECOM contract DAAB07-75-C-1329. Compared to deflected beam devices, this device is more simplified in design, compact and rugged. This device provided RF output pulses of 1 kW peak at a 1 percent duty cycle, and 1.5 kw peak at a 0.1 percent duty cycle with a 1 GHz center frequency and a 50 MHz bandwidth. Subsequently this design was improved and modified for a projected Joint Tactical Information Distribution System (JTIDS) application. This device had demonstrated 350 to 500 W peak across the 960 to 1215 MHz band at a 20 percent duty cycle with over 18 dB gain. Further development could improve these figures to 500 W across the band at a 50 percent duty with 20 dB gain for a pair of devices operated in parallel.

This basic design concept has also been adapted for lower frequency communications/communications-jammer (COMM/COMM-JAM) applications. Though initially a narrowband device, sophisticated broadband circuit techniques have developed the gridded EBS into a practical multi-octave power amplifier. By mid-1979 Watkins-Johnson had demonstrated a band-pass of 20 to 200 MHz with a 150 W CW RF output capability in a laboratory version of the gridded EBS.

Based on these and other results, and the lack of real progress with deflected beam devices, a decision was made to concentrate all EBS device development on the gridded EBS design concept. This technology shift was jointly agreed upon by ERADCOM and Watkins-Johnson and has impacted upon several development programs.

Effort on contract DAAB07-78-C-2958 with Watkins-Johnson to develop a low noise EBS jammer device was shifted to the gridded EBS approach. The goal of this program was to reduce spurious noise, intermodulation (IM) and harmonic distortion through improved beam optics and diode characteristics. Test results showed that the given efficiency and IM products were all interrelated and were determined largely by the electron gun characteristics. The results indicated that the gun parameters and diode characteristics could be optimized to obtain a gridded EBS push-pull pair with a 200 W CW output capability. This power module would cover the 50-400 MHz band with 23 dB gain and 40 percent efficiency, -23 decibels referred to carrier (dBc) IM, and harmonics of -25 dBc. This module would have a volume of approximately 80 cubic inches (in^3) or 1311 cubic centimeters (cm^3) and would be water cooled. Projections indicated the power level could be ultimately increased to 400 W CW by increasing the diode area to reduce the diode thermal impedance. Circuit improvements would extend the frequency band to 500 MHz. A second program involved the development of an integrated 1 kW CW EBS amplifier package covering the 1.5 to 100 MHz band. Initially, the objective was to be achieved by combining the power outputs of 4 deflected beam EBS amplifiers connected in parallel. GTE Sylvania was the prime contractor and Watkins-Johnson was supplying 4 gridded EBS modules and high voltage power supplies under a subcontract. Each EBS module was to consist of a push-pull pair of gridded EBS devices, and was to provide a minimum of 275 W CW across the band. The 4 combined outputs were to provide a net CW output power of 1 kW.

Recent results have been impressive. A single gridded EBS amplifier delivered to a commercial customer had an output capability of 160 W CW or better across the 25 to 200 MHz band with 23 dB gain and 37 percent overall efficiency. Another single tube amplifier developed for Naval Ocean Systems Center (NOSC) covers the 10 to 100 MHz band with 100 W CW and similar gain and efficiency. Additional development effort is needed on a 50-400 MHz device to deliver 200 W CW from a push-pull pair as part of the Low Noise EBS Jammer program. Single gridded EBS devices have demonstrated 100 W CW across the 20 to 450 MHz band. It is believed that the power-bandwidth goal could be met, although some high frequency rolloff would be present.

CONCLUSIONS AND THE FUTURE OF EBS

The life test results have established that the EBS is a reliable device. Device life figures of 40,000 to 50,000 hours can be projected for field equipment operation. The major items affecting EBS life appear to be cathode life and diode wearout.

The deflected-beam EBS concept is viable for a single pair of diodes illuminated by a pencil beam, but many problems remain with higher power deflected beam devices containing a multiple diode array and an electron sheet beam gun. The sheet beam is non-uniform in shape, width and current density, and requires considerable design work before it is perfected. The deflection modulated device also suffers from an inherent magnetic susceptibility due to the long drift region, and from outgassing problems due to large internal surface areas. The device is also inherently more complex and difficult to fabricate and align.

The series-connected diode EBS concept is a viable concept. This is evidenced by the fact that it is used in gridded devices to produce high peak voltage outputs. However, it was impossible to evaluate the concept for RF power amplifiers. The investigation was hindered by device defects which included heater leg emission, outgassing and ionization, and non-uniformities in the electron sheet beam. This concept would only become practical if a true sheet beam gun can be perfected. With the advent of the broadband gridded EBS, the deflected beam EBS is no longer a practical vehicle for the series diode approach. The series diode concept can be adapted to the gridded EBS to improve its power and frequency capabilities as an RF amplifier. The gridded EBS is currently limited to an upper frequency of about 200 MHz for multi-octave broadband power amplifier applications requiring in excess of 100 W CW. A single tube device has achieved in excess of 160 W CW across the 25 to 200 MHz band with a saturated gain of over 20 dB across the band. The reduced capacitance effect of series-connected diodes along with other broadband techniques can extend this frequency range to the 400 to 500 MHz range with an expected power level of 200 W for a single device. A pair of devices in push-pull should provide at least 300 W CW across the 20 to 400 MHz band with at least 20 dB gain.

(In December 1979 the Watkins-Johnson Company gave notice that for business reasons it would cease all activity on EBS devices. This decision was immediate and irreversible. Since there are no other companies with a demonstrated EBS capability, this decision impacted seriously upon the technology. A number of companies have been approached as possible alternate sources for EBS devices, but without success. These companies were reluctant to enter this technological field due to the high initial capital investment required to develop the expertise and assemble the necessary equipment. A second major factor is the lack of a large commercial or military market for EBS devices in the near future. The services have tried for several years without success to develop a second source for EBS devices. The decision to stop all EBS work came at a time when the EBS had demonstrated operational feasibility and was emerging as a mature technology with potentially broad applications. As a result of this decision, the 1 kW CW EBS integrated amplifier will not be realized, and the JTIDS EBS amplifier will not be developed. In the numerous cases where the EBS device was being considered for possible military system applications, alternative approaches will be sought unless the EBS can be revived. Future plans to extend the frequency and power capabilities of EBS devices have been discontinued. It is evident that the EBS will disappear from the scene, and will only reappear if industry believes that further development and production will result in a profitable return on investment.)

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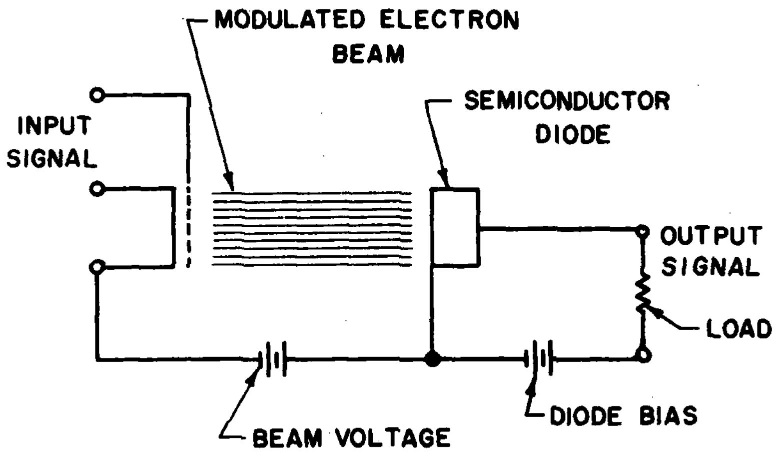

Figure 1. Basic EBS Device Diagram

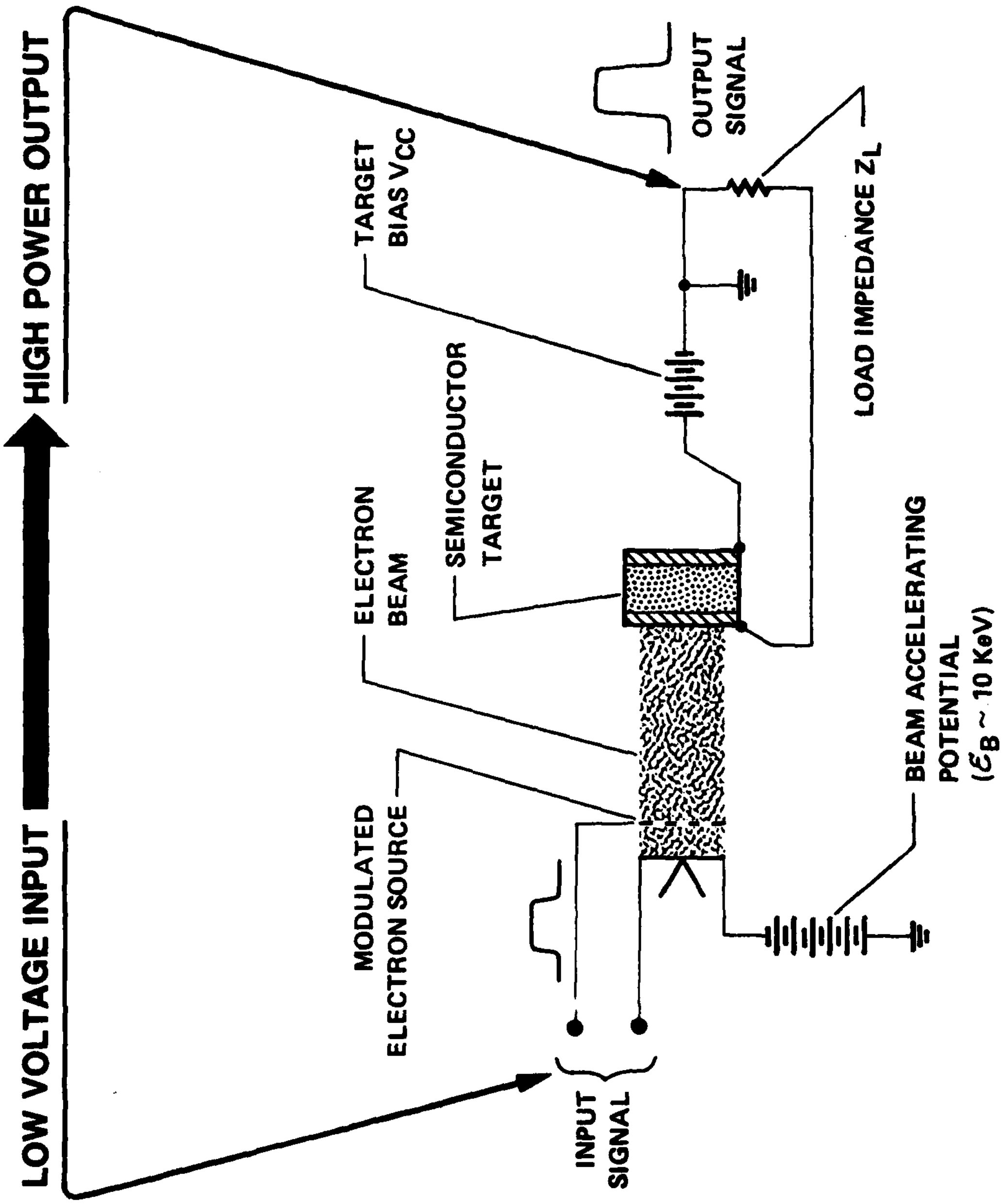

Figure 2. Grid Modulated EBS Circuit Diagram

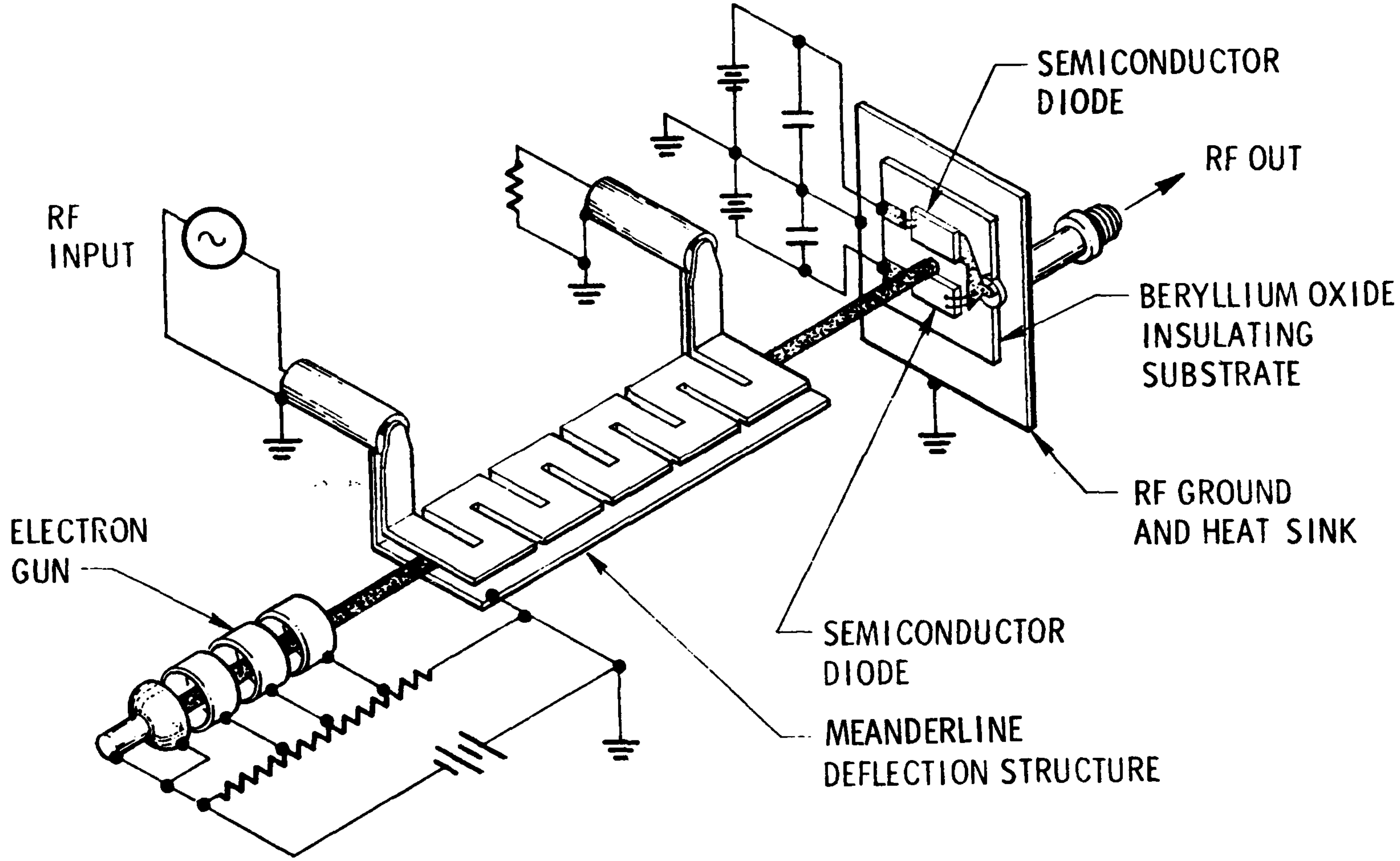

Figure 3. Deflection Modulated EBS Circuit Diagram

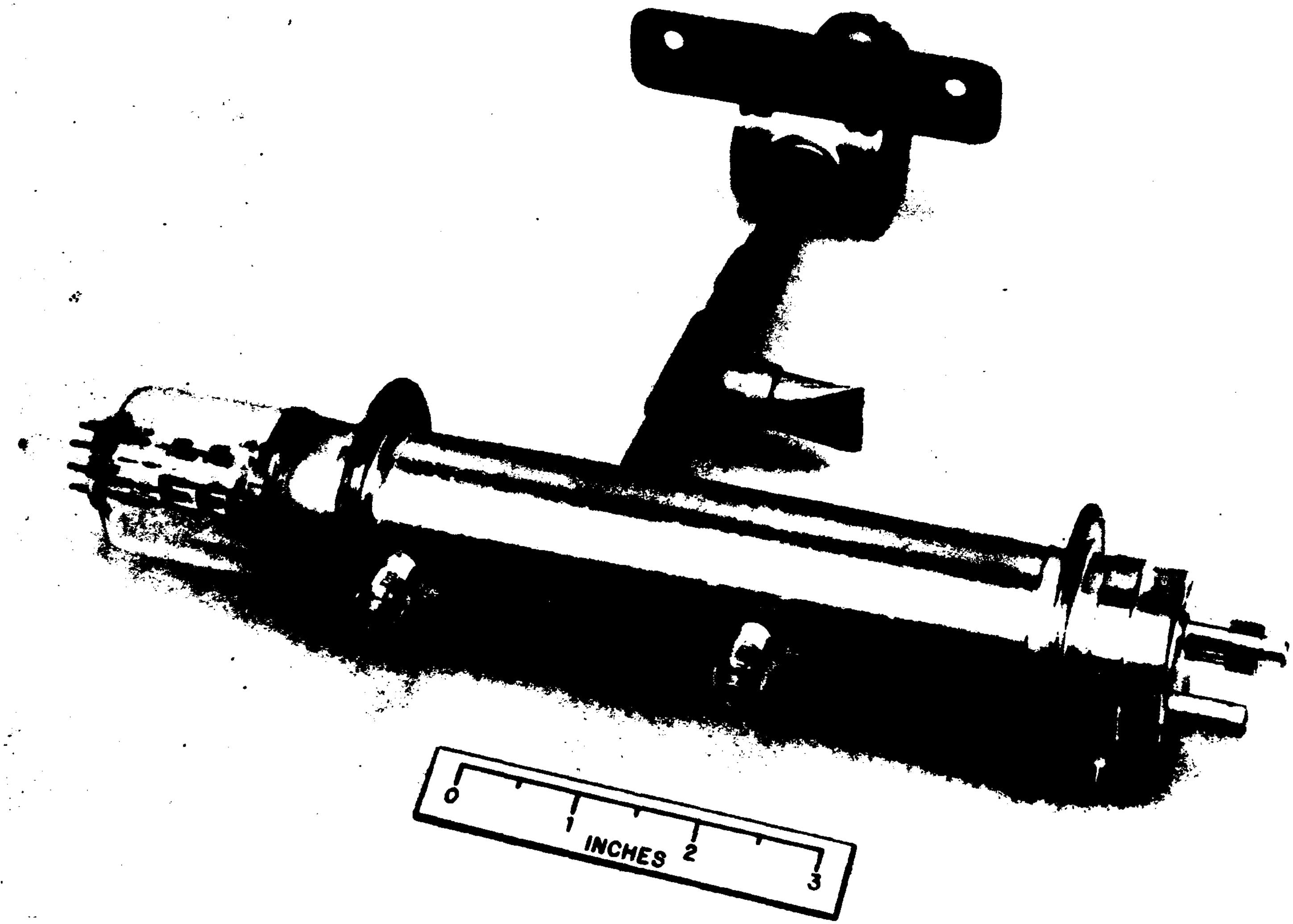

Figure 4. WJ 3650-4 RF EBS Amplifier

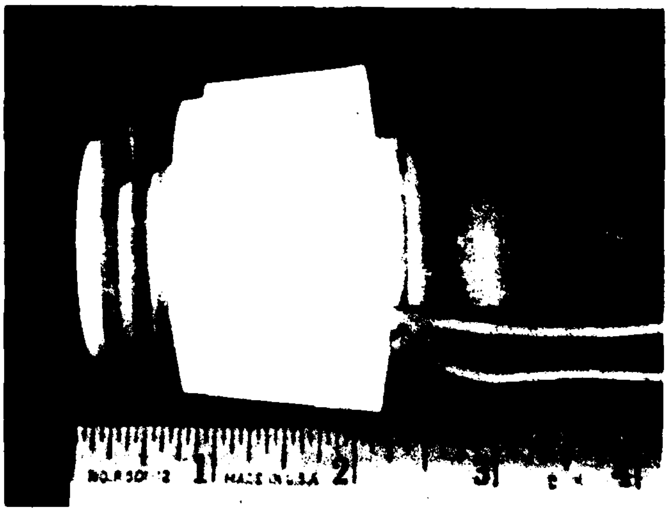

Figure 5. WJ 3652 Video Pulse EBS Amplifier

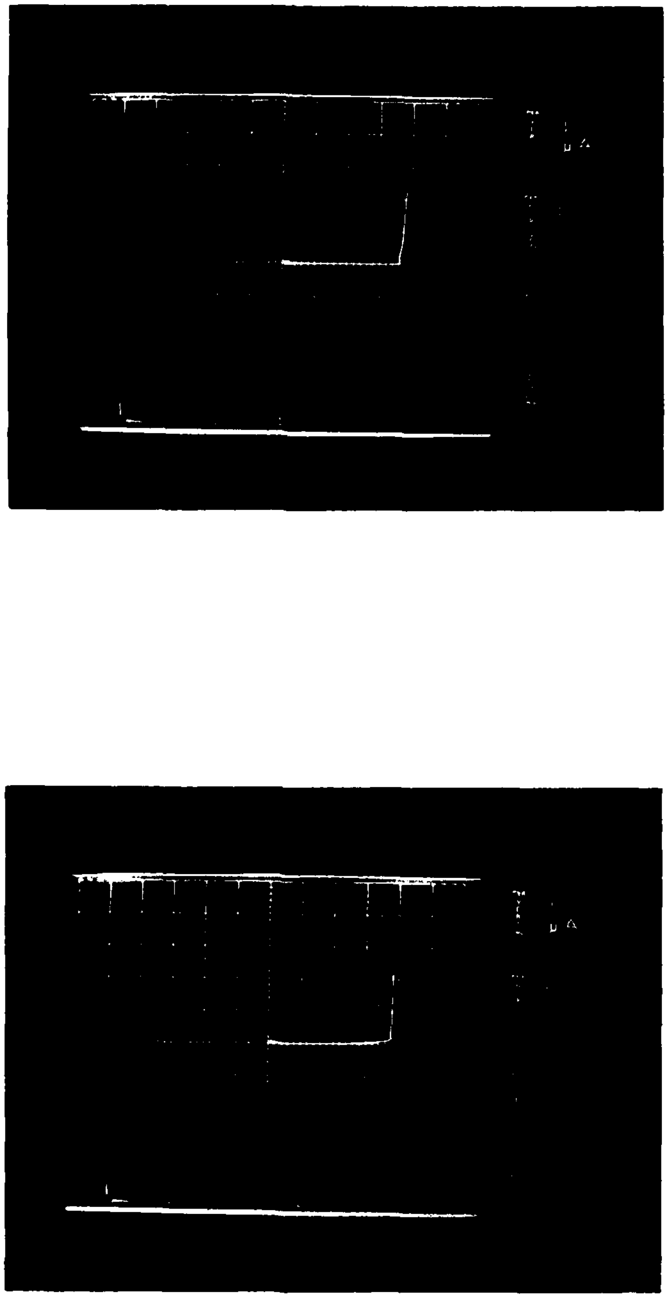

Figure 6. Initial RF EBS Diode Characteristic Curves

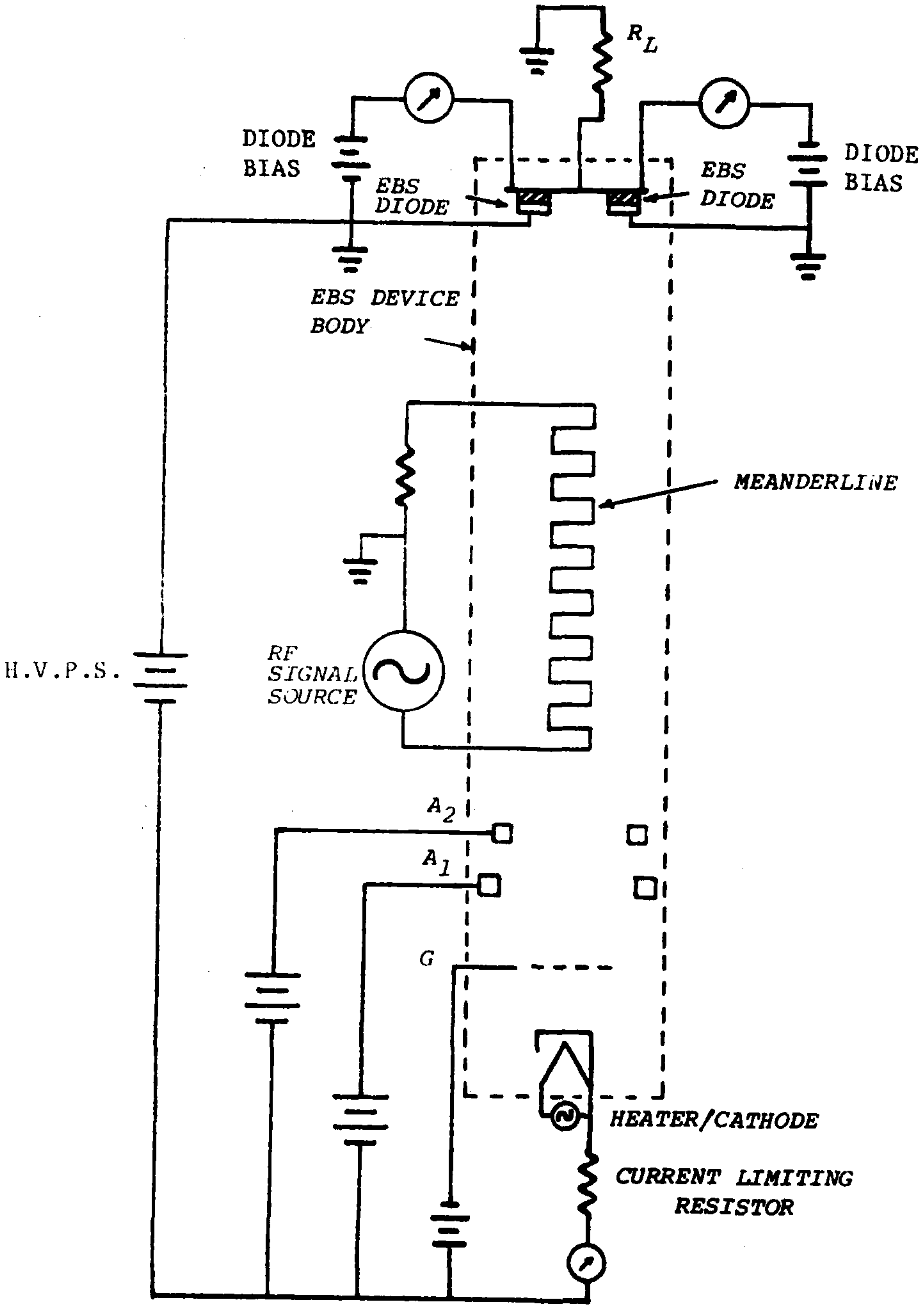

Figure 7. EBS RF Amplifier Life Test Circuit Diagram

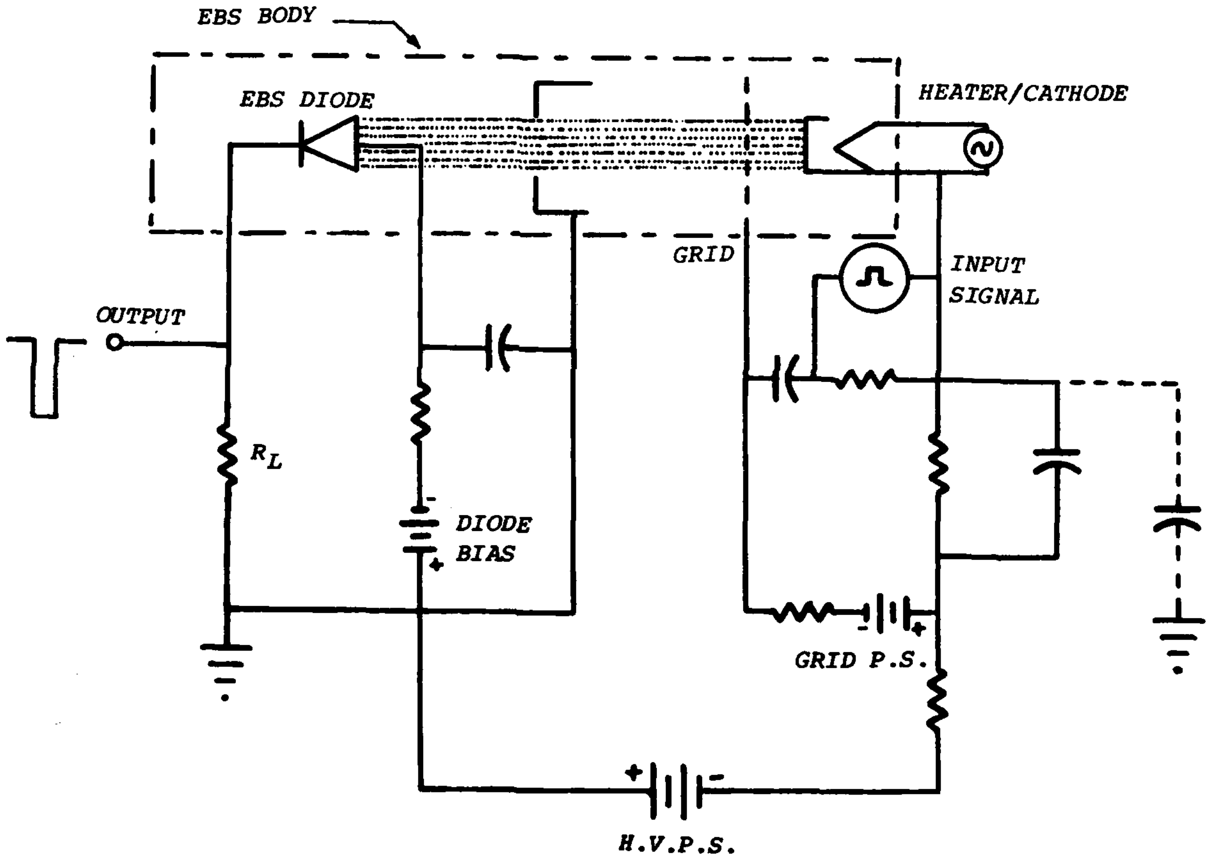

Figure 8. EBS Video Pulse Amplifier Life Test Circuit Diagram

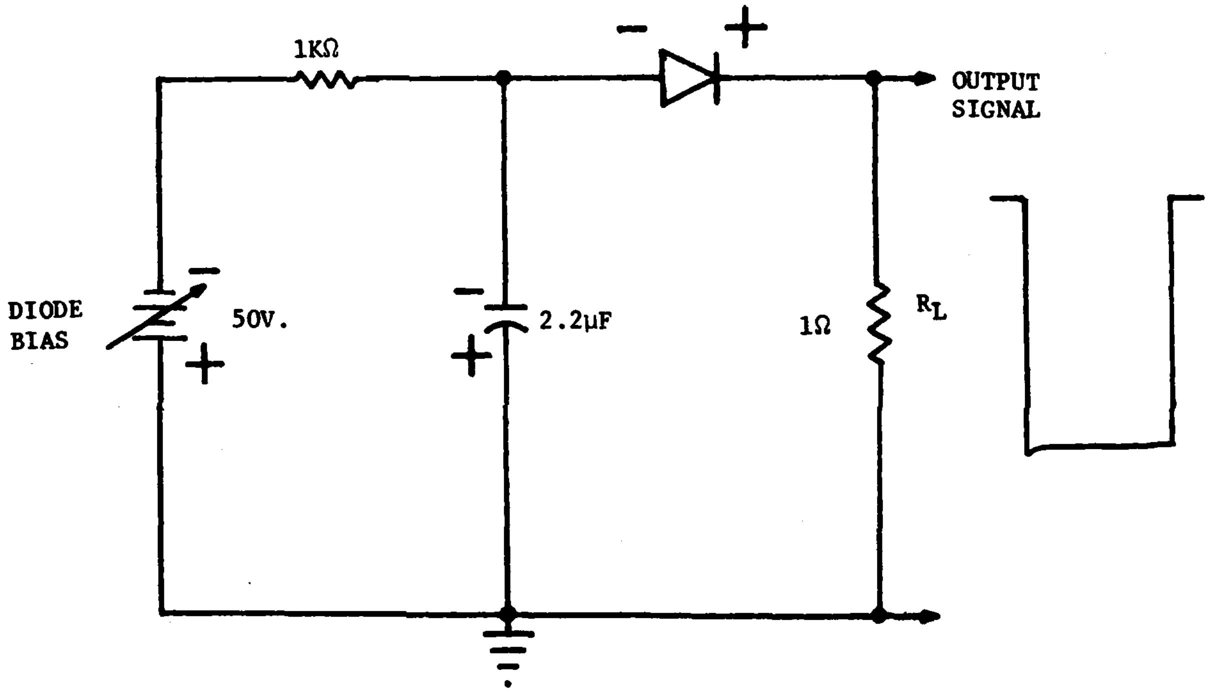

Figure 9. Simplified Diode Circuit

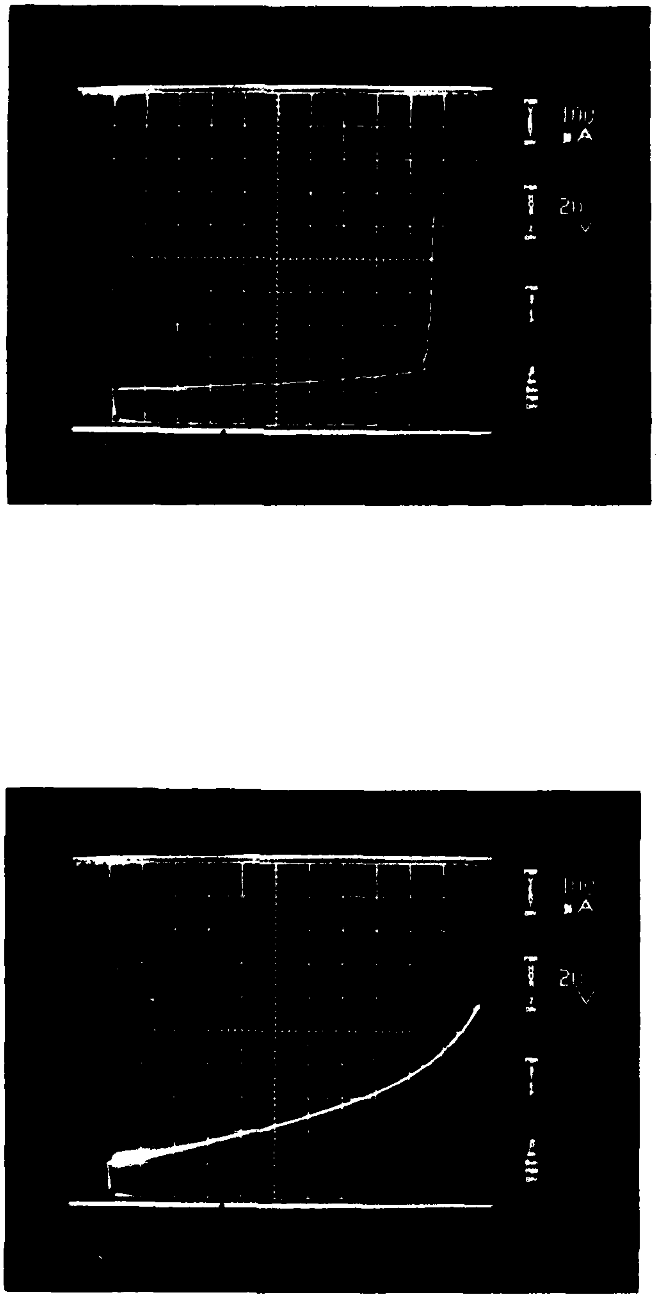

Figure 10. Final RF EBS Diode Characteristic Curves

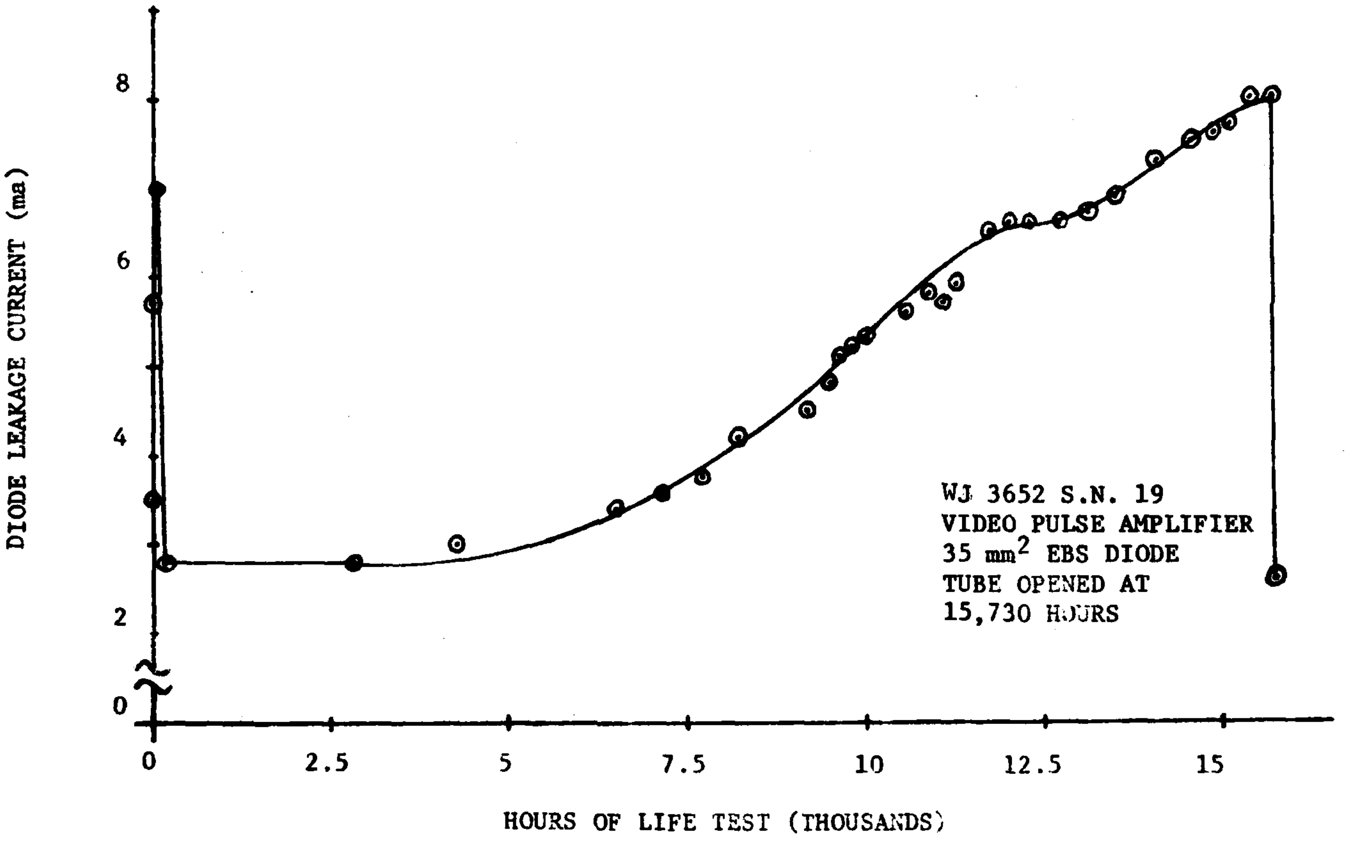

Figure 11. Diode Leakage Versus Time

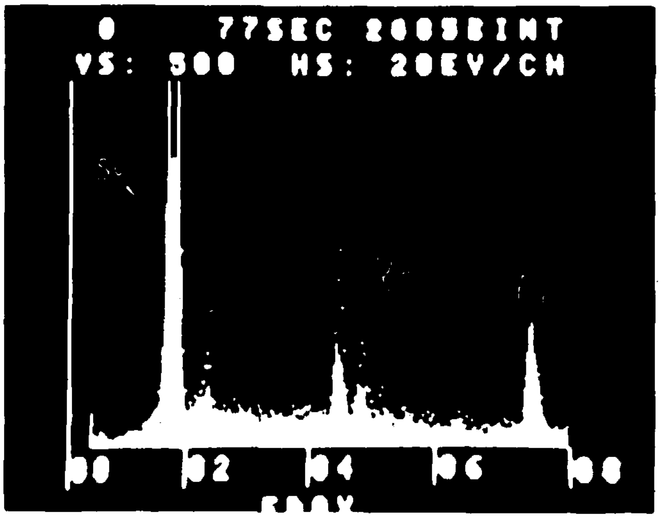

Figure 12. EDX Scan of Diode Surface Contamination

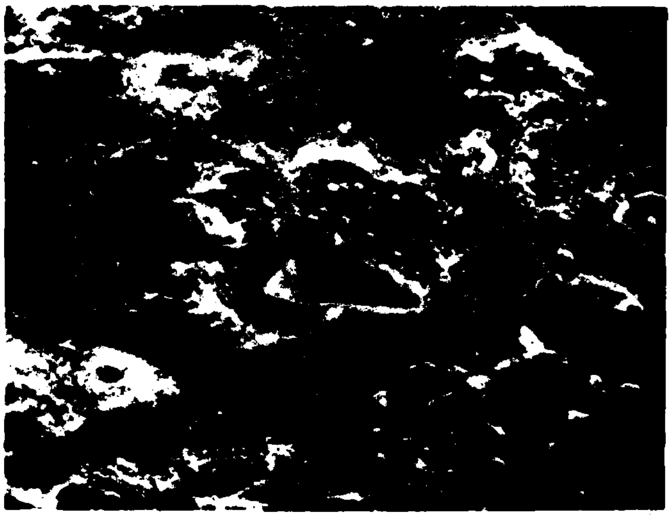

Figure 13. SEM Photograph of Diode Surface Contamination

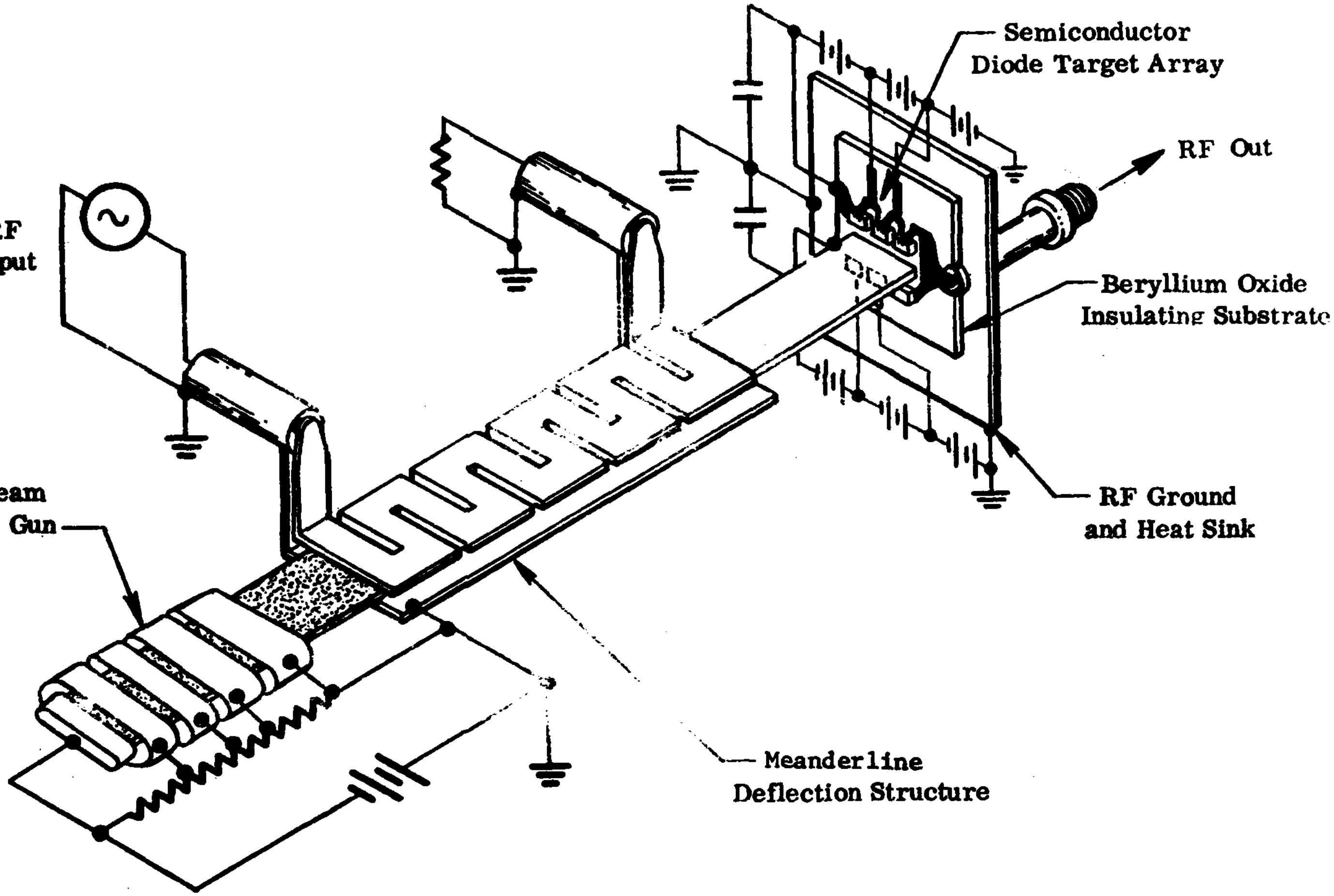

Figure 14. Series-connected Diode [illegible] Deflected Beam Amplifier

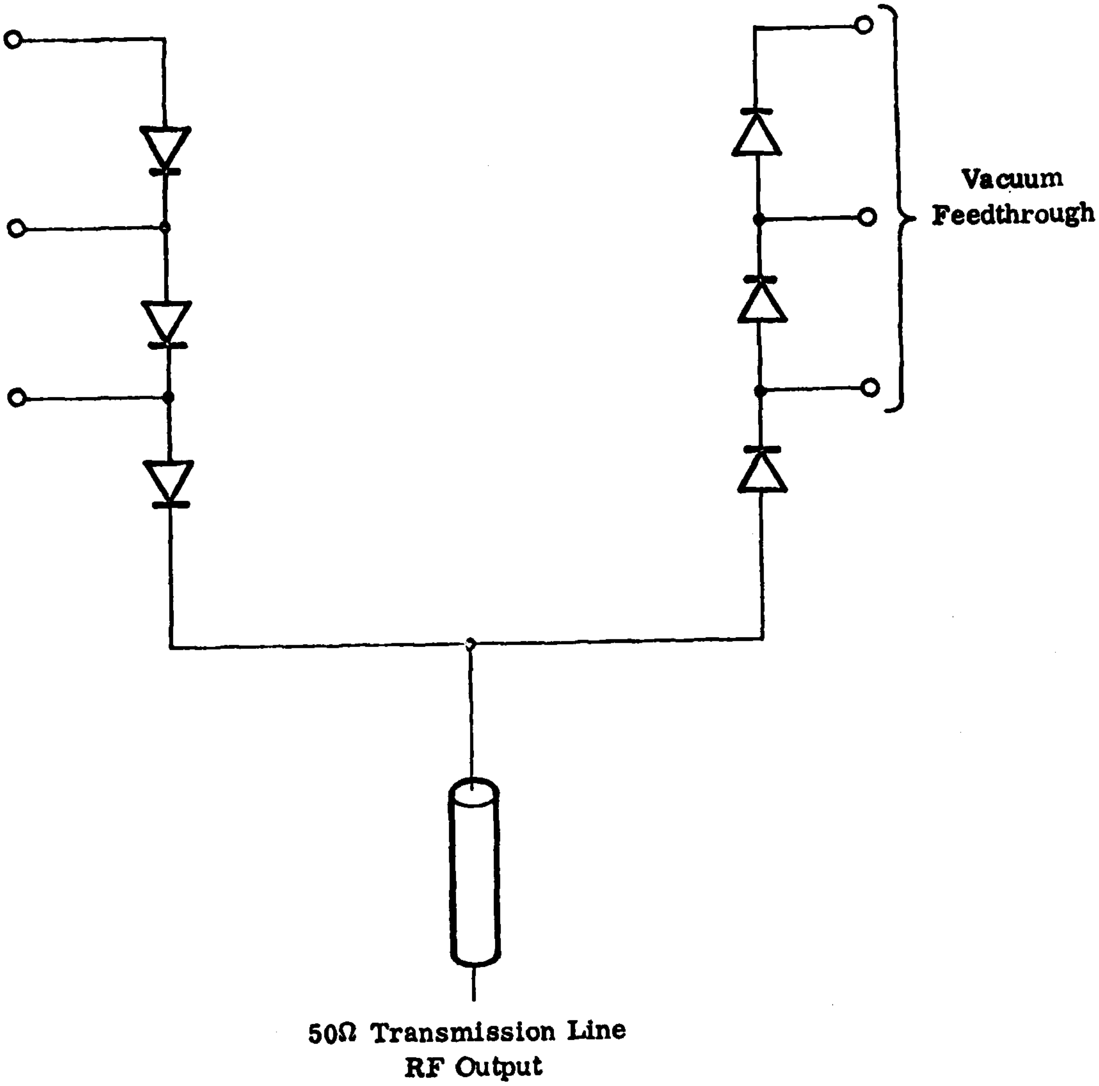

Figure 15. Series-connected Diode Configuration

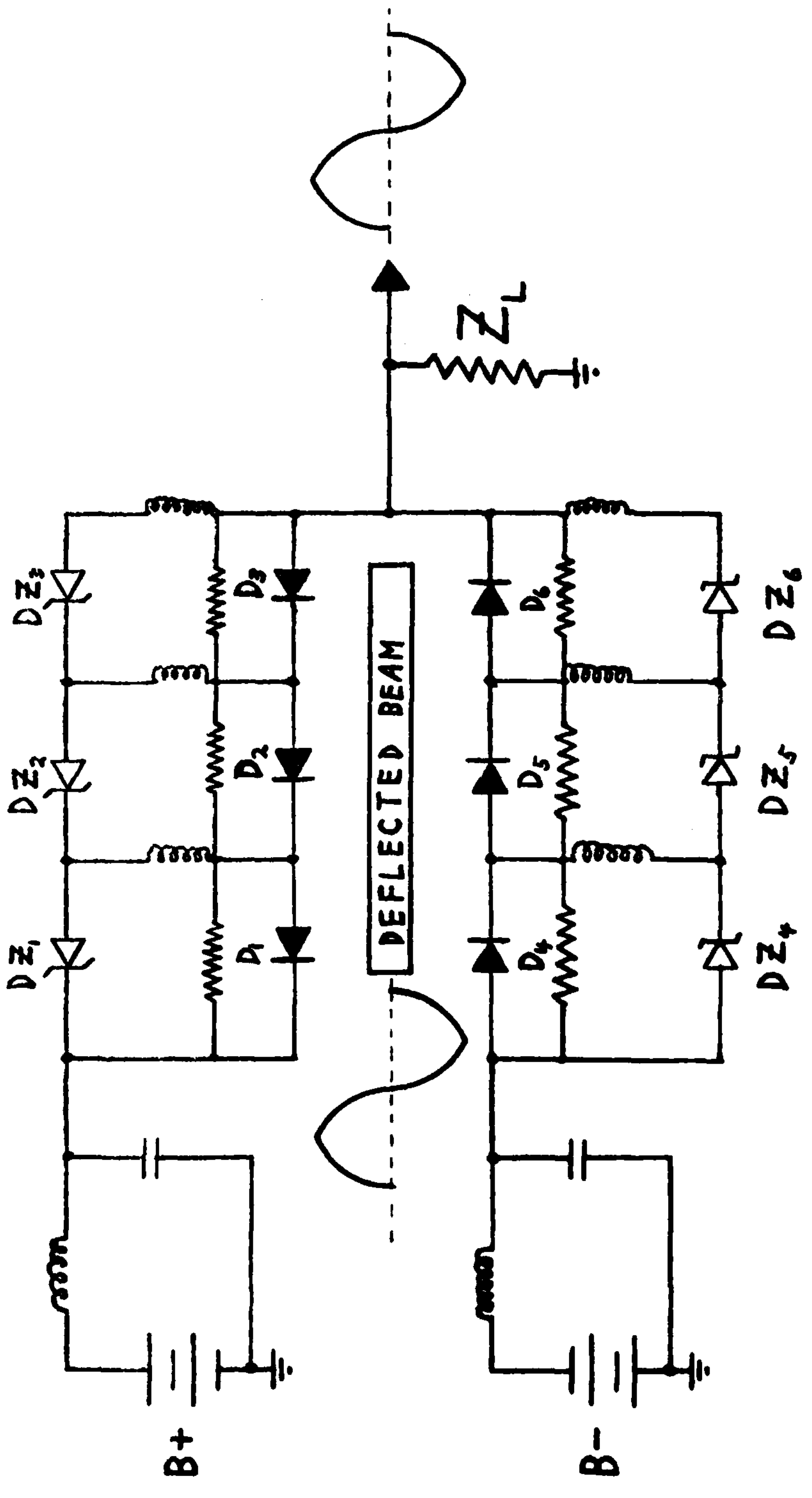

Figure 16. Series-connected Diode Balancing Network

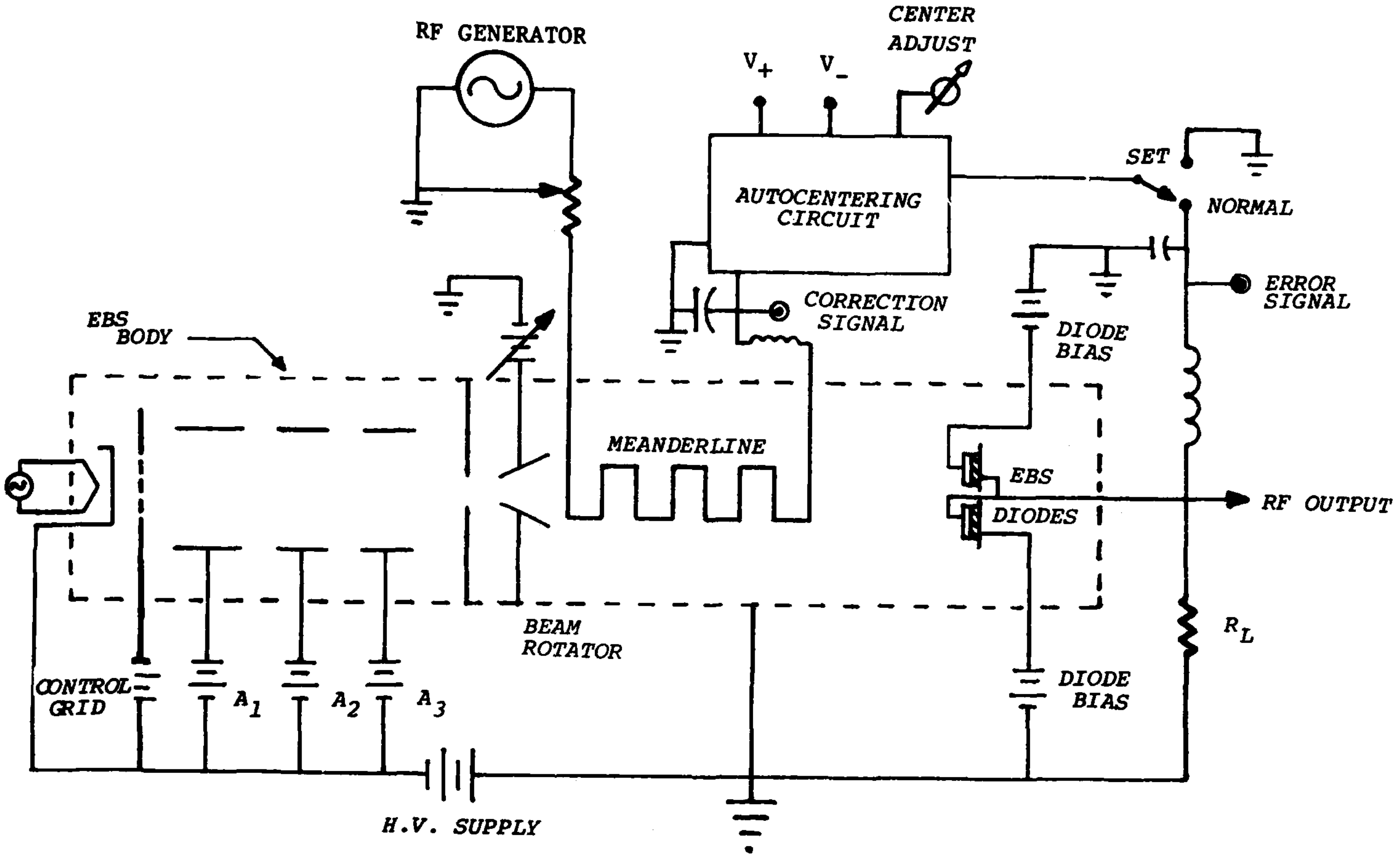

Figure 17. Complete Autocentering Servo Loop

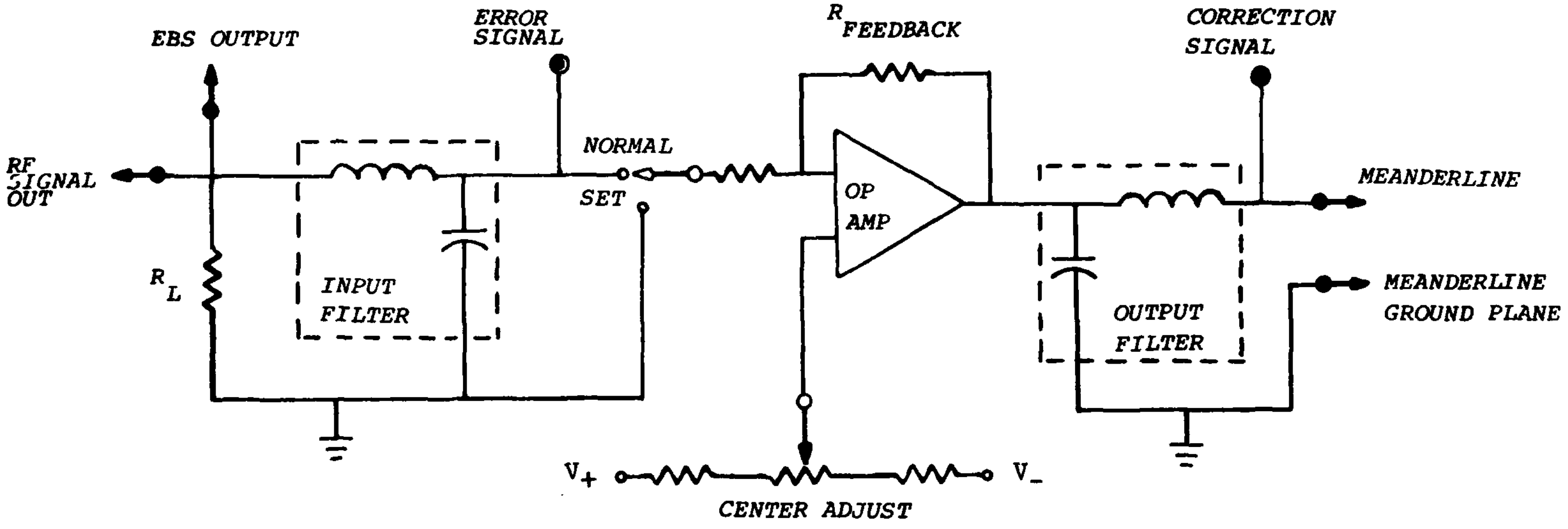

Figure 18. EBS Beam Autocentering Circuit

Table 1

CW RF EBS Amplifier Reliability Summary

MODEL	SERIAL NUMBER	HOURS	TEST CONDITIONS	REMARKS
WJ 3650-4 CLASS B RF AMPLIFIER	2	5,000 17,985	20 $^{W}/\text{mm}^{2}$ 35 $^{W}/\text{mm}^{2}$	50 ohm R_L 20 ohm R_L
	3	5,000 17,985	20 $^{W}/\text{mm}^{2}$ 35 $^{W}/\text{mm}^{2}$	50 ohm R_L 20 ohm R_L
	4	5,400 16,045	25 $^{W}/\text{mm}^{2}$ 35 $^{W}/\text{mm}^{2}$	33 ohm R_L 20 ohm R_L
	5	5,006 35,004	30 $^{W}/\text{mm}^{2}$ 40 $^{W}/\text{mm}^{2}$	25 ohm R_L 16.7 ohm R_L
	6	6,150 16,045	25 $^{W}/\text{mm}^{2}$ 35 $^{W}/\text{mm}^{2}$	33 ohm R_L 20 ohm R_L
	9	40,000	30 $^{W}/\text{mm}^{2}$	25 ohm R_L
TOTAL DEVICE RELIABILITY CW Test Time		169,630		No Failures
Average Per Device		28,272	32.2 $^{W}/\text{mm}^{2}$	
MTTF		183,200 73,800		At 60% Confidence At 90% Confidence

Table 2

Video Pulse EBS Amplifier Reliability Summary

MODEL	SERIAL NUMBER	HOURS	TEST CONDITIONS	REMARKS
WJ 3652	19	15,730	28A, 1 ohm load, 0.027% duty	135 ns pulse
	25	35,020	40A, 0.5 ohm load, 0.027% duty	135 ns pulse
	27	19,855	40A, 0.5 ohm load, 0.05% duty	250 ns pulse
	30	33,023	35A, 0.5 ohm load, 0.05% duty	250 ns pulse
TOTAL DEVICE RELIABILITY Pulse Test Time		103,268		No Failures
Average Per Device		25,817	36.7A	
MTTF		111,918 44,921		At 60% Confidence At 90% Confidence