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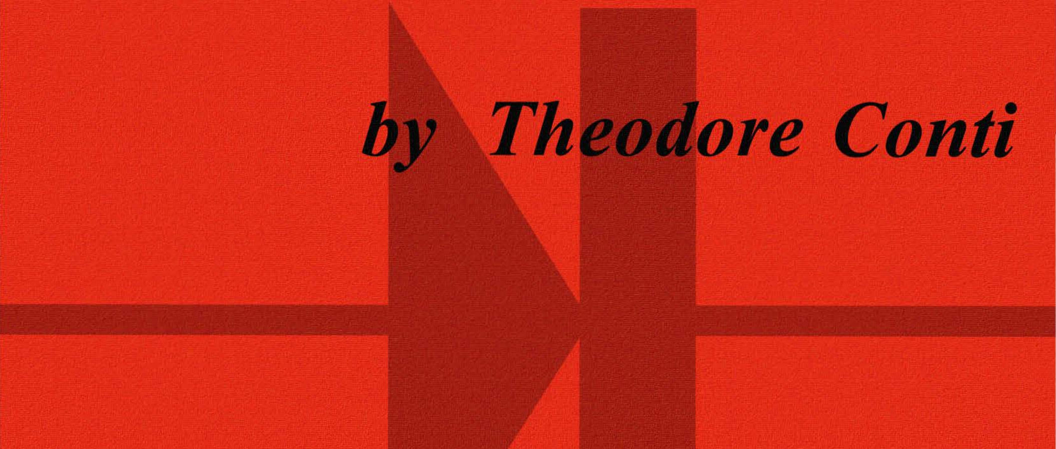
METALLIC RECTIFIERS and CRYSTAL DIODES

by Theodore Conti



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THEODORE CONTI

METALLIC RECTIFIERS
AND
CRYSTAL DIODES

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preface

Metallic Rectifiers and Crystal Diodes is a compilation, in one book, of the most useful basic information on these semiconductor units. Included in the text is a brief summary of historical background, a description of the manufacturing techniques employed in single-cell assembly and stacking methods, basic circuit design data and testing procedures for ascertaining the quality of new and used metallic rectifiers and crystal diodes. The basic theory and construction of metallic rectifiers and crystal diodes, their varied applications and practical possibilities, are all discussed. There is a comprehensive appendix at the back of the book containing such useful information as the standard for coding industrial dry-disc rectifiers, a complete listing of silicon- and germanium-diode specification data.

The author wishes to acknowledge, with thanks, the help rendered by the various metallic rectifier and crystal diode manufacturers for their assistance in providing information and illustrations for this book. Particular thanks are due to Bradley Laboratories, Incorporated, for their contribution of application data and other illustrations; and for supplying photographs and other technical information thanks are also due to International Rectifier Corporation; Radio Receptor Company; Transistron Electronics Corporation; General Electric Corporation; Westinghouse Electric Corporation; Federal Telephone and Radio Corporation; Automatic Manufacturing Corporation; Sylvania Electric Products, Incorporated; Fansteel Metallurgical Corporation; Kemtron Products, Incorporated; and Raytheon Manufacturing Corporation.

Thanks are also due to Monroe Corn for his assistance in the preparation of the outline and research material. Michael A. Benanti must receive special thanks and sincere appreciation for his contribution to chapter three and for his valuable suggestions, and the efforts of Mr. John Clarke of Radio Receptor Company for technical checking of many parts of the manuscript are gratefully acknowledged.

It is a pleasure for the author to express his gratitude and appreciation to his wife, Frances, for her helpful assistance and for her care in typing the manuscript.

THEODORE L. CONTI

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1. introduction

During the past decade millions of metallic rectifiers and crystal diodes have been produced; they are now being used in practically every phase of the electronics industry. These new types of rectifiers are lighter in weight, more compact, easier to handle, and more rugged than previous vacuum tubes. They are also more dependable and economical to operate. Most electronic technicians, radio and television servicemen, experimenters, students, and ham operators have become acquainted with these devices.

History

Crystal diodes. The need for compact and efficient electric-wave detectors dates back to Heinrich Hertz's discovery of radio waves in 1888. In 1895, Guglielmo Marconi invented the antenna, which extended the distance electric waves could be projected in space. Detection of the electric wave at the receiver was originally accomplished by an instrument called a coherer or by a crystal. In his early experiments with the coherer, Marconi was limited to receiving dots and dashes. In 1906, Pickard filed a patent for a crystal detector resembling units in production today. It consisted of a silicon crystal and a piece of fine wire. In 1915, Carl Beredicks discovered that germanium had rectifying properties; later discoveries showed that galena, silicon, carbide, tellerium, and iron pyrites, among others, also could rectify with satisfactory results. Silicon detectors were found to be the most stable, and galena the most sensitive.

In the early days of radio, the receiver-detector consisted of a galena or silicon crystal that rectified and detected the modulated signal. A typical detector was made by soldering a piece of crystal into a small receptacle. A thin, flexible wire (cat's whisker) was used to contact the surface of the crystal. By moving the cat's whisker to different places on the crystal, the exact point could be found which gave the best signal. Frequent adjustments had to be made before a good signal could be obtained.

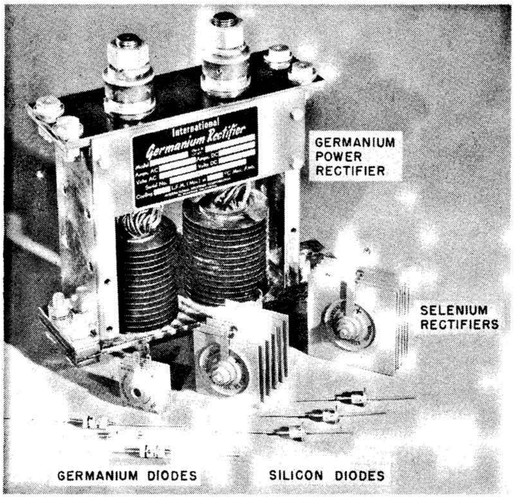


Fig. 1-1. A group of typical metallic rectifiers, crystal diodes, and power diodes.

The development of the vacuum tube made crystal detectors obsolete in radio receivers, and from 1925 until 1940 the crystal was merely a laboratory curiosity. During the early part of World War II, however, interest in the crystal detector was revived. Radar and microwave equipment required receivers with high signal-to-noise ratios in the ultra high-frequency range. Vacuum tubes were not satisfactory, but properly designed crystals accomplished the necessary mixing and detecting functions. Later developments have placed crystal diodes in virtually every field of the electronics industry.

Metallic rectifiers. Although metallic rectifiers are relatively new components, the asymmetrical conductivity of selenium, copper oxide and other semiconductors was recognized as early as 1883. The first practical use of a selenium rectifying cell was reported by Pochettino in 1809. In 1920, Grondahl discovered the rectifying properties of the copper-oxide cell; in 1924, the first commercial copper-oxide rectifier was produced in this country. The first commercial selenium rectifier was introduced in the same year, but was abandoned because it was too eratic and too dependent on heat to offer serious competition to the copper-oxide cell. By 1931 copper-oxide rectifiers were major competitors of vacuum tubes and d-c generators. Continued improvement in efficiency has rapidly increased the number of copper-oxide rectifier applications until these rectifiers are now employed in nearly all fields of the American electronics industry.

In the early 1930's, the rectification properties of selenium were re-examined and the first practical commercial cells were built in Germany.

During World War II the use and development of rectifiers were accelerated; immediately after the war rectifiers became part of the standard d-c power supplies for many units that formerly used vacuum tubes or generators. Present-day selenium rectifiers are extremely versatile and have been used successfully in many applications.

Fields of Application

Metallic and crystal rectifiers have become increasingly popular because they can operate over a wide range of voltages and currents, satisfactorily perform under difficult operating conditions, are small and light-weight, and have excellent electrical characteristics, long life, and instant conduction properties. Table I-I lists some of their most useful applications.

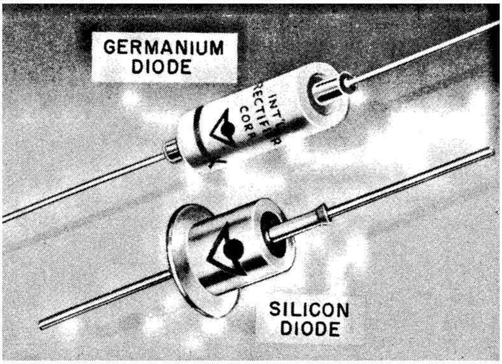


Fig. 1-2. Typical germanium diode and silicon power rectifier.

This list covers only a few of the many industrial and commercial applications of metallic rectifiers and crystal diodes. Other

TABLE 1-I

Typical Applications of Metallic Rectifiers and Crystal Diodes

Industrial Applications	Commercial Applications
Arc welding	Audio amplifiers
Aviation equipment	Automobile panel instruments
Battery chargers	Battery eliminators for farm radios
Battery eliminators	Burglar and fire alarms
Business machines and office equipment	Electric shavers
Circuit breakers	Model railroads
Coin machines	Motion picture exciter lamps
Computers	Motion picture projectors
D-c field supply for a-c rotating equipment	Phonograph oscillators
D-c solenoids	Radios and amateur radio equipment
Dust precipitators	Record players
Electric musical equipment	Telephones
Electroplating rectifiers	Television boosters
Elevators: power, controls, and brakes	Television sets
Exciter lamps	Therapeutic equipment
Facsimile	Toys and games
Fire alarm circuits	
Guided missle controls and instruments	
High-voltage testing and power supplies	
Magnetic amplifiers	
Magnetic breaking drums, chucks and clutches	
Meters and meter protectors	
Motion picture projectors	
Photoelectric equipment	
Polarized relays	
Radar	
Railway signaling	
Relay power supplies	
Speaker field power supplies	
Telegraph	
Time clocks	
Voltage regulators	

uses, not listed, include circuit applications such as uhf mixers, video and audio detectors, modulators, d-c restorers, clampers, limiters, and r-f probes.

Types of Dry-Disc Metallic Rectifiers

The most common metallic rectifiers (sometimes called metallic-oxide, or dry-disc rectifiers) may be classified into three distinct types:

1. Copper oxide and copper (copper-oxide rectifiers)
2. Selenium and aluminum (selenium rectifiers)
3. Copper sulfide and magnesium (magnesium-copper sulfide rectifiers).

Copper-oxide rectifiers. The copper-oxide rectifier was the first metallic rectifier used commercially in this country. Originally, it consisted of one or more elements (cells) held together by a mounting stud. Each element was of the two-piece type (an oxide-coated copper disc matched to a lead disc). Unfortunately, the thermal expansion of the mounting stud made the unit unstable and inefficient.

The modern copper-oxide cell is constructed as a single plate assembly (see Chap. 2), eliminating the mounting stud. Although the copper-oxide rectifier is considered a low-voltage, high-current unit, current and voltage extremes can be obtained by *stacking* (placing cells in series, parallel, or series-parallel). Combination stacks are found in high-power electroplating equipment and in low-power radio receivers.

The modern copper-oxide cell is very reliable, and has a life expectancy much greater than either the selenium or copper-sulfide rectifier. Units operated at normal current density can be expected to deliver their originally rated outputs indefinitely. The efficiency of the copper-oxide cell is about 65% to 75%. The voltage that each cell can withstand, however, is considerably lower than that which the selenium cell can withstand. Thus, for many applications, a suitable copper-oxide rectifier would have to be heavier and larger than a suitable selenium rectifier. The copper-oxide rectifier is, however, comparatively inexpensive to manufacture.

Selenium rectifiers. Selenium rectifiers are the most commonly used metallic rectifiers. The selenium cell is of single-plate construction and is usually built with an aluminum base plate that gives a durable and light stack.

In the manufacture of these cells, pure selenium is sprinkled over the aluminum back plate and subjected to high temperatures. The selenium melts and distributes itself evenly over the aluminum plate. A low melting point alloy is sprayed over the selenium, and the entire cell is subjected to electroforming (an electrical process by which the electrical characteristics of the cell are stabilized). After the electroforming process, the characteristics of this cells are checked and graded. The completed selenium rectifier is an assembly of individual selenium cells, arranged in series, parallel, or series-parallel to achieve the current and voltage outputs required.

The life expectancy of the selenium rectifier is less than that of a copper-oxide rectifier. The selenium cell, however, withstands greater voltages per cell. The accepted standard for industrial applications is 26 volts per cell, although many companies are producing cells for television and radio applications which can withstand 45 volts. Greater voltage permits reduction of size and cost for a given application. As with all metallic rectifiers, heat is a serious problem. Selenium rectifiers become very inefficient if their rated operating temperatures are exceeded. After extended periods at higher-than-rated temperatures, the unit becomes permanently damaged.

The number of selenium-rectifier applications is so great that it would be impossible to enumerate all of them. Applications are found in radio and television receivers, mobile d-c power supplies, battery chargers, magnetic amplifiers, electroplating rectifiers, generator voltage regulators, magnetic brakes, etc. (See Table 1-I).

The copper-sulfide and magnesium rectifier. The copper-sulfide and magnesium rectifier is probably the least known of the metallic rectifiers. It is about as old as the copper-oxide rectifier and is physically similar to it. Because of its low efficiency (less than 50%) it has not been used extensively. The copper-sulfide and magnesium rectifier is constructed in a manner similar to the copper-oxide rectifier. A magnesium disc and a copper disc, with a copper-sulfide surface, are held together by a mounting stud. The pressure applied to the stud is very important: too little will decrease the efficiency, too much will short-circuit the cell. The disadvantage of the cell is its low efficiency, which steadily decreases throughout the life of the rectifier. Partially offsetting this and other drawbacks are the cell's several advantages: low price, ruggedness, and the ability to withstand high temperatures with little or no effect. Nevertheless, since World War II the use of these cells has steadily decreased; at present their principal use is limited to rectification in low-voltage d-c power applications.

Relative Advantages of Metallic Rectifiers

In many power applications, selenium rectifiers have replaced both copper-oxide and magnesium-copper-sulfide rectifiers, which are now used only in specialized applications. The relative advantages and disadvantages of the three units are listed above. Regarding their respective merits, individual advantages would have to be analyzed before arriving at a choice.

Selenium rectifiers have replaced the magnesium-copper-sulfide type because of their higher efficiency and higher voltage-per-cell rating. Copper oxide also was replaced by selenium, which withstands higher voltages per cell and higher ambient temperatures. However, some advantages of the magnesium and copper-oxide cells cannot be overlooked. For example, magnesium-type units withstand greater temporary overloads and temperatures than do selenium units. Copper-oxide units neither age nor lose their shape when not operating, thus they provide instant action and uniform characteristics after prolonged periods of idleness. This attribute is especially desirable in ring rectifiers for modulators and meters. The copper-oxide unit is also capable of withstanding large current and voltage overloads if they occur for extremely short periods, as in the reclosing of circuit breakers.

Types of Crystal Diodes

Crystal diodes may be divided into two distinct groups: those silicon or germanium diodes used for low-power applications (Fig. 1-3) and those used for high-power applications (germanium or silicon power diodes, Figs. 1-4 and 1-5).

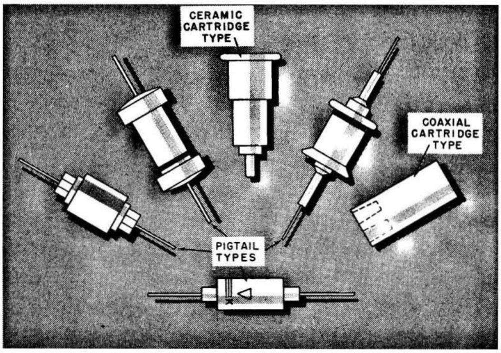


Fig. 1-3. Silicon and germanium crystal-diode cartridges.

Low-power units usually have a rectifying element enclosed in ceramic, coaxial, or pigtail cartridges (Fig. 1-3). Units used for high-power applications are similar. They are discussed in Chap. 2

The semiconductor elements used in crystal and power diodes are germanium and silicon. Silicon is more popular for microwave, radar, and power-diode application; germanium is generally used for low-frequency and low-power applications. Although silicon has more advantages there are areas in which the merits of silicon and germanium are equal.

The ceramic cartridge. The ceramic-type cartridge is probably the oldest commercially available unit. The base is connected to the semiconductor (usually silicon) through a screw-type connector. This end is equivalent to the cathode of a diode vacuum tube. The pin-end is connected to the semiconductor through a screw-type connector to the cat's-whisker. The pin and cat's-whisker screw into the threaded ceramic shell. The base is equivalent to the plate of a diode vacuum tube and consists of a threaded pin upon which a small silicon wafer is mounted. The pin and silicon screw into the brass end-plate. The manufacturer adjusts the base-plate mounting screws for optimum contact between the cat's-whisker and the silicon. Prior to the placement of the base into the ceramic shell the unit is filled with wax to increase mechanical damping. When in use, the cartridge is mounted in a crystal holder by means of spring-finger grips on the pin and a screw-type cap. For this reason they are as readily replaceable as a vacuum tube or a fuse. This unit was designed primarily for mixer applications in radar and high-frequency radio receivers. The size of these units makes them convenient for coaxial line or wave-guide mounting.

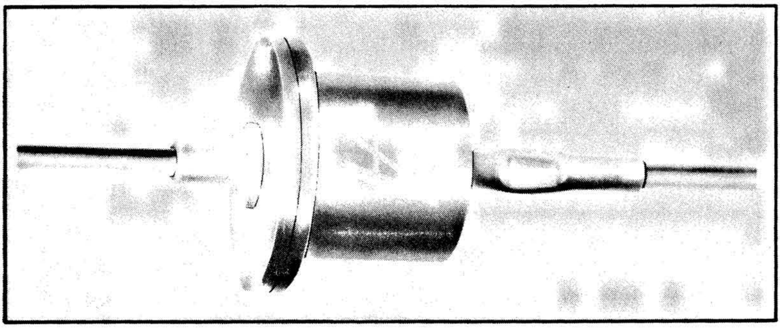


Fig. 1-4. Pictured is a silicon power diode, hermetically sealed in a glass envelope.

The coaxial cartridge. In the coaxial-type cartridge the silicon is connected to a base plug which is fastened into the shell. The inner conductor, held by a polyglass insulating bead, is moved out until optimum contact is made with the silicon. The inner conductor is equivalent to the plate of a vacuum tube while the outer conductor or sleeve is equivalent to the cathode. This crystal is normally used in applications above 10,000 mc. Mounting and replacement is similar to that of the ceramic cartridge.

Pigtail cartridge. This diode, designed to be soldered into a circuit, is by far the most generally used of all crystal diodes, because its use is not limited to uhf or microwave applications.

The unit consists of a pin-and-pellet assembly (usually germanium) mounted in a ceramic or glass case. A cat's-whisker and the pin assembly are than mounted, forming a junction with the germanium pellet. Current is passed through the unit, fusing the cat's whiskers to the germanium pellet. The terminal or pin assembly that is marked K, or that is so banded or color-coded, is equivalent to the cathode of a vacuum tube. The whisker or terminal which is either unmarked or marked with an "A" is equivalent to the plate. The germanium diode is used in video detectors, computers, uhf mixers, d-c restorers, dampers, power supplies, etc.

Power diodes. Silicon and germanium power diodes (sometimes referred to as power rectifiers, Figs. 1-4 and 1-5) are relative newcomers to the diode-rectifier field. Their physical and electrical characteristics, including compactness and efficiency, partially account for their increasing use in equipment demanding instantaneous action and small size. These units are finding widespread applications in guided missiles, aircraft, microwave radio relays, and other fields.

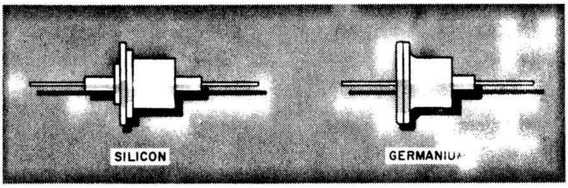


Fig. 1-5. Silicon and germanium power rectifiers.

Germanium and silicon power diodes are compact, hermetically sealed units consisting of a wafer-thin crystal disc into which a metal pellet (aluminum for silicon and indium for germanium) is diffused. The junction barrier is formed by the diffusion of these two materials at a high ambient temperature. The junction is hermetically sealed in an all-welded shock-proof housing with either pigtail leads or mounting studs welded to the terminals.

Silicon power diodes are available in two types: those used for industrial applications to convert ac to dc, as in a conventional power supply; and those with very little leakage current used in special applications, such as magnetic amplifiers. Either unit, when mounted within a cooling fin or on the chassis, can be operated at higher-than-rated ambient temperatures.

Silicon power diodes have an advantage over the germanium power diode in their ability to withstand greater operating temperatures with little or no effect. However, germanium units are much less expensive. Table I-II lists the relative advantages and disadvantages of germanium and silicon power diodes.

TABLE 1-II

Power Diodes

GERMANIUM	SILICON
Advantages	
1. Low voltage drop (half that of selenium).	1. High inverse voltages (up to 500 volts per junction).
2. Low leakage (less than that of select selenium cells of equal rating).	2. Much lower leakage current than germanium and select selenium cells of equal rating .
3. High voltage per junction (up to 80 volts).	3. Operates at higher temperatures.
4. Negligible aging.	4. Negligible aging.
5. Small size.	5. Small size.
Disadvantages	
1. Temperature at junction cannot exceed 90°. Higher temperatures will alter the diffusion and damage or destroy the cell.	1. High cost compared to germanium or selenium.
2. Low voltage drop makes protection difficult. A short circuit in the output will destroy the junction almost instantly.	2. Leakage current increases at a faster rate with increased operating temperatures.

2. construction

Metallic Rectifiers

Although it is true that all metallic rectifiers perform essentially the same function, their construction, size, weight, and shape vary considerably from one manufacturer to the next. Manufacturing of metallic rectifiers involves specialized knowledge and techniques in the fields of electrical engineering, metallurgy, chemistry, and applied mechanics.

Selenium rectifiers. The selenium cell *appears* to be simple. The basic cell, shown magnified in Fig. 2-1, is a microscopically thin layer of crystalline selenium sandwiched between two conductors. In the production of the cell a layer of amorphous selenium is spread over an aluminum base plate. The unit is then subjected to high temperatures and pressure. To produce cells with high inverse voltages an artificial barrier coated with a low melting point alloy is added to the selenium. Varied techniques and methods are used in the manufacture of a commercial cell, some of which are described below.

Preparation of the supporting plate. The square or circular fin, usually associated with the selenium diode, is called the metallic supporting plate, and serves as the support of the selenium and counter-electrode. Aluminum is generally used because of its light weight, high corrosion resistance, and ability to dissipate heat, although any good, rigid conductor would be suitable. One side of the supporting plate is roughened by sandblasting or chemical etching. The plate is treated and coated with a thin film of barium or nickel to insure an intimate, even contact between the supporting plate and the selenium. Prior to the use of nickel plating, iron or steel was used as the back plate material, resulting in much heavier units.

Applying the selenium. Finely powdered, highly purified amorphous selenium is evenly distributed over the supporting plate. (The addition of reagents, such as the halides, tends to decrease the forward resistance, increasing the conductivity and efficiency of the cell.) The plates are placed in a temperature- and humidity-controlled oven and subjected to 1200°C temperature and 1500 pounds per square inch pressure. This heat-pressure treatment causes the selenium to adhere to the plate and starts the transformation from the amorphous to the crystalline state.

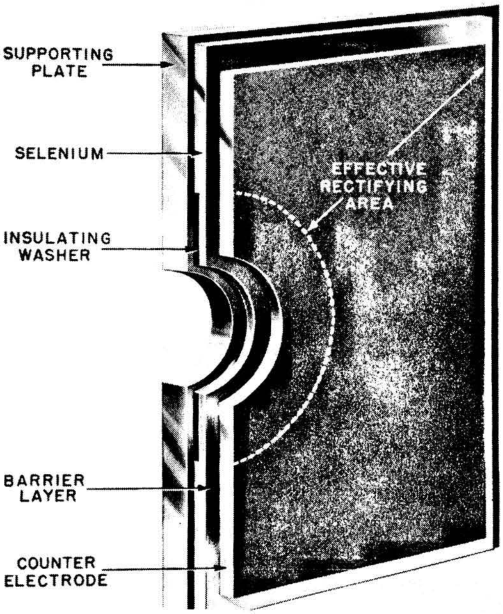


Fig. 2-1. Sectional view of a selenium rectifier cell.

Some manufacturers deposit the selenium on the base plate by evaporation. The treated plate is placed in a vacuum or in an atmosphere of inert gas. The selenium is heated and allowed to condense on the plate. These processes are critical, since they affect the adhesion of the selenium to the base plate. Poor adhesion results in decreased efficiency, premature aging, and subsequent reduction of cell life.

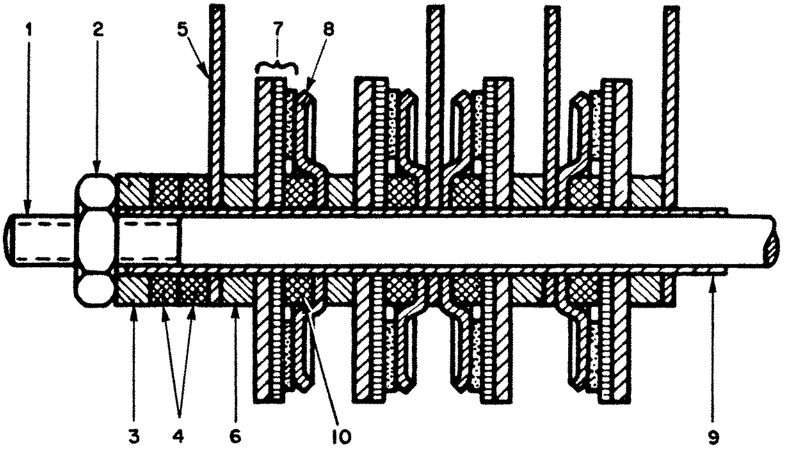
Once the selenium is deposited on the base plate, the selenium surface is subjected to a series of controlled heat treatments that complete the crystallization process begun in the first heat-pressure treatment. In addition, a thin barrier layer is formed. A very thin artificial barrier, consisting of alkaline and oxidizing agents, is applied to the original barrier layer to increase the inverse voltage characteristic of the cell and to increase the reverse or blocking resistance.

Addition of the counter-electrode. To obtain good electrical contact between the barrier layer and the circuit to which the cell is to be connected, a front or counter-electrode is sprayed over the entire surface of the barrier layer. This electrode is a low melting point metal alloy (tin, cadmium, lead, zinc, or bismuth). The selection of the electrode is determined by its ability to provide a low-resistance layer for the current passing through the cell in the forward direction, and at the same time offer a strong barrier for the current passing in the reverse direction. Prior to the application of the front electrode, the cell is masked around the edges and the center mounting hole so that it will not be short circuited once the counter-electrode is applied. The effective rectifying area is that area which is covered by the counter electrode. (See Fig. 2-1.)

Forming the rectifier. Completion of the barrier layer is accomplished by subjecting the cell to high d-c voltages in the blocking direction for several hours. This process (known as electroforming) stabilizes the electrical characteristics of the cell and increases its back (or blocking) resistance. In the initial stages of the electroforming process low d-c voltages are applied to the cell. These voltages are gradually increased until the process is complete. After the cells have been electroformed, their reverse and forward characteristics are checked and the cells are graded.

Assembling the selenium stack. The selenium-rectifier cells can be stacked in a variety of combinations in order to obtain the desired voltage and current output. In the standard rectifier, shown in Fig. 2-2, the selenium cells (7) are slipped over a metal mounting stud (1). The stud is separated from the plates by a phenolic insulating tube (9). A small insulating spacer-washer (10) is placed over the mounting stud and against the spacer-counter-electrode. A disc or spring contact (8) is then placed over the washer and against the counter-electrode surface to provide a current-collecting point and a terminal lug. An insulating washer (10) is placed between the cell and the collecting disc to limit the pressure that can be applied to the unit. If too much pressure is applied, the disc punctures the barrier layer, ruining the cell. Another method of collecting the current from the cell involves the use of a solid washer instead of a spring contact. When this method is used, an area under the counter electrode equal to the area of the contact washer is de-activated with an insulating paint. Thus, heating is reduced in this area, and the possibility of a short circuit between the counter-electrode and selenium (caused by pressure created in stack assembly) is also eliminated.

Each cell is then separated either by metal (6) or by insulating washers (4), depending on the circuit requirements of the final stack. If the cells are to be placed in series, a metal washer is used; if the cells are to be mounted in parallel, an insulating washer is used. Input (a-c) and output (d-c) terminals (and if need be, jumpers) are then added. Finally, insulating washers and mounting hardware are placed on the ends of the units and stacks. To reduce the unit cost, the cells may be mounted on a phenolic stud or tube, a metal eyelet, or a stud covered with an insulating sleeve, eliminating the mounting stud, end washers, and the mounting hardware. Most light applications of stacked selenium cells, such as radio and television, use this type of mounting. Those used for high voltages are encased in a tubular housing. Figure 2-3 shows various selenium rectifier housing constructions.



1. MOUNTING STUD
2. END NUT
3. STEEL WASHER
4. INSULATING WASHERS
5. TERMINAL LUG
6. STEEL WASHER
7. SELENIUM CELL
8. SPRING CONTACTOR
9. INSULATING TUBE
10. INSULATING WASHER

Fig. 2-2. Cutaway view showing the construction of a typical selenium-rectifier stack assembly.

Rating of selenium cells and stacks. Selenium cells are rated on their ability to pass unidirectional current per effective unit of surface area. The normal current-density rating of a single selenium cell is 0.25 ampere per square inch of active surface area. (This is the present standard as adopted by NEMA, the National Electrical Manufacturers Association.[1]) The cell is rated while operating in an ambient temperature of 35° C. Typical values of d-c voltage output are 12, 15.5, 19, 26 and 45 volts. Typical values of reverse a-c voltage are 18, 22, 26, 33 and 53 volts. (These typical values may vary considerably from those issued by manufacturers for special cells.)

Recent advances have made possible current densities double those considered standard, with a lower forward-voltage drop than in cells operating at standard density. This creates a much lower ratio of forward aging, or drop in the output voltage, resulting in a rectifier with an estimated life of 100,000 hours. By halving the area, there is a corresponding approximate reduction in the reverse leakage current.

Considerations entering a typical application. To illustrate a typical application, assume that the output of a selenium rectifier is to feed into a resistive load. This output will be 3 amperes at 70 volts dc, and half-wave rectification will be employed.

The stack arrangement is determined as follows: since the voltage rating of available standard cells is 12, 15.5, 19, 26, or 45 volts, the number of cells needed in series will be 6, 5, 4, 3, or 2, respectively, depending on which cells are used. (Number of series cells = volts output/volts per cell.) Assume that four 19-volt cells are selected.

The number of parallel cells is determined by the current requirements; in this case 12 square inches of active surface are required. (Current requirements/0.25 = square inches of active area.) Thus, any combination of cells which gives 12 square inches of active surface area can be used. Assume that 2 × 2 inch cells are chosen. The total number of cells required would be 12, arranged so that the stack contains 3 parallel branches with 4 cells in series in each branch. Cells stacked in series are generally used in radio and television applications, since their power is supplied by 117-volt lines at relatively small currents.

Recent developments. Unique selenium-stack assemblies have been developed by certain European firms. Figure 2-4 (A) shows

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[1] NEMA "Standard for Metallic Rectifiers," Pub. No. MR1-1953 National Electrical Manufacturers Association, New York, N.Y.

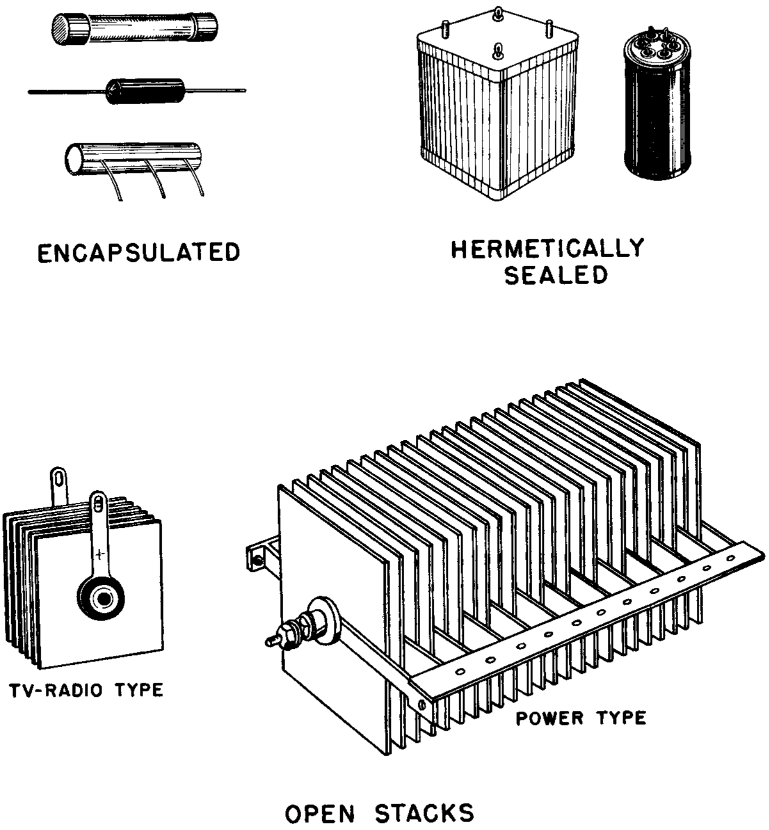
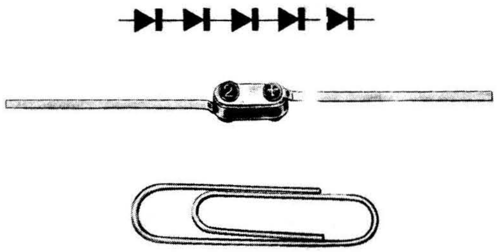


Fig. 2-3. The appearance of various housings and construction of selenium rectifiers.

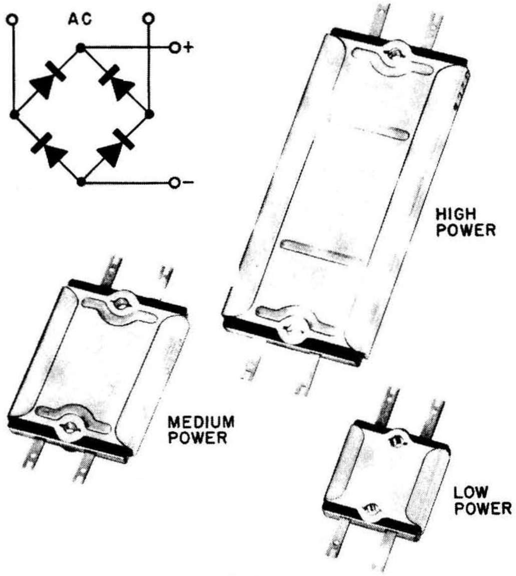
an unusually small diode, containing up to five cells. The flat rectifiers shown in Fig. 2-4 (B) are highly compact, and can be mounted flat against a chassis as a "heat sink," where the chassis dissipates the heat.

Another unique development is shown in the circular stack of Fig. 2-4 (C). This stack contains a great number of series cells in rectangular compartments around a plastic ring. This assembly allows for a high-voltage rating stack that occupies a minimum amount of space. Groups of these circular stacks can be combined into even higher voltage-rectifier assemblies as illustrated in Fig 2-4 (D). This unit is rated at 38,000 volts at 35 ma. With such groupings, ratings as high as 296,000 piv (peak inverse volts) can be obtained by immersing the unit in an oil-filled ceramic tube, as

Fig. 2-4. Recent European developments of selenium rectifier stack assemblies. (A) A "dwarf"-type diode containing five cells. The one illustrated is rated at 5 ma d-c half-wave operation and will handle up to 125 volts a-c with a resistive load.



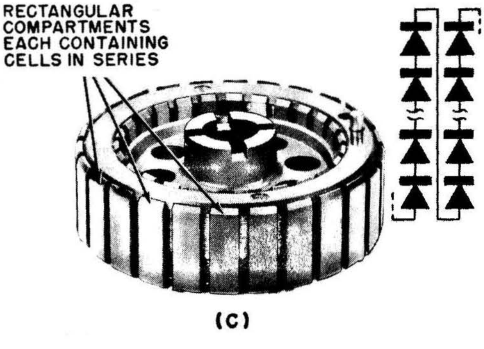
(A)



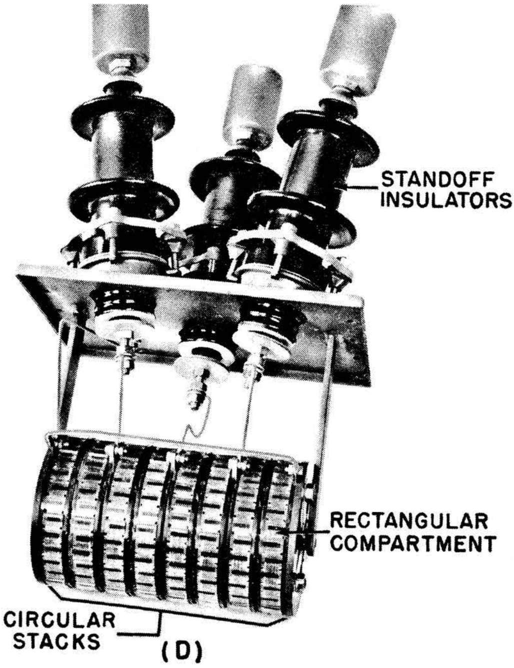
(B)

(B) "Flat" type compact rectifiers for mounting on chassis as a "heat sink." Those illustrated are designed for single-phase bridge circuitry. Dimensions range from approximately 1 3/8 x 1 3/16 to 1 1/2 x 3 1/2 inches.

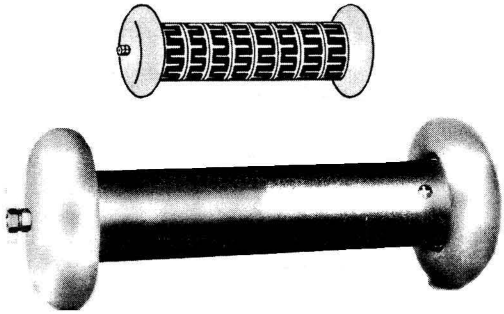
(C) High-voltage ring-type (circular) stack containing many rectangular compartments. The stack illustrated has a dimension of about 2 1/2 inches diameter.



(C)



(D) Use of ring-type rectifier stacks for an oil-immersed single-phase bridge circuit. The assembly illustrated is rated at 38,000 piv volts at 35 ma.



(E) A completed stack assembly of individual circular stacks in an oil-filled tube for air-cooled operation. This unit is rated at 148,000 piv volts at 5 ma and has a length of about 17 inches.

shown in Fig. 2-4 (E). This rectifier is rated at 148,000 piv at 5 ma for air cooled operation. Its length is approximately 17 inches.

All of these units are ideal for high-voltage testing, have a long life and are free from noise and x-ray emanations. Plans are under way to manufacture these various rectifier units in the United States.

Copper and Copper-Oxide Rectifiers

Preparation of the copper-oxide cell. In the construction of the modern copper-oxide cell, specially selected and processed cop-

Fig. 2-5. Cross-section of (A) plate-type rectifier and (B) copper-oxide disc.

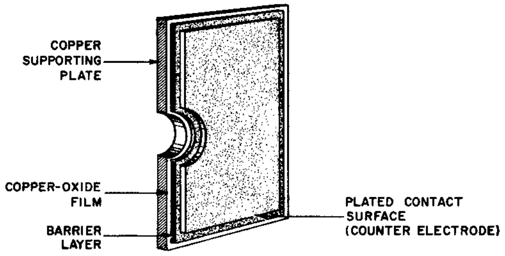
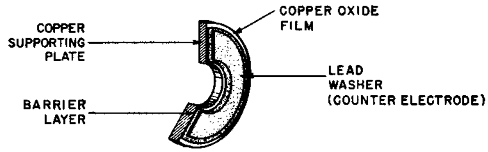


PLATE TYPE CELL (A)



CIRCULAR-TYPE CELL (B)

per is heated to a high temperature (upwards of 1000° C) and then cooled. (Some manufacturers allow the copper to cool gradually at room temperature while others prefer to cool the heated copper in water.) This process leaves a layer of cuprous oxide on the base copper and a layer of undesirable cupric oxide on the outside. The cupric oxide is removed, either by sandblasting or by bathing the cells in mineral acids to expose the red cuprous oxide.

As with the selenium cell, the next step in the process is to provide contact with the copper-oxide surface by applying a counterelectrode (outside contact). This process is quite critical, since the forward resistance of the cell depends on the continuous contact between the cuprous oxide and the front electrode over the entire surface. Several methods are employed to produce this contact. Most manufacturers coat the cupric oxide with a thin layer of graphite or carbon before applying the front electrode. This front electrode is a low melting point alloy and serves to provide a good electrical contact between the copper-oxide film and the circuit to which the cell is connected.

Other manufacturers coat the copper with a thin layer of gold, silver, or aluminum. The expense of this procedure limits its adaptation to small cells. Copper rectifiers require no artificial forming, and are ready for use after application of the counterelectrode. The finished copper-oxide cell may be shaped as a rectangle or disc (Fig. 2-5A and B) depending on its use.

Stacking copper-oxide cells. One or more copper-oxide cells are assembled on an insulated rod with washers of lead or other soft metal placed between them. This is similar to the stacking of selenium cells. The entire assembly (Fig. 2-6) is then tightly clamped together to provide rigidity and maximum electrical contact between the elements. The pressure, applied by an assembly bolt, must be uniformly distributed over the entire cell and maintained for the life of the unit. A spring washer is used to compensate for variations (caused by temperature changes) in the thickness of the discs and washers and in the lengths of the bolts. Fins which radiate excessive heat are often spaced between the discs, improving the efficiency of the stack and the rating of group cells.

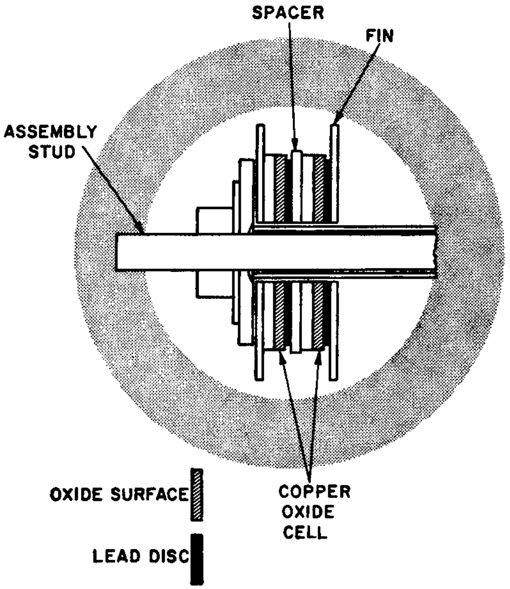


Fig. 2-6. Cutaway of a typical copper-oxide rectifier stack assembly.

Copper-oxide rectifiers used in instruments, modulators, balanced bridges, etc. are similar to those shown in Fig. 2-7. The terminals and lead wires of these units are specially designed to facilitate soldering into meters and other assemblies. Rectifiers A and B are hermetically sealed whereas C through E are not.

The direction of electron flow through a copper-oxide rectifier is from the copper to the copper oxide.

Copper-oxide cells and stack-rating standards. Tables 2-I and 2-II list the ratings for unit copper-oxide cells assembled into stacks, as established by NEMA[2]. These tables are intended to serve only

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[2] NEMA "Standard for Metallic Rectifiers," Pub. No. MR1-1953, National Electrical Manufacturers Association, New York, N.Y.

as a guide. The ratings given are for the most commonly used rectifier stacks and are based on operation at an ambient temperature of 35° C. If the stacks are to be operated at higher temperatures it is necessary to derate (reduce) the output ratings 10% for each 5° of temperature increase. The ratings are given in terms of both voltages and current d-c output of a unit-rectifier cell. These cells can be mechanically stacked in combination to obtain the desired circuit requirements and electrical output characteristics.

The ratings listed in Table 2-I are given for typical cells which are naturally cooled or with natural ventilation aided by cooling fins.

TABLE 2-I

Copper-Oxide Stack-Cell Ratings

Naturally Cooled or with Cooling Fins

	Half-Wave	Center-tap	Single-Phase Bridge	Radiating Fins (inches)	Cell Size or Active Area
Volts	1.55	1.55	3.1	2.25 × 2.25	1.2 sq. in.
Amperes	0.13	0.25	0.25		
Volts	1.65	1.65	3.3	2.75 × 2.75	1.2 sq. in.
Amperes	0.11	0.21	0.21		
Volts	2.25	2.25	4.5	3.625 × 3.625	1.2 sq. in.
Amperes	0.25	0.5	0.5		
Volts	1.8	1.8	3.6		4.65 in. × 3.625 in.
Amperes	2.0	4.0	4.0		
Volts	1.8	1.8	3.6		4.65 in. × 4.65 in.
Amperes	2.5	5.0	5.0		

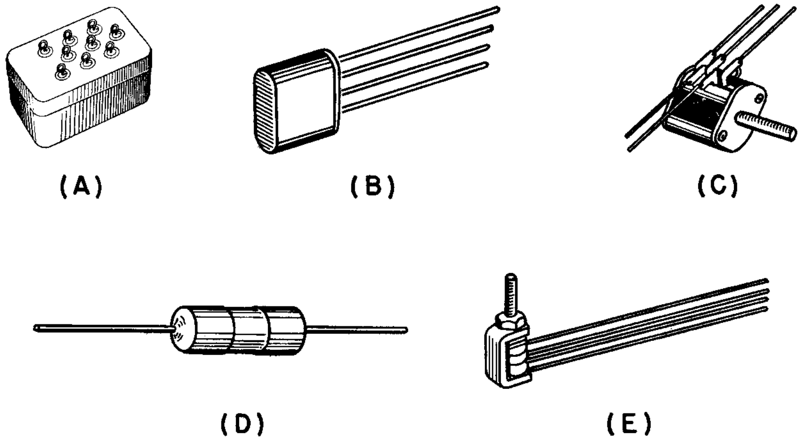


Fig. 2-7. Copper-oxide rectifier housings.

The ratings listed in Table 2-II are for typical cells with natural cooling only.

TABLE 2-II[3]

Copper-Oxide Stack-Cell Ratings
Naturally Cooled Only

	Half-Wave	Center-tap	Single-Phase Bridge	Cell Size (inches)
Volts	1.5	1.5	3.0	.187
Amperes	0.002	0.005	0.005	
Volts	1.5	1.5	3.0	.72
Amperes	0.032	0.064	0.064	
Volts	1.5	1.5	3.0	1.125
Amperes	0.062	0.124	0.124	
Volts	1.5	1.5	3.0	1.5
Amperes	0.1	0.2	0.2	

[3] Actual ratings may vary from those given in this table, depending on the number of cells assembled in a stack and the temperatures at which the cells are operated.

When using these charts, it is necessary to first select the type of circuit desired. (Chapter 5 describes and illustrates the circuits and furnishes the basic design data for half-wave, centertapped, and bridge-type rectifiers.) The next step is to examine the current ratings in the table until a value is found that is slightly higher than that required. The corresponding voltage rating divided into the total voltage required will give the number of cells required in the *series* element.

If the current rating is greater than that supplied by the single cell, it will be necessary to add cells in *parallel.* The current divided by the total current capacity of the cell will give the number of cells required. The combination giving the least number of cells in series is the more practical one. For example, a stack is required that will have a direct current output of 35 volts at 0.2 ampere using a single-phase bridge circuit. The current requirements are satisfied by using a 1.2-square inch cell with 2.5 inch square radiating fins. (See Table 2-1.) A corresponding voltage rating for the cell is 3-1 volts, thus the stack requires 12 cells (35/3.1) in series.

Note: When it is necessary to use a rectifier that requires more than 48 cells, two stacks should be used.

Crystal Diodes

As in the case of metallic rectifiers, there are several distinct techniques used in manufacturing silicon and germanium diodes. Each manufacturer uses his own special methods for processing and assembling. Typical steps used in the manufacture of a crystal diode are shown in Fig. 2-8.

Germanium diodes. More popular than silicon diodes, germanium diodes fill virtually every application formerly reserved for the vacuum-tube diode.

Purification of the germanium. The first step in germanium diode manufacture and assembly is the purification of the germanium. This is absolutely essential. In this country, the principle source of germanium is germanium dioxide, a by-product of zinc mining operations. The conversion of germanium dioxide into pure germanium takes place in two steps. First, the germanium-dioxide powder is placed in a hydrogen furnace at controlled temperatures. The intense heat plus the hydrogen atmosphere reduces the germanium dioxide to a molten mass. It is allowed to cool and solidify, forming an ingot of germanium. The impurity content at this point is less than one part in 10,000, yet even this impurity cannot be tolerated in diode manufacture and it is necessary to reduce the impurity content still further. Also, the germanium ingot is usually polycrystalline (composed of many individual crystals in random orientation). In this state the crystal would rectify, but may have a short operating life. Consequently its crystalline structure is usually modified.

The zone purification process is used extensively to improve the purity of the germanium ingot. Induction coils are spaced at intervals along the path of travel of the ingot. The passage of current through the coils heats and melts a short section of the ingot. This molten region is moved slowly along the bar. The impurities tend to move forward and concentrate at one end. That end is cut off and the remaining ingot consists of germanium that is nearly 100% pure.

Seeding. It is then necessary to reduce the polycrystalline mass to a monocrystal (single crystal) state. To accomplish this there is a process called seeding. The purified germanium is again reduced to a molten state, and a small single crystal or "seed" of monocrystalline germanium is lowered into the mass. As the seed is slowly withdrawn germanium adheres to it, forming a single-crystal germanium ingot. During this process, controlled amounts of impurities are added to the germanium crystal to either increase or decrease

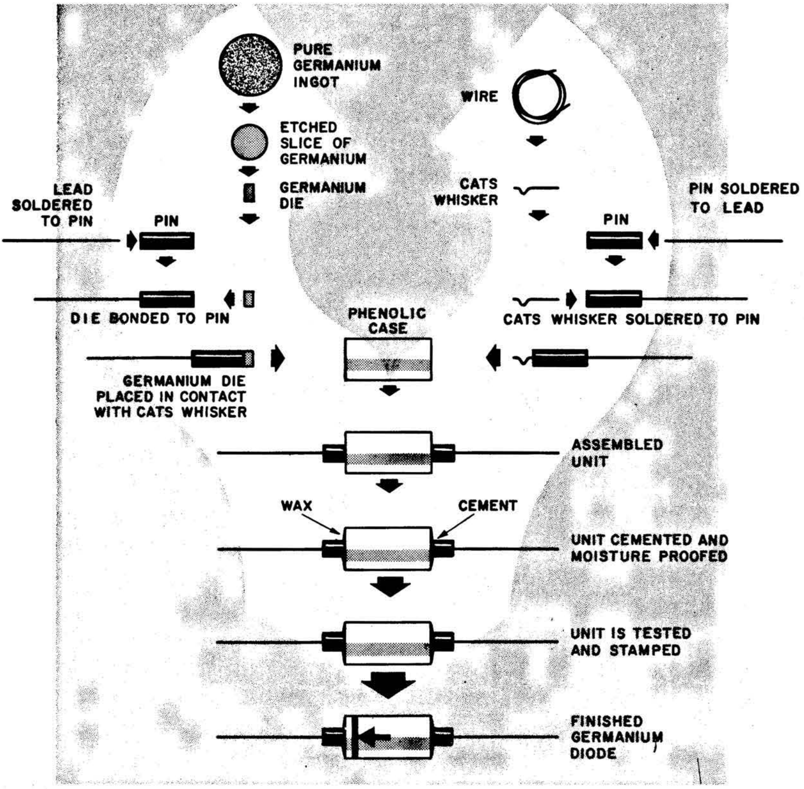


Fig. 2-8. The many steps (shown in the order in which they occur) in the manufacture of a germanium crystal diode.

the resistivity to a desired value. The germanium is now tested for purity and structure; acceptable ingots are sliced and further processed, rejected ingots are reprocessed.

Slicing. A precision diamond saw slices the germanium ingot into thin wafers, 0.200 to 0.250 of an inch thick. To guard against surface contamination (a frequent occurance during the slicing operation) the wafers are polished and etched in acid baths. This polishing and/or etching also reduces the size of the wafers. An etchant commonly used for this purpose consists of 50% hydrofluoric acid and 50% nitric acid.

The wafers are next cut into small cubes, 0.050 of an inch on a side, either by another precision diamond saw or by "dicing" (use of supersonic vibrations to cut the slice via a liquid cutting compound). When these cubes have been cut, they are etched again to remove surface films and oxides before final diode assembly.

Cat's-whisker assembly. Fabrication of the cat's-whisker assembly is an independent operation. The unit consists of an S- or C-shaped wire welded to a nickel or silver contact pin. The wire is cut to the required size and its tip etched to a fine point. High grade tungsten-gold alloy, or phosphor-bronze wire is generally used for the contact-type junction. Platinum-rutherium alloy is used for welded diodes.

Germanium assembly. The tiny cubes are soldered directly to nickle-silver pins. The pin and ends are generally pretinned to facilitate soldering.

Main assembly. The final step in assembling a germanium diode consists of mounting the whisker and germanium assemblies within a protective case. (See Fig. 2-9.) They are inserted into

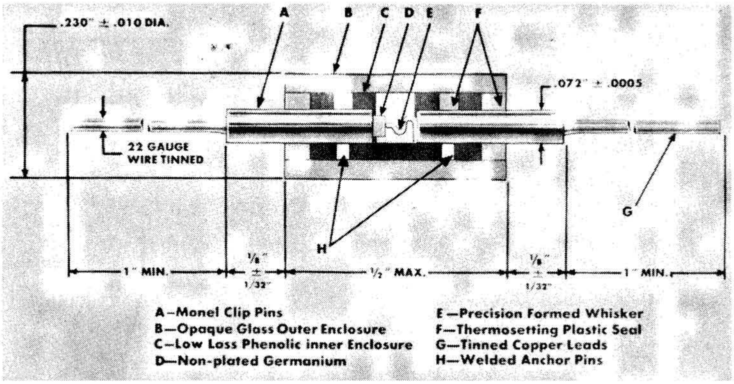


Fig. 2-9. Cross section of internal structure of a germanium diode.

opposite ends of glass tubing or a phenolic case, and the whisker (E) is positioned for optimium contact between its point and the germanium. The assemblies are then sealed in place. As a final qualitative check, a short pulse of energy, (several hundred ma dc), is applied to the terminals. This application of power helps to both fuse the whisker point to the germanium and to control the formation of the contact areas.

The case is coated with wax to provide mechanical stability and moisture resistance. Terminal leads are added,and the assembled diode is ready for testing and classification.

Silicon diodes are manufactured in a way similar to that of germanium diodes. The process includes; (1) purification of the semiconductor, (2) preparation of the ingot (seeding), (3) slicing or cutting of the purified ingot into wafers, and (4) assembling and adjustment. Operating temperatures and materials are, however, quite different. The temperatures required for producing silicon units are much higher then for germanium, due to silicon's high melting point. Also silicon must be handled with extreme care because it is very fragile in its solid state.

Power diodes. Germanium and silicon have recently been placed in the power-rectifier field. Examples of power rectifiers are

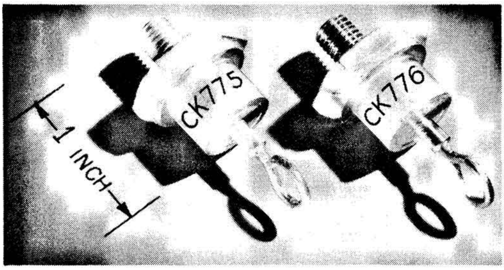


Fig. 2-10. Silicon power rectifiers, single-cell units.

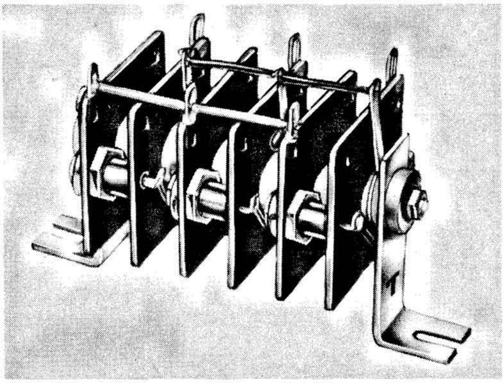


Fig. 2-11. Silicon power-rectifier stack.

shown in Figs. 2-10 and 2-11, and a cross section of one is shown in Fig. 2-12. These units are designed for power applications. The size of the rectifing element (silicon or germanium) in these power rectifiers is considerably smaller than in metallic rectifiers.

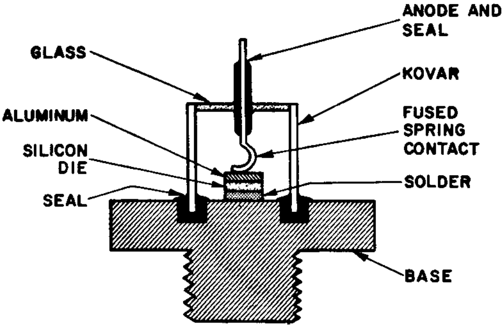


Fig. 2-12. Cross-section of a silicon power rectifier.

Where large currents may cause the temperature to rise beyond safe rated values, adding fins helps dissipate the excessive heat.

3. metallic rectifier characteristics and notation

Polarity of Metallic Rectifiers

For some time theory maintained that current flow through a closed circuit was from the positive terminal to the negative terminal. This concept was firmly entrenched during the early days of the development of copper-oxide and selenium rectifiers. Consequently, the symbols adopted used the conventional method for the direction of current flow. Later, when the electron theory was developed, manufacturers and scientists were reluctant to change the symbol, and it is still in use today.

The schematic symbol for a metallic rectifier is shown in Fig. 3-1A. For comparison, a conventional diode symbol is also shown (Fig. 3-1B). The arrow on the rectifier symbol corresponds to the plate or anode of a vacuum tube while the bar corresponds to the cathode. The flow of electrons in a diode is from cathode to plate, therefore the arrow in the metallic rectifier symbol points opposite to the direction of electron flow. This apparent inconsistency is a result of the convention in which current flow in a circuit was assumed to be from the positive to the negative terminal. When considering current flow through a rectifier one should remember

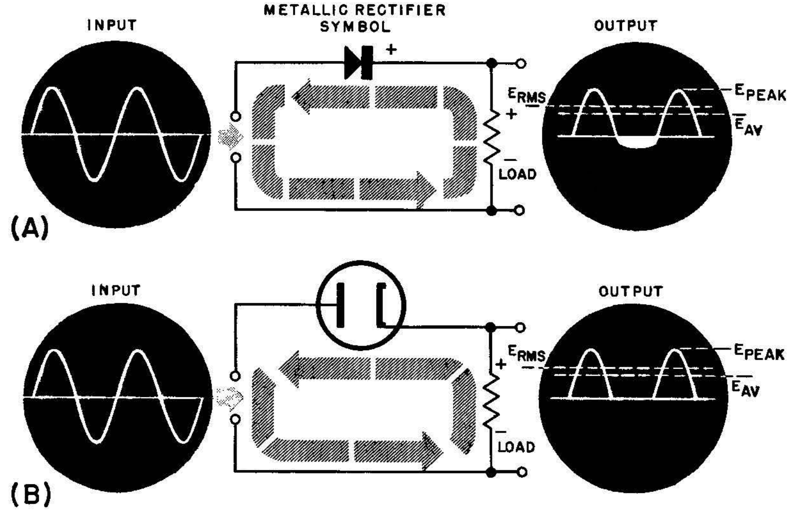
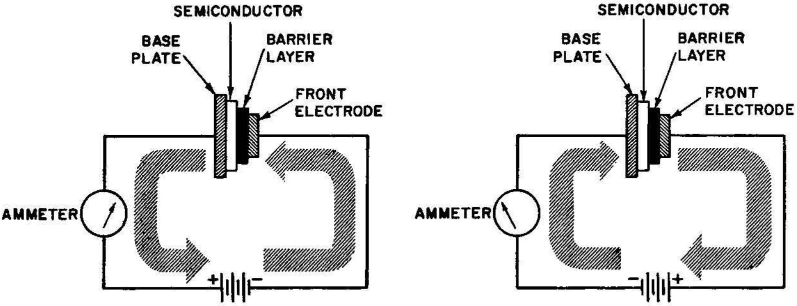


Fig. 3-1. Waveforms and direction of current flow in metallic and vacuum-tube half-wave rectifier circuits.

whether the "conventional current" flow or electron flow is used as a reference. Throughout this book electron flow is used rather than current flow.

Method of Notation

The semiconductor is usually mounted on the metallic base-plate that is equivalent to the plate of a diode rectifier (the arrow on the schematic). The low melting point alloy or front electrode is equivalent to the cathode of the diode (the bar on the schematic)



FORWARD (EASY) FLOW
(A)

REVERSE (LEAKAGE) FLOW
(B)

Fig. 3-2. Electron flow through a selenium rectifier.

The positive point in a circuit is the cathode of a diode or the bar of the metallic rectifier. (See Fig. 3-2, noting the polarity of the voltage developed across the load.)

It is this point that manufacturers frequently mark. When a rectifier is taken from the shelf it should be examined closely. If it is a half-wave unit there will be a plus sign (+) or a red dot on one side. This is the front electrode and corresponds to the cathode of the diode vacuum tube. If there are no markings, or if the mark has become indistinguishable, the polarity may be determined by examination. The roughened or dull side of the plate is the front electrode and is therefore the positive (d-c) terminal.

Mechanics of Rectification

Metallic rectifiers exhibit nonlinear characteristics with respect to electron flow similar to their d-c thermionic counterparts, the vacuum diodes. The electron flow in metallic rectifiers proceeds easily in only one direction. The basic theory underlying the operation of metallic rectifiers and vacuum diodes is, however, quite different.

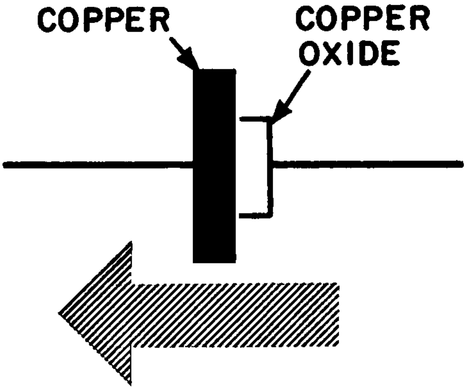


Fig. 3-3. Direction of easy electron flow through a copper-oxide rectifier.

A study of the two devices under similar conditions will assist in understanding the operation of each type of rectifier. Figure 3-1 shows a typical rectifier circuit and its vacuum-tube counterpart. When an alternating current is applied to either circuit, each conducts for one-half the cycle. The diode tube conducts when the plate is made positive with respect to the cathode; the metallic rectifier conducts when the arrowhead is made positive with respect to the base or bar. When the vacuum diode is conducting, electrons flow from the negative terminal of the power source, through the resistive load to the cathode, to the plate, and finally to the positive terminal of the power source, completing the circuit. This path is indicated by the arrows. When the metallic rectifier conducts, electrons flow in a path from the negative terminal through the resistive load to the rectifier and then to the positive terminal. Note the polarity of the voltage across the load.

When the arrowhead of the metallic rectifier is positive with respect to the base, the rectifier acts as an insulator and little or no current flows. Similarly, when the plate of the vacuum diode is negative with respect to the cathode, no current flows. The relationship between the input and output voltage of each unit is shown in Fig. 3-1. The output currents for each unit flows only during the positive half of the input cycle. A small negative conduction appears in the output of the metallic rectifier, due to leakage current. The rectified pulses need to be filtered to give a usable direct current.

Several theories (one of which is discussed below) have been advanced explaining the "leakage" associated with metallic rectifiers.

A metallic rectifier consists of a good conductor (front or negative electrode) and a semiconductor (positive electrode) separated by a thin insulating, or barrier, layer. Although this layer is in itself an insulator, some electrons pass through it in both directions. The front electrode is a good conductor, having an abundance of free electrons (electrons available for conduction). The semiconductor (copper oxide or selenium) is a poor conductor and has relatively few free electrons. If a d-c potential is applied to the rectifier, so that the front electrode is made negative and the semiconductor positive (as shown in Fig. 3-2A), an electric field is applied to the barrier layer. A large number of free electrons are accelerated to a velocity sufficient to penetrate the barrier layer and pass through the semiconductor to the metal base-plate. In this manner a flow of electrons is established through the rectifier. When the polarity of the battery is reversed (Fig. 3-2B), the same action takes place, but in the opposite direction, from the semiconductor through the barrier layer to the front electrode. Since there are fewer free electrons in the semiconductor than in the front electrode, the resulting electron flow is smaller than before. An ammeter placed in the circuits exemplify. In Fig. 3-2 (A) the meter registers a relatively large amount of current flow, and in (B) the meter is deflected only slightly. This latter current is called *leakage current.*

The asymmetrical characteristics of metallic rectifiers are explained by the static field (positive-negative boundary) set up within the barrier layer. When the barrier layer is formed either electrically or physically, the section that comes in contact with the front electrode assumes a negative charge, while the section that is bonded to the semiconductor is positively charged. The charges are a direct result of the forming process. Electrons freed from their valence bonds accumulate at the junction of the good conductor with the barrier layer and are forced from the semiconductor side of the barrier, leaving a deficiency of electrons (or a positive charge) at the boundary-semiconductor junction.

The resistance of the barrier is extremely high. An external voltage applied to the rectifier is dropped across the barrier layer and builds a strong field across it. If, however, the polarity of the voltage applied to the rectifier causes the front electrode to be negative and the semiconductor to be positive, the field causes the charged areas to move toward each other. This effectively reduces the size of the barrier layer and the resistance of the rectifier. For high voltages, the layer dissappears completely. This is the direction of low resistance and high current flow.

When the applied voltage causes the semiconductor to be positive and the front electrode negative, more electrons accumulate at the front electrode junction leaving a greater deficiency at the semiconductor junction. The size and resistance of the barrier layer are effectively increased, and the current in this direction is low. The path of high current flow through a copper-oxide cell is shown in Fig. 3-3.

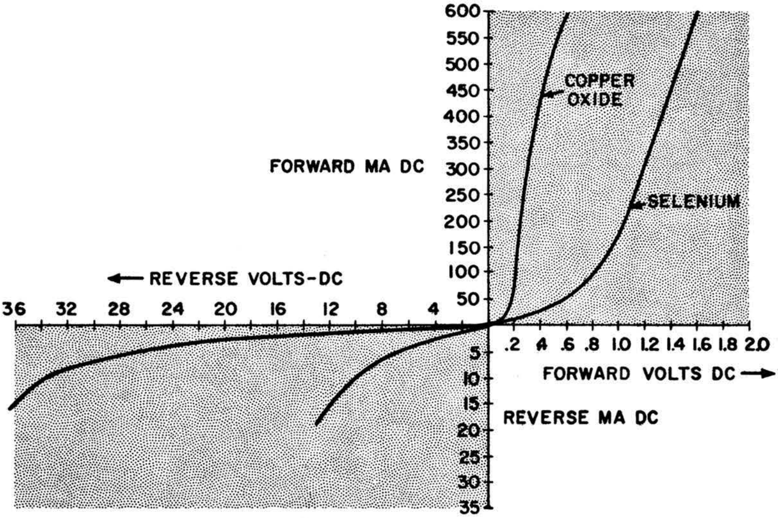
Basic Characteristics of Metallic Rectifiers

Metallic rectifiers exhibit most of the electrical properties of vacuum-tube rectifiers. Such characteristics as peak inverse voltage and forward resistance apply to both. In addition, rectifiers have properties important to their function, including aging and the effect of temperature. Since it is impossible to make all rectifiers exactly alike, the following curves and characteristics are a representative average.

Current and voltage. The function of the ideal rectifier is to pass current in the forward direction and to block the flow of current in the opposite direction. These actions are best described by applying a d-c voltage first in one direction and then in the other direction, and plotting the results. The static volt-ampere characteristics for both the forward and reverse directions of current flow of a selenium and a copper-oxide cell are shown in Fig. 3-4. These curves determine the operating characteristics of the rectifier.

Essentially, the rectifier is a resistive device; when current flows through it a voltage is developed across it. The current flow through the cell is equal to the voltage divided by the resistance of the cell. (By Ohm's law $I = E/R$). The resistance offered by a rectifier, however, is nonlinear. For small increases in applied voltage the current increases considerably. If a d-c voltage is applied in the reverse direction the rectifier shows similar characteristics. The cell's resistance to current in the reverse direction is considerably greater than to that in the forward direction, and consequently the reverse current flow is much smaller.

In Fig. 3-4 the voltage in the forward direction is calibrated in tenths, in the reverse direction the voltage is calibrated in whole numbers. The graph shows that resistance is neither fixed nor linear.



NOTE. BASED ON ONE SQUARE INCH OF RECTIFYING AREA.

Fig. 3-4. Typical voltage-ampere curves for a single selenium and a single copper-oxide cell.

At extremely low voltages the flow of current in the forward direction is small, indicating that the resistance of the circuit is large. As the forward voltage is increased, the current flow increases quite rapidly (indicating that the resistance decreases). The reverse resistance is also nonlinear. If a small inverse voltage is applied to the rectifier, the resistance will be high and only a small current will flow through the circuit. As the applied voltage increases the reverse resistance decreases and the reverse current increases. Note, however, that the current flow in the forward direction is much greater than the reverse (or leakage) current, and therefore the value of the reverse resistance is many times that of the forward resistance. The efficiency of the rectifier is measured as the ratio of

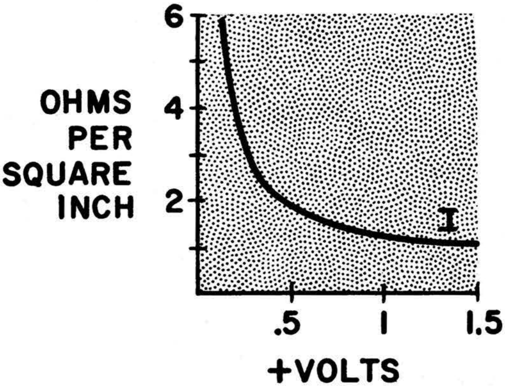


Fig. 3-5. Typical voltage-resistance curve for a copper-oxide cell.

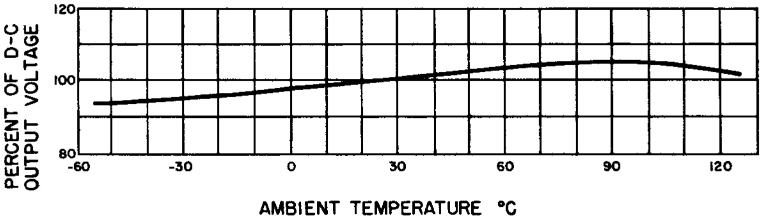
the forward-to-back resistance. The curves shown in Figs. 3-4 and 3-5 are based on current flow per square inch of rectifying area and are applicable to virtually all rectifiers.

Thermal effects. Metallic rectifiers are thermal as well as electrical devices. Special consideration must be given to these thermal effects.

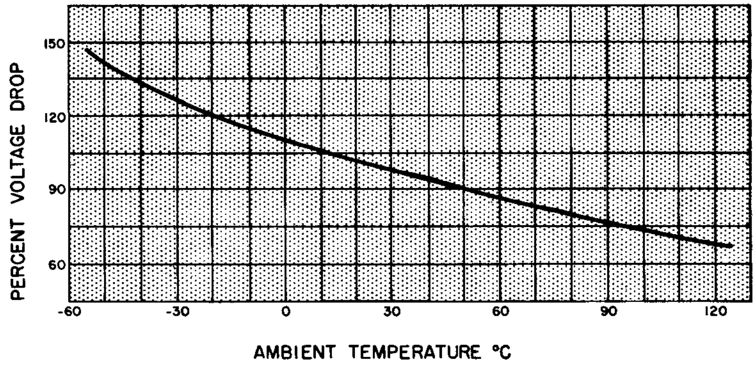
Metallic rectifiers have a negative temperature coefficient; as the temperature of the cell increases, the resistance of the cell decreases. Conversely, as the temperature decreases the resistance increases. By Ohm's law it follows that for a given current flow the voltage drop across the cell decreases as the temperature increases and there is an increase in voltage drop as the temperature drops. An increase in temperature will also decrease the back resistance, resulting in an increase in the leakage current. The effects of temperature and current in the forward and reverse directions are such that any increase in the operating temperature causes a corresponding increase in reverse current. This further increases the operating temperature. The effects "snowball," destroying the rectifier. Thus it is important to keep well within the manufacturer's prescribed limits. Usually the reverse voltage is set at a value that limits the leakage current and the corresponding heat loss. Under normal operating conditions, heat losses caused by leakage currents should be kept at a value under one-third of the total rectifier losses.

Graphs A, B and C of Fig. 3-6 indicate the general variations of rectifier characteristics with temperature changes, and show how these variations affect output voltage. The values indicated on the charts are relative (based on 25° C operating temperature) and were obtained under actual operating conditions of a half-wave rectifier with a resistive load.

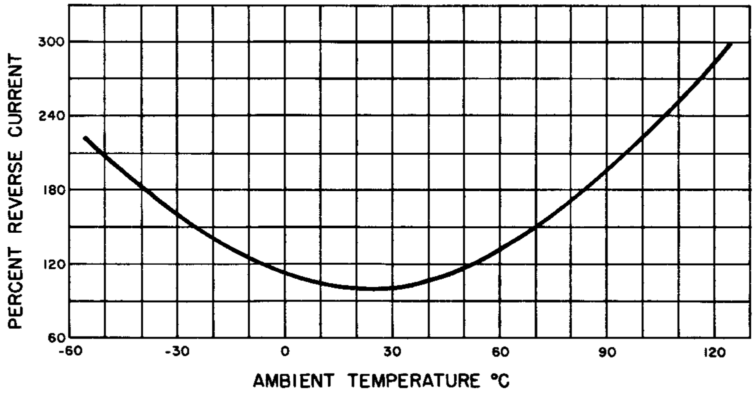
Graphs A and B clearly depict the *decrease* in forward resistance with *increased* operating temperature. (These are evident, since



(A) OUTPUT VOLTAGE VARIATION WITH TEMPERATURE



(B) FORWARD VOLTAGE DROP VARIATION WITH TEMPERATURE



(C) REVERSE LEAKAGE CURRENT VARIATION WITH TEMPERATURE

Fig. 3-6. Variations of rectifier characteristics with temperature changes. (A) Output voltage. (B) Forward voltage drop. (C) Reverse leakage current.

in A the percentage of output voltage increases with increased temperature, whereas in B the percentage of voltage drop decreases with increased operating temperature.) Graph C clearly indicates that any increase or decrease from rated operating temperature results in an increase in reverse current.

When the rating of a rectifier has been exceeded beyond a given length of time, the rectifier may be damaged. Although the specific causes of rectifier failure are not understood, it has been proven that the ultimate cause of failure is heat. When ratings have been exceeded, either by faulty circuitry or excessive overloading, the resulting increase in current flow through the rectifier causes the temperature to rise. The rectifier's negative temperature coefficient decreases its opposition to current flow and more current flows in the circuit, causing the cell to get still hotter. Each cell can withstand only a given amount of current, voltage, and temperature before the molecular stress becomes too great and the barrier layer is punctured. Once the cell is punctured, its rectifying properties are impaired.

Power losses in a metallic rectifier are calculated in the conventional manner; power in watts is equal to the square of the current times the resistance ($P = I^2R$). These losses are controlled so that the power loss in the reverse direction (square of the leakage current multiplied by the reverse resistance) is equal to, or less than, one-third the power loss in the forward resistance. Note that there are two voltages to be considered (reverse and forward) and two currents (leakage and forward). They should never be confused. If the peak voltage applied to the rectifier in the reverse direction exceeds the rated value, there is a rapid increase in leakage current and reverse power loss. Consequently, the temperature will rise and the rectifier may fail. It must be remembered that the heat the rectifier dissipates is equal to the sum of the reverse and forward power losses. The rectifier can, however, withstand momentary surges in one direction with little or no effect.

Excessive heat may cause another type of rectifier failure. The counter-electrode is metal sprayed onto the semiconductor. To flow freely and be readily sprayed during manufacture it must have a low melting point. If the rectifier is submitted to high overloads or current surges that cause the temperature to rise to 100° C or more, the counter-electrode will melt.

High operating temperatures may be found even where voltages and currents have been kept within the rated values. On occasion, current flow through the cell will not be evenly distributed over the entire surface of the barrier layer and "hot spots" will result in areas where the current concentrations are greatest. These hot spots are caused by small particles adhering to the rectifier cell during the manufacturing process. They can also be caused by uneven pressure of the lead take-up washer. (See Fig. 2-2 and 2-5.) These hot spots cause the temperature in the rest of the cell to rise and both forward and back resistance are decreased, resulting in further damage.

The heat that can be dissipated efficiently from a surface is limited by the size of the radiating surface and by the quantity of the cooling medium that passes over it. Selenium cells have, for their radiating surfaces, aluminum back plates upon which the selenium is mounted; copper-oxide cells (used for power applications) must have cooling fins as well. It is very important that temperatures be kept to a minimum, not only for efficient operation but also for long cell life. To insure proper cooling, the rectifier must be located where there is adequate ventilation.

Derating. Operation above rated ambient temperature (25° C to 50° C) will result in materially reducing the life of the rectifier. To obtain a life expectancy equivalent to that obtainable at rated ambient temperatures, the input voltage, output current, or both, must be reduced. This is known as derating. Optimum operating conditions may be ascertained from graphs A, B, C of Fig. 3-6. Operation at high ambient temperature, however, introduces problems of size, cost, and output. In most cases some compromise must be made between these factors and shorter rectifier life.

Figure 3-7 can serve as a guide in the applications of selenium rectifiers at elevated ambient temperatures. The solid curves give voltage and current derating factors for normal rectifier life. The dashed curves give less conservative derating factors for a rectifier life of 2000 or more hours. (Because of continuing developments it is suggested that individual data be obtained from the manufacturers.)

When operating copper-oxide rectifiers at ambient temperatures higher than those given, the output ratings must be reduced by 10% for each 5° C increase in the limiting daily average ambient temperature. The current and voltage patterns closely resemble those shown for a selenium cell.

Aging. Aging in crystal diodes means any persistent change (except failure) in either the forward or reverse resistance characteristics.

The characteristics of a new metallic rectifier are very stable. The forward and reverse current, however, may vary with time. This is due to the gradual variation of the forward resistance. Any increase in the forward resistance is accompanied by an equivalent decrease in the d-c output voltage. Coincident with this voltage loss

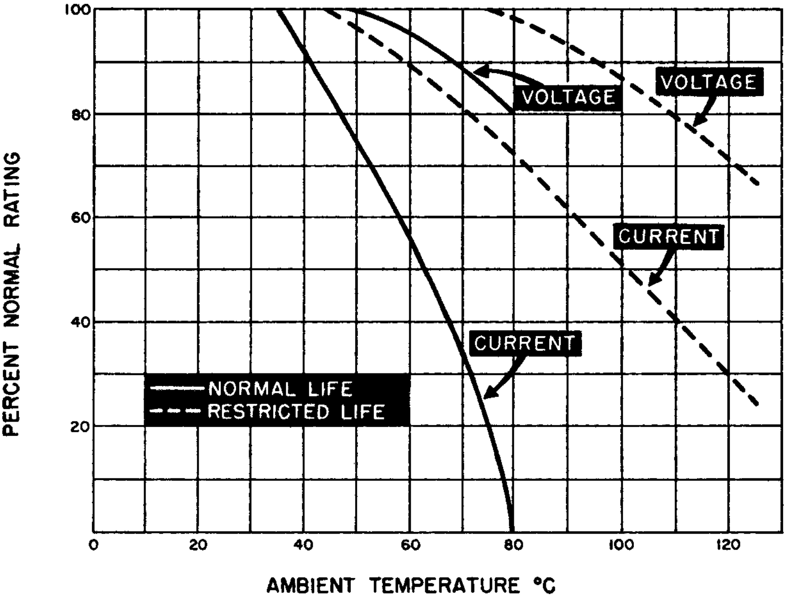
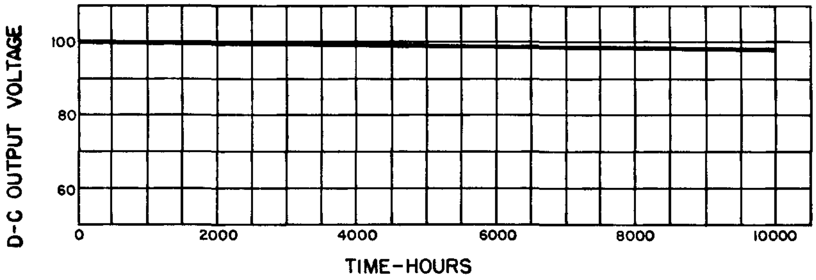


Fig. 3-7. Graph showing voltage and current versus temperature derating curves.

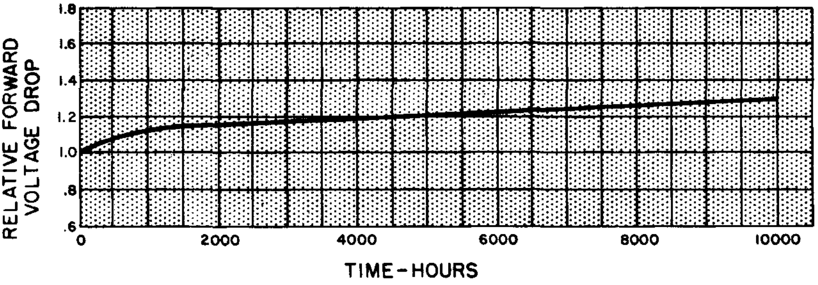
is a loss of efficiency and an increase in operating temperature. Changes in the reverse resistance are not important so long as the leakage current remains within the rated limits. If the reverse voltage increases beyond its rated value the power loss in the reverse direction will also increase and will cause a more rapid aging of the cell.

Figure 3-8 indicates the variations in d-c output voltage (A), forward voltage drop (B), and reverse-leakage current (C) with time. These graphs show how aging affects the output voltage. It is evident that throughout the life of the rectifier there is a steady decrease in output voltage (A) caused in part by the increased forward voltage drop (B), and accompanied by a steady increase in a reverse current (C). The values on the graphs are relative, based on initial conditions. They were obtained with a selenium cell operating in a single-phase half-wave rectifier circuit with a resistive load operating at rated values under normal operating conditions. Note the decrease, due to reformation of the selenium cell, in forward current (C) during the initial hours of operation.

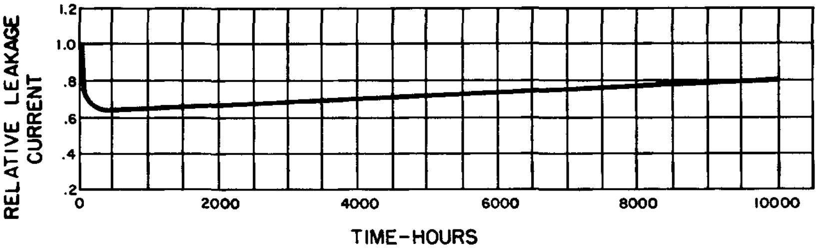
The temperatures at which the rectifier operates also affect the aging process. If the ambient temperature is high, the increase in forward resistance will be accelerated; and vice versa.



(A) OUTPUT VOLTAGE



(B) FORWARD VOLTAGE DROP



(C) REVERSE LEAKAGE CURRENT

Fig. 3-8. Graphs illustrating the variations of rectifier characteristics with time.

Since all rectifiers are subject to aging it is good practice to make allowances for the increased forward resistance and subsequent decrease in d-c output. One way of controlling the aging of a cell is to provide taps on the input power transformer. As the efficiency of the cells decrease, more a-c input voltage may be applied. Another method is to place a load resistor in the output circuit and to adjust it to compensate for the decreased output.

Aging among individual rectifiers will vary, depending on the characteristics of the individual cells, the process used in their manufacture, and the circuits in which they are used.

Shelf aging of selenium rectifiers is attributed to the deforming of the barrier layer after prolonged periods of storage. This aging is not serious, for soon after the cell is placed in a circuit and power is applied the selenium cell reforms and the characteristics stabilized.

Physical Marking and Stack Coding

Manufacturers of metallic rectifiers generally follow the NEMA (National Electrical Manufacturers Association) standards when designating polarity or tap connections on metallic-rectifier stacks. An explanation of these markings is given below. Care must be exercised when installing or replacing metallic rectifiers; should they be connected with polarity reversed, not only the rectifier but also the input filter capacitor may be damaged. The polarity marked on the rectifier indicates the polarity of the load into which the rectifier is to be connected. The marking does *not* indicate the polarity that will cause it to pass current. If this fact is kept in mind there should be little or no trouble replacing these units.

The terminal of the half-wave rectifier stack shown in Fig. 3-9 is marked "+" or colored red, and is the positive end of the load. It is the equivalent of the cathode of a vacuum-tube rectifier and should be well insulated from ground. One manufacturer identifies the negative terminal by yellow coloring. Others identify it with a negative (−) sign or by black coloring. This terminal is usually connected to the a-c power source.

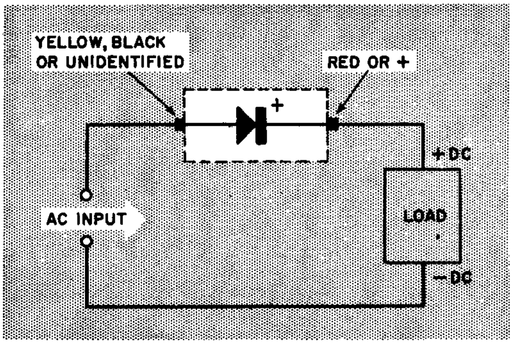


Fig. 3-9. Polarity identification of half-wave stack.

A full-wave bridge-stack rectifier is shown in Fig. 3-10. The positive terminal of this rectifier system is colored red or marked

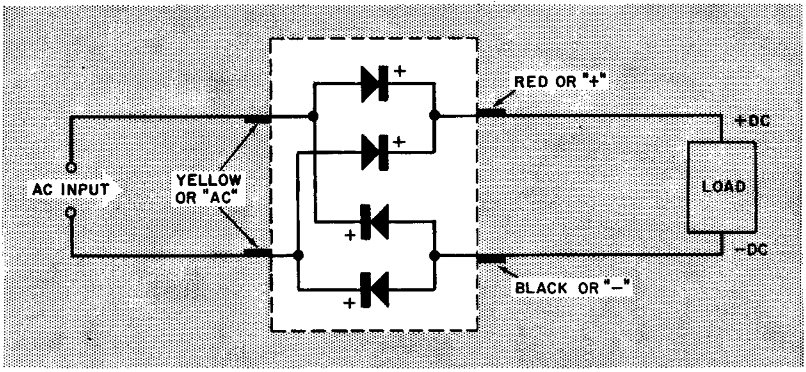


Fig. 3-10. Polarity identification of full-wave bridge stack.

with a positive sign (+). This sign indicates that this terminal is to be connected to the positive side of the load. The negative terminal is colored black or marked with a negative (—) sign. The input terminals to the bridge are colored yellow and should be connected to the a-c power source. In many cases the a-c input terminals are simply stamped or marked "AC".

A double-stack rectifier is shown in Fig. 3-11. The positive terminal on this stack is identified by either the red color or the plus sign. The negative terminal is stamped with the minus sign or is colored black. The a-c input terminal is colored yellow. Note that one side of the a-c line is applied to the centertap connection and that the other side is connected to the voltage-doubler circuit.

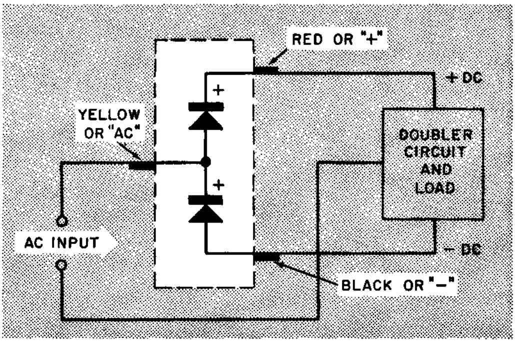


Fig. 3-11. Polarity identification of double-stack rectifier.

To summarize: the positive terminal of the rectifier will be colored red or stamped "+"; the negative terminal will be colored black or stamped "—"; and the a-c input terminals will be colored yellow or stamped "AC".

The coding system used for metallic rectifiers provides an easy and convenient description of their electrical and physical characteristics. The industry has yet to establish a single system, although a set of standards has been prepared by NEMA (See Appendix, Table I). Each manufacturer uses a special coding and provides a complete rundown of his unit. Facts such as cell size, number of series cells, number of parallel cells, circuits for which the unit is best suited, inverse voltage ratings, type of semiconductor used, spacing between cells, types of finish, etc are given in these stack codes. Individual manufacturers should be contacted for this information.

Electrical Characteristics

Operating characteristics (current, voltage and temperature) of a metallic rectifier are listed in tabular form or are plotted on graphs. These characteristics are interdependent and each one affects the life of the rectifier. When the rectifier is operated within its limits, its full life expectancy will be realized.

Ratings are usually based on continuous operation into resistive or inductive loads under convection cooling at ambient temperatures of 35° C. Rectifiers for television, a-m and f-m receivers are usually rated in terms of voltage and current. If a rectifier stack is rated at 117 v 350 ma it can deliver a maximum of 350 ma when 117 volts are applied to it. The type of filter employed after the rectification stage is also an important design consideration. For a capacitive load, the maximum current ratings may be reduced by as much as 80% of the standard rated value. This reduction is necessary to hold the heat-rise of the rectifier within safe limits. Peak inverse voltage must also be considered, for with capacitive loading this value is doubled. These are some of the more important factors that must be taken into consideration (they are discussed in detail below)

Types of Loads

Since the majority of rectifier applications work into resistive loads, ratings are based on pure resistive loads. Choosing the proper rectifier to operate into a resistive load is a straightforward process, easily followed once the load requirements have been ascertained. Inductive loads are generally treated as resistive loads. However, the magnetic field around an inductive element collapses with current reversal or interruption, producing a counter-emf which may be greater than the applied voltage. The rectifier must be capable of withstanding these peak voltages present with inductive loads.

When a rectifier is used with a capacitive load, its ratings are different from those given in the reference tables and charts, which are tabulated for resistive and inductive loads. Derating is required because of the different wave shapes that are applied to the rectifier.

While the rectifier is conducting, energy is stored in the capacitor; when the rectifier is not conducting part of the energy is discharged through the filter to the load. The capacitor increases the average voltage across the load. The waveform of the capacitor voltage is shown in Fig. 3-12 and may be considered in two parts: the portion during the charging period, A to B, C to D, and the portion during the discharging period, B to C, D to E. If the capacitor were made to discharge through a resistor, the discharge portion of the curve would decrease exponentially.

When the anode (arrow) of the rectifier is positive, the capacitor charges to the peak voltage (A to B). Theoretically, the capacitor charges to the peak value of the wave. The magnitude of this voltage is $E_C = 1.41 (E_L - E_P)$; where E_L is the rms line voltage and E_P the rms voltage drop across the resistor and rectifier.

Actually, there are small leakage losses in all capacitors and this, with any small drain through the load, causes the capacitor to be charged to a potential slightly less than the peak voltage (approximately 160 volts). During the alternate half cycle, the rectifier has

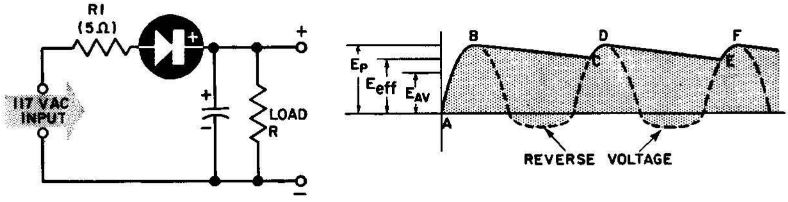


Fig. 3-12. Schematic diagram and wave shapes of a half-wave circuit with capacitor-input filter.

to block the full peak line voltage of 165 volts, ($E_P = E_L \times 1.414$; where E_P is the peak and E_L is the line voltage). The capacitor, meanwhile, discharges through the load (R). When the negative a-c cycle is at its peak these two voltages are added to each other. The rectifier must be able to withstand this peak voltage applied to it in the reverse direction. This voltage is equal to the peak input voltage plus the remaining charge on the capacitor. (Some of the charge on the capacitor will have been dissipated across the load.) Actual measurements show this voltage to be around 290 volts. The standard radio, TV, and combination stacks are rated at a maximum peak-inverse voltage of 380 volts and consequently will block this voltage. Most design engineers, however, assume full peak load (330 volts) in their calculations (165 volts peak from power source plus

165 peak from capacitor). This insures long rectifier life and compensates for surge voltages that are encountered during initial power application.

The magnitude of the increase in average (d-c) voltage with a capacitive load over that with a pure resistive load depends on several factors. For a given amount of capacitance, the output voltage decreases with an increase in load current. Therefore, as the load current increases, the size of the capacitor must be increased to obtain the same output voltage. Figure 3-13 shows regulation curves for a typical selenium rectifier with three values of capacitance, when 117 volts is applied to the stack. (See Fig. 3-12). At 150 ma, a voltage of 138 volts dc is obtained with a 100 mf input filter. If the load current is increased to 200 ma dc, the output voltage drops to 133 volts. In order for the voltage to remain at its original value, the size of the capacitor must be increased to 350 mf. Figure 3-14 shows the voltage regulation curves for the same stack when two rectifiers are connected as a half-wave voltage doubler. Figure 3-15 shows the voltage regulation curves for the same rectifier when operated as a full-wave, voltage-doubler circuit.

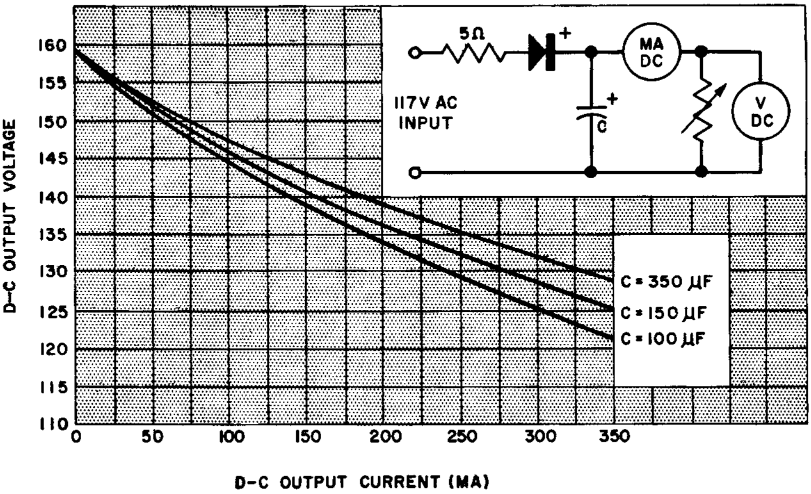


Fig. 3-13. Voltage-regulation curves for the Federal Telephone and Radio 1023 rectifier in a half-wave rectifier circuit.

For a given capacitance value, the voltage boost obtained through the use of a capacitor-input filter decreases with any decrease in applied a-c voltage. Consequently, if the applied voltage should decrease, the size of the capacitor must be increased to compensate for the decrease in the d-c output voltage. By utilizing larger capacitors, better regulation with higher voltage outputs can be obtained.

To increase the life of all components, most manufacturers recommend that a limiting resistor, many of which can also serve as a fuse in case of a short circuit, be inserted in series with the rectifier. When power is first applied and the capacitor is initially charged, there is a high instantaneous current passing through it. This current is called a charging, initial transient, or surge current. Under normal conditions a rectifier can withstand such current without damage. However, if the rectifier is repeatedly subjected to the charging current, or if the a-c power is applied at the positive peak of the a-c wave, it becomes necessary to limit the current. A protective resistor, inserted in series with the rectifier, prevents a breakdown by limiting the heating value of the large rms current applied to the rectifier circuit. Current flowing through the surge-limiting resistor minimizes the large initial surge currents prevalent in half-wave circuits. The current flowing through R_1 (Fig. 3-12) causes a voltage drop which is greater when the surge current is at its peak and assumes a steady value when, after a few cycles, the capacitor becomes fully charged. Consequently, the presence of the resistor decreases the high voltage that would normally be applied to the

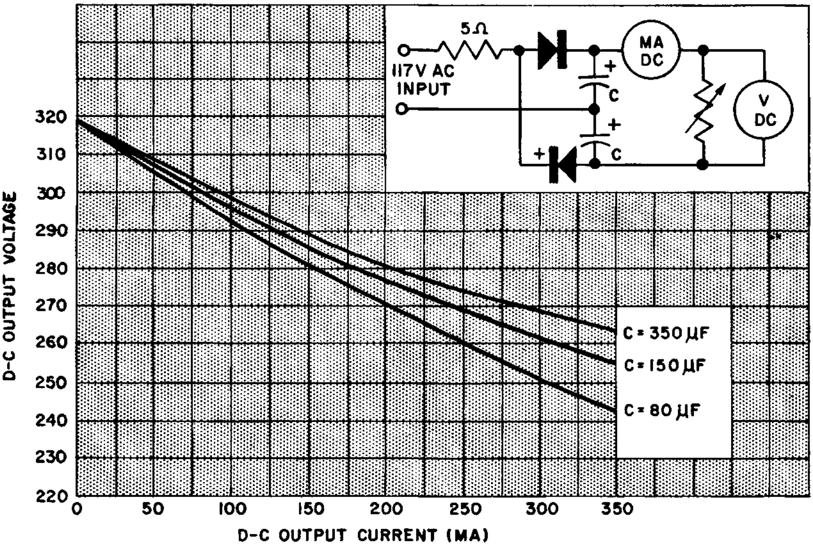


Fig. 3-14. Voltage-regulation curves for the Federal Telephone and Radio 1023 rectifier in a half-wave voltage-doubler circuit.

rectifier, lessening the possibility of destroying or damaging it during initial surges or transient peaks. The resistor also acts as a fuse in the circuit, protecting the relatively expensive components in the event of a short circuit across the load. Manufacturers place practical minimum limits on the size of these resistors. The recommended size is included in their electrical characteristics charts.

Ratings of Metallic Rectifiers

Metallic rectifiers are generally rated according to the following:

Rated rms-input voltage: the voltage at which the rectifier is designed to operate. Operating the cell at this voltage will give optimum results.

Maximum rms-input voltage: the limit that should be applied to the rectifier. Operation beyond this value would cause excessive reverse current and overheating of the rectifier.

Maximum peak-inverse voltage: the maximum value of voltage that the rectifier can safely withstand. For transient conditions this value may be exceeded for short periods.

Maximum peak current: is that which may be passed through the stack without rupturing the individual cells.

Maximum rms current: the limit of current that can be obtained before the temperature rise exceeds a safe operating limit. Exceeding this value and allowing an excessive amount of heat to develop invites rectifier failure due to premature aging.

Maximum d-c output: the maximum safe value of direct current that the rectifier will deliver without an excessive temperature rise.

These ratings are not fixed values but vary with the type of rectifier and the loads with which the rectifiers operate.

Also included in the rating charts are:

D-c rectifier voltage drop: the voltage drop of the stack in the forward direction. This is also the normal voltage drop of a typical radio- or television-type selenium rectifier.

Minimum series resistance: the recommended minimum value of the series resistance which limits the initial surge current. This value is chosen for a capacitive-type input filter. The series resistance acts as a fuse in the event of excessive current drain and limits transient peaks during each cycle.

Maximum cell-operating temperature: the maximum temperature of the surrounding air at which the rectifier should be operated. Rectifier stacks subject to temperatures above their maximum rated value (without adequate means of dissipating the heat) may be damaged or prematurely aged. Temperature ratings for selenium stacks are nominally 50 to 85° C. The output ratings for selenium rectifier cells are generally based on operation at an ambient temperature of 35° C.

Frequency response (interelectrode capacitance)

Diffused-type metallic rectifiers have an inherent capacitance which limits their operating range to the lower frequencies. The counter-electrode may be considered as one plate of a capacitor and the mounting plate as the other — the barrier layer acts as the dielectric. Capacitance varies inversely with the voltage applied, and directly with frequency. Increasing the applied voltage decreases the capacitance, and vice versa. For frequencies between 20 and 2000 cycles there is very little change in the forward characteristics and the efficiency of the rectifiers. As the frequency is increased above 2000 cycles, however, the leakage current increases appreciably and the interelectrode capacitance of the cell becomes an important consideration. Consequently, to maintain the leakage current within the rated values, the cell must be operated below its allowable maximum frequency. Forward current and forward impedance are not affected by changes in the frequency of the applied emf. Manufacturing methods, the size of barrier layers, and other factors affect

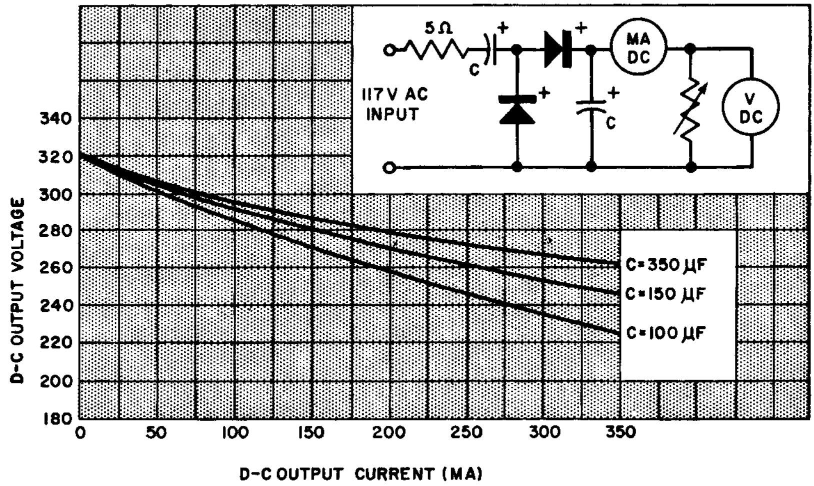


Fig. 3-15. Voltage-regulation curves for the Federal Telephone and Radio 1023 rectifier in a full-wave voltage-doubler circuit.

cell characteristics. A nominal capacitance from .01 to 2 mf per square inch of rectifying area can be expected.

Voltage regulation

The nonlinear characteristics, with respect to applied voltage and its negative temperature coefficient, increase the effectiveness of the rectifier in a d-c power supply. When a rectifier is kept within its rated characteristics the forward resistance remains constant. If the load current is increased, however, the heat applied to the rectifier rises, decreasing the internal forward resistance. This decrease in resistance partially offsets the voltage lost by the increased current passing through the rectifier. When the load current decreases, the temperature of the rectifier also decreases, increasing the resistance of the rectifier. Thus, the voltage developed across the rectifier remains relatively constant during small changes in current loads.

Table 3-I gives the electrical characteristics of a typical selenium rectifier (Federal Telephone and Radio Co. Model 1023). The characteristics listed are typical in that most other selenium rectifiers will have values very close to those given.

TABLE 3-I

Electrical Characteristics of a Selenium Rectifier

(350 ma 117 volts)

Rated rms voltage	117 volts
Maximum rms-input voltage	130 volts
Maximum peak-inverse voltage	380 volts
Maximum peak current	3500 ma
Maximum rms current	945 ma
Maximum d-c current output	350 ma
Approximate rectifier d-c voltage drop	7 volts
Minimum series resistance	5 ohms
Maximum cell-operating temperature	85°C

4. crystal diode structures and characteristics

Like metallic rectifiers, the functioning of crystal diodes is dictated by the inherent characteristics of the materials of which they are made. The principles of operation discussed below apply to all crystal diodes. The *junction* type will be considered first because its action is more easily explained than that of the *point-contact* type.

Atomic Structure

Crystal diodes are so named because the germanium, silicon or other substance used in them appears in crystal form. It is easy to

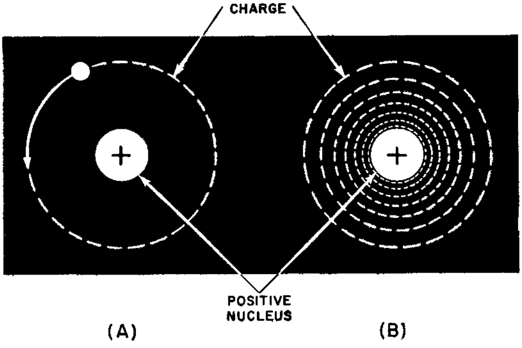


Fig. 4-1. Two conceptions of the hydrogen atom.

understand how these materials can become crystalline when we relate the process to a similar one involving the simple hydrogen atom.

Each hydrogen atom consists of one proton in its nucleus and one orbital electron. Two conceptions of this structure are shown in Fig. 4-1. In (A) the proton and electron are considered as point electric charges, with the proton stationary and the electron whirling about it in a circular path. In (B) the electron is considered as a distributed charge existing in a diffused sphere around the proton. The overall atomic charge is zero, since the negative charge of the electron is neutralized by the positive charge of the proton. When two atoms are brought near to each other, the negative charge patterns overlap as shown in Fig. 4-2. The heavier negative-charge density between the two protons causes each nucleus to be attracted toward the other. This attraction tends to bind the two atoms together, forming a hydrogen molecule. Such binding is accomplished by an *electron-pair bond,* the important cohesive property that holds elements of a material together. When more than two atoms are involved, a regular pattern that becomes characteristic of the substance is created.

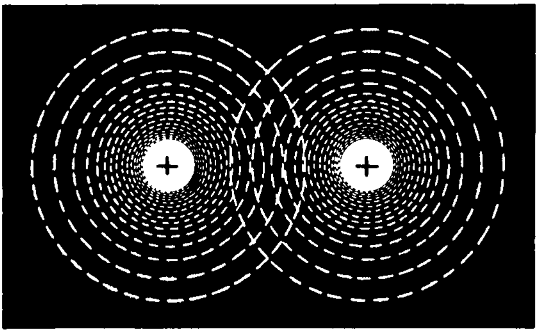


Fig. 4-2. Representation of an electron-pair bond.

Crystal Structure

Certain elements, such as carbon, silicon, and germanium, have one feature in common: they each form crystalline molecules by the electron-pair bonds of four of their outermost electrons. This similarity is probably because the electrons in the molecules arrange themselves in shells about the nucleus and the outermost shells of these elements contain only four electrons. The remaining electrons of these atoms are arranged in the inner shells and are not involved in molecular structure or chemical action. When electron-pair bonds are formed by the four outermost electrons of germanium, each atom attaches itself to four other atoms. The interattachment of the atoms in the material forms a pattern called a crystal lattice, represented two-dimensionally in Fig. 4-3.

Part (A) of Fig. 4-4 is a view of the bonding between germanium atoms and shows the atoms arranged in a diamond pattern. The bonding could be illustrated by use of the electron cloud shown in Fig. 4-2, but it is easier to show it with minus signs for the four electron-pair bonds. The plus signs represent the nucleus plus all but the four outermost electrons. A crystal formed as shown in Fig. 4-4 (A) is not a good conductor because all the outer electrons are

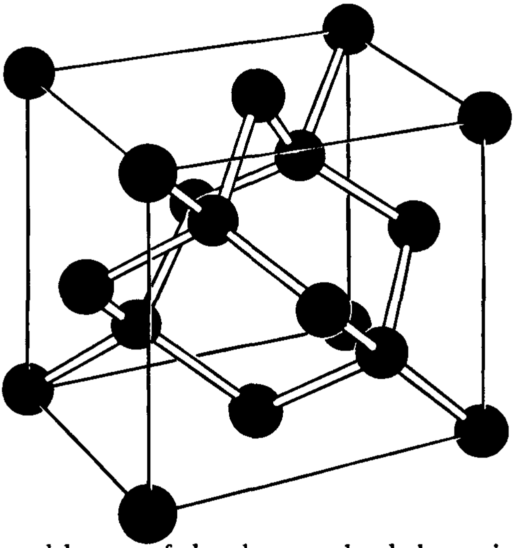


Fig. 4-3. Crystal of germanium showing the lattice pattern.

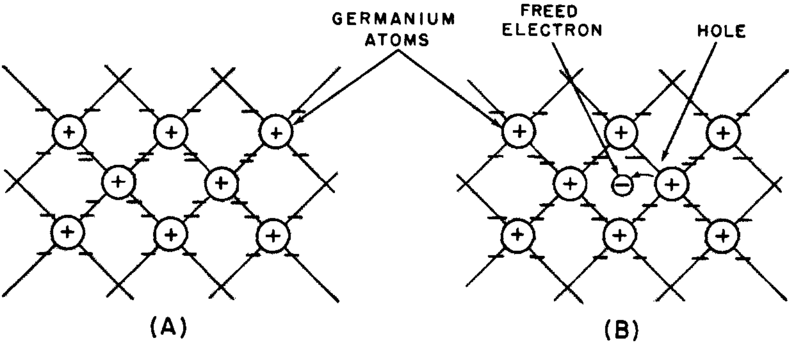


Fig. 4-4. Two-dimensional views of crystal lattice. (A) A crystal of poor conductivity. (B) A free electron and a hole.

tightly bound to their atoms and the lattice. As a result, none are free for the conduction of electric current.

Current Flow — Electrons and Holes

The crystal material shown in Fig. 4-4A acts as a conductor when a force sufficient to break the bonds between the atoms is applied, freeing electrons. Some of the external forces that can do this are heat, voltage, and radioactivity. If a bond is broken, the freed electron will roam around the lattice without being attracted or disturbed because all the other atoms have their full complement of electrons and are electrically neutral.

When the freed electron was dislodged, the parent atom acquired a positive charge because it then had fewer electrons than protons. The overall positive charge of an atom is concentrated at the empty bonding position, called a *hole.* The freed electron and hole are shown in Fig. 4-4B. If the situation pictured here remains unchanged, the freed electron will eventually be attracted back into the hole, because of the attraction between positive and negative charges. If, however, a voltage is applied across the material, any freed electrons will be attracted toward the positive terminal. The applied voltage will also strain the bonds between other atoms, breaking some of them. This provides more free electrons and holes for the conduction of current. The strain on the electron-pair bond is further increased by the local attraction of holes, since each hole is a local positive charge which attracts nearby electrons. When the applied voltage and the local attraction are enough to break a neighboring bond and release an electron, the freed electron flows into the attracting hole, but in so doing creates a hole in the atom it just left. This process is repeated over and over again in definite pattern. The atom with the hole moves in the direction shown in Fig. 4-5. The holes are always filled by an electron from a nearby electron-pair bond.

Because the applied voltage is pushing electrons away from the negative terminal toward the positive terminal, the electrons move in steps from one hole to the next, until they arrive at the positive terminal. Every time an electron moves, a hole is moved, because one cannot exist without the other. The movement of holes and electrons is in opposite directions; the holes are attracted toward the negative terminal, the electrons are attracted to the positive terminal. The movement of holes through the material is equivalent to an electric current of positive charges. When the hole arrives at the negative terminal of the applied voltage, it is neutralized (filled) by an electron flowing from the terminal. This process accounts for the flow of current through the semiconductor material. Current

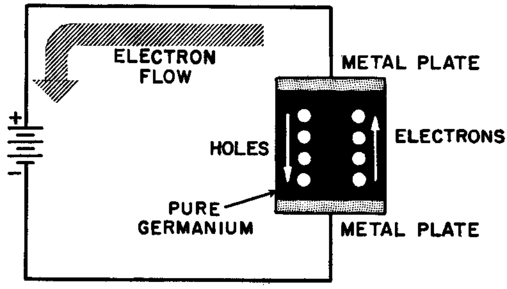


Fig. 4-5. Diagram of the flow of electrons and holes.

flow in a perfect semiconductor crystal depends primarily upon the force exerted by the applied voltage in breaking the bonds between atoms, producing current carriers. Certain impure semiconductors have imperfect crystal structures which make current carriers more readily available.

Semiconductor Impurities

The balance between free electrons and holes is upset when a controlled quantity of impurities is added to the semiconductor material. Impurities can be chosen to add either extra electrons or extra holes to those normally present in the crystal of a pure semiconductor. This is a desirable feature because it increases the number of available current carriers, and it enables the semiconductor to make and break bonds more easily when small voltages are applied.

Not all impurities produce the desired effects in the semiconductor. The only impurities needed are those whose outer electron shell contains either three or five electrons. If arsenic is added to silicon in small quantities, atoms of arsenic replace some of the atoms of silicon in the crystal lattice, as shown in Fig. 4-6A. Arsenic has five electrons in its outer shell, and four of these five electrons form electron-pair bonds with atoms of silicon. The fifth arsenic electron is left free to participate in the flow of current. Therefore the arsenic atom is called a *donor*. Since the free charge is negative, the crystal is called an *N-type* semiconductor. Other donor substances include phosphorous and antimony.

If boron is used as the impurity, a different situation results. The boron atom has only three electrons in its outer shell. When a boron atom replaces a silicon atom in the crystal lattice, only three electron-pair bonds will be formed. This leaves one vacant hole for each boron atom, which makes boron an *acceptor*. The effect is the same as if an electron were removed from the lattice. Since the crystal is left with a free positive charge it is called a *P-type* semiconductor. Aluminum and gallium are also acceptor impurities. Figure 4-6B shows the crystal lattice arrangement with a boron acceptor impurity.

Although the addition of impurities results in the existance of either free electrons or holes, the overall charge of either N- or P-type material is zero. For example, N-type germanium has many electrons which move freely when a voltage is applied because a donor impurity has been added. These free electrons, however, belong to neutral atoms of the donor material, and are only "extra" as far as the crystal lattice is concerned. There is still a proton for every electron in the semiconductor, making the overall charge of the material zero. Since the impurity atoms do not fit precisely into the lattice, freely moving holes or electrons exist.

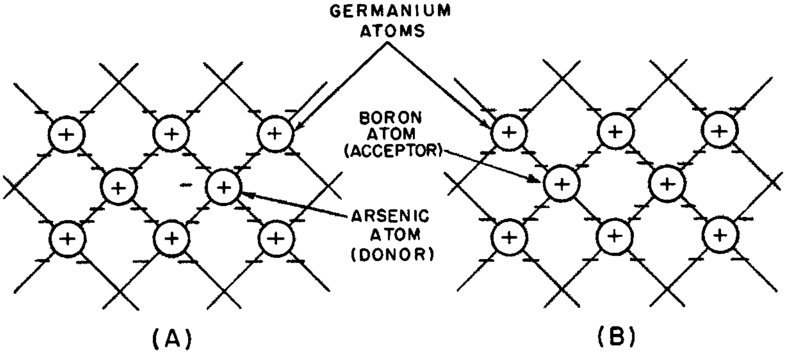


Fig. 4-6. N- and P-type silicon. (A) N-type, with an arsenic donor. (B) P-type, with a boron acceptor.

As explained earlier, when current flows in pure semiconductors there is a constant making and breaking of electron-pair bonds. This is also true of N- and P-type semiconductors. Electrons traverse the material by filling holes in the direction of the positive electrode. The holes, meanwhile, flow in the opposite direction because each time an electron vacates a bond to fill a hole a new hole is created in the direction of the negative electrode. Conduction of current in semiconductors by the hole-and-electron process is the basis of crystal diode rectification.

Rectification with Junction Diodes

When N-type and P-type semiconductors are brought into contact, the junction of the two behaves as a rectifier. Figure 4-7A shows the simple construction of this type of diode. The two metal plates create a low-resistance connection to the semiconductors by virtue of their large areas. At the junction there is a natural attraction and flow of free charges from one semiconductor to the other. Free electrons on and near the surface of the N-type material are attracted to and fill in the holes at and near the surface of the P-type material. Each combination of an electron and a hole in this region neutralizes some of the attraction between the two faces of the junction. Eventually, the junction between the two materials becomes devoid of free electrons and holes, and since there are no free charges in it the region behaves as an insulator. The charges that go into the combining action at the junction cause a change within the semiconductors. Each of these semiconductors is now missing some of its mobile charges. Free electrons drift from the N-type material into the barrier or junction region as shown in Fig. 4-7B. This creates an imbalance of charges in the N-type material, making it positive with respect to the junction. In the same manner, the P-type material becomes negative with respect to the junction because of the loss of holes to the barrier region. The barrier at the junction acts as a neutral region which shields the N-type material from the P-type material. A stalemate is established as far as current flow is concerned.

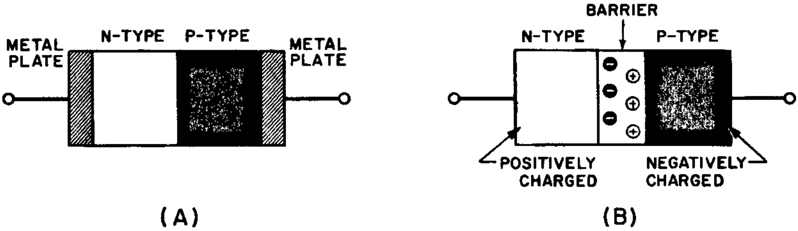


Fig. 4-7. Junction diode. (A) Simple construction. (B) How free electrons drift from N-type material into junction region.

In order to have current flow, electrons from the N-type material must pass through the barrier into P-type material, through the external circuit, then back into the N-type material. Simultaneously, holes must travel from the P-type material, through the barrier, and into the N-type material. This condition is possible when voltage of the proper polarity is applied. Figure 4-8 shows the condition of (A) no voltage, (B) forward voltage, and (C) reverse voltage for a P-N junction diode. With no voltage applied, the insulating barrier at the junction prevents current flow. In (B) the polarity of applied voltage helps the current overcome the barrier and flow

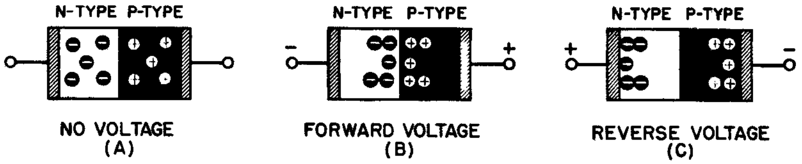


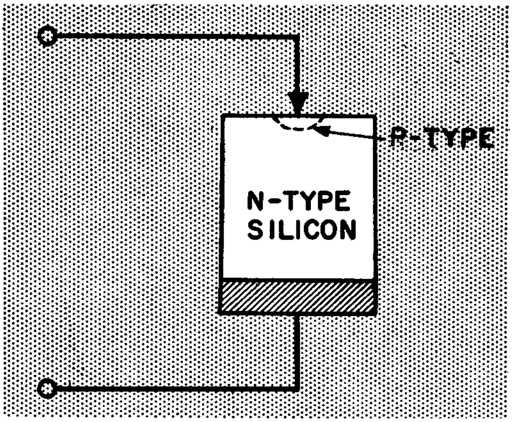
Fig. 4-8. Current flow in the junction diode.

through the semiconductors. Polarity causes free charges to move into the barrier region, increasing conductivity. Free electrons move through the barrier into the P-type material and are collected by the positive electrode of the battery. The holes move through the barrier into the N-type material to be neutralized by the negative electrode. In (C) the applied potential is opposite that shown in (B). The effect is to aid the barrier region in suppressing current flow. Electrons in the N-type material and holes in the P-type material are pulled away from the barrier, creating an even greater depth of mobile charges. The barrier region becomes a better insulator and the crystal as a whole becomes a poor conductor. This assymmetrical characteristic explains how the junction diode acts as a rectifier, and also applies to the point-contact diode discussed below.

Rectification with Point-Contact Diodes

When a sharp metallic point is brought into contact with a semiconductor, their is created a junction which is able to pass current more easily in one direction than in the other. Although a point-contact diode is manufactured with only a single type of semiconductor material, a P-N barrier forms under the metallic point. Figure 4-9 shows the location of the barrier in an N-type silicon-crystal diode. The P-type region forms because the donor electrons adjacent to the metallic whisker wander away into the highly conductive metal more freely than do other electrons elsewhere in the semiconductive material. In N-type material, electrons are essential to the conduction of current, and when the electrons vacate the material, it acts as a barrier. The barrier is reduced when electrons are forced into the region. The polarity of applied voltage proper for urging electrons into the barrier is one which makes the base connection negative and the point contact positive. When this is the case, electrons flow from the semiconductor to the point contact (the forward direction of current). When the polarity is reversed, electrons in the P-material flow away from the barrier and preserve it as an opposition to current flow. The action is similar for P-type diodes

Fig. 4-9. Point-contact diode, showing location of barrier.



except that the forward conducting polarity is the opposite — the point contact is negative and the base is positive. The resemblance is clear if one considers the flow of holes instead of electrons.

Current and Voltage Relationships

Static characteristics. The basic feature of the vacuum-tube diode is that it is able to pass current in one direction but not in the other. The functions of the cathode and plate elements are duplicated within the crystal diode (by the semiconductor) as described above. The forward current characteristic of the crystal device is

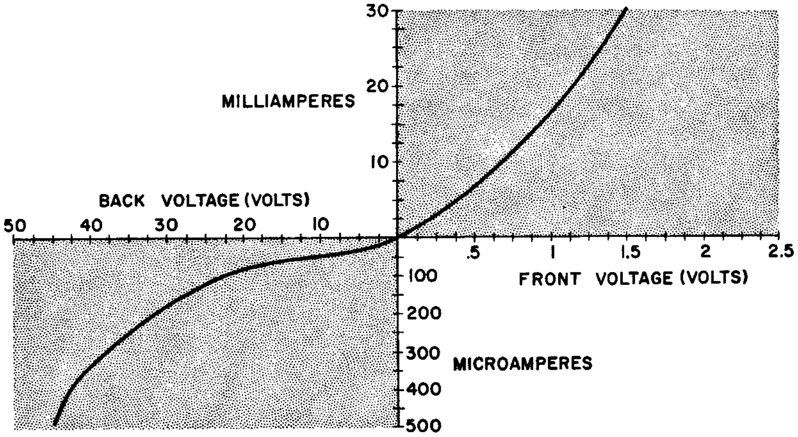


Fig. 4-10. Crystal-diode characteristic curve.

superior to the equivalent diode vacuum-tube characteristic because less voltage is required to cause any given current. In addition, the crystal diode has the important advantage of small size, and it requires no heater. Unlike the vacuum tube, however, the crystal diode will permit a small current flow in the reverse direction, even for small reverse voltages. Figure 4-10 is a typical graph of crystal-diode current for both forward and reverse voltage. Note that the reverse current scale is calibrated in mocroamperes. When the applied voltage is 1 volt in the forward direction, the current is 15 ma. But the same voltage applied in the reverse direction results in current too small to be measured. Sometimes, the forward and back resistances are of interest. For the crystal under discussion, these resistances may be found as follows:

$$R_{\text{forward}} = \frac{E_{\text{forward}}}{I_{\text{forward}}} = \frac{1\text{ volt}}{15\text{ ma}} = 67\text{ ohms}$$

$$R_{\text{back}} = \frac{E_{\text{reverse}}}{I_{\text{reverse}}} = \frac{1\text{ volt}}{\text{less than }10\ \mu\text{a}} = \text{more than }100{,}000\text{ ohms}$$

As in the case of metallic-oxide rectifiers, the comparison of forward resistance to reverse resistance is a measure of the quality of rectification. The ratio of the two is called the *front-to-back ratio.*

Maximum peak inverse voltage. The crystal diode is similar to a vacuum tube in that it breaks down if too much reverse voltage is applied. In the vacuum-tube diode, the breakdown occurs when the reverse voltage is sufficient to arc over the gap between the plate and cathode. In the crystal diode, the breakdown occurs when the insulation of the barrier region is punctured by the high voltage. This breakdown voltage is often called the piv, voltage-for-zero resistance, or Zener voltage. The static characteristic of the diode is modified in Fig. 4-11 to show the piv voltage and the resulting current. In effect, when the back voltage across the diode reaches the piv value, the diode becomes a good conductor. When conducting under these conditions the diode is not necessarily damaged because the barrier region reconstitutes itself, when the excessive reverse voltage is removed. Values of the piv voltage for low-power diodes start with about −5 volts and go to high values in rectifiers designed for higher power applications.

High-Frequency Characteristics

At frequencies of several thousand megacycles, the rectifying properties of ordinary crystal diodes decrease. The diode operational analysis given in the previous paragraphs must be supplemented in order to explain this high-frequency characteristic. Figure 4-12 shows a resistance in series and a capacitor in parallel with the barrier region of the rectifier. These elements are actually part of the internal features of the crystal diode. For example, in the junction diode, the capacitance C is formed by the two semiconductors separated by the insulationg barrier. (The barrier region is the place where rectification actually takes place.) Resistance R represents the resistance of the semiconductor material and of the contacts between elements within the crystal, exclusive of the barrier. Neither R nor C produces desirable effects in the operation of the crystal.

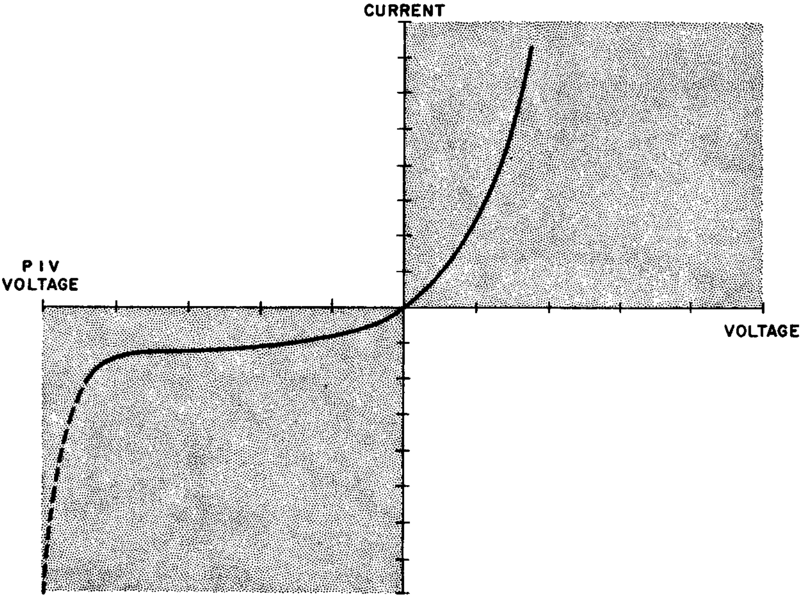


Fig. 4-11. Graph illustrating a static curve with piv voltage.

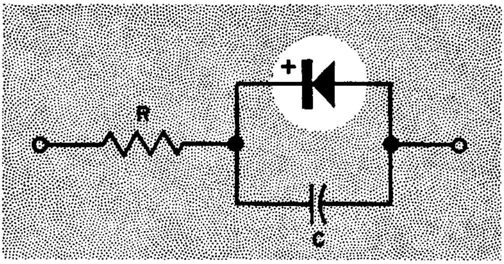


Fig. 4-12. High-frequency equivalent circuit of a crystal diode.

R dissipates signal power that would otherwise appear in the diode output circuit; it also isolates C by preventing a direct shunt across it.

If direct connection could be made, the effects of C could be neutralized by resonating it with an external inductance. The capacitance C is harmful because it shunts the rectifying part of the diode. When forward potential is applied and the diode is conducting, the barrier region is nearly a short circuit and capacitor C has little effect. With reverse polarity, however, when the diode is not supposed to pass current, the capacitor bypasses the signal current around the barrier. In effect, C reduces the front-to-back ratio of the crystal, thus reducing the quality of rectification. The values of R and C can be controlled to some extent by preselecting point sizes in the case of point-contact diodes and by controlling the barrier layer thickness of junction diodes.

Power Rectifiers

It is not unusual to think of crystal rectifiers as low-power devices. The early cat's-whisker type, and even the modern point-contact type,are susceptible to burnout at high-power levels. This poor power-handling capacity is due to the small area of contact between the needle point and the semiconductor. Even though the average crystal current is low, the passage of all of this current through a small area (such as the tip of the point) results in a very large currents-per-unit area at the point of contact. The development of the junction diode, however, opens a new field for the uses of crystal diodes.

Since the junction forms a large barrier region, the current no longer has to funnel through a bottleneck. This enables the junction diode to perform the functions of the vacuum-tube power-supply rectifier. The crystal power diode surpasses the vacuum-tube diode in almost every rectifier quality. It is nearly 100% efficient compared with about 70% for vacuum-tube rectifiers. The power consumed or dissipated by the crystal is nearly zero. As a result, very small units may be made since almost no heat has to be radiated. Compared with the conventional vacuum-tube rectifier,the crystal rectifier has the following advantages:

1. No heater voltage required.
2. Much smaller size.
3. Much higher efficiency.
4. Longer life.
5. Shockproof.

Polarity Markings

The schematic symbol for the crystal diode is the same as that for the metallic rectifier. Sometimes this symbol is stamped on the diode to indicate which terminal is the cathode and which terminal is the anode. Aside from identifying the internal elements, some method of indicating the diode number is also necessary. This corresponds to marking the individual tube-type numbers on vacuum tubes. With crystal diodes, however, the numerals of the diode number are sometimes indicated with the RETMA color code instead of being stamped or lettered on the diode case. Reading the two or three bands of colors from left to right indicates the figures following the standard "1N" prefix. Thus, a brown-red-green branding indicates a 1N125-type crystal. (The polarity markings and color code are shown in Fig. 4-13.) The various marking schemes are consistent in that the marking is always done at the cathode terminal. Markings take the form of color bands, color dots, or variously shaped notches. In the case of cartridge-type crystals, the cathode is always the smaller of the two contacts. Figure 4-13 does not show special-purpose diodes. These are usually multicrystal units sealed within special containers. For diodes of rms type, it is necessary to consult the manufacturer's literature for information on anode and cathode connections.

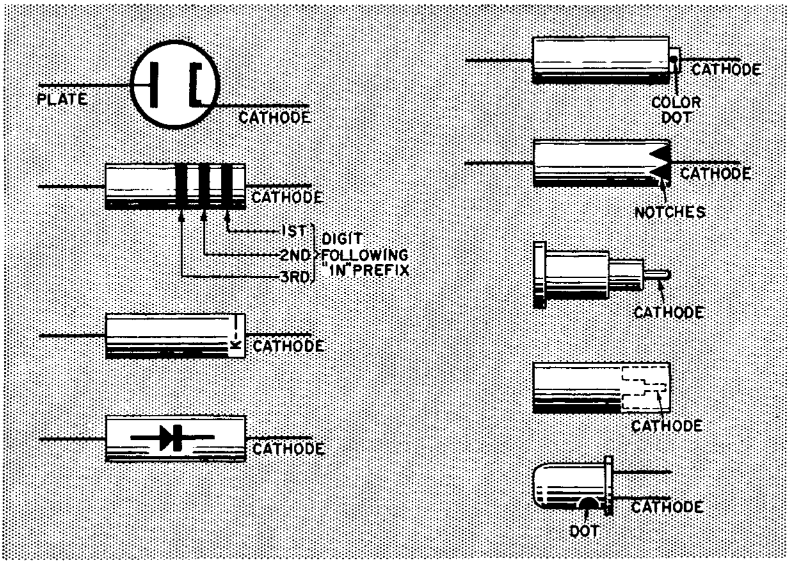


Fig. 4-13. Polarity markings of crystal diodes.

5. basic design data

The many excellent electrical and mechanical characteristics of metallic rectifiers have rendered them useful in numerous electronic applications. The continuing advances in metallic-rectifier design and research will eventually extend these applications far beyond those envisioned today. In the paragraphs that follow, basic design data and various types of rectifier applications will be discussed to show how metallic rectifiers are fitting into the design of modern electronic equipment.

Most of the circuits built around metallic rectifiers utilize the rectifier properties discussed in Chap. 1. The major advantage of metallic rectifiers is that they produce *higher voltage supplies* at less cost than do equivalent devices. Prior to the advent of these rectifier units, the conversion of alternating current to direct current was handled entirely by vacuum-tube and motor generators. Power supplies, especially those that had to deliver either high current or high voltage, were large, cumbersome, and inefficient (due to power consumed by the filaments).

Basic Circuit-Design Data

The design of power-supply circuits employing metallic or crystal rectifiers is much the same as that for vacuum tubes. Such designs are based on the type of load, duty cycle, ambient temperature, and the circuit in which the rectifier is to operate.

Cell stacking. The rectifier cells may be connected in series, parallel, or series-parallel, providing devices that are adaptable for many applications. Chapter 2 gave complete details on cell stacking to obtain desired voltages and currents.

The six basic circuits. A vast majority of rectifier-circuit designs employ one of six basic circuit configurations. These six basic rectifier circuits are conveniently classified according to the phase of the input power – single phase or polyphase – and the circuit in which the basic unit is employed. The basic circuit configurations, their output waveshapes and related formula and constants are given in Table 5-I. The values given in the table will, of course, vary somewhat with different circuits and load conditions and should be verified by empirical test data. The table is, however, accurate enough for comparative and design purposes. The data in Table 5-I is based on ambient operating temperatures within those rated for the rectifier with convection cooling. Special considerations are required at extreme temperature or overload applications (see Chap. 2).

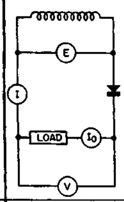
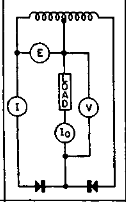
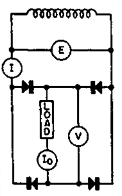
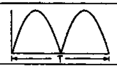
A-c input voltage. In designing a circuit the a-c input voltage is determined by the requirements of the circuit (type of load), the circuit configuration, and the voltage dropped by the rectifier. The fundamental design formula for four of the six circuits is given as follows:

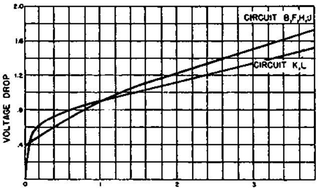
$$\text{Input } E = KV + ND$$

This formula applies to the four basic circuits shown in Table 5-I having the circuit code of H, B, J, and L. It is an application of Kirchhoffs law, which states that the input alternating voltage (E) is equal to the voltage developed across the load [desired voltage V times the circuit form factor (K)], plus the voltage developed across the rectifier [number of cells (N) in series in each arm of the circuit multiplied by the voltage drop (D) per cell, at (K)

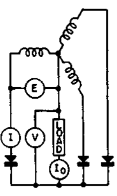
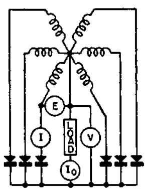
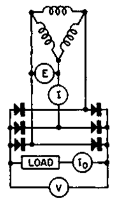
TABLE 5-1

GENERAL DESIGN INFORMATION

SCHEMATIC				
CIRCUIT		1 ∅ HALF WAVE	1 ∅ CENTER TAP	1 ∅ BRIDGE
CIRCUIT CODE		H	B	F
OUTPUT VOLTAGE WAVE SHAPE				
% RIPPLE		121	48	48
INPUT E*		KV + ND	KV + ND	KV + 2ND
FORM FACTOR (K)		2.3	1.15	1.15
*APPROX. RATIO OF AC/DC	R,L	2.47	1.30	1.30
	C	2.15	1.0	.67
PEAK INVERSE VOLTAGE	R,L	1.41E	2.83E	1.41E
	C	2.83E	2.83E	1.41E
I_0		1	1	1
I		1.57	.785	1.11
$I_{AVG/LEG}$		1	.5	.5



FORWARD VOLTAGE DROP PER CELL

SCHEMATIC				
CIRCUIT		3 ∅ HALF WAVE	3 ∅ CENTER TAP	3 ∅ BRIDGE
CIRCUIT CODE		J	L	K
OUTPUT VOLTAGE WAVE SHAPE				
% RIPPLE		18	4	4
INPUT E*		KV + ND	KV + ND	KV + 2ND
FORM FACTOR(K)		.85	.74	.74
*APPROX. RATIO OF AC/DC	R,L	.93	.81	.81
	C	.93	.81	.81
PEAK INVERSE VOLTAGE	R,L	2.45E	2.83E	1.41E
	C	2.45E	2.83E	1.41E
I_0		1	1	1
I		.585	.408	.815
$I_{AVG/LEG}$		.333	.166	.333

ALL VALUES ARE FOR RESISTIVE (R), INDUCTIVE (L) LOADS UNLESS OTHERWISE SPECIFIED.

E = AC INPUT VOLTAGE
V = DC OUTPUT VOLTAGE
D = VOLTAGE DROP/CELL (SEE GRAPH)
K = FORM FACTOR
N = NUMBER OF SERIES CELLS/ARM
I = AC LINE CURRENT (R.M.S)
I_0 = DC OUTPUT CURRENT (AVERAGE)
T = PERIOD OF 1 CYCLE

*APPROX. VALUES FOR RATED INPUT AND OUTPUT CONDITIONS. SINCE OUTPUT VOLTAGE FOR CAPACITIVE LOADS IS DEPENDENT UPON LOAD TIME CONSTANT, THE VALUES INDICATED ARE FOR A TIME CONSTANT OF APPROX. 1 μF./MA.

values.] Input (E) as obtained by the equation, is the rms alternating voltage that must be supplied by the transformer to the rectifier stack (or stacks), filter elements, and load impedance. Note from Table 5-I that input (E) for the single-phase half-wave and bridge circuits is the full secondary voltage, whereas in the single-phase centertap circuit it is one-half the full secondary voltage. Table 5-I also shows that the single-phase bridge circuit has its secondary voltage applied across two parallel branches, each containing two rectifiers in series, thereby doubling the voltage drop (2ND).

The fundamental design formula for the other two of the basic circuits [having the circuit code of (F) and (K) in Table 5-1] is given as

$$\text{Input E} = \text{KV} + 2\text{ND}$$

This design formula is the same as that given above, except that the last part is multiplied by two.

Rectifier voltage drop. The rectifier voltage drop (D) is determined by the cell size, the output current per parallel cell, and the number of series cells. The graph below Table 5-I shows the typical forward voltage drop per cell plotted against the ratio of actual to rated current per cell. Although the graph is only approximate it is sufficiently accurate to satisfy design or comparative requirements.

Ripple component. Although the object of the rectifier unit is to convert alternating current into direct current, no rectifier accomplishes this exactly. Both single-phase and poly-phase rectifiers deliver a unidirectional current with periodic fluctuations in the output. The output voltage waveshapes for each of the six basic rectifier circuits are also shown in the Table 5-I. (The T below the waveshape designates the fundamental frequency of the input voltage). These periodic fluctuations, or *ripple factor,* as it is more commonly called, is equated:

$$\text{Ripple factor} = \frac{\text{rms value of the a-c component of the wave}}{\text{average d-c value of the wave}}$$

For a single-phase half-wave rectifier this ripple factor value is approximately 1.21 or 121%; for the single-phase center tap or bridge it is approximately .48 or 48%. Thus the rms value of the ripple voltage for the half-wave circuit is greater than the d-c potential of the output. In either case additional filtering is necessary for almost all applications.

Single-Phase Half-Wave Rectifier

The single-phase half-wave rectifier shown in Fig. 5-1 finds many applications where low current and voltage are required. The use of metallic or crystal rectifiers for this application has resulted in smaller, lighter, more compact supplies. It has become popular because it provides a small transformerless supply that can be operated directly from the a-c line. Its more common applications include radio and television boosters, test equipment, interoffice equipment, relay supplies, business machines, and telephone circuits.

The applied a-c voltage is converted by the characteristics of the rectifier into pulsating dc, which needs only to be filtered. When positive half-cycles of a-c voltage are applied to the anode, a large current flows, charging capacitor C1 to a value near the peak value of the applied voltage (1.41 times the rms line voltage). Resistor R1 is included in the circuit to hold this charging current to limits recommended by the rectifier and capacitor manufacturers. It is this voltage plus the applied voltage that the rectifier must be able to withstand during the nonconducting cycle. (See Chap. 3 for maximum inverse voltage considerations.) On the negative half-cycle no current flows, and capacitor C1 partially discharges through the load. On the next cycle, when current flows through the circuit, C1 again charges to a peak value. After a few cycles only a short pulse of current flows through the rectifier.

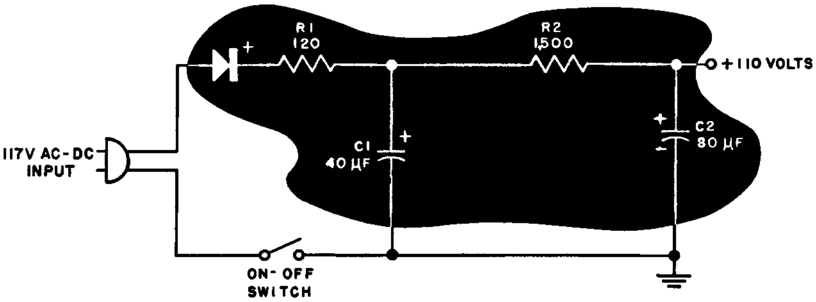


Fig. 5-1. Schematic diagram of a typical half-wave rectifier.

The charging and discharging action of input capacitor C1 produces a fluctuating waveform. Resistor R2 and capacitor C2 add further smoothing (filtering) action by resisting any sudden changes caused by the rise and fall of current pulsations. The d-c voltage obtained across C2 is more constant than that developed across C1. However, the fluctuations cause C2 to charge and discharge in a manner similar to C1.

The half-wave rectifier described is limited to applications in which the current drain is small, resulting in only a small voltage drop across the filter resistor. If larger currents are drawn, the efficiency and regulation of the circuit deteriorate rapidly. Even when operated with light loads, the efficiency, compared to full-wave and bridge circuits, is low. In order to improve the filtering action, an inductor may be substituted for resistor R2.

Single-Phase Centertap Rectifier

A typical centertap (full-wave) rectifier circuit, shown in Fig. 5-2, consists of two half-wave assemblies. The rectifiers may be individual half-wave stacks or may be assembled as one stacked assembly. Each rectifier functions on one of the alternations of the applied input voltage. A step-up transformer may be used to increase the voltage to the circuit. The secondary of the transformer that feeds the full-wave rectifier is centertapped to insure that equal but opposite voltages will be applied to each of the rectifier units. When the applied voltage is such that terminal 3 of the transformer is negative, terminal 5 will be positive and rectifier CR2 will conduct. This charges C1 to near peak voltage (the rms voltage developed across one-half of the secondary of the transformer multiplied by 1.414). This value is the same as that obtained for a half-wave rectifier.

During the alternate-cycle transformer, terminal 3 becomes positive and rectifier CR1 conducts, replacing any charge that C1 may have lost when the voltage went through zero. Conduction occurs alternately in each half of the full-wave center-tap rectifier in conformance with the charging polarity of the input voltage. The direction of the charging current through capacitor C1 and the pi-type filter consisting of C1, L1, and C2 is always the same. Filtering of a full-wave rectifier is much simpler than that of a half-wave rectifier because the ripple frequency of the output is twice that of the input frequency, and the ripple components is approximately 47% of the output voltage. (This is because there are two positive peaks for each cycle.) Resistor R1 and capacitor C3 provide additional filtering for the second output (+ 220v, dc). Regulation and efficiency are also much improved.

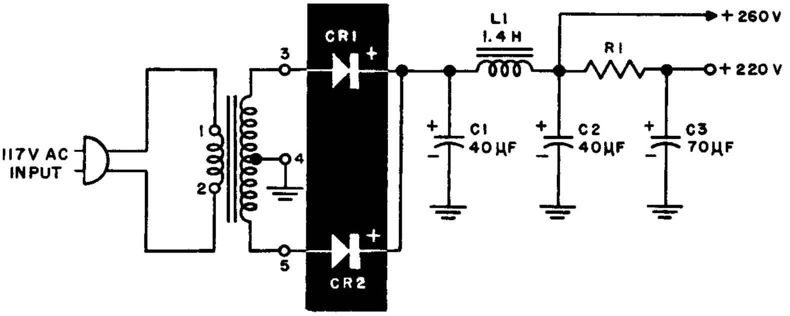


Fig. 5-2. Schematic diagram with emphasis on the full-wave rectifier circuit.

The full-wave rectifier makes use of only one-half the secondary voltage during each half cycle of input. Full-wave centertapped rectifier circuits are employed in many applications where low d-c voltages are required. In these cases, a step-down transformer rather than a step-up transformer is required.

Single-Phase (Full-Wave) Bridge Circuit

When four half-wave rectifiers are connected as in Fig. 5-3, the circuit is called a bridge circuit. The ac is applied to two diagonally opposite corners of the bridge and the resulting d-c output is taken from the two remaining corners. In this manner, full-wave rectification is obtained and the full secondary winding of the transformer is utilized. Therefore, an output equivalent to that from the full-wave rectifier is obtained from a transformer of only half the size. This amounts to a considerable saving in cost and an improvement in operating efficiency. (To obtain equivalent d-c outputs from the two circuits, the power rating of the transformer shown in Fig. 5-2 must be 1.414 times greater than that in Fig. 5-3.) Another advantage of this (full-wave) bridge circuit is that it uses the transformer more efficiently than does the centertap circuit.

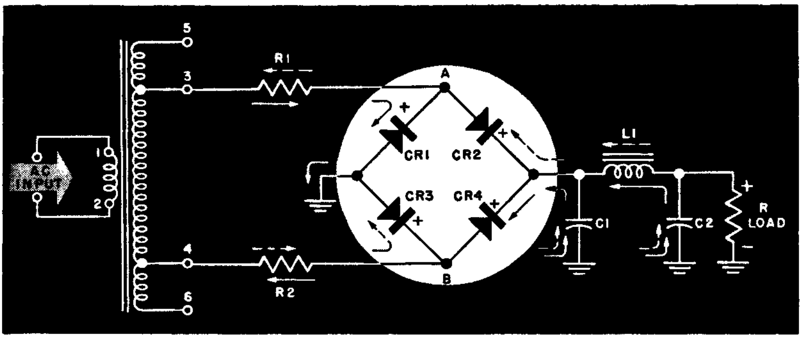


Fig. 5-3. Schematic diagram of a full-wave bridge rectifier.

Referring to Fig. 5-3, assume that the applied ac makes terminal 3 positive with respect to terminal 4. The positive voltage at 3 is applied to point (A) of the bridge, and large currents will flow through CR2. Simultaneously, the negative voltage at terminal 4 is applied to point (B), and large currents flow through CR3. Little current flows through CR1 and CR4 because the resistance of these units is relatively high compared to that of CR2 and CR3. The path of the electron flow through the rectifiers is indicated by the dashed lines. During the next half cycle the polarity across the secondary of the transformer is reversed and electron flow through the bridge takes place through CR4 and CR1, as indicated by the solid lines. Regardless of the polarity of the voltage applied to the secondary, the current charging the capacitors and the current through the load is always in the same direction. Since current flow through the load takes place during both cycles of the applied ac, full-wave rectification takes place.

The output waveform of the bridge rectifier is the same as that for centertap rectifiers, therefore, the filtering requirements are also the same. A conventional pi-type filter consisting of C1, L1, and C2 is used to filter the pulsating d-c output of the bridge. Resistors R1 and R2 limit the initial charge as they do in the half-wave power supply.

Bridge circuits with copper-oxide rectifiers are used extensively in electrical measuring equipment. With selenium rectifiers, bridge circuits are found in many low-voltage plate-supply circuits.

In order to compensate for losses in output voltage caused by increased forward resistance (aging), extra taps may be provided at the secondary of the power transformer. As the rectifiers age, the d-c output voltage of the circuit will decrease slowly. When the value has dropped below a predetermined value, moving the a-c connections of the bridge rectifier to terminals 5 and 6 of the power transformer will increase the input voltage and restore the output to its original value.

Three-Phase Circuits

Half-wave. The three-phase half-wave circuit is occasionally used. In the circuit shown as circuit code J in Table 5-I a delta-wye transformer is used to supply the input ac. Note that the ripple frequency is three times the line frequency and that the percentage of ripple component to d-c component in the output has dropped to 18%. Therefore the filtering is much simpler. The regulation and efficiency is also improved over that of the single-phase half-wave rectifier.

Centertap (full-wave). Three-phase centertap (full-wave) rectifier circuits (L in Table 5-I) are employed in many industrial applications where large d-c currents are required. Each secondary is centertapped and feeds a pair of rectifiers. The operation of each leg is identical to that of the single-phase centertap circuit described earlier. However, Table 5-I shows the frequency of the ripple component in the output is six times that of the input ac and the percentage figure is 4%.

Full-wave bridge. The basic three-phase bridge circuit is shown in K of Table 5-I. The economical design of the transformer requires a lower power rating than the three-phase centertap. This, plus the high degree of flexibility of full-wave bridge circuits, makes them extremely popular for commercial and industrial applications needing relatively high-power outputs. Since this circuit needs no centertapped transformer it can be used directly across a three-phase power line.

Voltage Multiplier Circuits

By far the most popular application of selenium rectifiers has been in transformerless voltage-doubler circuits. Voltage multipliers can obtain voltages in excess of line voltage by the use of rectifiers and filter capacitors properly designed in special circuits. This system eliminates the heaviest, bulkiest, and costliest item of the power supply – the transformer. Theoretically, there is no limit placed on the voltage that can be obtained from these multiplier circuits, but there are practical limits on the components that make up these units. Most design engineers place this limit at approximately four times peak-line voltage.

Full-Wave voltage doubler. Figure 5-4 is a schematic of a popular full-wave doubling circuit. The two capacitors, C1 and C2, are charged on alternate half-cycles and are so connected that their discharges add to make up the output. This circuit is capable of delivering almost twice the peak voltage of the applied ac. On the positive half cycle of a-c input, when point A is at a positive poten-

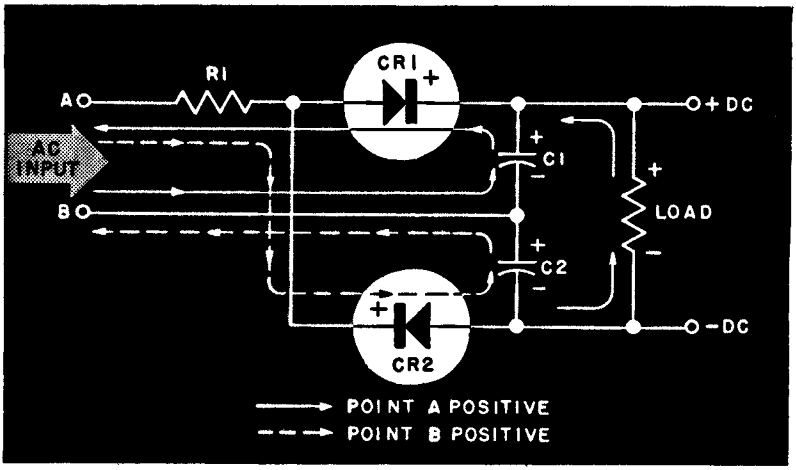


Fig. 5-4. Schematic diagram of a full-wave voltage doubler.

tial with respect to point B, current will flow through CR1 as indicated by the solid lines. Thus capacitor C1 is charged to its peak value. This action is exactly the same as that of a conventional half-wave rectifier.

During the alternate half-cycle, when point B is positive with respect to point A, CR2 conducts and capacitor C2 charges to a value approximately equal to the applied peak voltage, assuming the potential shown in the figure. The outside plates of the capacitors are opposite in polarity. Therefore, the total output voltage developed across the load will be the sum of the voltages across C1 and C2. For very low values of load current, the potential across the load approaches twice the peak-line voltage. In practice, however, each capacitor discharges through the load during its negative cycle so that the voltage is somewhat less than this theoretical value. This doubler has a higher efficiency and better regulation that the half-wave circuit described below; filtering is less of a problem because the ripple frequency of the output is equal to twice the a-c input frequency.

Half-Wave (common-line) doubler. The half-wave, series-fed voltage-doubler circuit, shown in Fig. 5-5, can operate directly from the a-c line. It is used primarily when one side of the line is to be grounded or connected to a common return. This circuit operates on a principal different from that of the full-wave doubler discussed above.

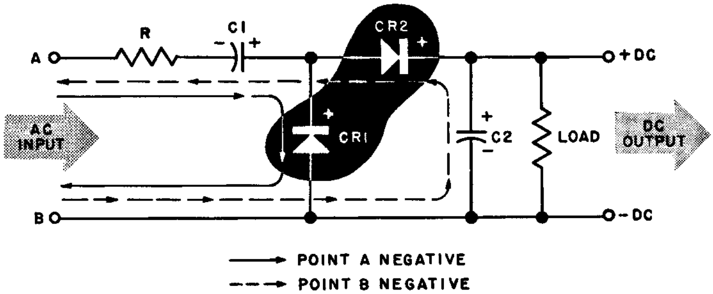


Fig. 5-5. Schematic diagram of a half-wave series-fed voltage doubler.

When the alternating voltage is such that point (A) is negative with respect to point (B), electron flow will take the path shown by the solid line, charging series capacitor C1 to the peak applied potential. During the alternate half cycle, when point (A) is made positive with respect to point (B), the line potential is added to that of C1, and the potential applied to the CR2-C2 circuit will be the sum of the potential across C1 and the applied a-c voltage. Rectifier CR2 conducts as indicated by the dotted arrows, charging capacitor C2 to a potential equal to the peak-line voltage plus the potential across capacitor C1. The theoretical potential across C2 (assuming no losses and no load) will thus be twice the peak voltage of the line. C1 acts as a reservoir, charging during the CR1 conducting cycle and discharging during the CR2 conducting cycle. It therefore contributes little to the filtering action of the circuit. Since capacitor C2 charges only during the CR2 conducting cycle, its effects on the load are the same as those of a simple half-wave rectifier. The efficiency and regulation of this circuit are quite poor. If its d-c output is used as a plate supply for conventional audio amplifiers or radio-frequency amplifiers, additional filtering is required.

Voltage Triplers, Quadruplers, and Other Multipliers

As shown in Fig. 5-6, the principles of the half-wave voltage-doubler circuit can be extended to make voltage triplers, by having the voltage across C2 add to the line voltage to drive another rectifier (CR3) and charge another capacitor (C3). Further additions will result in a voltage quadrupler, or multiplier circuits that increase the voltage by five, six, etc. times. The number of such additions to the circuit, and the number of times the voltage may be multiplied is limited only by the peak voltages that the individual components will withstand. In the voltage-tripler schematic diagram shown in Fig. 5-6, the arrows indicate the direction of charging currents. The circuit shown will deliver slightly less than three times the peak a-c

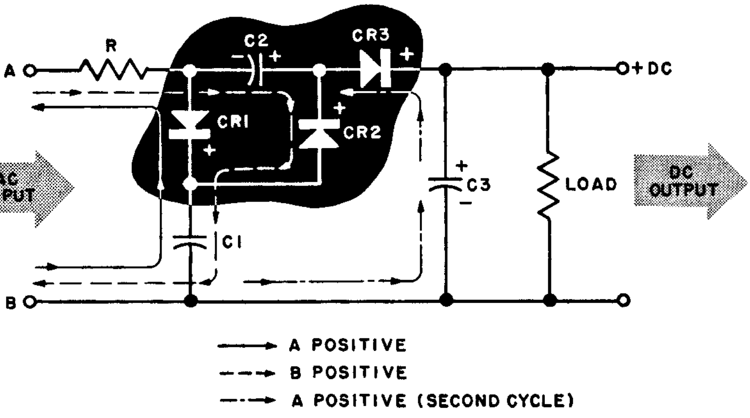


Fig. 5-6. Schematic diagram of a half-wave series-fed voltage tripler.

input voltage. The actual value depends on the requirements of the circuit that the rectifier is to supply.

It must be remembered that as the voltage applied to the capacitor and rectifiers in a multiplier circuit increases, the voltage ratings of the units must be increased. Inverse voltages (voltages which the rectifiers must withstand during the nonconducting cycles) must be given special consideration.

Basic Circuit-Design Data

Basic circuit designs and design data for crystal-diode applications are similar to those of the vacuum-tube diode. Thus the only circuit problem is the choice of the proper crystal diode whose characteristics most closely meet the demands of the circuit. If the diode is properly chosen, the circuit will perform efficiently. (When there is no diode that performs exactly to the circuit's requirements, a diode that will give optimum performance must be selected.)

Thus the circuit design data for crystal diodes is used to help in the selection of the proper diode. The following are the four major points to consider when selecting a diode for a particular application.

1. Maximum inverse voltage.
2. Impedance of the circuit (input and output).
3. Forward conduction (peak and average forward current).
4. Frequency of operation.

Keep in mind that items 1, 2 and 3 are interrelated. The impedance of the diode is determined by the value of applied voltage. Consequently, the forward conduction is also dependent on this value.

Tables III and IV of the Appendix to this book list diodes according to their type number and give capabilities and limitations of each. These tables contain the data necessary for the proper selection of diodes. Although many diodes are designed for similar applications, note from Table III and IV that no two exhibit the exact same electrical and physical characteristics. Thus there is usually only one diode which will best fit the requirements of any specific circuit. The following pages explain the importance of diode characteristics and design data (Tables III and IV in the Appendix) in choosing the proper diode for any circuit.

Maximum Inverse Voltage

First consideration is given to a diode's maximum inverse voltage. A diode should be selected whose maximum inverse voltage characteristic is equal to or slightly greater than the circuit voltage.

Operation beyond this limit will shorten the life of the unit, and may permanently damage it. For example, if the circuit requires that a 50-volt potential exist across the diode, the type selected must be able to withstand a slightly higher voltage. From Appendix Table III it can be seen that a type similar to the 1N54A may be used, but a 1N34A would be more desirable in a circuit with a 50-volt potential. (Of course, other electrical and physical characteristics would have to be taken into account before it were known if the 1N34A diode were the proper one to use.)

Impedance Matching

Selection of a diode with proper resistance values is necessary to achieve the full advantage of impedance matching. Most efficient operation can occur only when the impedance of the source, including the diode, matches the impedance of the load. It is preferable that the diode's forward resistance be much less than the other impedances in the source, to minimize the effects of the diodes with slightly different forward characteristics. The forward resistance should be slightly less than the load. The ideal diode is, of course, a short circuit in the forward direction and an open circuit in the reverse direction. With today's high-conductance type of diodes, impedance matching is more reliably and consistently achieved with series resistance of known tolerances than with diode resistance.

Since the diode resistance is dependent on both the forward and reverse voltage, it must be considered with the following in mind:

1. The diode resistance will vary with the magnitude of the applied voltage.

1a. In order to select a diode that will work efficiently in a circuit, the magnitude of the load impedance must be known. A diode is said to be operating efficiently if the forward voltage drop across the load is at a maximum when the reverse voltage drop across the load is at a minimum. A diode should be chosen that exhibits low leakage at maximum inverse voltage.

2. The reverse resistance reaches a maximum at a specific voltage, and then approaches the point of zero dynamic resistance as the voltage is increased in the negative direction.

2a. Divide the current rating listed in the "Minimum forward current at +1 volt" column of Table III (Appendix) into 1 volt. The value obtained is the maximum specified d-c resistance, but not necessarily the actual resistance of the diode in the forward direction at 1 volt.

3. The forward resistance decreases as the voltage is increased; the reverse resistance reaches a maximum at a specific value and

then tapers off to some lower value as the reverse voltage is increased.

3a. Divide the voltage listed by the current listed in the "Maximum inverse current at specified voltages" column of the Table III of the Appendix. The value obtained will be the minimum specified reverse d-c resistance, but not necessarily the actual reverse resistance, of the diode.

For most diodes two values are listed. If the applied voltage is between the values given in the table, determine each resistance value, then interpolate if necessary. Although interpolation can be considered as only approximate, the results obtained may be used to give satisfactory circuit performance. (When absolute values are required the specific diode manufacturer's curves should be consulted.)

Forward Conductance Peak and Average Currents

The final consideration should be given to forward conduction. Care should be exercised to be sure that the forward currents are kept slightly below rated value. If operated near peak or beyond, ambient temperature will maximize heating effects and change the characteristics of the diode (see Chap. 4).

Frequency Response

Frequency response is very important when the diode is operated at high frequencies; it is also important in pulse work at relatively low pulse rates. When operated at high frequencies (generally in a mixer) the important diode characteristics are conversion loss and noise factor. In determining the quality of these diodes the static d-c measurements are not too useful. Manufacturers test these diodes at frequencies and in circuits for which they are designed to perform, recording the conversion loss and noise factor. Tables III and IV in the Appendix list these specific diodes, the frequency spectrum, and the type of circuit for which they are designed. For example, the 1N82 diode is specifically designed for use as a mixer at uhf frequencies (800mc).

Temperature Characteristics

Crystal diodes exhibit a negative-resistance coefficient in both the forward and reverse direction. Accordingly, both the forward and reverse currents increase as the temperature surrounding the diode increases. On the other hand, most load impedances increase with any increase in temperature. If the two are properly matched, a response of rectification efficiency can be obtained that will be reasonably flat over a wide span of temperature variations.

6. applications

The size, weight, and dependability of metallic rectifiers and crystal diodes, plus their instant response, lack of filament voltage, and reduction of heat and hum, have made them economic and versatile performers in every type of industry. Their uses extend from electroplating devices drawing thousands of amperes to complex computer machines using microamperes.

Magnetic Amplifiers

Saturable reactors. A magnetic amplifier uses saturable reactors (sometimes in combination with other circuit elements) to secure amplifications or control by magnetic methods. The magnetic amplifier owes its amplifying ability to the simple saturable reactor, which is nothing more than an arrangement of an inductor and a metallic core in which the inductance is adjusted by a controlled magnetomotive force. The inductance of an iron-core coil is lower when dc flows through the coil than when no dc is present. This ability to change the inductance of an iron-core coil, and its reactance to ac elicited by passing a direct current through the coil, is the basic mechanism of a magnetic amplifier.

Self-saturation. The simple magnetic amplifier, including a saturable reactor, has been used for many years. With the development of modern selenium rectifiers and low-leakage silicon rectifiers, however, the self-saturating type has come into greater prominence. Self-saturation in magnetic amplifiers refers to the addition of rectifiers in series with the output winding to prevent demagnetization of the reactor by the a-c supply voltage. Without rectifiers the a-c supply voltage would counteract, during one-half of each cycle, the direction of magnetization established by the control winding. With the rectifiers present, however, the control winding will only establish the core magnetic state during the nonconducting half-cycle, since the output current will always saturate the core in the same direction. Figure 6-1A shows a full-wave bridge magnetic-amplifier circuit using two self-saturating rectifiers in series with the output windings. These

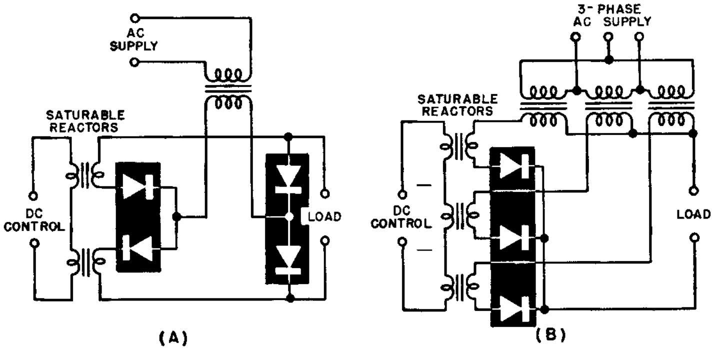


Fig. 6-1. Magnetic amplifiers. (A) Full-wave bridge circuit using two self-saturating rectifiers in series with the output winding. (B) Self-saturating circuit using a three-phase wye-connected rectifier.

self-saturating rectifiers provide a conducting path for windings, but block the supply voltage in the reverse direction. Two "complementary" rectifiers, connected in series across the load, are used to provide a d-c output. The self-saturating magnetic-amplifier circuit shown in Fig. 6-1B employes a three-phase wye-connected rectifier.

For magnetic-amplifier applications, the self-saturating rectifiers should be either the silicon or selenium low-leakage type, since they must block the a-c supply voltage in the reverse direction. Leakage in these rectifiers produces some demagnetization of the core, reducing the gain of the magnetic amplifier. Leakage in the comple-

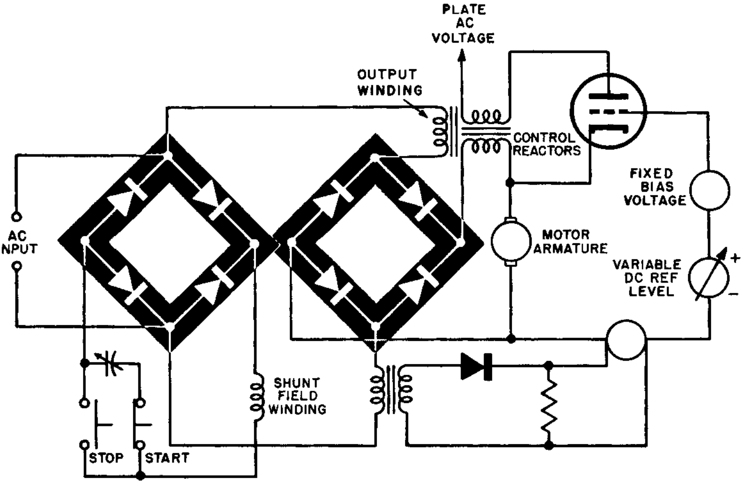


Fig. 6-2. Magnetic amplifier with two full-wave bridge-rectifier circuits controlling a two-phase servosystem a-c meter.

mentary rectifiers, however, causes only a slight reduction in output.

Applications. One major application of magnetic amplifiers is the control of the a-c motor in a servo system. Figure 6-2 shows a magnetic-amplifier circuit for the control of a two-phase a-c motor. Two full-wave bridge rectifier circuits are employed. The direction of bias-current flow through the thyratron tube is chosen to aid the magnetic force developed by the control current in one reactor, and to buck it in the other. In the absence of a d-c control signal, the direct currents are the same in each reactor, and the control field of the motor is not energized. Both reactors are partially saturated to begin with. In the presence of a d-c control signal sufficiently large to overcome the adjustable d-c reference voltage, the thyratron fires and an additional control current flows through both reactors. This control current further saturates one of the reactors, while reducing the saturation of the other. As a consequence, the control field of the motor is energized and the motor operates. The speed of the motor is set at the desired rate by a potentiometer which controls the adjustable d-c reference voltage. The reference level in turn determines the amplitude of the d-c control signal at which the thyratron tube will fire and conduction take place.

Computers

In the following computer application, copper-oxide rectifiers are used in a diode matrix for a high-speed storage unit. The storage unit is employed in the Eniac high-speed function table to store decimal digits and present its information to the computer as a series of pulses (nine or less) along a number of parallel transmission lines. Figure 6-3A shows that Row 1, via its patch wires, is storing an 8(2P + 2P + 4P), and Row 2, by means of its patch wires, is storing a 3 (1P + 2P). Two numbers are stored and either one may be transmitted by the application of a positive potential to its respective row.

Isolation between rows and parallel lines is necessary because a positive pulse on both Rows 1 and 2 could open the pulse gate. The contents of both rows would appear at the common output and a 9 (1P + 2P + 2P + 4P) would be transmitted even though only an 8 were stored in Row 1. Such crosstalk prohibits the use of common gate tubes for both rows, unless a system of isolation is employed. The required isolation may readily be achieved by the use of copper-oxide rectifiers.

When a unidirectional current device such as a copper-oxide rectifier is inserted in the connecting patch wires, (Fig. 6-3B), the

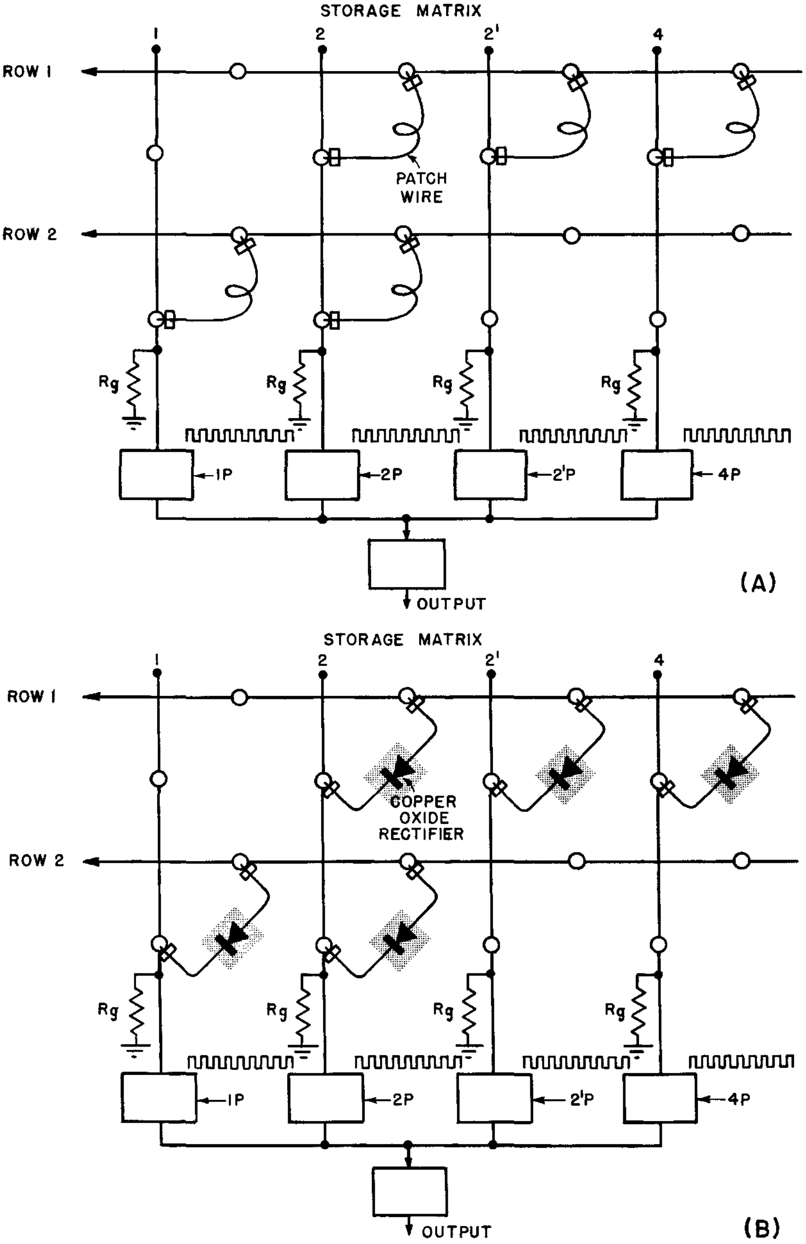


Fig. 6-3. High-speed computer circuits with (A) connecting patch wires, (B) isolating copper-oxide rectifiers.

positive voltage applied from Row 1 on the input of the number 2 pulse gate is divided between the back resistance of the diode connected to Row 2 and the input resistance R_g of the number 1 pulse gate. When this back resistance is much larger than R_g, very little voltage appears across it. Row 2 is effectively isolated when Row 1 is energized. In like manner, isolation is attained for Row 1 when Row 2 is energized. Consequently, only the information stored on the energized row will be transmitted.

The forward resistance of the copper-oxide rectifier acts as a series diode connecting the line to the gate, and does not interfere with the gating action. If the resistor R_g is very large compared to the forward resistance of the rectifier, the greater portion of the voltage of the energized row will appear across the resistor R_g and voltage loss will be negligible. It is necessary, however, to compromise on the value of R_g so that it is sufficiently large with respect to the forward resistance of the rectifier, yet small enough compared to the back resistance of the rectifier.

The important factors affecting the choice of diodes for computer applications include high back resistance, high conductance, and good switching characteristics. They can be separated into three functional groups: high-conductance types with good switching characteristics for low-impedance circuits; high resistance-high conductance types for efficient coupling, clamping, and matrix service; forward and inverse pulse recovery-type for critical pulse applications.

The recovery time of a crystal diode is measured by its ability to return to a stable or specified value of reverse resistance when subjected to a negative voltage after it has been conducting in the forward direction. This factor determines the speed at which computer circuits operate.

Modulators

In a modulator, a nonlinear element is utilized to superimpose a signal of one frequency upon a carrier of another (higher) frequency, which transports the intelligence contained in the modulating signal. Since the nonlinear characteristics and capabilities of copper-oxide and selenium rectifiers are superior to those of vacuum tubes, metallic rectifiers are often used as modulators.

Circuits. Copper-oxide rectifiers have been widely used for many years as modulators in carrier-frequency telephone systems. These modulators transmit equally well in either direction, and permit suppression of the carrier or bands of undesired frequencies more effectively than do tube modulators. In most carrier telephone systems, single-sideband (carrier-suppressed) transmission is used for

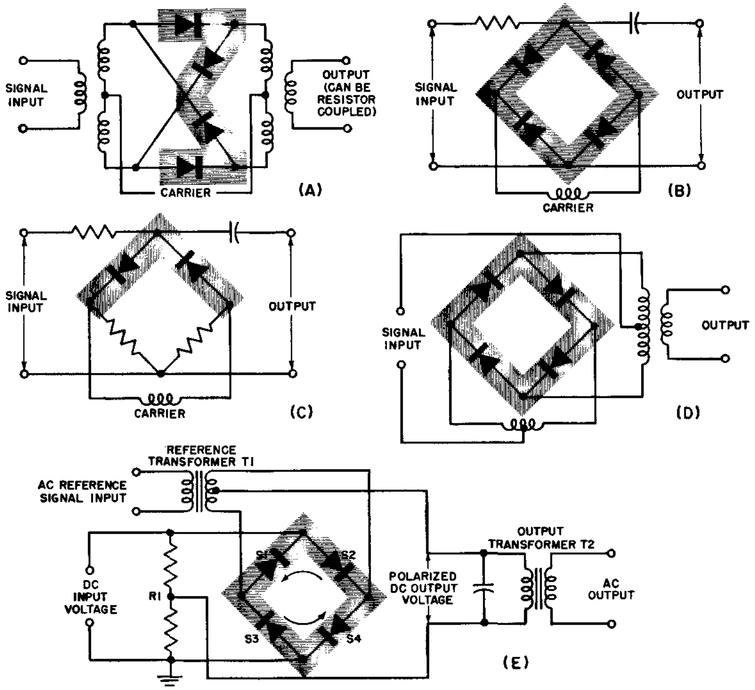


Fig. 6-4. Schematic diagrams of various modulator circuits.

reasons of frequency space economy. Figure 6-4 shows a few simple circuit arrangements which have been developed for this purpose. These modulator circuits suppress the carrier by balancing it out in both the signal-input and the signal-output circuits. In the first four circuits modulation results from either a reduction or reversal of the current flow between the input- and output-signal circuits at periodic intervals. The carrier varies the interval resistance of the rectifiers between high and low values. In effect, each signal is balanced by the other's circuit.

Another type of rectifier modulator (Fig. 6-4E) utilizes a bridge circuit, consisting of selenium rectifiers, to convert a d-c signal to a properly phased a-c signal for application in a servo system. The modulator acts essentially as a synchronous switch. During one half-cycle of signal input, an a-c reference voltage causes current to flow through rectifiers S1 and S2; during the other half-cycle current flows through S3 and S4, as indicated.

The ungrounded side of input resistor R1 is connected to the junction of S1 and S2, which acts as a divider across the secondary of the reference transformer T1. Consequently, this side of resistor

R1 is at the same potential as the centertap on the transformer secondary. The output voltage is taken off between the centertaps of R1 and secondary of T1 and is effectively equal to that voltage appearing across one-half of this input resistor. Because of the rectifier switching action during the a-c signal input the output circuit sees the voltage across the upper and lower halves of the input resistor alternately, measuring each voltage to the resistor center.

The resulting polarized d-c output voltage is equal to half of the input voltage during one half-cycle of the ac reference signal input, and equals the negative of this during the other half of the a-c cycle. The action is the same as that of a mechanical chopper. Since one side of the input resistor usually is grounded, it is necessary to take the output through an isolating transformer T2 to remove the d-c component. This obtains the required phased a-c signal.

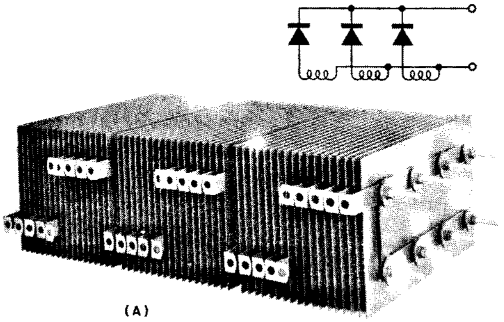
Electroplating, Anodizing, Pickling, Etc.

Industrial electrochemical processes, such as electroplating, anodizing, pickling, chlorine generation, and electrocleaning, generally require very high currents at relatively low voltages. For these applications only metallic rectifiers have the low internal voltage drop and high efficiency to be practical. Even after initial installation, if higher currents or voltages should be desired, it is a simple matter to add additional selenium rectifiers in either parallel or series connections. The voltage and current output is generally easy to control by means of transformers, induction regulators, saturable reactors, or by other manual or automatic methods.

Selenium power supplies for electroplating and other electrochemical processes are now widely available, covering a current range from 250 to more than 30,000 amperes in voltages of from 6 to 48 volts. An attempt is usually made to obtain a power unit with a maximum d-c voltage closest to the voltage at which the electrochemical process is to operate, thus securing optimum efficiency. Practically all high-power units (in the order of 1kw or more) utilize three-phase circuits. A typical selenium-rectifier power stack constructed for three-phase operation is shown in Fig. 6-5A.

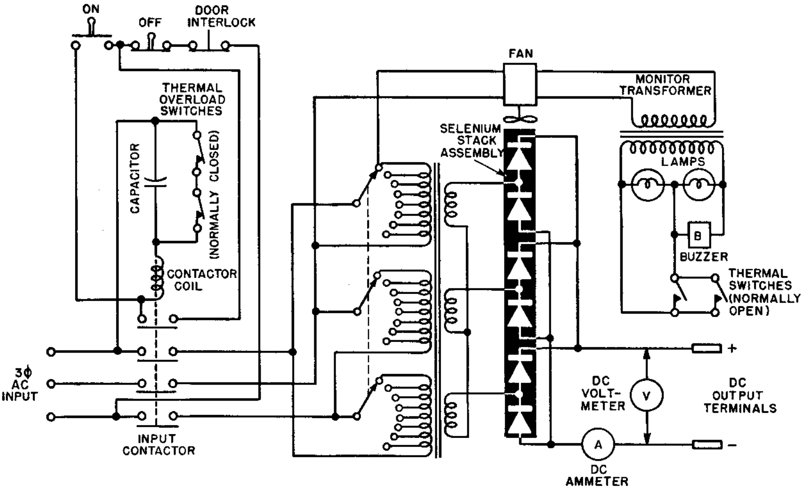
Circuts. Electroplating units are generally comprised of selenium, copper diode, or magnesium rectifier stacks; a main step-down transformer; voltage control (usually in the primary of the transformer) ; a cooling system (usually consisting of fans) to prevent overheating of the stacks; output d-c voltmeters and ammeters; and devices to protect against over-voltage, current overloads, excessive temperature, corrosion, etc. All these components are usually built into a metal housing with the plating electrodes, meters, and controls available on the outside.

The circuit for a typical electroplating selenium power supply is shown in Fig. 6-5B. A simple primary tap-switch is used for voltage control. Some protective devices including fan monitor, thermal overload switches, and door interlocks, are shown. More elaborate units have additional refinements such as automatic controls, output filters, and switching arrangements to obtain a variety of voltage- and current-output characteristics. These refinements are usually incorporated into industrial rectifiers for high-speed, fully automatic, electrochemical processing. In some of these industrial processes, very high currents (about 100,000 amperes) may be required, with d-c voltages as high as 50 volts. Selenium rectifiers may be advan-



(A)

Fig. 6-5(A). A three-phase half-wave rectifier of high current rating.



(B)

Fig. 6-5(B). Electroplating power supply.

tageously used in these applications, operating at overloads up to 250% of their normal rating, with forced air ventilation.

Battery Charges

Proper charging of a battery requires that the total ampere hours withdrawn from the battery be returned to it, plus an additional amount to make up for internal losses. Selenium rectifiers are highly suitable as power sources for battery charging and are commonly used for this purpose. Selenium-rectifier battery charges can be used to charge any type of storage cell at either low or high rates. Adjustments of the charging rate is often accomplished by a variable transformer which controls the current output.

Booster-type charging. Due to the inherently low forward resistance of selenium rectifiers, the charging current in selenium battery charges is initially high, but tapers off as the battery nears full charge. This is advantageous because, during the first few hours when the battery is cool, the rate of charge can be high without harming the battery, and charging may be accomplished rapidly. Selenium rectifiers are thus well suited to booster-type battery charging.

The selenium assembly's inherently high back resistance is another important advantage. If the a-c supply to a charger fails, the high back-resistance of the selenium rectifiers will prevent the battery from discharging itself through the rectifiers.

Circuits. In standby applications, the charger output is usually left across the battery, which is then maintained in a fully charged condition by a low "trickling" rate of charge. This charge is supplied continuously, and should be adjusted so that the power input is equal to the internal battery losses. Selenium rectifiers make excellent trickle charges.

Another application is "float charging;" the battery-charging rate is adjusted to supply the average battery drain plus the internal battery losses. As current is withdrawn from the battery the resulting drop in its terminal voltage causes the battery charger to deliver a charging current, until the original battery terminal voltage is restored. Float-charging automatically maintains the terminal voltage of a battery or set of batteries at a relatively constant value, regardless of load conditions.

A typical selenium-rectifier battery charger is shown in Fig. 6-6. A single-phase (full-wave) bridge rectifier circuit is employed, having taps for adjusting the a-c input voltage. A voltmeter and an ammeter are provided for monitoring the d-c output, a standard

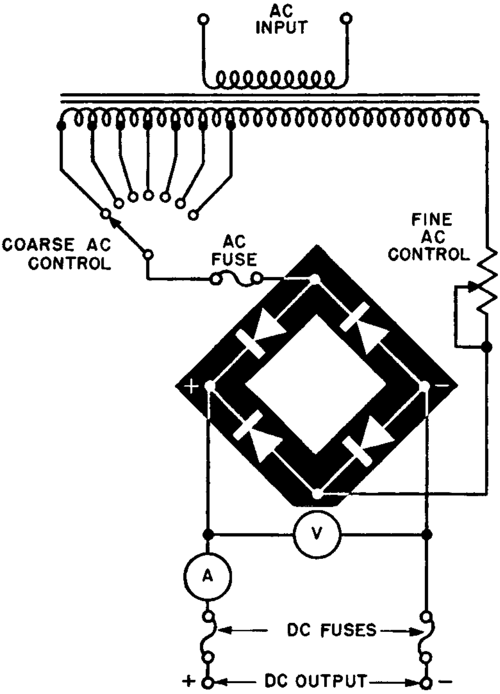


Fig. 6-6. A battery charger using a single-phase full-wave bridge rectifier.

feature of most battery chargers. Both the a-c and d-c circuits are fused for complete protection. An even simpler full-wave charger, for low-voltage charging, is shown in Fig. 6-7. Its operation is easily discernable.

The smaller selenium-rectifier battery chargers generally have no moving parts and require no adjustment. Since such chargers are entirely noiseless, they can be connected directly across the battery terminals without danger of causing hum or interference.

Magnetic Brakes

Selenium-rectifier power supplies are extremely useful for supplying d-c voltage for the operation of magnetic-braking devices. In such devices the duty cycle of operation is rarely continuous. Because of the intermittent condition of operation, relays and contactors are provided in the braking circuits.

A typical magnetic-brake power supply appears in Fig. 6-8. It employs a single-phase full-wave bridge circuit. A-c is applied directly to the rectifier and d-c output voltage is applied across the magnetic brake, which is in a standby position. Operation is initiated

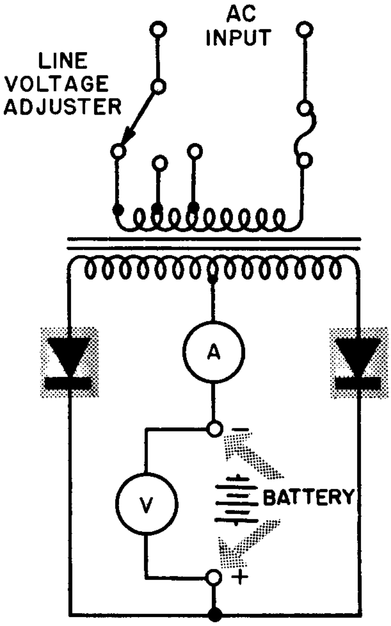


Fig. 6-7. A low-voltage full-wave battery charger.

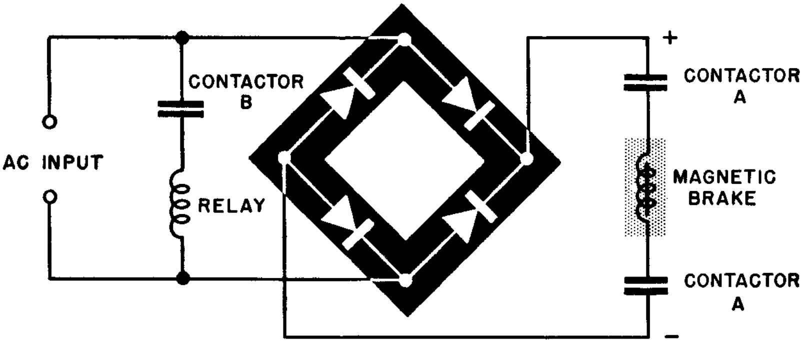


Fig. 6-8. A magnetic brake power supply.

by contactor (B), which is connected across the a-c line in series with the relay. Closing of contactor (B) energizes the relay coil, which in turn closes the two contactors (A) on either side of the magnetic brake, applying d-c voltage across the magnetic brake.

Aircraft Power Supplies

The generation of high-voltage a-c power using light-weight transformers, with a subsequent conversion to d-c by means of selenium rectifiers, is an established method of providing electric power in aircraft. Such systems avoid both the problems connected with commutation machinery and the voltage limitations of high-altitude operation.

Selenium rectifiers have proved very satisfactory under climactic conditions. For extreme temperature, humidity, and altitude conditions, they exhibit fairly stable characteristics. In addition, they are normally unaffected by vibration and, with air cooling, are capable of maintaining good operating characteristics for a considerable period of time. The combined efficiency of transformer-rectifier units remains practically constant for varying temperatures and degrees of air cooling.

A typical aircraft power-supply system circuit is shown in Fig. 6-9. It employs a three-phase, full-wave selenium-rectifier circuit which receives its a-c input voltage from the wye secondary of the transformer. Note the motor generator and voltage regulator of the system. This particular system is rated at a maximum of 800 amperes at 30 volts dc. One distinct advantage of this system is that, by having an a-c device as the primary source of electric power, d-c as well as a-c operated equipment can readily be used, the d-c-operated equipment receiving its power through the selenium rectifiers.

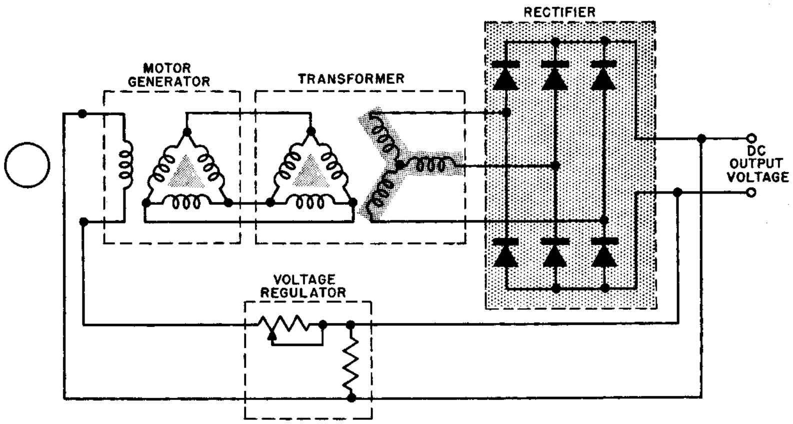


Fig. 6-9. Aircraft power supply using a three-phase full-wave selenium rectifier circuit.

Arc-Suppressor Circuits

Arcing. Undesirable arcing between contacts in electrical circuits occurs to a severe degree in inductive circuits. For example, when an inductive circuit is opened, a high self-induced voltage is built-up in the inductive element. This voltage cannot be immediately dissipated through the open circuit. If there is no provision for dissipating this energy, the full voltage present (the line voltage E plus the induced voltage e) will appear across the contacts, as indicated in Fig. 6-10A. Even though this occurs for only an instant, it will cause arcing across the contacts, possibly of magnitude sufficient to cause the contacts to burn or pit. The degree to which arcing can be suppressed or "quenched" is probably the most important factor governing the life of circuit contacts.

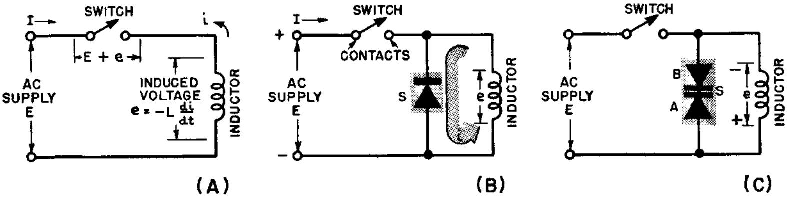


Fig. 6-10. Typical arc-suppressor circuits. (A) Line voltage E plus induced voltage e will appear across the contacts, causing arcing. (B) Selenium rectifier connected across an inductive load will reduce arcing. (C) Arc-suppressor circuit used for a-c or d-c operation, Selenium cells are back-to-back.

Circuits. A selenium rectifier connected across an inductive load, Fig. 6-10B, is one of the most effective means of reducing or eliminating the arc. Because of the polarities, the rectifier blocks the current when it is closed. When the circuit is interrupted, the back-voltage of the coil sets up a reverse current. Hence the rectifier conducts as shown, and the energy is dissipated in the internal resistances of the inductor and rectifier.

Figure 6-10C shows an additional arc-suppression circuit, useful for both ac and dc. As indicated, a back-to-back arrangement of selenium cells is used. One-half of the cells act as rectifiers and the other half present a nonlinear impedance. With the polarities as shown in the figure, and the switch closed, the A cells act as blocking rectifiers, and the circuit operates normally. When the switch is opened, a high voltage of reverse polarity is induced in the coil. The A cells now conduct and apply the full voltage (line voltage plus coil voltage) across the backward-connected B cells. Because of the nonlinear resistance characteristic of selenium rectifiers, the reverse resistance of the B cells, while at first high, decreases rapidly as the reverse-voltage across the cells increases. As a result, the voltage across the switch contacts is rapidly and harmlessly dissipated in the low resistance of the inductor and rectifier cells. The total effect is that the voltage across the contacts does not rise to the arcing potential since the rectifier presents a low resistance to high voltages. When the polarities in the circuit are reversed, the functions of the A and B cells are interchanged, permitting a-c operation.

The design factors which must be considered when using selenium rectifiers in arc-suppressor circuits are the voltage and current ratings, the rate of opening and closing of contacts, and the time constant of the circuit.

Generator Voltage Regulators

Metallic rectifiers are excellently suited as voltage regulators in various circuits. One such application is for the regulation of a generator used to supply a-c voltage for high-speed electric tools. For commonly used motor-operated tools (such as those used for grinding and polishing) the turning power of the shaft does not vary in direct proportion to the applied voltage, but varies approximately as the square of the voltage. Since the voltage of this type of a-c generator tends to fluctuate with load variations, an automatically regulated voltage source is an essential requirement for consistently good tool performance.

Circuits. The circuit in Fig. 6-11 illustrates the applications of selenium rectifiers as voltage regulators. It employs selenium recti-

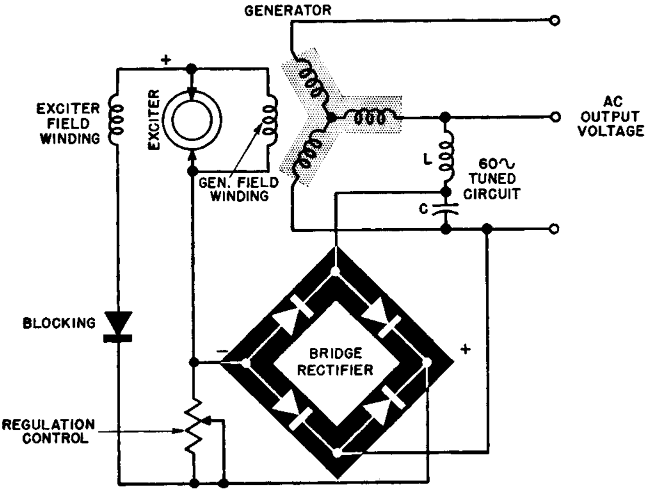


Fig. 6-11. Schematic of a generator voltage regulator. Selenium rectifiers are used in a full-wave bridge circuit and for blocking.

fiers in a (full-wave) bridge-rectifier circuit and as a blocking rectifer. The circuit includes a capacitor and a reactor which are normally resonant at 60 cycles. The a-c voltage output of the generator is applied to the regulating circuit. The voltage is rectified by the bridge rectifier, and the d-c output voltage is then impressed across the generator field winding in opposition to the already existing regular field. The resultant voltage across the exciter field winding is the difference between the exciter voltage and the opposing rectifier voltage. The resonance effect causes the voltage across the capacitor-regulator to increase in much greater proportion if the output voltage of the generator increases. This voltage is rectified and then applied to the generator field opposing the increased a-c voltage applied across the exciter field winding. In turn, the reduced exciter voltage decreases the generator output voltage, effectively regulating it. If the output voltage of the generator decreases, the action is reversed.

The additional half-wave blocking rectifier shown in the circuit acts as a d-c valve to permit the flow of direct current in one direction only, thus preventing polarity reversal of the excited field current.

Current-Limit Controls

Selenium rectifiers are being increasingly utilized in complex control circuits. In the circuit shown in Fig. 6-12, a (full-wave) bridge rectifier circuit is used in conjunction with two half-wave blocking rectifiers to provide a current-limit control for a motor-generator system.

Single-phase a-c input to the bridge rectifier is obtained from a constant-voltage transformer. The d-c output voltage from the bridge-rectifier circuit is smoothed by a capacitor and is then applied to an adjustable voltage divider. A permanent tap on this resistor is connected to the generator circuit; the two variable taps are electrically connected to the motor circuit via the blocking rectifiers and current-limit field coil. The over-all operation of the circuit allows the currents drawn by the motor-generator system to be held within the desired limits.

Dust Precipitators

An electrostatic dust precipitator is a device which electrically charges dust and other foreign particles, then removes them from the air by passing them between oppositely charged plates. Very high d-c voltages are necessary to obtain effective dust removal.

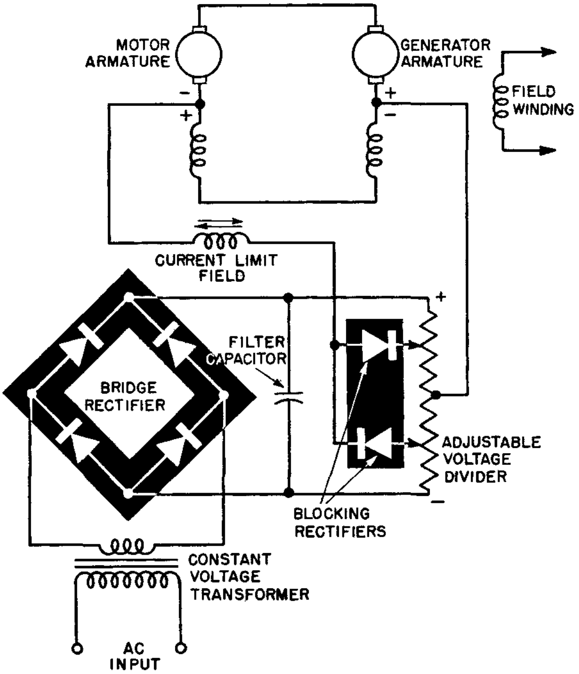


Fig. 6-12. Diagram of a current-limiting control circuit using a full-wave bridge rectifier circuit and two half-wave blocking rectifiers.

A typical dust precipitator using selenium rectifiers is shown in Fig. 6-13. The high-voltage supply for the precipitator is a conventional transformer-fed full-wave bridge rectifier. As shown, an ammeter is inserted into the high-voltage circuit for monitoring purposes.

Voltage control. The low-voltage input circuit must provide close voltage control in small increments (for maximum efficiency of precipitation) as well as protection against the effects of flashover arcs (which are unavoidable in this type of high-voltage equipment).

A precipitator can be damaged if a relatively large current is left on for any appreciable time, therefore the arc must be quickly interrupted during a flashover. Restoration of the voltage following an arc interruption must be rapid, because precipitation is a very low efficiency with less-than-normal output voltage. Since flashovers are frequent, the arc must be interrupted as quickly as possible and the time lag in restoring the output voltage must be a minimum.

One method of control which meets these requirements involves the use of selenium-rectifier power stacks. A saturable reactor is inserted into the input circuit to the primary of the rectifier transformer. Voltage excitation for the reactor is taken from the input source, through an adjustable autotransformer and small bridge-type control rectifier, as was indicated in the control-circuit diagram of Fig. 6-13.

The short-circuit currents caused by flashover pass through the secondary coils of the saturable reactor, bringing about a large voltage drop across the reactor. As a result, the voltage at the rectifier terminals is reduced to a value that causes the arcing to stop in two or three cycles. Voltage recovery is rapid, since the d-c excitation on the reactor is still the same as for normal operation. The output voltage recovers to normal in approximately one cycle.

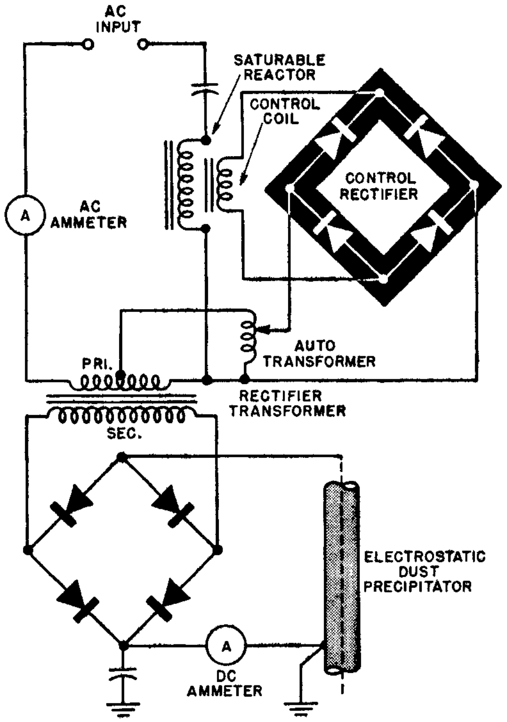


Fig. 6-13. Schematic diagram of an electrostatic dust precipitator using bridge-type control rectifier circuit.

Cathodic Protection

Cathodic protection prevents the corrosion of underground pipes or other metallic structures due to galvanic action.

Galvanic action is the flow of electrical current between two dissimilar metals, or between two sections of the same piece of metal with dissimilar surface conditions. Of course for this to occur a circuit must exist. There are many variations in pipes and soil conditions that permit such circuits to be formed. For example, one such circuit may exist between two dissimilar metal pipes located near each other and separated by moist soil. This case is similar to a battery; the two metals act as the electrodes and the surrounding soil acts as the electrolyte. Such galvanic action can destroy metals which are normally corrosion resistant. Cathodic-protection circuits effectively counteract corrosion produced by this action. Selenium rectifiers have been found to be ideally suited to these protective circuits.

Protection circuits. In establishing a cathodic-protection circuit, the negative d-c lead of a rectifier is attached to the pipe to be protected and the positive lead is attached to a ground-bed anode. The soil still acts as an electrolyte, but the direction of the galvanic action is reversed, halting the gradual corrosion of the pipe.

Such protection may be used for any underground metallic surfaces exposed to galvanic corrosion. A typecial selenium-rectifier circuit for this purpose (shown in Fig. 6-14), uses a single-phase (full-wave) bridge rectifier. A variable-voltage transformer is used to adjust the voltage applied to the rectifier. Although a continuously variable unit is shown in the figure, a transformer with stepped taps may be used, provided that the available range of d-c current

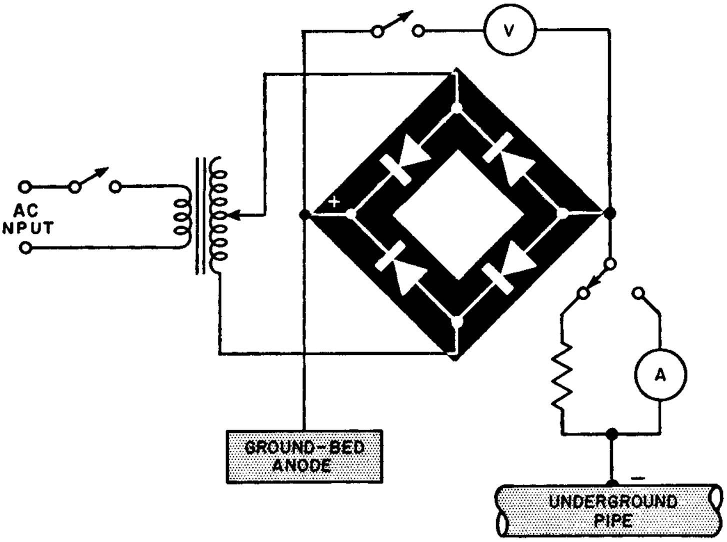


Fig. 6-14. Schematic representation of a cathodic-protection circuit using a single-phase full-wave bridge rectifier.

adjustment permits balancing the rectifier output to oppose the galvanic action. As shown, a voltmeter and ammeter may be switched into the circuit to monitor the rectifier output for correct balance.

Radio, Television, and Hi-Fi Systems

Selenium rectifiers are ideally suited for power-supply applications were moderate currents and voltages are required. They are being used in all the basic circuit arrangements formerly associated with vacuum-tube rectifiers and diodes.

The rectifier circuit previously shown in Fig. 5-1 has replaced the vacuum-tube rectifier in many a-c/d-c receivers. The increased power output obtained by selenium rectifiers increases the sensitivity of the set by supplying additional operating voltages and currents. The same half-wave circuit has virtually replaced the vacuum tube in portable receivers. The selenium rectifier also enables the circuit to retain the instant starting feature of the portable because the rectifier requires no warm-up time.

The voltage-doubler circuit shown in Fig. 6-15, is used in many TV designs. Its operation is identical to that described in Chap. 5. The circuit provides voltage and current high enough to operate the set at peak efficiency without a costly high-voltage transformer. Larger capacitors, the inductor in the pi-type filter network, and circuit filtering, provide moderate voltage regulation.

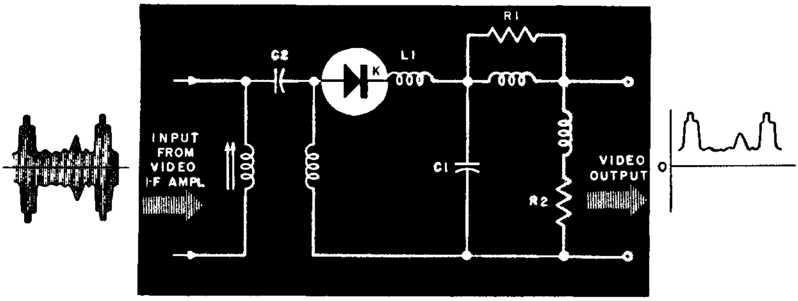


Fig. 6-15. Television receiver voltage-doubler circuit, shown in schematic representation.

Color TV power supply

Another popular application made practical through the use of selenium rectifiers is that shown in Fig. 6-16. Although not easily identified as such, this circuit is a full-wave doubler circuit designed for use in a color television receiver. The use of selenium rectifiers in this circuit has enabled the designer to reduce the transformer to a single secondary winding. The absence of filaments reduces filament hum and internal heat.

The circuit has all the advantages of the full-wave doubler rectifier: efficiency, power handling ability, and a ripple frequency that is twice the line frequency. It also provides a variety of d-c voltages.

The bridge-type rectifier has also affected radio and television receivers. The use of this circuit, prior to the 45-volt selenium unit, was restricted to high-current/low-voltage meters and similar applications utilizing copper-oxide rectifiers. This was so because operation of a circuit with vacuum tubes necessitated separate filament supplies for each tube in each branch of the bridge. However, for high voltage applications, the large size made copper-oxide stacks impractical. Using a 45-volt selenium rectifier with a single stack saves space and makes the circuit practical.

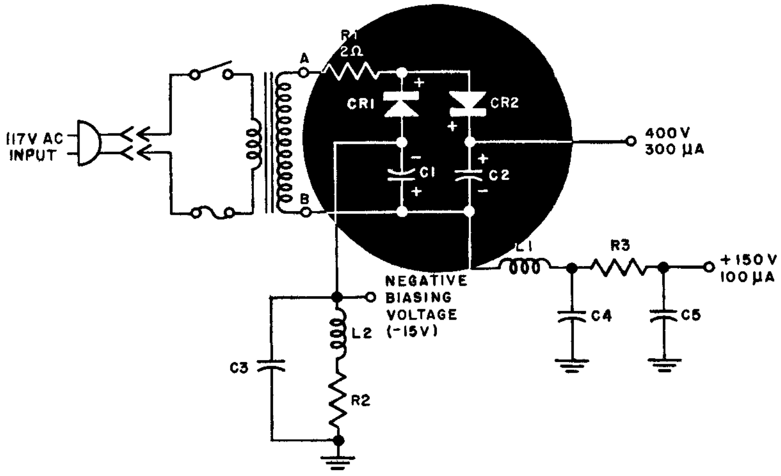


Fig. 6-16. Schematic of a color television-receiver power supply using full-wave doubler circuit.

Crystal-Diode Applications

The crystal detector is probably the oldest type of detector and receiver known. It has been used by the experimentor, hobbyist, and engineer as long as energy has been transmitted by radio waves. The circuit operates simply and effectively. When a signal is picked up by the antenna and applied to the crystal detector, the rectifying property of the crystal allows current to flow in one direction. The amount of current that flows is dependent on the strength of the incoming signal and the quality of the crystal. When the cat's-whisker side of the crystal is positive with respect to the grounded side, the resistance of the crystal is low and current flows. When the cat's-whisker is negative, the resistance of the crystal is very high and little current flows. This action is repeated for every cycle of the signal.

When a capacitor is placed across the output it charges to the peak value of each cycle, and the amplitude of the voltage developed across it varies in accordance with the amplitude variations of the radio-frequency wave. This is the audio component. The crystal provides no amplification: for a usable audio signal it is necessary to have a long antenna, a good ground, and a very selective tuned circuit. (A conventional broadcast-band tuned circuit can be used to provide the tuning.) For best results, a high-impedance headphone should be used across the output.

Radio Receivers

A-M detector and avc circuit. A typical detector and avc circuit is shown in Fig. 6-17. A diode with low forward resistance is used for this application. The circuit operates as a conventional detector with the crystal diode substituted for the diode vacuum tube. The audio signal is developed across the variable resistor, which also serves as a volume control. The r-f signal applied to the diode detector circuit is also applied to the shunt-diode biasing circuit, providing an avc biasing voltage for the r-f circuits.

Frequency discriminators. Figure 6-18 shows a typical frequency-discriminator circuit. Operation of this circuit is similar to the familar vacuum-tube discriminator circuit.

Unlike vacuum-tube diodes, each individual crystal diode has a finite back resistance which must be considered in frequency-discriminator circuit applications. Since it is costly to match two diodes exactly, circuit balance is obtained by placing resistors R1 and R2 (Fig. 6-18) in parallel with the crystal diodes. These resistors are chosen to compensate for the difference in the diodes, and stablize the resistance of the circuit during the diodes' nonconductive periods. R1 and R2 then act as finite back resistances, giving predictable results. Circuit imbalance, regardless of the back resistance of the

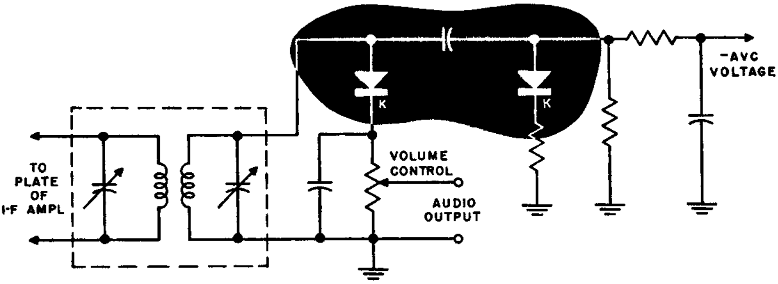


Fig. 6-17. Detector and avc circuit of a radio receiver shown schematically.

diodes, is thus compensated for by the proper resistors. This also simplifies replacement problems.

A germanium duo-diode "matched pair" may be substituted for the two diodes shown in Fig. 6-18. (A matched pair of two diodes whose characteristics are closely matched, providing circuit balance due to similar forward conductance.) The high back resistance of the crystal diodes permits use of high-load resistors (R3 and R4, up to 100,000 ohms) to assure high efficiency, good linearity, and low input loading.

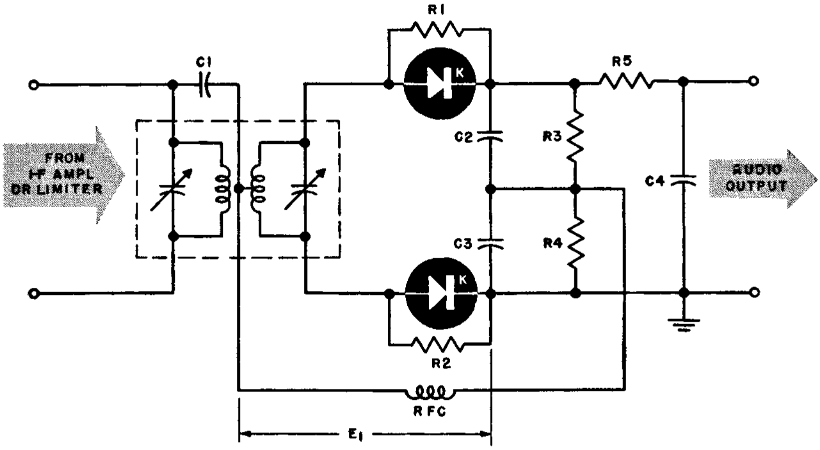


Fig. 6-18. Diagram of a typical frequency-discriminator circuit.

Television Receivers

Detection of video signals in a television receiver is accomplished in much the same manner as detection of radio signals in a broadcast receiver. Typical detector circuits are shown in Figs. 6-19 and 6-20. These circuits are the most common TV crystal-diode applications.

In the *series video detector* (Fig. 6-19) the crystal diode operates as a rectifier, conducting during the positive portions of the signal and blocking during the negative portions. The potential difference developed across the load is a unidirectional voltage, nearly equal to the peak voltage of the input signal. Here, the peak charge on C1 varies directly with the peaks of the input signal. It is this voltage, plus the peak of the incoming r-f voltage, that the diode must withstand. Crystal diodes (particularly those with excellent forward resistance characteristics) provide much greater efficiency and better linearity, particularly at low signal levels, then their thermionic counterpart. Proper selection of a diode for this application is critical, because an increase in bandwidth and a decrease in overall gain accompany a diode with high forward conduction. The increase in bandwidth is desirable but the decrease in gain it not. Conversly, a diode with high forward resistance decreases the forward conduction and increases the overall gain but reduces the bandwidth. Circuit components must be chosen so that an optimum position between the two extremes is obtained. Table III of the Appendix gives data for proper diode selection.

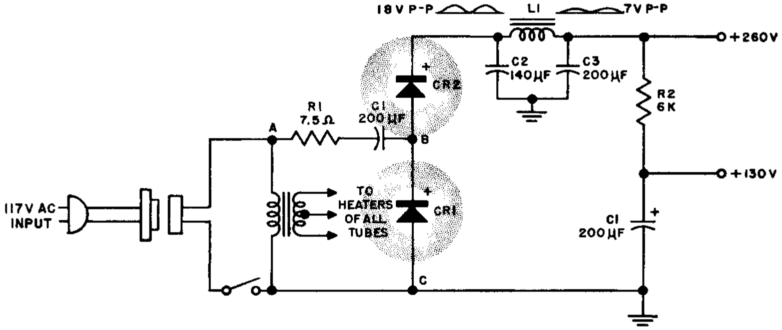


Fig. 6-19. Schematic diagram and waveshapes of a series video detector.

The *shunt video detector* (Fig. 6-20) operates in much the same manner as a diode limiter (discussed later in this chapter). When the incoming signal is such that the anode is negative, the diode acts as a high impedance across the secondary of the transformer. The entire negative half-cycle is thus developed across the load, as shown in Fig. 6-20. Conversely, when the anode is positive, the crystal acts as a very low impedance path and no voltage is developed across the load.

In many series and shunt video-detector circuits, the crystal diode faces the opposite direction from that shown in Figs. 6-19 and

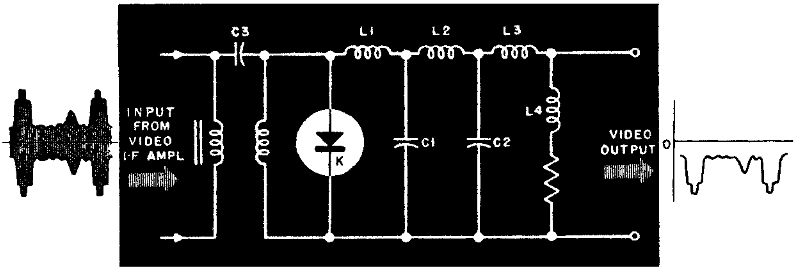


Fig. 6-20. A shunt video detector, represented schematically.

6-20. This is not an error in marking or polarity. If the TV set requires that the output of the detector be of the opposite phase from that shown, the simplest method of altering the circuit is to reverse the connections of the crystal detector. Since the same viedo information is contained in both halves of the input signal, nothing is lost. The polarity across the load is simply reversed.

D-c restorer. A circuit that holds either the positive or negative extreme of the amplitude of a waveform to a given reference level (potential) is called a d-c restorer, clamper, or baseline stabilizer. In television receivers d-c restorers are used to establish the black level of a scene, automatically adjusting for variations in picture brightness.

A typical d-c restorer circuit employing a crystal diode is shown in Fig. 6-21. For this application a crystal diode with a low forward resistance and high back resistance (over 250,000 ohms at 50 v) should be used. Its peak inverse voltage rating should be high enough to withstand the normal and peak signal levels encountered. The low forward resistance clamps the amplitude extreme of the sync pulses, allowing the remaining waveform to be extended in only one direction from the reference level.

The action of the video restorer allows only the sync voltages extending below the zero reference line to cause diode conduction, producing a voltage across R2 that is added to the incoming video signal at the grid of the picture tube. The polarity of the other portion of the signal, containing the video information, is above the line and is not passed by the diode.

Crystal mixers. Due to its low noise figure, the silicon diode has been one of the more widely used mixer devices. Recently, however, germanium diodes have been produced which perform equally well at uhf frequencies.

The most important diode charteristics in mixer applications are conversion loss and noise factors. Maximum conversion efficiency is obtained by making the small signal characteristics nonlinear. The uhf and silicon mixers listed in the Appendix do not contain d-c static measurements because all uhf and microwave diodes must be tested in comparable circuits to insure optimum performance.

The uhf signals to be mixed are applied to the crystal by a resonant cavity or tuned line (generally used in place of the conventional tuned circuit). The output of the local oscillator differs from the received signals by the desired intermediate frequency. This output is tuned to one of the channels in the uhf band. The local oscillator and receiver signals are combined by the crystal mixer to produce a current that contains several frequency components, including the signal frequencies of the received and local oscillator signals, their higher harmonics and their sum and difference. The frequency of the local oscillator determines which signal is selected and fed to the front end of the television receiver.

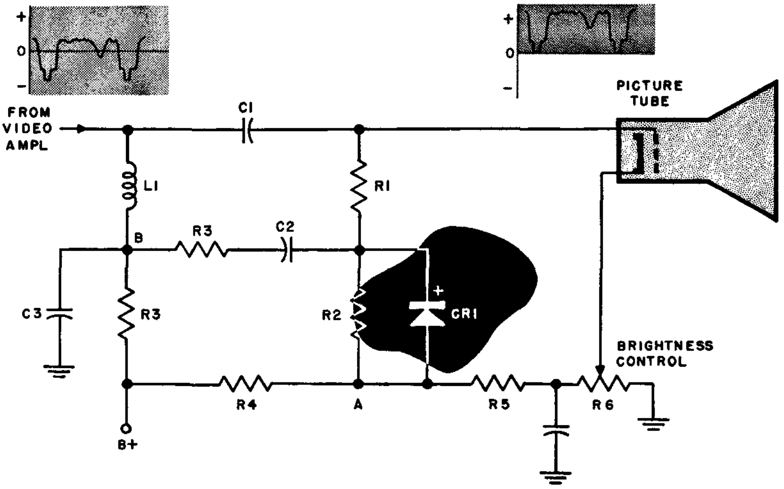


Fig. 6-21. A d-c restorer circuit diagram.

Counting Circuits

A counting circuit receives a number of uniform pulses. Each circuit, sometimes referred to as a frequency divider, represents a unit to be counted. A series of voltages proportional to their frequencies is produced. A counting circuit (Fig. 6-22) may be used in conjunction with a blocking oscillator to produce trigger pulses which are submultiples of the frequencies of the applied pulse. The pulses fed to the counting circuit must all be of the same amplitude and time duration if accurate frequency division is to be made. Counting circuits are ordinarily preceded by shaping and limiting circuits to insure uniformity of amplitude and width.

Positive and negative counter circuits. When pulses varying only in repetition frequency are applied to the input of a positive counter (Fig. 6-22) and cause K of CR2 to be negative with respect to ground, CR2 conducts through R1 and charges capacitor C1 during the pulse time. At the end of the pulse the charge on capacitor C1, as indicated in the figure, is such that CR1 conducts and discharges C1. This second action is necessary; otherwise C1 would build up a charge during succeeding positive pulses, rendering the circuit insensitive to the applied pulses. The current through R1 is proportional to the pluse repetition rate whose increases parallel increases in the average current flow. Conversely, when the repetition rate decreases, the average current flow decreases. The voltage drop developed across R1 can be used to control a succeeding stage. By reversing the crystal diodes, the circuit may be made to respond to negative pulses.

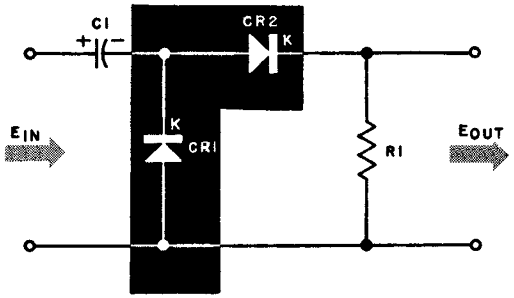


Fig. 6-22. Positive counting-circuit digram.

Limiters, Clippers, and Slicers

In pulse and transient applications special voltage waveforms are often required. These waveforms are frequently obtained by limiting or clipping the positive or negative peaks of an input signal. In *limiter* and *clipper* circuits, the output voltage is proportional to the input voltage *up to a certain level,* and is maintained at a constant value for all input voltages exceeding this limiting level, which may be positive or negative.

A *slicer* circuit is similar to the other two, except that here the voltage is maintained between a positive and a negative limiting level. All input voltages above the positive limiting level appear at the output as a constant maximum level, and all input voltages below the negative limiting level appear in the output as a constant minimum level. Between these two levels the output voltage is proportional to the input voltage.

Germanium, silicon, and selenium-diode rectifiers are suitable components for such circuits because of their low forward and high reverse resistance.

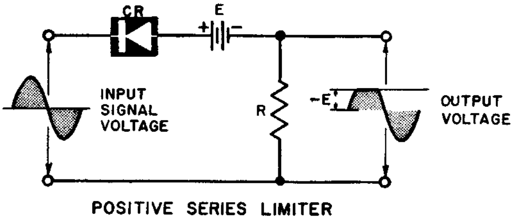


Fig. 6-23(A). Positive series limiter.

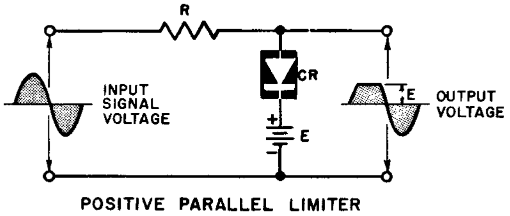


Fig. 6-23(B). Positive parallel limiter.

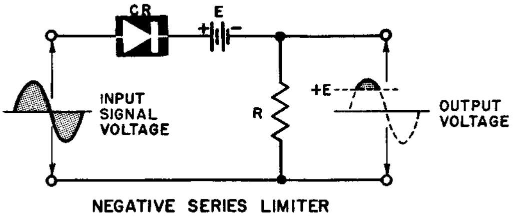


Fig. 6-23(C). Negative series limiter.

Figure 6-23 illustrates different types of limiter and slicer circuits. The circuit shown in 6-23A is a series-diode limiter with a positive bias of E volts, used for positive limiting. This circuit conducts for all negative values and all positive values of input voltage up to +E volts. For input voltages above +E, the rectifier stops conducting and acts like a closed switch, hence limiting occurs at this level. Circuit B is a parallel diode with a positive bias of E volts, also used for positive limiting. For all values of input voltage up to +E volts, the rectifier is an open switch, and the output voltage is the same as the input voltage. When the input voltage exceeds +E volts, the circuit conducts and the output voltage remains constant at +E volts. Circuit C is a series-diode clipper with a positive bias of +E volts, used for clipping voltages below +E. This circuit only conducts when the input voltage exceeds the bias and the output voltage is proportional to the input voltage for all values exceeding the bias. There is a constant (zero) output voltage for all values of input voltage below the bias voltage. Circuit D is a parallel diode clipper with a negative bias of —E volts, used for negative limiting.

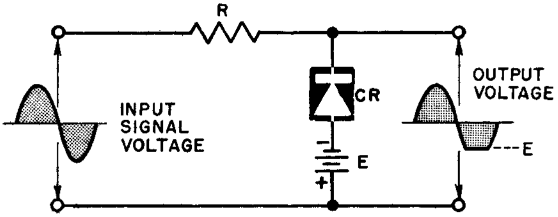


Fig. 6-23(D). Parallel diode clipper, negative limiting.

For all negative values of the input voltage to —E volts the rectifier conducts and the output voltage is constant. For values of the input voltage above —E volts, the rectifier is in a nonconducting state and the output voltage is proportional to the input voltage.

Figure 6-23E is a typical slicer circuit with bias applied. It is a combination of a positive parallel limiter CR1 and a negative parallel limiter CR2. The maximum (constant) output voltage of the circuit is equal to +E1 volts and occurs when CR1 conducts; the minimum (constant) output voltage is equal to —E2 volts and occurs when CR2 conducts. Between these maximum and minimum values the output voltage is directly proportional to the input voltage.

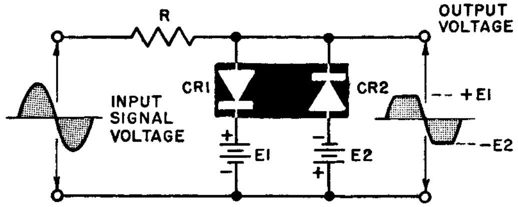
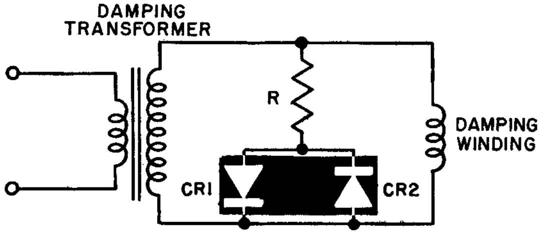


Fig. 6-23(E). Typical slicer circuit with bias applied.

A commercial application of a slicer circuit is illustrated in Fig. 6-23F. When small damping signals are applied neither rectifier conducts, and the small voltage across the secondary of the damping transformer appears across the damping winding. Above this small voltage, on positive half-cycles, CR1 conducts; on negative half-cycles CR2 conducts. Input signals are therefore clipped on both half-cycles and signals exceeding the conducting levels of the rectifiers do not reach the damping winding. The value of resistor R determines the slicing level.

Another application of a slicer circuit is shown in Fig. 6-23G; this circuit is used to produce a square wave output from a sinewave input. The connections are similar to those in Fig. 6-23E, and their easy current flow is in opposite directions. Crystal diode CR1 conducts when point B becomes positive with respect to point A, charging capacitor C1. On alternate half cycles, CR2 conducts, charging C2. The C1-R1 and C2-R2 combinations are chosen so that the charge on C1 and C2 leaks off slowly, biasing the crystals to suit the signal frequency and the degree of clipping. The crystal diode CR1 is made to conduct whenever point A reaches a positive potential higher than E1, limiting the positive half cycle to that value. Crystal diode CR2 conducts whenever the input reaches a negative value higher than E2.

Fig. 6-23(F). Commercial application of a slicer circuit.



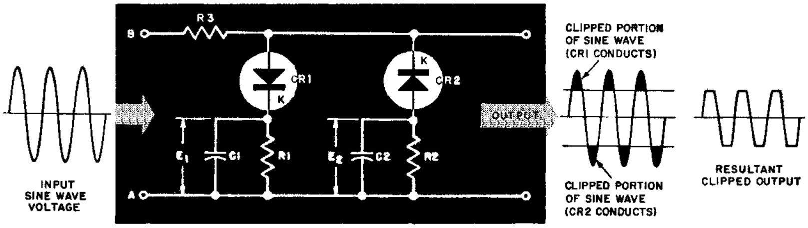


Fig. 6-23(G). Slicer produces square-wave output from sinewave input.

Meter and Measuring Circuits

Copper-oxide and crystal diodes are used for rectifier meter applications. When a d-c instrument is used to measure ac, the current to be measured is passed through the meter rectifier, then the resultant dc output is applied to the meter coil. The basic circuits shown in Fig. 6-24 are used for this application. Figure 6-24A shows a half-wave meter rectifier that is often used in multimeter applications when accuracy requirements are not too stringent. Where more accurate results are desired, the bridge circuit shown in Fig. 6-24B is used.

Regardless of the circuit configuration, the basic considerations are the same. Any unstable characteristic of the rectifier will result in meter inaccuracy. The possible inaccuracies that can be directly attributed to rectifier characteristics are; the high voltage drop of the rectifier (as much as one volt may be dropped across a rectifier in a 1ma meter), and nonlinear characteristics caused by temperature variations. These causes can be minimized by proper circuit design.

Crystal-diode types to be used in the half-wave circuit (Fig. 6-24A), must have excellent forward characteristics with a nearly linear forward resistance.

In the bridge circuit (Fig. 6-24B), copper-oxide cells are the more popular because they are easier to match and are generally more dependable. The characteristics of the rectifier instrument is directly dependent on the properties of the rectifier unit. The most important, as described above, is the resistance of the rectifier. However, this resistance is dependent on the applied a-c voltage being greatest when the voltage is small. This resistance increases so rapidly when the current decreases that increasing the current density (by reducing the cross-sectional area of the rectifier) reduces the resistance of the rectifier at low currents. For this reason copper-oxide cells designed for instrument rectifier applications have small cross-sectional areas, even though a larger area would result in less voltage drop per cell. (The voltage drop per cell is sacrificed for linear resistance).

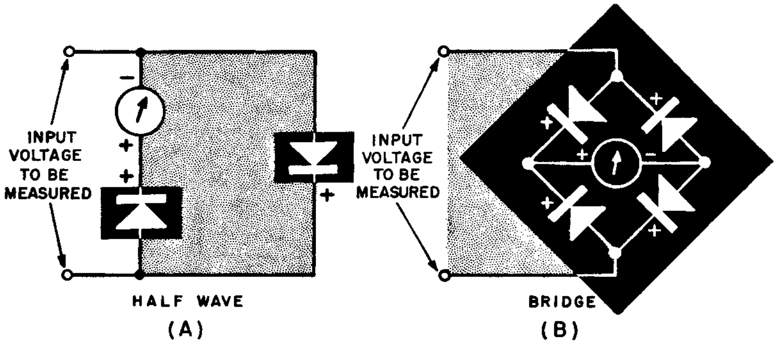


Fig. 6-24. Schematic diagrams of two basic meter rectifier circuits.

Efficiency of a meter rectifier is defined as the ratio, in percent, of the d-c output (meter) current to the a-c input current. For a given cell size, the efficiency depends on the circuit used. The full-wave circuit gives high efficiency because both halves of the input are utilized. For a given circuit, the efficiency varies inversely with cell area.

For the single-phase full-wave bridge circuit:

$$\text{Efficiency} = \frac{100}{F}\left[\frac{1}{1 + \frac{R_m}{R_r} + \frac{R_f}{R_r}}\right]$$

(This equation is derived from a simplified equivalent circuit with constant voltage input and fixed frequency.) Where: F = form factor of the current waveform (see Table 5-I) ; R_m = meter resistance; R_f = twice average forward resistance of one cell over a cycle; and R_r = one-half average reverse resistance of one cell over a cycle.

Assuming the forward-to-reverse resistance ratio R_f/R_r is constant for all cell sizes, the efficiency increases as reverse resistance R_r increases (i.e. as cell size decreases). It may be modified for temperature compensation (at the expense of reduced efficiency) by replacing two arms of the bridge with resistors.

The frequency response of the circuit improves with decreasing cell sizes, since the rectifier shunting capacity varies inversely with cell area. In general, the efficiency of the unit is reduced at higher frequencies and large cell sizes. Besides the shunting effect of the rectifier capacity, other effects (increased meter impedance, changes in multiplier resistor, impedance, power-factor changes), may also reduce efficiency.

A decrease in cell size produces an improvement of frequency response and efficiency, and a reduction in the variation of current with temperature. An increase of cell size reduces the voltage variation with temperature.

To increase the range of a voltmeter, a specific resistance is inserted in series with a unit. Its response is therefore directly related to the current flowing through this resistance. Similarly, to increase the range of a milliammeter, a specific resistance is shunted across the unit. *Its* response is therefore directly related to the voltage across *this* specific resistance.

If the requirement is a voltmeter only, a small-diameter rectifier cell would be desirable because of its minimal variation of current with temperature. Similarly, if the requirement is a milliammeter only, a large-diameter cell should be utilized because of its minimal variation of voltage with temperature. However, if the unit must function not only as a current-indicating device but also as a voltmeter, a compromise in cell size is required to produce the best overall results.

Probes

Because of their smaller size, lower capacitance, negligible transit time, and lack of filaments, crystal diodes have almost replaced diode vacuum tubes in probe applications. Figure 6-25 shows the circuits to two types of probes. The capacitor in the series-circuit probe charges to the peak value of the r-f. This voltage is applied to a vtvm or oscilloscope. The d-c indication will then be the peak voltage of the r-f signal measured. The effects are similar for the shunt circuit, since the diode functions as an open circuit during its nonconducting cycle and a short circuit during its conducting cycle. The voltage applied to the vtvm or oscilloscope is the same pulsating dc as in the series circuit. (To calculate rms voltage from peak, multiply the peak reading value obtained by .707.) The line capacitor, in series with the voltage being measured, isolates the crystal from d-c voltages that may be present in the circuit under test. The accuracy of the probe should be checked at frequent intervals.

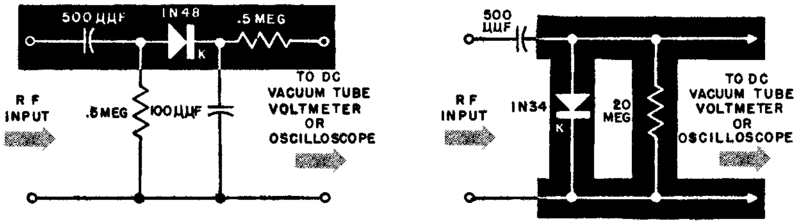


Fig. 6-25. Schematic diagrams of (A) Series probe. (B) Shunt probe.

All precautions should be taken to keep the probe as small as possible. This is desirable not only because it makes it easier to handle, but also because the smaller the probe, the smaller its distributed capacitance.

7. troubleshooting, repair, and replacement

Troubleshooting circuits which use metallic rectifiers or crystal diodes are no different from troubleshooting vacuum-tube rectifier circuits. Vacuum diodes fail, and so do metallic rectifiers and crystal diodes. In most cases there is little else to do but replace the defective unit with a new one. In a few instances, however, a crystal diode or a metallic rectifier can be restored to normal operation by adjustments described later in this chapter. It is advisable, however, that the units be replaced whenever they are suspected of being faulty, or when tests show them to be substandard. Although metallic rectifiers are reliable and give very little trouble, it is important to know how to install and replace these units. It is also important to be able to recognize faulty units.

In failure, metallic rectifiers exhibit many of the same symptoms as their counterparts, the vacuum-tube diodes. Rectifier supply failure may be caused by open circuits, short circuits, low output, etc. In the vacuum-tube rectifier the most common cause of low output voltage is caused by low emission, The equivalent failure in metallic rectifiers is caused by an increase in forward resistance and a resulting rise in operating temperature. A rectifier may also fail because of decreases in reverse resistance. This increases reverse current beyond allowable limits. Consequently, the temperature of the unit will rise, causing damage which may be irrepairable. Whether a rectifier has been damaged to an extent that demands replacement can only be judged by inspection and the tests given below.

Visual Inspection — Metallic Rectifiers

Dark spots. A faulty metallic rectifier can sometimes be detected by careful examination of its plates. The actual reason for failure within a metallic rectifier is heat, whether generated within the cell itself or induced from some external source. When the rectifier reaches a sufficiently high temperature, a physical rupture of the barrier layer will occur. The rupture appears as a round dark spot. If this spot is small, there is no permanent damage (the plates are self-healing). However, the effective rectifying area is decreased. Subsequent passage of current through this decreased area may cause high heat concentrations and ultimately bring about complete failure. Normally if more than 20% of the plate area is punctured, the rectifier is considered damaged beyond the allowable limits and should be replaced.

Solder-like blotches. Excessive heating can also cause melting of the counter electrode. If this occurs, the alloy of which it is made will liquify, run to the bottom edge of the cells and drop off. Thus, a discolored plate or solderlike blotches beneath a rectifier stack indicate that the unit has been heated excessively and must be replaced.

The washer. High heat and subsequent failure of the rectifier may also be caused by a concentration of current density on the surface. This is usually attributed to a poor contact between the current-collecting washer and the front electrode. Inspection of the washer and the area surrounding it will reveal this condition. Any discoloration or burned spots here indicate that the rectifier is faulty. Discolorations near the contact washer are not considered serious if their area keeps within 20% maximum. These spots are caused by an application of higher-than-rated voltage. They may also occur when voltage is first applied after long periods of idleness. If rectifier arcing is persistent, however, the rectifier should be replaced.

Crystal diode failures cannot be detected by visual means; tests must be made of their electrical characteristics.

Typical Metallic-Rectifier Troubles and Symptoms

Troubles that can be attributed directly to the rectifier are:

1. Open-circuited rectifier.
2. Short-circuited rectifier.
3. High-leakage current.
4. High forward-voltage drop.
5. Over-heated rectifier (caused by excessive loading or poor ventilation.

Faults 1 and 2 result in no output from d-c supply, 3 and 4 result in lowered output plus excessive heat, and fault 5 results in lowered output. Faults 3 through 5 will cause the rectifier to overheat beyond safe limits and will materially shorten the life of the unit or destroy is completely.

Typical Crystal-Diode Troubles

Troubles due to crystal-diode failure usually are limited to an open or shorted element. There have been instances, however, where a faulty diode has been the cause of noisy or intermittent operation. The effects of these failures are peculiar to the circuit in which the diode operates and cannot be explained by general statements.

The easiest and most practical crystal-diode test for determining whether a crystal diode is open or shorted is made with an ohmmeter. However, since an ohmmeter usually applies voltage to the crystal, it is not a perfectly reliable instrument for testing quality. (The resistance of a diode varies under applied voltage and must be checked under rated conditions if the results are to be a conclusive indication of quality.) A relatively low resistance (a few-hundred ohms) in both directions indicates that the unit is shorted; relatively high resistance (several thousand ohms) indicates that the diode is open. The resistance of a good crystal is high in one direction and low in the other. (The actual value resistance is, of course, dependent on characteristics of the crystal.)

Testing Metallic Rectifiers

Some simple tests for determining the quality of a metallic rectifier are similar to the conduction, or dynamic, tests given a vacuum-tube diode with a standard tube tester. It is impossible to duplicate in one test instrument or test circuit the multitude of circuits and loads in which the rectifier will operate. Therefore, the most convincing test is to substitute the suspected component with one known to be good. The best evaluation of quality is obtained with the rectifier actually operating in the circuit for which it was intended. The tests that follow will serve as a guide for all such testing.

Continuity testing. A continuity test of a metallic rectifier will quickly determine whether a rectifier is shorted or open, although it will not determine the quality of the rectifier. When using an ohmmeter it must be remembered that the rectifier is neither a symmeterical nor a linear device. The resistance of the unit in either direction depends upon the amount and polarity of the voltage applied. Since most ohmmeters have various ranges, and at each range there is a different voltage at the test probes, the d-c forward or reverse resistance of the rectifier varies when read on different ranges. Therefore, the values of the actual resistance readings are not truly meaningful.

To check the rectifier for an open or short circuit, the ohmmeter is set to its highest range and the probes are placed across the rectifier, first in one direction and then in the other. If the meter indicates that the resistance in one direction is much greater than in the other, the rectifier will probably work. If the reading is extremely high in both directions, the unit is open. If the meter reading is low in both directions, the unit is partially shorted.

Dynamic tests. An idle metallic rectifier exhibits marked differences from one that is in use. This may be evidenced by a change in either the forward or reverse characteristics of the unit. An idle unit (particularly a selenium rectifier) presents high initial-leakage current through the circuit. Gradually, the reverse resistance increases and the reverse current through the unit decreases. Such initial "aging" should not be confused with actual metallic-rectifier aging, for it occurs over an extended period of use.

Reforming (increasing the rectifier reverse resistance), is caused by the molecular realignment that takes place within the crystalline selenium semiconductor when reverse voltages are applied to the rectifier. High initial reverse currents, followed by an exponential decay, are a characteristic of rectifier reforming. Since copper-oxide rectifiers are natural rectifiers, little or no reforming occurs during the initial voltage application phase. Other characteristics that must be remembered when testing the performance of rectifiers are time, temperature, applied voltage and current, and the test circuit employed.

Load test. The circuit shown in Fig. 7-1 is useful in determining whether a rectifier is capable of delivering its specified output. The circuit is a simple half-wave rectifier containing a resistive load. The input is variable (an auto-transformer may be used for this purpose). An a-c voltmeter (V1, 0-150v) across the secondary of the transformer measures the voltage applied to the rectifier, while a d-c ammeter (A) in series with the rectifier measures the current flow through the circuit. The second d-c voltmeter (V2, 0-250V) measures the voltage developed across the load and gives a good indication of the quality of the rectifier. Any conventional vtvm may be used.

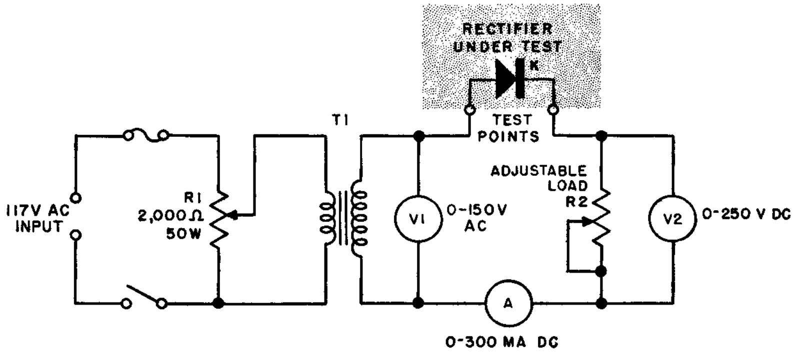


Fig. 7-1. Load-test setup for metallic rectifiers.

When testing the rectifier, a voltage equal to its rated input is applied to its a-c terminal. Whenever the test is performed on rectifiers that have been "on the shelf" for extended periods, the input voltage should be increased from zero to the rated voltage in steps of 25 volts. If the stack begins to spark and sputter the input voltage should be decreased slowly until the sputtering or sparking stops. If, after a few minutes, an increase in the voltage still causes the rectifier to sputter and spark, the rectifier is damaged or deformed.

Upon the application of rated a-c voltage, resistor R2 (Fig. 7-1) is adjusted until the rated d-c output is indicated on the meter. (Always start with R2 at maximum resistance.) Measuring the d-c output voltage across R2 determines whether the rectifier output is as specified for a resistive load. If the measured output is within ±10% of the rated output, the rectifier can be considered good. If it falls outside these limits the rectifier should be considered faulty and discarded. To test the output for a circuit using a capacitor as a load, place a capacitor of equal size across the output and measure the output voltage. It, too, should fall within ±10% of the rating. To test a rectifier without removing it from the circuit, connect a pair of test leads to the test terminals. Place the leads across the rectifier and measure the d-c output across the input filter capacitor.

Forward voltage-drop test. The forward voltage drop, and consequently the forward resistance of a rectifier, can be measured with the test equipment shown in Fig. 7-2 (A). A variable input transformer with good voltage regulation is required to supply the ac to the circuit. Since a perfect transformer is not available, some loading can be expected and slightly different results will be obtained when the forward voltage drop is measured by a peak-reading rms or average-indicating voltmeter. The half-wave rectifying-type instrument, shown in Fig. 7-2 (B), may be used to minimize any error caused by loading; the voltmeter V2 from Fig. 7-2 (A) should be connected in the circuit of Fig. 7-2 (B) as indicated. The input voltage should be increased gradually from zero by means of the variable autotransformer. If the stack sputters or sparks as the voltage is increased, decrease the voltage slightly and wait a few minutes. The procedure should be repeated until the input voltage is up to rated voltage or the meter reads full scale. Allow approximately five minutes for the rectifier to stabilize. Meter V2 will then indicate the forward voltage drop of the rectifier.

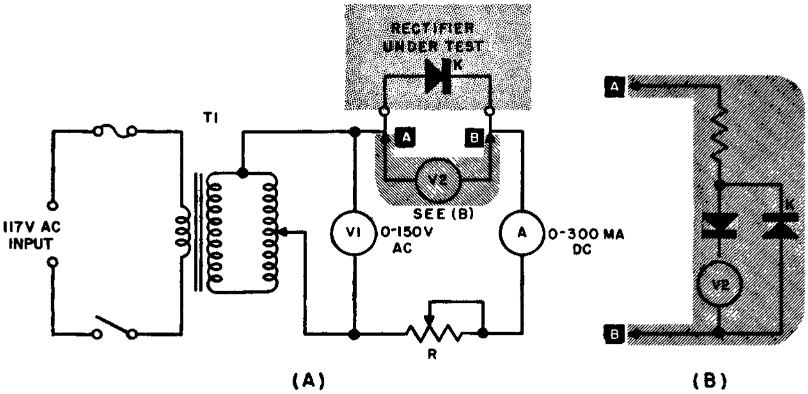


Fig. 7-2. (A) Basic test setup for measuring forward voltage drop. (B) Minimizing error caused by loading.

When the voltage across the rectifier is known, Ohm's law calculations can be used to determine the forward resistance of the rectifier. The forward resistance or voltage loss that can be tolerated depends on circuit requirements and the initial percentage of rectifier voltage drop to output voltage. For example, if the resistance of the rectifier is initially 10% of the total circuit resistance, an increase of 50% in rectifier resistance decreases the output voltage about 5%. However, if the rectifier resistance is 50% of the circuit resistance, the same increase causes a 20% reduction of output voltage. A rectifier can be considered good if its output voltage comes within 5 to 10% of its rated value. (In a few cases, rectifiers that come within these limits will not give satisfactory results.) It is good practice to replace a rectifier whose output voltage is near or beyond the operating limit.

Leakage current tests. The circuit shown in Fig. 7-3 provides a convenient method for determining the leakage current of a half-wave rectifier stack. The input voltage is made variable so that voltage may be increased gradually from zero to rated voltage. (A multitude of input voltages is provided for testing numerous rectifiers.) A variac or similar transformer may be substituted for the circuit arrangement shown. Voltmeter V provides a ready reference of applied voltage. Note that the circuit has two rectifiers, connected back-to-back. This limits the current flow in the circuit to that of leakage current. The flow is a composite of the leakage current of the circuit rectifier CR1 and the rectifier under test, therefore, a circuit rectifier of known quality and leakage current must be used. The leakage current for the circuit rectifier may be plotted and kept as a reference. In that way, when leakage current of a rectifier is measured, the current drawn by CR1 may be subtracted from total current, giving a true value for the rectifier being tested. (A vacuum tube rectifier may be substituted for CR1.)

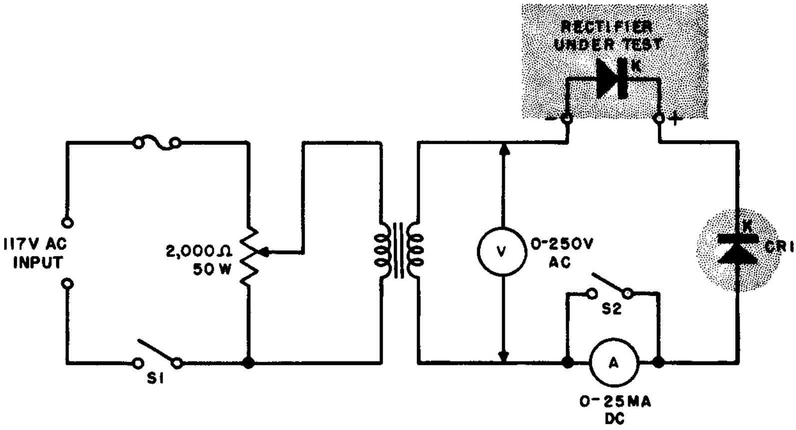


Fig. 7-3. Reverse (leakage) current-measuring setup for a half-wave rectifier.

To measure leakage current, increase the applied a-c voltage slowly, pausing at various voltages. If sputtering and sparking occur at the rated voltage, the rectifier is badly deformed. When the voltmeter indicates rated voltage, the milliammeter will indicate total leakage current for the two rectifiers. If the reverse current is not more than 5% of the rated load current the rectifier is considered good. If the millammeter indicates a reverse current from 5 to 10% of the rated output current, the rectifier is questionable. Rectifiers with reverse currents greater than 10% of rated forward current flow are considered faulty and should be discarded.

The leakage current of centertapped (A) or bridge (B) stacks may be measured by the circuits shown in Fig. 7-4. Note that the output connections of the two units are not terminated. No rectifier is needed, since the only currents that will be measured in either circuit will be total leakage current.

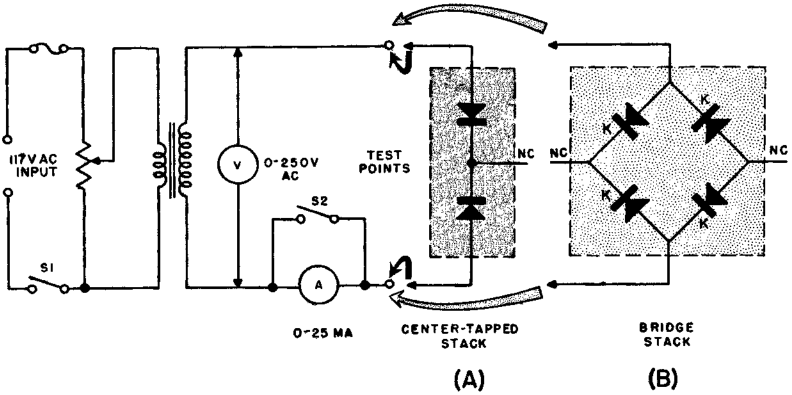


Fig. 7-4. Reverse leakage test setup for a centertap and bridge stack.

Testing Crystal Diodes

The forward and reverse currents of crystal diodes can be easily tested because the ratings and characteristics of most manufacturers are based on the application of 1 volt dc in the forward direction and 50 volts dc in the reverse direction (exceptions to this are gradually increasing). Consequently, if the applied voltage is known and the current is measured, a simple calculation ($R = E/I$) gives the resistance of the diode for that voltage. It must be remembered that these tests give only a general indication of the relative worth of the crystals. Final acceptance or rejection should be determined by their action in the circuits. In many practical applications of diode work, current values are considered more than the resistance (because of the danger of a diode resistance value at a point of operation being considered as a linear resistance and incorrect approximations being made).

Forward current test. The circuit of Fig. 7-5 (A) is used to determine the forward current flow of a crystal diode. The test circuit may operate from a battery or converted d-c supply. A low d-c voltage is applied via a potentiometer to the crystal in the forward direction. Many of today's high-conductance diodes are easily burned out at 1.5 volts. Even 1 volt, if applied for more than a few seconds, may burn out some diodes. The recomended technique is to use a 1.5 volt source and start the applied voltage at zero (with the arm of the potentiometer starting at its minus or ground side) and increase it until the specified current level is reached. Simultaneously, the voltage drop across the diode must be monitored with a voltmeter. In most cases the voltage will be less than 1 volt. If the current meter reads rated current flow ±10%, the diode is probably good.

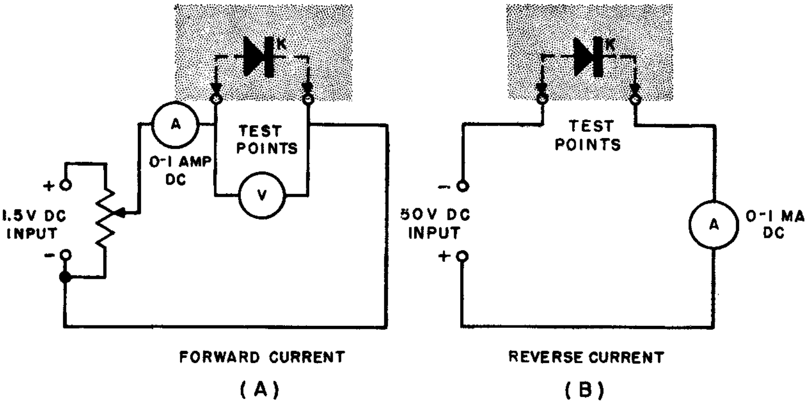


Fig. 7-5. Crystal diode testing circuit. Test for (A) forward current, and (B) reverse current.

Reverse current test. The circuit shown in Fig. 7-5 (B) can be used to measure the reverse current. A potential of 50 volts is applied to the crystal in the reverse direction. (Refer to the manufacturer's specifiications to be sure of this voltage.) If the value of the reverse current is within ±10% of rated reverse current the crystal is probably good. If the meter indicates a value greater than ±10% rated reverse current, the crystal should be replaced.

Television types. Although crystal diodes designed especially for television and uhf applications exhibit the same characteristics as general-purpose diodes, the tests given above are at best only quick and approximate. The procedures necessary and the equipment required to test these units are quite complex. To service a television receiver with no video output, check the crystal with an ohmmeter to be sure it is not open or shorted. If the video output is weak and washed out, or a distorted picture appears on the screen, the diode is the chief suspect and one known to be good should be substituted.

Repair and Replacement

The replacement procedures for a metallic rectifier may vary from a five minute job for soldering a few leads, snapping on a few wires or tightening a nut, to something much more involved. Where an exact replacement is available the work is extremely simple, since the same mounting hole may be used. If an equivalent rectifier is used, special attention must be given such details as adequate mounting strength, space limitations, size, position of rectifier fins for best heat dissipation, and correct polarity.

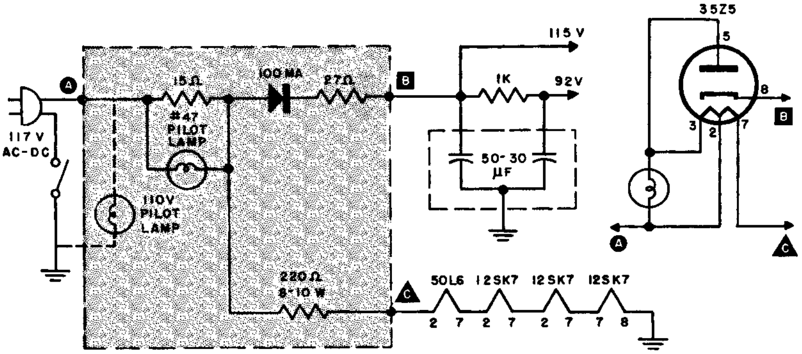


Fig. 7-6. Ac-dc power supply showing how a metallic rectifier and its associated components (shaded area) replace a vacuum tube (at right).

It is possible to replace a defective rectifier tube with a metallic rectifier if the two main differences between a metallic rectifier and a vacuum tube are considered. First, the metallic rectifier has no filament. If one is to replace a vacuum-tube rectifier in a circuit using a transformer to supply the rectifier-filament voltage, there is no problem. Simply tape the unused filament leads. However, if the metallic rectifier is to be substituted for a vacuum tube rectifier whose filaments are in series with the other tube filaments in the circuit, it is necessary to add a resistor in place of the filament removed.

Second, metallic rectifiers have less internal resistance than do vacuum tube rectifiers. It is necessary to increase the resistance in series with the metallic rectifier so that the total circuit resistance remains the same as with the vacuum-tube rectifier. The current-limiting resistor, usually found in series with the rectifier, can serve this function. When substituting a metallic rectifier for a vacuum tube, reasonable care must be taken that adequate ventilation is provided and that the rectifier plates do not come in contact with either the chassis or other components.

Direct Replacement of Metallic Rectifiers

When replacing a defective unit with an exact replacement, the procedures outlined below should be followed to insure long life and satisfactory operation.

1. The replacement unit should usually be placed in the exact position of the original. However, if it has been determined that the failure of the original was due to excessive temperatures, the rectifier should be moved to a new position which provides better ventilation. Best cooling is generally obtained when the fins of the rectifier are mounted in a vertical plane and when the passage of air at the top and bottom is not restricted.
2. Be sure that the rectifier is firmly mounted to the chassis so that it cannot accidentally come in contact with other components. Also, take special care that all insulators and barriers provided by the set manufacturer are replaced in their original position. Before wiring or fastening the replacement unit, inspect all wiring, insulators, mounting studs, and barriers for cracks or dirt. Replace or clean any damaged or dirty parts.
3. When soldering wires to the terminal lugs, do not allow the heated soldering iron to come in contact with the rectifier plate or the terminal lugs for extended periods. The heat from the iron may melt the front electrode or damage the coating. (Soldering techniques are discussed later is this chapter.)
4. Before applying power to the set, check the line resistor. If the cause of rectifier failure was due to excessive overloads, it is likely that this resistor was also damaged.

Replacement Units — Metallic Rectifiers

Table 7-I will aid the technician in selecting a suitable replacement for a selenium rectifier that has become defective. The table lists the more popular of the radio and television selenium rectifiers

and five manufacturers' stock numbers for each unit. The units' ratings are very similar and the units may be interchanged. For a more complete list, see Table II in the Appendix.

If a replacement is needed and there is no exact replacement part available, the rating of the rectifier can be obtained from the equipment schematic diagram. The values given are maximum continuous d-c output (in milliamperes) and maximum input (in volts). The ratings may be found either adjacent to the rectifier on the diagram or in the table of component parts accompanying the diagram. Once the values are obtained it is necessary only to match these values to the ones given in the chart to find suitable replacements. When the rectifier ratings fall between two values on the table, select the next highest rating.

For example, assume that a television receiver's rectifier is destroyed and that no exact replacement part is available. Investigation of the original parts list or schematic shows 300 ma, 130 volts adjacent to the rectifier. This would mean that the rectifier is rated at 300 ma maximum d-c output and 130 volts maximum input voltage. Referring to the chart, it is found that International Rectifier Part No. RS300SL, Sarkes Tarzian Part No. 300, Federal Part No. 1090, Radio Reccpter (Seletron) Part No. 6Q4, and Bradley Rectifier Part No. RS-300, all satisfy these requirements. Any one of these units could be substituted for the original to obtain satisfactory operation.

TABLE 7-I

Radio-TV Selenium-Rectifiers Reference Guide

Max D-C Output (ma)	Max Input (volts)	International Rectifier Part No.	Sarkes Tarzian Part No.	Federal Tel. & Rad. Part No.	Radio Receptor (Seletron) Part No.	Bradley Rectifier Part No.
65	130	RS065	65	1002	8J1	RS65
75	130	RS075	75	1003	5M4	RS75
100	130	RS100	100	1004	5M1	RS100
150	130	RS150	150	1005	5P1	RS150
200	130	RS200	200	1006	5R1	RS200
250	130	RS250	250	1010	5Q1	RS250
300	130	RS300SL	300	1090	6Q4	RS300
350	130	RS350SL	350A	1023	5QS1	RS350
400	130	RS400SL	400	1130	5S2	RS400
500	130	RS500SL	500	—	5S3	RS500

Substitution — Metallic Rectifiers

Selenium rectifiers have been designed which can replace almost all conventional rectifier tubes found in home receivers. Economy of operation and maintenance are two of the many practical advantages of substituting a selenium rectifier for a vacuum tube. This is particularly true in the case of portable and a-c/d-c receivers. Typical examples are given below.

Substituting a metallic rectifier in an a-c/d-c set. When a selenium rectifier is to replace a rectifier tube in an a-c/d-c receiver, it is necessary to supply a resistor to take the place of the tube filament, to maintain filament continuity, and to provide a potential for the pilot lamp. Table 7-II gives recommended resistance values that should be substituted for the tube's filament. Care must also be taken in selecting the proper rectifier to match the maximum d-c output of the tube. (Table 7-I gave manufacturers part numbers for substitute rectifiers.)

Figure 7-6 shows a typical a-c/d-c power supply utilizing a 100 ma selenium rectifier. The right side of the illustration shows how the original 35Z5GT/G vacuum tube circuit was connected at points A, B, and C. The shaded area shows how this 35Z5GT/G tube was replaced with the proper selenium rectifier and its accompanying resistors.

In the crcuit shown, it was necessary to add resistance in series with the rectifier because the internal resistance of the vacuum tube was nearly equal to the voltage drop across the 15-ohm pilot-lamp resistor and the rectifier. The filament of the rectifier tube was important because it was part of the series filament circuit, and the first half of the filament provides the voltage for the pilot light. Therefore, a resistor was added in series with the remaining tube filaments. Its value was determined by dividing the tube's voltage drop by the current that the series filament string will draw. These values are given in table 7-II, and can be calculated using the formula:

$$R \text{ (series resistor)} = \frac{E \text{ (voltage dropped by the rectifier tube filament)}}{I \text{ (heater current)}}$$

The voltage rating of the resistor can be calculated by using the power formula ($P = I^2R$), then doubling it to provide an adequate safety factor. The size of the pilot-light resistor can be calculated in much the same manner. A 110-voltage pilot lamp may be connected across the circuit, as shown by the dotted connection on Fig. 7-6.

TABLE 7-II

Filament Resistor Substitution Guide

Tube Type	Filament Voltage (volts)	Filament Current (milliamps)	Filament Resistor (ohms)	Wattage (watts)
25FT	25	0.15	170	15
25Y5	25	0.3	85	15
25Z4	25	0.3	85	15
25Z5	25	0.3	85	15
25Z6GT	25	0.3	85	15
35W4	35	0.15	230	10
35Y4	35	0.15	230	10
35Z3	35	0.15	230	10
35Z4GT	35	0.15	230	10
35Z5GT	35	0.15	230	10
35Z6G	35	0.30	120	20
40Z5/45Z5GT	45	0.5	300	10
45Z3	45	0.075	600	7
50X6	50	0.15	330	15
50Y6GT	50	0.15	330	15
50Y7GT	46	0.15	170	16
50Z6G	50	0.30	170	30
50Z7G	50	0.15	330	15

Placing the rectifier in the circuit. The rectifier may be placed in the circuit by soldering two extension leads on to it. They should be color coded with a red wire for the d-c terminal and a black or yellow lead for the a-c terminal. The rectifier may be mounted over the original tube socket by providing a suitable mounting bracket. The leads can be connected to the underside of the chassis by running them through the key in the tube socket. Solder the yellow lead to the a-c input and the red lead to pin 8 of the tube socket. (The a-c circuit will have to be modified to compensate for the addition of the pilot lamp and the filament-dropping resistor.)

An alternate method for connecting the rectifier to the circuit is shown in Fig. 7-7. Remove the glass envelope from a discarded octal-base vacuum tube. Unsolder all the leads from the pins and clean them, making sure that no solder remains inside the socket pins. Connect a single copper wire to each terminal of the rectifier. Insulate these leads with short pieces of spaghetti. As shown, insert the extension leads through the pins of the socket. Solder the leads to the socket and snap off the excess ends with a pair of diagonal pliers. Of course, the wiring to the terminal of the old socket will have to be modified to include the socket connections. It is recommended that the positive terminal of the rectifier be extended through pin 8 and the a-c lead through pin 5. These correspond to the cathode and plate of the 35Z5GT. The circuit just described can be applied to all a-c/d-c sets regardless of the type of rectifier tube used.

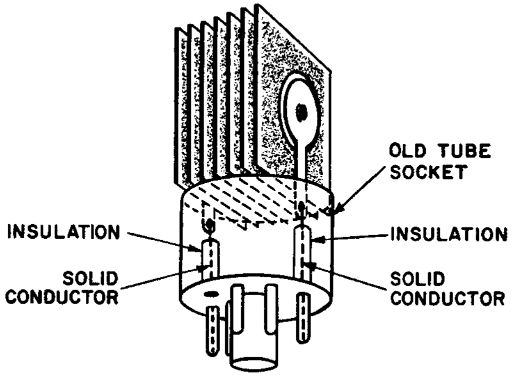


Fig. 7-7. Connecting a metallic rectifier to replace a vacuum tube in an ac-dc power supply.

Substituting a metallic rectifier in an a-c/d-c portable. A simple conversion involving a three-way portable is shown in Fig. 7-8. The right side of the illustration shows how the vacuum-tube circuit appeared when connected at points A, B, and C. The shaded area

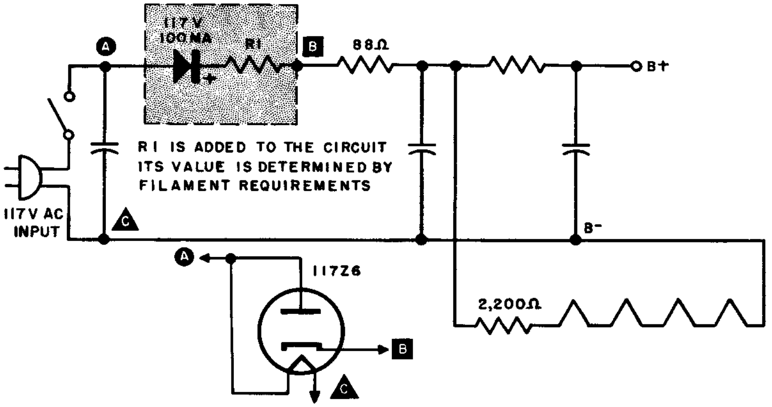


Fig. 7-8. Conversion of ac-dc portable, showing how a metallic rectifier and its associated component (shaded area) replace a vacuum tube (at right).

shows how the metallic rectifier is connected. The a-c problem here is simple, since elimination of the vacuum tube eliminates the need for filament power. The series resistor R1 is very critical; if it is omitted one or all the amplifying tube filament will probably open up upon application of power. (In an a-c/d-c portable, voltage for the filaments of the amplifying tubes is generally taken from the B+ supply, so any increase in voltage or current in that circuit may blow them.)

The conversions described generally apply to all sets regardless of the type of rectifier used. However, each circuit carries its own electrical requirements and is wired in accordance to its own needs. Therefore, no rules can be made governing the conversion of all sets. Study the schematic and the wiring of the set carefully, then plan the modification on paper. If this is done properly no difficulty should be encountered.

Reforming Selenium Rectifiers

Metallic rectifiers, particularly selenium rectifiers, exhibit properties which cause an increase in forward resistance and a decrease of back resistance which vary with time. In all but a few instances the change is only temporary and not serious. However, extended storage causes a deformation action which may destroy the rectifier upon application of rated voltage. Selenium rectifiers that have been stored for prolonged periods should not be placed in immediate service.

Most metallic rectifiers will reform themselves upon application of rated voltage (the initial current through the stack will cause an increase in reverse resistance). This may or may not be accompanied by sparking and sputtering, depending upon the degree of deformation. If the stack begins to sputter and spark, the power should be allowed to remain on for a very short period. Normally, the voltage applied to a rectifier will cause the rectifier to reform, increasing reverse resistance and decreasing reverse leakage current. If the sparking continues, however, the rectifier should be reformed as outlined below.

Typical Reforming Circuit

A typical reforming circuit for a half-wave stack was shown in Fig. 7-3 (the circuit is the same as that used in measuring leakage current). The voltage applied is gradually increased until a value slightly higher than the rated voltage of the rectifier stack is reached.

If the stack begins to sputter or spark during the initial application of voltage, the voltage must be decreased to some value slightly less than that at which the arcing occurs, and maintained for five minutes. This is necessary to allow time for the rectifier to reform. This step should be repeated with gradual increases in voltage until the rated voltage is attained. When the rated voltage is reached, the rectifier must remain in the circuit for about 10 minutes. The rectifier is now reformed. The leakage current should be checked and if it falls within ±10% of the rated value, the rectifier is ready for service.

If the rectifier continues to sputter or does not fall within the tolerance, it should be discarded. Some damaged or badly deformed rectifiers will sputter and spark at every increase in applied voltage. Upon completion of the reforming process, inspect the rectifier for excessive blow-out patches. If more than 20% of its conducting area has been damaged the unit will rectify, but with reduced output voltage and increased operating temperatures.

Typical reforming circuits for half-wave centertapped stacks or bridge stacks were shown in Fig. 7-4. The output terminals of the stacks are left open, restricting current flow in the circuit to leakage current only.

Soldering

A great deal of care must be exercised when soldering either metallic rectifiers or crystal diodes. The units can be permanently damaged by the application of excessive heat. When soldering or unsoldering leads and terminals, the heated iron or solder should not touch either the plates of a metallic rectifier or the housing of a a crystal diode. If the areas of the surface to be soldered are large they will dissipate heat, and the iron must be applied for longer periods to insure proper heating and a good solder connection. If this is necessary, grasp the lead between the unit and the terminal being soldered with a pair of long-nose pliers or other metal conductor. The pliers will conduct the heat away from the unit, and thus protect it.

Replacement Techniques — Crystal Diodes

Replacement techniques for crystal diodes involve only two important considerations: the careful and skillful use of the soldering iron and the intelligent selection of a substitute unit where a direct replacement is not available. Physical size may be a problem in industrial applications.

In some circuits, particularly those involving high frequencies, it is best to place the new crystal in exactly the same position as the original. When selecting a replacement, the electrical characteristics must be carefully examined, especially when working with video detectors, f-m discriminators, and uhf mixers, since some crystals have frequency limitations.

The most important single consideration to be observed when replacing a crystal-diode unit is to use as little heat as possible to produce a good solder joint. It is common practice to keep leads to components as short as possible. With crystal diodes, however, the practice is reversed; slack is usually preferred. This is to insure that the tension ordinarily encountered when leads are made short will *not* be present, lessening the chances of damage caused by thermal expansion or prodding (however, the leads should not be so long or loose that danger of a short circuit exists.)

The tolerances encountered when replacement is necessary are usually much smaller. Be extremely careful when soldering, and use the techniques given below. In many cases, the diode is not soldered into the circuit but is placed in a crystal holder. If a screw-type unit is involved it is only necessary to be sure that the unit has sufficient pressure to insure good contact. When a diode with leads is used, it is suggested that the leads be cut to the size of the defective unit and the crystal diode be inserted into the clip.

When soldering a replacement to a terminal or socket, be sure that the heat from the iron does not damage the crystal. Protection can be provided by a heat shunt placed between the body of the crystal and the terminal to which it is to be soldered. Gripping the lead between these points with a pair of long-nose pliers will help.

Substitution of video detector and other types of diodes requires careful attention to polarity. As with metallic rectifier schematic symbols, greatest electron conductivity takes place from the bar to the arrowhead. However, unlike metallic rectifiers, the physical marking will appear according to the mode of operation, as previously explained. This coincides to vacuum-tube diode applications in similar circuits.

The effect of reversed diode polarity is probably the most noticable in a video detector. The output of the detector will be 180° out of its proper phase. Consequently, a negative picture will appear on the screen. In a half-wave meter circuit, a reverse diode will give a negative reading on the meter.

Repair Procedures — Crystal Diodes

Once a diode rectifier is defective there is very little that can be done to restore its rectifying properties. It is simplier to replace the defective unit with a new one than to try to repair it.

Since a crystal diode is delicately adjusted to near-optimum performance during assembly, any attempt to restore the diode to near normal is highly unsatisfactory (and practically impossible in hermetically sealed glass diodes).

If the diode has a small screwdriver slot at one end, restoring the rectifying properties of the unit is possible. Turn the adjustment screw in a clockwise direction to place the cat's-whisker in contact with the silicon at a new, sensitive spot. This method is similar to the hunting and searching that had to be done with the old galena-type cat's-whisker. After each move, the crystal should be checked with an ohmmeter. When a high-resistance reading is obtained in one direction and a low resistance in the other, the crystal will probably rectify. The quality of rectification is questionable, however, and should be tested by measuring the forward and reverse currents and comparing them to the rated values. (This is *not* recommended in industrial applications where noise, insertion losses, etc. are of prime importance).

appendix

The reference data in the following tables contain information on the electrical and mechanical characteristics of selenium rectifiers, crystal diodes, and microwave silicon diodes. The data and listings reveal the most important characteristics. For additional information, refer to the manufacturer's specifications. The information contained herein has been compiled from the most reliable sources available.

TABLE I

NEMA Code Designations

The chart shows the NEMA (National Electrical Manufacturers Association) standards for code designations of industrial, selenium and copper-oxide stacks. This does not imply that all manufacturers use these coding designations. The chart is presented as a guide and is intended to provide an easy method of interpreting clearly the electrical characteristics of a rectifier when the manufacturer uses this code.

Individual stack-rectifier characteristic listings are not included: the number of such units available runs into the thousands, and there are infinite possible combinations and designations for such stacks.

Type of Finish

1. No finish
2. Type A*
3. Type B†
4. Type C§
5. Type A } with fungicide
6. Type B } with fungicide
7. Type C } with fungicide
8. Finish not covered by code

* Type A provides general-purpose protection from normal atmospheric corrosion for all metallic rectifiers.

† Type B protects metallic-rectifier cell or stack after exposure to a 50-hour 20% salt spray test at 40°C so it performs to applicable electrical specifications with no excess corrosion.

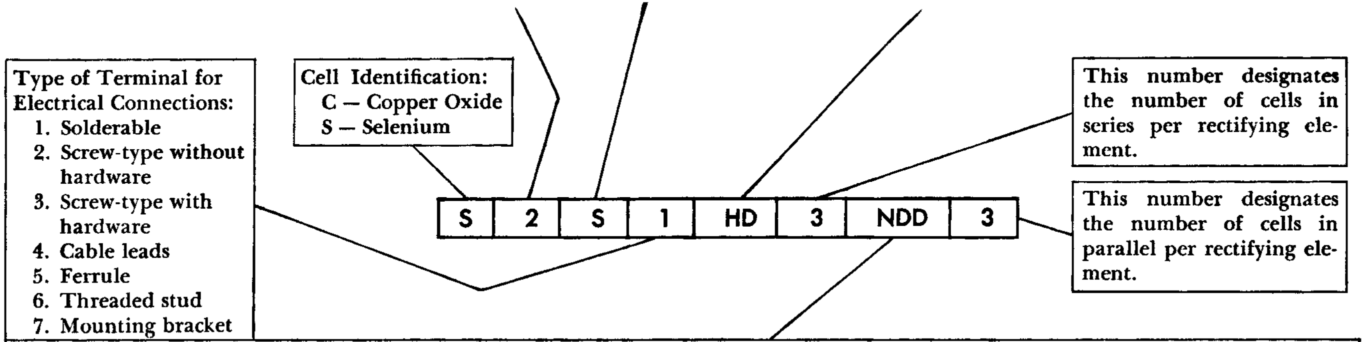
§ Type C finish protects a metallic rectifier cell or stack after exposure to a 100-hour 20% salt spray test at 40°C so it performs to applicable electrical specifications and shows no excess corrosion.

Type of ASSY or Stock Mounting:

B — Bolt
S — Stud
G — One mounting bracket
H — Two mounting brackets
F — Ferrule
E — Eyeletted
R — Mounting from own terminals or leads

Type of Circuit Arrangement of the Rectifiers in the Stack and Interconnection of the Stack

1st Letter		2nd Letter
H — Half-wave	1 phase ungrounded	None — one rectifier
B — Bridge		D — two rectifiers
C — Centertap		T — three rectifiers
D — Doubler		Q — four rectifiers
S — Half-wave	1 phase grounded	
K — Bridge		
L — Centertap		
M — Doubler		
Y — Wye	3 phase ungrounded	
S — 6-phase star		
T — Bridge		



Type of Terminal for Electrical Connections:
1. Solderable
2. Screw-type without hardware
3. Screw-type with hardware
4. Cable leads
5. Ferrule
6. Threaded stud
7. Mounting bracket

Cell Identification:
C — Copper Oxide
S — Selenium

This number designates the number of cells in series per rectifying element.

This number designates the number of cells in parallel per rectifying element.

These Letters Designate The Spacing and Method of Cooling, Cell Size, and Voltage Ratings.

First Letter — spacing and method of cooling

N — normal spacing*
W — Wide spacing*
F — Fan cooled†

* convection cooled
† only one type spacing

Second Letter — cell size

2nd letter	rated current output (amperes) *	cell size (in)
A	0.15	1 × 1
B	0.30	1.25 × 1.25
C	0.60	1.60 × 1.60
D	1.20	2.20 × 2.20
E	2.40	3.0 × 3.0
F	4.00	4.0 × 4.0
G	6.00	4.0 × 4.0
H	8.00	5.0 × 6.0

* for single-phase bridge circuit, resistive-inductive load at 35°C ambient

Third Letter — the voltage rating of a cell

3rd letter	Reverse a-c rms voltage (volts)	D-c output voltage (volts) *
A	—	—
B	—	—
C	—	—
D	18	12
E	22	15.5
F	24	(undetermined)
G	26	19
H	30	(undetermined)
J	—	—
K	33	25
L	36	(undetermined)
M	40	(undetermined)
N	—	—
P	45	(undetermined)

* for single-phase bridge, one series cell per element.

TABLE II

Electrical Ratings and Dimensions of Half-Wave Selenium Power Rectifiers for Radio, Television and Similar Electronic Applications

MANUFACTURER (Alphabetically arranged)	Rectifier Type No.	Max D-c Output Current (Ma)	Rms Voltage (Max)	Peak Inverse Voltage (Max)	Peak Current (Ma)	Peak Current Limiting Resistor	Approx. Rectifier Voltage Drop	Dimensions (inches) *			
								A	B	C	D
BRADLEY LABS., INC.	RS65	65	130	380	650	33	5	13/32	1	1	13/16
	RS75	75	130	380	750	22	5	13/32	1	1	13/16
	RS100	100	130	380	1000	15	5	23/64	1-3/16	1-3/16	13/16
	RS150	150	130	380	1500	5	5	23/64	1-3/16	1-3/16	1
	RS200	200	130	380	2000	5	5	23/64	1-1/2	1-1/2	1
	RS250	250	130	380	2500	5	5	7/16	1-1/2	1-1/2	1-5/16
	RS300	300	130	380	3000	5	5	7/16	1-1/2	1-1/2	1-7/8
	RS350	350	130	380	3500	5	5	9/16	2	2	1-5/16
	RS400	400	130	380	4000	5	5	9/16	2	2	1-7/8
	RS500	500	130	380	5000	5	5	9/16	2	2	1-7/8
FEDERAL TELEPHONE & RADIO CORP.	1002	65	130	380	650	22	7	19/64	1	1	9/16
	1003	75	130	380	750	22	7	19/64	1	1	3/4
	1004	100	130	380	1000	22	7	23/64	1-1/4	1-1/4	3/4
	1005	150	130	380	1500	15	7	23/64	1-1/4	1-1/4	1
	1006	200	130	380	2000	5	7	7/16	1-17/32	1-17/32	1
	1007*	75	160	460	750	22	9	19/64	1	1	2-1/16
	1008*	100	160	460	1000	22	9	23/64	1-1/4	1-1/4	2-1/16
	1009*	200	160	460	2000	5	9	7/16	1-17/32	1-17/32	2-23/32

* Doubler Stack

TABLE II (Cont'd)

MANUFACTURER (Alphabetically arranged)	Rectifier Type No.	Max D-c Output Current (Ma)	Rms Voltage (Max)	Peak Inverse Voltage (Max)	Peak Current (Ma)	Peak Current Limiting Resistor	Approx. Rectifier Voltage Drop	Dimensions (inches) *			
								A	B	C	D
FEDERAL TELEPHONE & RADIO CORP. (Cont'd)	1010	250	130	380	2500	5	7	7/16	1-17/32	1-17/32	1-1/4
	1014	100	160	460	1000	22	9	23/64	1-9/32	1-13/64	1
	1021	450	130	380	4500	5	7	7/16	2	2	2-7/32
	1022	450	160	460	4500	5	9	7/16	2	2	2-13/16
	1023	350	130	380	3500	5	7	9/16	2-1/2	2-1/2	2-17/32
	1028	250	130	380	2500	5	7	7/16	1-17/32	1-17/32	1-1/8
	1090	300	130	380	3000	5	7	35/64	1-17/32	1-17/32	2-7/32
	1101	100	130	380	1000	22	7	19/64	1	1	1-1/8
	1130	400	130	380	4000	5	7	7/16	2	2	1-1/4
	1200	600	130	380	6000	5	7	1/2	2-1/2	2-1/2	2-1/16
	1223	750	130	380	7500	5	7	1/2	1-3/4	1-3/4	2-11/16
	1231	325	130	380	3250	5	7	13/32	1-5/8	1-5/8	2-7/32
INTERNATIONAL RECTIFIER CORP.	RS050	50	130	380	Not Available	22	9	13/32	.67	.67	3/4
	RS065Q	65	130	380		22	9	13/32	.67	.67	3/4
	RS065	65	130	380		22	9	13/32	1	1	3/4
	RS075	75	130	380		22	9	13/32	1	1	3/4
	RS100A	100	130	380		22	9	13/32	1	1	1-1/8
	RS100	100	130	380		22	9	13/32	1.2	1.2	3/4
	RS150	150	130	380		15	9	13/32	1.2	1.2	1
	6RS150	150	156	456		15	9	13/32	1.2	1.2	1
	RS200	200	130	380		5	9	13/32	1.5	1.5	1
	RS250	250	130	380		5	9	13/32	1.5	1.5	1-1/4
	6RS250	250	156	456		5	9	13/32	1.5	1.5	1-1/4

TABLE II (Cont'd)

MANUFACTURER (Alphabetically arranged)	Rectifier Type No.	Max D-c Output Current (Ma)	Rms Voltage (Max)	Peak Inverse Voltage (Max)	Peak Current (Ma)	Peak Current Limiting Resistor	Approx. Rectifier Voltage Drop	Dimensions (inches) *			
								A	B	C	D
INTERNATIONAL RECTIFIER CORP. (Cont'd)	MR300	300	130	380	Not Available	5	9	13/32	1.5	1.5	1-1/4
	RS300SL*	300	130	380		5	9	13/32	1.5	1.5	2-1/4
	MR350	350	130	380		5	9	13/32	1.5	1.5	1-1/4
	RS350	350	130	380		5	9	13/32	2	2	1-1/4
	RS350SL	350	130	380		5	9	13/32	2	2	1-5/8
	6RS350SL	350	156	456		5	9	13/32	2	2	1-5/8
	RS400	400	130	380		5	9	13/32	2	2	1-1/4
	RS400SL	400	130	380		5	9	13/32	2	2	1-5/8
	RS450SL	450	130	380		5	9	13/32	2	2	2-1/4
	MR500	500	130	380		5	9	13/32	2	2	1-1/4
	RS500SL	500	130	380		5	9	13/32	2	2	2-1/4
	6RS500SL	500	156	456		5	9	13/32	2	2	2-1/4
	RS650MSL	650	130	380		5	9	13/32	2	2	2-1/4
	RS1000S	1000	130	380		2	9	13/32	3	3	3
RADIO RECEPTOR (SELETRON)	1M1	100	25	75	1000	—	—	7/16	1	1	3/8
	5M1	100	130	380	1000	22	7	7/16	1	1	7/8
	5M4	75	130	380	750	22	7	7/16	1	1	11/16
	5P1	150	130	380	1500	15	7	11/32	1-3/16	1-3/16	7/8
	5R1	200	130	380	2000	5	5	7/16	1-1/2	1-1/4	7/8
	5Q1	250	130	380	2500	5	5	7/16	1-1/2	1-1/2	1-1/8
	5QS1	350	130	380	3500	5	5	7/16	1-1/2	2	1-1/8
	5S2	400	130	380	4000	5	5	5/8	2	2	1-1/8

* Rectifiers ending in S are stud mounted, those ending in SL are stud locking lug construction.

TABLE II (Cont'd)

MANUFACTURER (Alphabetically arranged)	Rectifier Type No.	Max D-c Output Current (Ma)	Rms Voltage (Max)	Peak Inverse Voltage (Max)	Peak Current (Ma)	Peak Current Limiting Resistor	Approx. Rectifier Voltage Drop	Dimensions (inches) *			
								A	B	C	D
RADIO RECEPTOR (SELETRON) (Cont'd)	5S3	500	130	380	5000	5	5	5/8	2	2	1-3/8
	6M1	75	156	456	750	22	5	7/16	1	1	7/8
	6M2	100	156	456	1000	22	5	7/16	1	1	1-1/8
	6P2	150	156	456	1500	15	5	11/32	1-3/16	1-3/16	1-3/16
	6QA1	300	130	380	3000	5	5	7/16	1-1/2	1-1/2	1-3/8
	6QA2*	350	130	380	3500	5	5	7/16	1-1/2	1-1/2	1-3/4
	6Q1	250	156	456	2500	5	5	7/16	1-1/2	1-1/2	1-1/8
	6Q2	250	156	456	2500	5	5	7/16	1-1/2	1-1/2	1-3/8
	6Q4*	300	130	380	3000	5	5	7/16	1-1/2	1-1/2	1-3/4
	6QS2	350	156	456	3500	5	5	7/16	1-1/2	2	1-3/8
	6QS4*	350	156	456	3500	5	5	7/16	1-1/2	2	1-3/4
	6R4*	250	130	380	2500	5	5		1-1/2	1-1/4	1-3/4
	6S4	400	156	456	4000	5	5	5/8	2	2	1-1/8
	6S2	500	156	456	5000	5	5	5/8	2	2	1-3/8
	6SQ1	350	156	456	3500	5	5	7/16	2	1-1/2	1-3/8
	8J1	65	130	380	650	33	7	3/8	11/16	11/16	1/2
	8Y1	30	130	380	300	47	5	3/8	1/2	1/2	1/2
	16Y1	25	260	760	250	47	5	3/8	1/2	1/2	7/8
	* Stud mounted										
SARKES TARZIAN	65	65	130	380	650	22	5	1/2	1	1	11/16
	75	75	130	380	750	22	5	1/2	1	1	13/16
	78D	75	175	440	750	22	8	1/2	1	1	1-5/8

TABLE II (Cont'd)

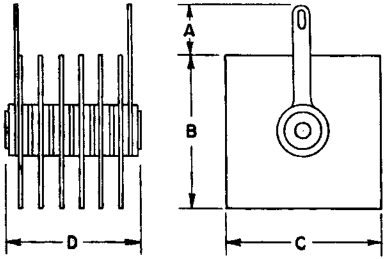
MANUFACTURER (Alphabetically arranged)	Rectifier Type No.	Max D-c Output Current (Ma)	Rms Voltage (Max)	Peak Inverse Voltage (Max)	Peak Current (Ma)	Peak Current Limiting Resistor	Approx. Rectifier Voltage Drop	Dimensions (inches) *			
								A	B	C	D
SARKES TARZIAN (Cont'd)	(voltage doubler stack)										
	100	100	130	380	1000	22	5	1/2	1-1/4	1-1/4	13/16
	100A	100	130	380	1000	22	5	1/2	1	1	1
	108	100	175	440	1000	22	8	1/2	1-1/4	1-1/4	31/32
	108D (voltage doubler stack)	100	175	440	1000	22	8	1/2	1-1/4	1-1/4	1-5/8
	150	150	130	380	1500	15	5	1/2	1-1/4	1-1/4	1-11/64
	200	200	130	380	2000	5	5	1/2	1-3/5	1-3/5	1
	208D (voltage doubler stack)	200	175	440	2000	22	8	1/2	1-3/5	1-3/5	1-5/8
	250	250	130	380	2500	5	5	1/2	1-3/5	1-3/5	1-5/16
	250A	250	130	380	2500	5	5	1/2	1-1/4	1-1/4	1-7/8
	300	300	130	380	3000	5	5	1/2	1-3/5	1-3/5	1-7/8
	350A	350	130	380	3500	5	5	1/2	1-3/5	1-3/5	2-5/32
	400	400	130	380	4000	5	5	1/2	2	2	1-5/16
	500	500	130	380	5000	5	5	1/2	2	2	1-15/16
	600	600	130	380	6000	5	5	1/2	2	2	2-5/32

TABLE II (Cont'd)

MANUFACTURER (Alphabetically arranged)	Rectifier Type No.	Max D-c Output Current (Ma)	Rms Voltage (Max)	Peak Inverse Voltage (Max)	Peak Current (Ma)	Peak Current Limiting Resistor	Approx. Rectifier Voltage Drop	Dimensions (inches) *			
								A	B	C	D
SYLVANIA ELECTRIC PRODUCTS, INC.	NA5	65	130	380	750	33	7	19/64	1	1	3/4
	NB5	75	130	380	900	22	7	19/64	1	1	3/4
	NC5	100	130	380	1200	22	7	23/64	1-1/16	1-9/32	7/8
	ND5	150	130	380	1200	15	7	23/64	1-3/8	1-9/32	1-1/16
	NE5	200	130	380	2000	5	7	7/16	1-5/8	1-5/8	1-3/32
	NF5	250	130	380	2000	5	7	7/16	1-5/8	1-5/8	1-11/32
	NK5	350	130	380	3000	5	7	9/16	1-3/4	1-3/4	2-7/32
	NM5	450	130	380	4000	5	7	7/16	2	2	2-7/32
	NO5	400	130	380	4000	5	5	7/16	2	2	1-5/16
	NP5	300	130	380	3000	5	5	7/16	1-17/32	1-17/32	2-7/32
	NR5	450	160	460	4500	5	5	7/16	2-1/16	2-1/16	2-13/16

NOTES:

1. Ratings based on 35°C ambient temperature.
2. Maximum cell operating temperature 85°.
3. Outline dimensions.



TABLES III AND IV

The specifications and characteristics of the crystal diodes listed in these charts have been compiled from manufacturers' data. However, since production techniques, testing procedures, and quality controls may vary, the specifications should be considered only typical.

The author wishes to thank the many manufacturers who have supplied specification data, including: General Electric Company, International Rectifier Corporation, Kemtron Products Incorporated, Semiconductor Division, Ratheon Manufacturing Company, Seletron and Germanium Division, Radio Receptor Company Incorporated, Sylvania Electric Products Company, Transitron Electronics Corporation.

TABLE III

Germanium and Silicon Crystal Diode Characteristics

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N34	60	75	50	150	500	5.0	.050 @ −10	.500 @ −50	General purpose
1N34A	60	75	50	150	500	5.0	.030 @ −10	.500 @ −50	General purpose
1N35[1]	50	75	22.5	60	100	7.5	.010 @ −10	.800 @ −50	Twin-matched 1N34's
1N38	100	120	50	150	500	3.0	.006 @ −3	.625 @ −100	100-volt back voltage
1N38A	100	120	50	150	500	4.0	.005 @ −3	.500 @ −100	100-volt back voltage
1N39	200	225	50	150	500	1.5	.200 @ −100	.800 @ −200	200-volt back voltage
1N39A	200	200	50	150	500	3.0	.200 @ −100	.800 @ −200	200-volt back voltage
1N40[2]	25	75	22.5	60	100	12.75 @ +1.5v	.035 @ −10	—	General purpose varistor
1N41[2]	25	75	22.5	60	100	12.75 @ +1.5v	.040 @ −10	—	General purpose varistor
1N42[2]	100	120	22.5	60	100	12.75 @ +1.5v	—	.800 @ −100	High-voltage varistor

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Re-curring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N43	60	60	40	125	100	5.0	.020 @ −5	.900 @ −50	General purpose
1N44	115	120	35	100	50	3.0	—	.410 @ −50	
1N45	75	75	35	100	400	5.0	—	.410 @ −50	
1N46	50	60	40	125	400	3.0	—	.410 @ −50	
1N47	115	115	30	90	500	3.0	.004 @ −3	.410 @ −50	
1N48	70	85	50	150	350	4.0	—	.833 @ −50	Detector (video or audio)
1N49	50	—	50	150	400	4.0	—	.200 @ −20	
1N50	50	—	50	150	400	4.0	—	.080 @ −20	
1N51	40	50	25	100	300	2.5	—	1.667 @ −50	General purpose
1N52	70	85	50	150	400	4.0	—	.150 @ −50	High-back resistance
1N54	35	75	40	150	500	5.0	.010 @ −10		
1N54A	50	75	50	150	500	5.0	.007 @ −10	.100 @ −50	
1N55	150	170	50	150	500	3.0	.300 @ −100	.800 @ −150	150-volt back resistance
1N55A	150	170	50	150	500	4.0	—	.500 @ −150	
1N55B	150	190	50	180	300	5.0	—	.500 @ −150	
1N56	40	50	60	200	1000	15.0	—	.300 @ −30	High conduction
1N56A	40	50	60	200	1000	15.0	—	.300 @ −30	High conduction
1N57	80	120	50	150	500	4.0	—	.500 @ −75	Rectifier
1N58	100	120	50	150	500	4.0	—	.800 @ −100	100-volt back voltage
1N58A	100	120	50	150	500	4.0	—	.600 @ −100	100-volt back voltage
1N59	250	275	50	150	500	3.0	—	.800 @ −250	250-volt back voltage
1N60	25	30	50	150	500	5.0	.040 @ −20	—	Video detector
1N60A	25	60	50	15	—	5.0[3]	.035 @ −10	.800 @ −50	Video detector
1N61	130	140	40	150	500	5.0	.300 @ −100	.700 @ −125	Rectifier

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N62	110	120	40	150	500	5.0	—	.700 @ −100[5]	Rectifier
1N63	100	125	50	150	400	4.0	—	.050 @ −50	Harmonic distorter (UHF)
1N64[4]	15	20	50	—	—	.05 @ +.25v	.025 @ −1.3	—	Video detector
1N64A	25[3]	60	5[3]	15[3]	—	5.0	.035 @ −10	.800 @ −50	Video detector
1N65	70	85	50	150	500	2.5	—	.200 @ −50	D-C restorer
1N66	60	70	50	150	500	5.0	.050 @ −10	.080 @ −50	General purpose
1N67	80	100	35	100	500	4.0	.005 @ −5	.050 @ −50	D-C restorer high back resistance
1N67A	80	100	50	180	300	5.0	.005 @ −5	.050 @ −50	D-C restorer high back resistance
1N68	120	120	35	100	500	3.0	—	.625 @ −100	D-C restorer
1N68A	100	130	50	180	300	5.0	—	.625 @ −100	D-C restorer
1N69	60	75	40	125	400	5.0	.050 @ −10	.085 @ −50	General purpose
1N70	100	125	30	90	350	3.0	.025 @ −10	.300 @ −50	100-volt, high back resistance
1N71[6]	40	50	60	200	1000	15.0	.300 @ −30		Matched low impedance varistor
1N72	5	5	25	75	—	0.8 @ +0.5			UHF mixer
1N73	—	75	22.5	60	100	12.75 @ +1.5			Bridge rectifier
1N74	—	75	22.5	60	100	12.75 @ +1.5			Bridge rectifier
1N75	100	125	50	150	400	2.5			High back resistance
1N76		Minimum output voltage: 5v							Video detector (coaxial silicon)
1N77A		for operation in infrared regions (.050 @ −10)							Junction photo diode
1N79		Forward current @ 0.25v (min) = .250 ma Reverse current @ 2v (max) = .250 ma							Instrument rectifier
1N81	40	50	30	90	350	3.0	.010 @ −10		Discriminator
1N82	5	—	50	150	500	—	Max. noise at 500 mc: 10 db. Max. back resistance 1500 ohms.		UHF mixer

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N86	70	85	50	150	400	4.0	.050 @ −10	.833 @ −50	General purpose
1N87A	25	60	5	15	—	5.0	.035 @ −10	.800 @ −50	Video detector
1N88	85	100	5	15	500	2.5	.008 @ −5	.100 @ −50	D-C restorer
1N89	80	100	50	180	300	3.5	.008 @ −5	.100 @ −50	Detector
1N90	60	75	50	180	300	5.0	—	.500 @ −50	Detector
1N91						470 @ +.5v	Junction Rectifiers		Power Rectifier See Note 8
1N92						310 @ +.5v			
1N93						250 @ +.5v			
1N94						1570 @ +.7v			
1N95	60	75	50	180	300	10.0	—	.500 @ −50	Medium Voltage Rectifier
1N96	60	75	60	200	250	20.0	—	.500 @ −50	
1N96A	60	75	70	250	400	40.0	—	.500 @ −50	
1N97	80	100	50	180	300	10.0	.008 @ −5	.100 @ −50	
1N98	80	100	60	200	350	20.0	.008 @ −5	.100 @ −50	
1N98A	80	100	70	250	400	40.0	.008 @ −5	.100 @ −50	
1N99	80	100	50	180	300	10.0	.005 @ −5	.050 @ −50	
1N100	80	100	60	200	350	20.0	.005 @ −5	.100 @ −50	
1N100A	80	100	70	250	400	40	.005 @ −5	.050 @ −50	
1N105	25	30	50	150	500	—	See Note 4	—	Video detector
1N106	300	—	—	—	—	20	.070 @ −100	.200 @ −300	High reverse voltage
1N107	10	—	—	—	—	150	.200 @ −10	—	High forward current
1N108	50	—	—	—	—	50	—	.200 @ −50	General purpose
1N109	15	20	50	150	500	.260 @ +.25v	.260 @ −25	.350 @ −10	Harmonic generator
1N110	Noise figure: 10 db at 75 mc. (See Note 9)								UHF converter

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N111	60	75	25	150	500	5.0	.050 @ −10	.250 @ −50	Computer
1N112	60	75	25	150	500	5.0	.050 @ −10	.250 @ −50	
1N113	60	75	25	150	500	2.5	.025 @ −10	.125 @ −50	
1N114	60	75	25	150	500	2.5	.050 @ −10	.125 @ −50	
1N115	60	75	25	150	500	2.5	.100 @ −10	.500 @ −50	
1N116	60	75	50	180	300	5.0	—	.100 @ −50	Medium voltage
1N117	60	75	50	180	300	10.0	—	.100 @ −50	Medium voltage
1N118	60	75	60	200	350	20.0	.008 @ −5	.100 @ −50	Rectifier
1N118A	60	75	70	250	400	40.0	.008 @ −5	.100 @ −50	Rectifier
1N119	60	75	25	150	500	5.0	(See Note 10)		Computer
1N120	60	75	25	150	500	5.0	(See Note 11)		Computer
1N124A	—	—	—	—	—	10 @ +.75	—	—	UHF converter
1N125	—	30	40	125	400	.05 @ +.25v	.025 @ −1.3	—	UHF pulse rectifier
1N126	60	75	50	180	300	5.0	.050 @ −10	.800 @ −50	Detector
1N127	100	125	50	180	300	5.0	.025 @ −10	.300 @ −50	
1N128	40	50	50	180	300	5.0	.010 @ −10	—	
1N132	25	30	50	150	500	3.0	.010 @ −10	—	Video detector
1N133	—	6	50	150	500	3.0 @ +.5v	3.0 @ .5v	.300 @ −0.6	UHF mixer
1N135	65	75	—	—	—	5	—	—	General purpose
1N137A	—	36	30	150	—	3	103 @ −20	—	
1N138A	—	18	50	250	—	5	.01 @ −10	—	
1N139	40	50	70	250	500	20	—	1.500 @ −50[12]	High forward conductance
1N140	70	58	85	250	750	40	—	.300 @ −50[12]	
1N141	70	70	70	200	500	20.040 @ +2v		.050 @ −50[12]	
1N142	100	125	60	350	400	5		.100 @ −100[12]	

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Re-curring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N143	100	125	85	55	750	40		.100 @ −100[12]	High peak inverse voltage
1N147	8	2	25	55	—	(See Note 13)		—	UHF converter
1N148	15	20	—	150	500	.260 @ +.25v	.350 @ −10	—	Harmonic generator
1N151	30	100	500[17]	1570	25 amp.	1570 @ +0.7v	Full load voltage drop: 0.7v	2.400 @ −100v	Power rectifier
1N152	65	200	500[17]	1570	25 amp.	1570 @ +0.7v		1.900 @ −200v	
1N153	100	300	500[17]	1570	25 amp.	1570 @ +0.7v		1.200 @ −300v	
1N158	185	(See Note 14)							
1N182	Noise figure 16 db (See Note 9)								UHF 7v mixer
1N188									Junction phototube
1N189									Junction phototube
1N191	60	—	50	180	300	5.0	Back resistance 400K between −10v & −50v (Note 7)		Computer
1N192	70	—	50	180	300	5.0	Back resistance 200K between −10v & −50v (Note 7)		
1N193	40	—	30	40	100	1 @ +2v	.020 @ −10	.040 @ −50	
1N194	40	—	30	40	100	1.5 @ +2v	.060 @ −40	—	
1N195	40	—	30	40	100	2 @ +2v	.080 @ −40	—	
1N196	40	—	30	40	100	1 @ +2v	.040 @ −40		
1N197	See Silicon Microwave Crystal Chart								Converter
1N198	50	—	30	100	150	5.0	.075 @ −10	.250 @ −50 at 75°c	High temperature
1N200	6.8	—	—	—	—	5.0	Zener current: 12.5ma Max. zener impedance: 20 ohms		
1N201	8.2	—	—	—	—	35	Zener current: 10ma Max. zener impedance: 70 ohms		

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)	Remarks
1N202	10	—	—	—	—	30	Zener current: 7.5ma Max. zener impedance: 100 ohms	Low voltage
1N203	12	—	—	—	—	23	Zener current: 6ma Max. zener impedance: 120 ohms	
1N204	15	—	—	—	—	17	Zener current: 5ma Max. zener impedance: 200 ohms	
1N205	18	—	50	150	—	12	.0001 @ −18 Zener current: 4ma	Intermediate voltage
1N206	22	—	45	135	—	9	.0001 @ −22 Zener current: 3.3ma	
1N207	27	—	40	120	—	7	.0001 @ −37 Zener current: 2.7ma	
1N208	33	—	35	105	—	5.5	.0001 @ −33 Zener current: 2.2ma	
1N209	39	—	30	95	—	4.5	.0001 @ −39 Zener current: 2ma	
1N210	47	—	27	85	—	3.5	.001 @ −47 Zener current: 1.7ma	
1N211	56	—	23	72	—	2.7	.001 @ −56 Zener current: 1.3ma	
1N212	68	—	19	60	—	2	.001 @ −68 Zener current: 1ma	
1N213	82	—	16	50	—	1.5	.001 @ −82 Zener current: 0.7ma	

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Re-curring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N214	100	–	12.5	40	–	1.2	.001 @ –100	Zener current: 0.7ma	
1N215	120	–	11	35	–	0.9	.001 @ –120	Zener current: 0.6ma	
1N216	150	–	9.5	30	–	0.7	.005 @ –150	–	High voltage
1N217	180	–	9	28	–	6.5 @ +4v	.005 @ –180	–	
1N218	220	–	8	26	–	6 @ +4v	.005 @ –220	–	
1N219	270	–	7.5	24	–	3 @ +4v	.005 @ –220	–	
1N220	330	–	7	22	–	2.2 @ +4v	.005 @ –330	–	
1N221	390	–	6	20	–	2 @ +4v	.005 @ –390	–	
1N222	470	–	5.5	18	–	1.5 @ +4v	.005 @ –470	–	
1N259		Characteristics identical to 1N23B.			(See microwave diode chart)				Converter (9000 mc)
1N264		Characteristics identical to 1N21B.							Converter (3000 mc)
1N265	90	–	30	–	300	3.2	.1 @ –60	–	Computer
1N266	60	–	30	–	300	4	.075 @ –30	–	
1N267	25	–	30	–	300	3.5	.012 @ –10	–	
1N270	60	75	100	350	500	200.0			Low-impedance fast switching
1N273	30	35	80	300	450	100.0	.020 @ –20	–	Low-impedance fast switching
1N277	100	125	50	180	300	5.0	.005 @ –3	.500 @ –100	High voltage
1N278	50	–	35	125	175	20.0	.125 @ –50	–	High temperature
1N279	30	35	80	300	450	100.0	.200 @ –20	–	Fast-forward switching
1N283	20	25	100	350	500	200.0	.020 @ –10		Low-impedance fast-forward switching

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At +1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N287	40	—	70	—	500	20	—	1.5 @ −50	General purpose
1N288	70	—	85	—	750	40	—	.350 @ −50	
1N289	70	—	70	—	500	20	—	.050 @ −50	
1N290	100	—	60	—	—	5	—	.100 @ −100	
1N291	100	—	85	—	—	40	—	.100 @ −100	
1N292	60	—	—	—	150	—	.200 @ −50	—	
1N294	60	70	50	150	500	5	.010 @ −10	.800 @ −50	Computer
1N295	40	50	35	125	300	—	.200 @ −10	—	Video detector
1N297	80	100	35	100	500	3.5	.010 @ −5	.100 @ −50	5-50v D-C restorer
1N298	70	85	50	150	500	30 @ +2	.250 @ −40	—	General purpose
1N300	12	15	40	120	400	8	.001μa @ −10	—	
1N301	60	70	35	110	350	5	.01μa @ −10	.05ma @ −50	
1N302	215	225	25	80	250	1	.01μa @ −10	.2ma @ −200	
1N303	110	125	30	100	300	3	.01μa @ −10	.1ma @ −100	
1N305	50	60	125	300	500	100 @ +.08v	.002 @ −10	.02 @ −50	Magnetic amplifier
1N306	12	15	150	300	500	100 @ +.08v	.002 @ −10	—	General purpose
1N307	100	125	50	300	500	100	.005 @ −10	.020 @ −100	Magnetic computer
1N308	8	10	100	350	500	300	.500 @ −8	—	Switching
1N309	30	40	100	300	500	100	.100 @ −20	—	Switching
1N310	100	125	40	100	500	15	.020 @ −20	.100 @ −100	General purpose
1N312	—	60	70	250	—	30	.050 @ −50	.100 @ −100	
1N313	—	125	40	100	—	15	.010 @ −50	.050 @ −100	
1N314	—	—	22.5	60	100	—	.050 @ −10	—	
1N332	280	400	400	2500	10,000	—	Forward voltage at specified current		

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max.)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At + 1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)	Remarks
							2.0v @ 800 ma	
1N333	280	400	200	1500	5,000	—	2.0 @ 400 ma	Max. av. inverse current .10 ma.[16]
1N334	210	300	400	2500	10,000	—	2.0 @ 800 ma	
1N335	210	300	200	1500	5,000	—	2.0 @ 400 ma	
1N336	140	200	400	2500	10,000	—	2.0 @ 800 ma	Max. av. inverse current .05 ma.[16] Magnetic Amplifiers
1N337	140	200	200	1500	5,000	—	2.0 @ 400 ma	
1N338	70	100	1000	6000	20,000	—	2.0 @ 2000 ma	Max. av. inverse current .10 ma.[16]
1N339	70	100	400	2500	10,000	—	2.0 @ 800	Max. av. inverse current .05 ma.[16]
1N340	70	100	200	1500	5,000	—	2.0 @ 400	
1N341	280	400	400	2500	10,000	—	2.0 @ 800	Max. av. inverse current .5 ma.[16] Power supply
1N342	280	400	200	1500	5,000	—	Forward voltage at specified current (volts @ ma) 2.0 @ 400	Max. av. inverse current .5 ma.[16]
1N343	210	300	400	2500	10,000	—	2.0 @ 800	Max. inverse current .5 ma.[16] Power supply
1N344	210	300	200	1500	5,000	—	2.0 @ 400	
1N345	140	200	400	2500	10,000	—	2.0 @ 800	
1N346	140	200	200	1500	5,000	—	2.0 @ 400	
1N347	70	100	1000	6000	20,000	—	2.0 @ 2000	
1N348	70	100	400	2500	10,000	—	2.0 @ 800	
1N349	70	100	200	1500	5,000	—	2.0 @ 400	

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max.)	Average Forward Current (ma)	Peak Recurring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At + 1v (ma)	Maximum Inverse Current at Specified Voltages (ma @ Volts)		Remarks
1N378 Thru 1N400	1N200 Thru 1N222								Double-ended construction
1N411	50	—	25[3]	40	—	—	—	—	Power supply
1N412	100	—	25[3]	40	—	—	—	—	
1N413	200	—	25[3]	40	—	—	—	—	
1N432	35	40	60	120	400	10	0.005 ma @ −10	—	General purpose
1N433	135	145	50	100	300	3	0.01 ma @ −10	.1ma @ −125	
1N434	170	180	45	100	300	2	0.01 ma @ −10	.1ma @ −160	
1N436	3	3	125	300	500	100	0.1 ma @ −1	(Note 15)	Voltage regulator when biased in zener region
1N437	5	5	125	300	500	100	0.1 ma @ −1	(Note 15)	
1N438	7	7	125	300	500	100	0.1 ma @ −1	(Note 15)	
1N439	9	9	40	120	130	5	0.1 ma @ −1	(Note 15)	Rectifier
1N440	100	—	300	1500	—	—	.3 @ −100v	—	
1N441	200	—	300	1500	—	—	.75 @ −200	—	
1N442	300	—	300	1500	—	—	.001 @ −300	—	
1N443	400	—	300	1500	—	—	.0015 @ −400	—	
1N444	500	—	300	1500	—	—	.00175 @ −500	—	
1N445	600	—	300	1500	—	—	.002 @ −600	—	
1N447	30	—	60	200	500	25	.020 @ −10	.060 @ −30	General purpose
1N448	100	—	60	200	300	25	.030 @ −30	.100 @ −100	
1N449	30	—	60	200	500	50	.010 @ −10	.030 @ −30	
1N450	100	—	60	200	300	50	.030 @ −30	.100 @ −100	
1N451	150	—	60	200	200	50	.150 @ −150	—	
1N452	30	—	80	250	500	100	.030 @ −30	—	
1N453	100	—	100	80	250	300	.030 @ −30	.100 @ −100	

TABLE III (Cont'd)

Type	Maximum Continuous Inverse Working Voltage	Reverse Voltage For Zero Dynamic Resistance (V. Max.)	Average Forward Current (ma)	Peak Re-curring Forward Current (ma)	Maximum Surge Current (Per One Sec. ma)	Minimum Forward Current At + 1v (ma)	Maximum Inverse Current at Specified Voltages[3] (ma @ Volts)		Remarks
1N454	50	—	200	100	300	500	.050 @ −50	—	General purpose
1N455	30	—	300	100	300	500	.030 @ −30	.050 @ −20	
1N460	85	90	40	120	130	5	0.1μa @ −10	0.1 μa @ −75	
1N480	60	—	5	35	—	—	.125 @ −50	—	

NOTES:

[1] Units are matched in the forward direction at + 1 volt so that the current through the low resistance diode is within 10 per cent of that in the high-resistance diode.

[2] There are four specially selected and matched diodes whose resistances are balanced within ± 2.5 per cent in forward direction at + 1.5 volts. Ambient temperatures range from − 10°C to + 45°C.

[3] Measured at + 75°C.

[4] Units are generally tested in a series-type detector circuit which employs an input of 1.8 volts at 40mc. Seventy-five per cent modulated at 400 cycles. The demodulated output taken across a 4,700-ohm load resistor in parallel with a 5μμf capacitor, should be a minimum of 1.8 volts peak-to-peak.

Table III (Cont'd)

[5] Measured at 60°C with 6 pulses-per-second, 20 millisecond pulse width, and 200 ma peak current.

[6] The unit consists of four diodes selected so that the + 1 volt current of all diodes is within 1 milliampere.

[7] Measured with 60 cycle sweep.

[8] Ratings: Absolute maximum at ambient 55°C (60-cycle resistive load)

	1N91	1N92	1N93	1N94
Peak inverse voltage	100	200	300	380
RMS input voltage	70	140	210	130
RMS input voltage capacitive load, half-wave circuit	35	70	105	350
D-C output current (ma)	150	100	75	500
Peak nonrepetitive surge curent (ma)	25	25	25	25
Continuous reverse working voltage	30	65	100	185
Operating frequency (kc)	50	50	50	50
Maximum storage temperature (°C)	85	85	85	85°
Maximum-peak leakage current at rated peak-inverse voltage (ma)	2.7	1.9	1.2	0.8
Maximum rms voltage drop at rated d-c output current (volts)	0.5	0.5	0.5	0.7

[9] Silicon diode for UHF television applications.

Max. local osc. drive	5 ma
Max. continuous reverse working voltage	5 volts
Frequency	700 mc

Polarity: Band denotes cathode.

TABLE III (Cont'd)

[10] Reverse resistance: 0.4 neg. (min)
Reverse recovery time at 0.5 microsecond (max): 700 ms.
Reverse recovery time at 3.5 microsecond (max): 87.5 ma.

[11] Reverse resistance: 0.2 meg.
Reverse recovery time at 0.5 ms. (max): 700 ma.
Reverse recovery time at 3.5 ms. (max): 175 ma.

[12] Average 100-mc rectified efficiency: 46%

[13] Maximum noise figure at 500 mc: 10db
Maximum back resistance: 1500 ohms
Minimum forward resistance: 75 ohms

[14] RMS input voltage: 130 v
Peak inverse voltage: 380 v
Continuous inverse working volts: 185 v
Peak forward current: 1.57 A
D-C output current: 500 ma
D-C output current (cap. load: 350 ma)
Peak full load voltage drop 1.4 v
Leakage current: 0.8 ma

[15] Zener voltage	1N436	1N437	1N438	1N439
Zener voltage	4	6	8	10
Average zener current (ma)	25	20	15	20
Peak zener current (1 sec.)	85	70	50	70
Zener impedance at 5 ma dc	10	10	10	10
Zener impedance at .5 ma dc	100	100	100	100

[16] Maximum-average inverse current taken over one cycle for full-wave choke-input circuit with rectifier operating at full rated power.

[17] D-C output current for capacitive load: 350 ma.

TABLE IV

Microwave Silicon Crystal Diodes

Type	Test Frequency (mc)	Power Level (mw)	Maximum Conversion (loss db)	Maximum Output Noise Ratio	Standard Load Impedance (ohms) DC	AC	Impedance (ohms)	Maximum VSWR in Std. Mixer	Burnout (ergs)	Remarks
1N21	3060	0.5	8.5	4.0	100	400	200-800*	—	2.0	General purpose
1N21A	3060	0.5	7.5	3.0	100	400	200-800*	—	2.0	General purpose
1N21B	3060	0.5	6.5	2.0	100	400	200-800*	—	2.0	Mixer
1N21C	3060	0.5	5.5	1.5	100	400	200-800*	—	2.0	General purpose
1N21D	3060	0.5	5.0	1.3	100	400	200-800*	1.5	2.0	General purpose
1N22	9000	—	—	—	—	—	200-800*	—	—	Detector peak
1N23	9375	1.0	10.0	3.0	100	400	300-600*	—	0.3	General purpose
1N23A	9375	1.0	8.0	2.7	100	400	300-600*	—	0.3	
1N23B	9375	1.0	6.5	2.7	100	400	300-600*	—	0.3	
1N23C	9375	1.0	6.0	2.0	100	400	325-475*	—	1.0	
1N23D	9375	1.0	5.0	1.7	100	400	350-450*	1.3	1.0	Mixer
1N25	9375	—	8.0	2.5	—	—	100-400	Peak pulsed power 6.5 watts		General purpose
1N25A	9375	—	6.5	2	—	—	100-300	Peak pulsed power 6.5 watts		
1N26	23984	1.0	8.5	2.5	100	500	300-600	—	.1	
1N28	34860	—	7	2	—	—	250	—	—	High burnout mixer
1N30	See Note Below									Video
1N31	See Note Below									Detector
1N32	See Note Below									Detector
1N53	34860	1.0	8.5	2.5	100	500	400-800	1.6	.01	Mixer
1N78	16000	1.0	7.5	2.5	100	500	325-625	—	.03	General purpose
1N78A	16000	1.0	7.0	1.5	100	500	365-565	1.6	.03	General purpose
1N79		Forward current @ 0.25 v. (min): 0.250 ma.								Instruments,
		Reverse current @ −2 v. (max): 0.250 ma.								rectifier in probe
1N136	1.3	—	—	13	—	—	400	—	—	Probe converter

TABLE IV (Cont'd)

Type	Test Frequency (mc)	Power Level (mw)	Maximum Conversion (loss db)	Maximum Output Noise Ratio	Standard Load Impedance (ohms) DC	Standard Load Impedance (ohms) AC	Impedance (ohms)	Maximum VSWR in Std. Mixer	Burnout (ergs)	Remarks
1N149	9375	1.0	5.5	1.5	100	400	325-475	1.5	1.0	General purpose
1N150	6750	1.0	6.0	2.0	100	400	250-500	1.5	1.0	
1N155	Same as 1N23B but of reversed polarity.									
1N155A	Same as 1N23C but of reversed polarity.									
1N156	Same as 1N23B but of reversed polarity.									
1N157	Same as 1N21B but of reversed polarity.									Mixer
1N160	6750	1.0	6.5	2.7	100	400	200-500*	—	1.0	General purpose
1N197	Matched pair of 1N21B's, one with reversed polarity.									
1N259	Matched pair of 1N23B's									
1N263	9375	—	6	1.4	—	—	150-250	—	1.3	
1N264	Matched pair of 1N21B's.									
1N286	10-22	—	8.5	2.5	—	—	250-450	—	—	
1N415B	Same as 1N123B.									
1N415C	Same as 1N123D.									
1N415D	Same as 121B.									
1N416B	Same as 121C.									
1N416C	Same as 121D.									
1N416D	Same as 1N123D.									

*Nominal impedance.

NOTES:

Maximum video operating frequency:	5.0 mc.
Minimum video operating frequency:	500 cps.
Forward voltage:	5.0 mv (max)
R-F power output:	5.0 μw (max)

	1N30	1N31	1N32
Max. video impedance:	21,000	24,000	20,000
Min. video impedance:	7,000	6,000	5,000

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