International Rectifier Corporation Engineering Handbook

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International Rectifier Corporation

Engineering Handbook

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A Combination of Theoretical and Practical Articles on the Application of Rectifying Devices to Today's Electronic and Electrical Equipment.

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Acknowledgements

We wish to acknowledge with gratitude the contributions made by the following engineers of International Rectifier Corporation whose work appears in these pages:

J. T. CATALDO
ED DIEBOLD
DR. C. A. ESCOFFERY
WERNER LUFT
HARRY NASH
F. W. PARRISH
L. W. PHINNEY
GEORGE PORTER
JOHN SASUGA
JOHN VICKREY

Many of the articles herein were written for and published by the leading technical publications in the electrical and electronics field. We take this opportunity to thank the editors of these publications for their service to the industry in originally printing these manuscripts:

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Executive Editor: J. T. CATALDO

Associate Editor: W. E. WILSON

Foreword

Each technical advance in the field of electronics, and particularly semiconductors, brings with it an obvious need for thorough and accurate information on the subject. To be sure, the strides in the semiconductor field in the past few years have been both great and numerous. In the field of rectifiers, significant achievements have been recorded at a startling rate. It is the purpose of this handbook to place in the hands of the design engineer useful, practical information on the application and protection of semiconductor rectifiers.

As each new development appeared, the engineering staff of International Rectifier Corporation has prepared articles of a basic nature to provide a successful foundation for the use of the device. Many of the articles were written for and appeared in the leading technical journals of the industry. Full credit is given elsewhere in this book to both the authors and the publications.

We hope that by transmitting the information in this compact manner, we will provide the solution to many of your application problems.

J. T. Cataldo
Executive Editor

Contents

INDEX TO INTERNATIONAL RECTIFIER CORPORATION SEMICONDUCTOR TYPES

A portion of the International Rectifier Corporation Periodic Table of the Chemical Elements. Highlighted are the three elements used in the company's extensive line of semiconductor rectifiers and photovoltaic devices.

First Principles of Semiconductors

by Dr. C. A. Escoffery, BCE, PhD
International Rectifier Corporation
Member APS, ES, Sigma Xi

The reader is introduced to some of the main points of semiconductor phenomena. Concepts of wave properties of electrons, discrete energy levels, free electrons in metals, and band theory of solids, show how semiconductors differ from metals and insulators. This is followed by a discussion of doping to create impurity conduction (n and p type), and of the relationship of conductivity to carrier concentration, lifetime, and mobility.

On the basis of electrical conductivity, solids can be broadly classified into metals, semiconductors, and insulators. Because of the rapidly growing prominence of semiconductors in electronic technology, the average engineer has become interested in acquiring a greater understanding of semiconductors but his efforts are hampered by the esoteric language of the physicist. It is hoped that this article may be of aid by presenting a brief review of some of the main points of semiconductor phenomena.

However, in order to obtain a reasonably clear picture of semiconductors, it is necessary to invade the field of solid-state physics and become partially acquainted with the band theory of solids. To do so, a review of some of the present-day concepts of the behavior of electrons, first in individual atoms, then in metals, and finally in semiconductors, must be undertaken.

Wave Properties of Electrons

In dealing with matter of very small dimensions such as atoms, electrons, and protons, modern physics makes it possible and even desirable to consider them as wave motion rather than as particles. Electrons can, in fact, be diffracted (scattered in definitely determined directions) by passing them through thin crystals.

The "wave length" of a moving electron is related to its mass and velocity by the De Broglie equation

$$\lambda = \frac{h}{m\,v} \tag{1}$$

where h is a very important constant of proportionality known as Planck's constant. Thus, for instance, the wave length of an electron with one volt of kinetic energy (traveling at a speed of 1½ million miles per hour) would be about 12×10^{-8} cm. This is of the same order of magnitude as the spacing between atoms in a crystal, and explains why electrons can be diffracted.

Since electrons can be considered as (mathematical) waves, many of the equations involved in their treatment resemble those used in describing familiar examples of wave motion such as vibrating strings and oscillating electrical circuits.

Now, it is necessary to define discrete energies. A system that can have any frequency of oscillation, such as a spinning wheel, can have any value of energy. But if only certain frequencies are permitted, as in the case of a violin string fastened at both ends, then only certain definite, discrete energies are permitted. In the case of the vibrating string, the permitted frequencies are, of course, the familiar overtones or harmonics.

The same considerations apply to electrons in an atom. Only certain energy overtones or energy levels are permitted because, like the violin string, the electrons are tied down. The mathematician would say they are subject to boundary conditions.

Electrons in Metals

From chemistry it is learned that only the outermost electrons in an atom determine its chemical valence. In discussing the conductivity of solids, only these electrons are considered "free," the rest being bound rather strongly to the nucleus. Only the "free" valence electrons are capable of conducting an electric current and, therefore, only valence electrons shall be considered from now on.

In order to study the behavior of these electrons in a metal, matters must first be simplified by considering these electrons as being confined to a potential field like that in Fig. 1. Here *O*, the potential energy of the electrons outside of the metal, is arbitrarily chosen as zero for convenience; inside of the metal, the potential energy *A* is constant. Because electrons do not ordinarily escape from a metal, they must have a lower (more negative) energy inside than outside. In this simplified

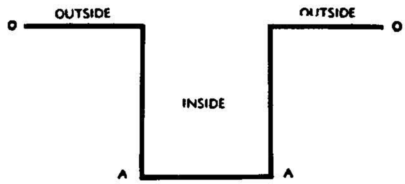


Fig. 1. Potential box of a metal.

model, the electrons move in the field, which is regarded as constant and equal to zero outside of the metal, and constant and equal to *A* within.

As in the violin string and in the individual atom, so too in Fig. 1 the "boundary restrictions" give rise to a discrete energy spectrum. But now there is a difference: due to the very large number of atoms, we find a very large number of energy levels, all very close together, giving rise to what is known as a quasicontinuous spectrum, as indicated schematically in Fig. 2(A).

In Fig. 2, the occupied levels are indicated by heavy horizontal lines, whereas the empty levels are indicated by light lines.

An examination of Fig. 2(A) reveals that there is a sharp transition between the filled and the vacant levels and, furthermore, that even at the absolute zero of temperature the electrons are distributed over a very wide range of energy. The reason for the latter follows

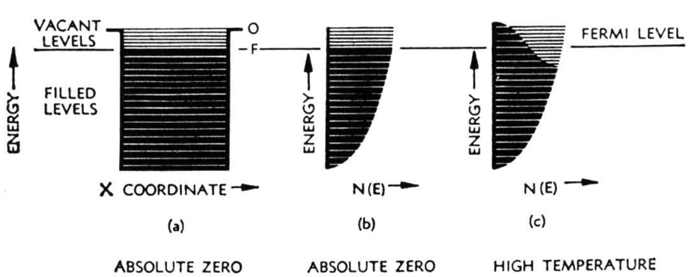


Fig. 2. (A) Schematic of electron energy levels in a metal with the potential field of Fig. 1. In (B) and (C), the number of electronic states for each energy interval shown for two different temperatures.

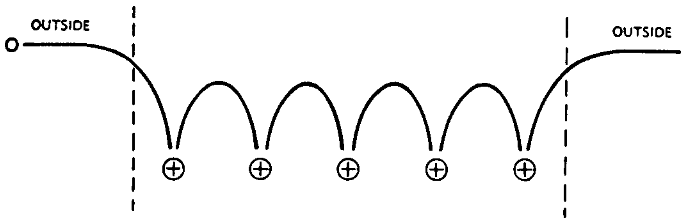


Fig. 3. Periodic potential field in a crystalline solid. The circled crosses represent atoms.

from what is known as the Pauli exclusion principle, which states that only one electron can be in a given energy state at one time. Two electrons can occupy a given energy level but they must have opposite spins.

Once an energy level is filled by a pair of electrons (with opposite spins), additional electrons must go to higher levels. The value of energy *OF* is called the work function of the metal, and it expresses the energy needed to liberate an electron from the metal.

If the number of allowed energy levels in each energy interval in Fig. 2(A) is plotted, the type of energy distribution shown in Figs. 2(B) and 2(C) is obtained. At absolute zero, the maximum electronic energy level is called the Fermi level; at higher temperatures, some electrons can have higher energies than the Fermi level, as shown in Fig. 2(C).

In order for an electron to conduct a current, it must be accelerated; that is, its energy must be increased. In the absence of an applied field, there is no net drift of electrons and, hence, no observable current even though some electrons are moving about with velocities as high as 250,000 miles per hour. By means of considerations such as outlined in this section, the conductivity of a metal can be expressed by an equation relating it directly to its electronic mean free path. Since the mean free path decreases as the temperature is raised (due to scattering of the electron waves by increasing lattice imperfections), the conductivity of a metal decreases with increase in temperature, as is actually observed in practice.

Band Theory of Solids

Thus far, in considering the movement of the valence electrons in a metal it was assumed that they move in a uniform electrostatic field within the crystal (Fig. 1). In effect, this is only an approximation. It is known that the atoms in a crystal are arranged in a regular array, and because of the concentration of a positive charge in the nucleus, the electric field would be expected to vary and to be strongest in the immediate vicinity of the atoms, as indicated schematically in Fig. 3.

Furthermore, inasmuch as the electrons have wave properties, the electron waves would be expected to interact with the crystal's varying electric field and to be diffracted by the lattice atoms just like X rays are diffracted. Therefore, electrons with certain critical velocities and directions would be reflected, with the result that the corresponding energy states would not exist. It will be seen shortly that these nonexistent energy states give rise to what is known as forbidden energy regions as shown in Fig. 5(B).

In the case of a free electron moving in a uniform field, the energy is given by the familiar relationship

$$E = \frac{mv^2}{2} \qquad (2)$$

whence, by substitution of the value of v from equation 1

$$E = \frac{h^2}{2m\lambda^2} \qquad (3)$$

If λ is replaced by a reciprocal quantity k, called the wave number, and then the relationship between E and k is plotted, the energy values fall on

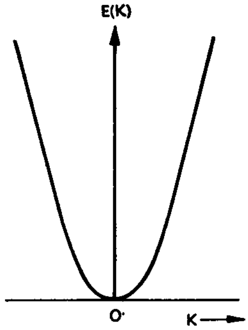


Fig. 4. ***(Left)*** **Energy of a perfectly free electron moving in a uniformly constant force field as a function of wave number *k*.**

a parabola, as shown in Fig. 4. This corresponds to the case of a perfectly free electron.

However, when the field in which the electrons move varies from one point to another (Fig. 3), the results correspond somewhat to those shown in Fig. 5(A), which is drawn for the one-dimensional case of electrons traveling in the same crystallographic direction. Wave numbers can be assigned for different crystallographic directions. Because the crystal periodicity may be different in different directions, the forbidden gaps in Fig. 5(A) may occur at different values of k. This may lead to overlapping bands as indicated in Fig. 6(B).

The significant aspect of Fig. 5(A) is that the allowed electronic energy levels lie on a parabolic curve except for certain regions (forbidden regions) where, because of diffraction effects, these energy values do not exist. Fig. 5 (B) schematically indicates how the allowed energy values of Fig. 5(A) fall into "bands" with energy gaps between them, whereas Fig. 5(C) illustrates the distribution of the energy bands within the so-called reduced zone. The quantity a is one of the dimensions of the unit cell crystal.

It must be emphasized that within the allowed bands the energy levels are so close together as to be almost continuous. Nevertheless, they are still separate (discrete) and must conform to the Pauli exclusion principle which determines how many electrons can occupy each energy state.

Band energy diagrams are very useful for they allow explanation of the

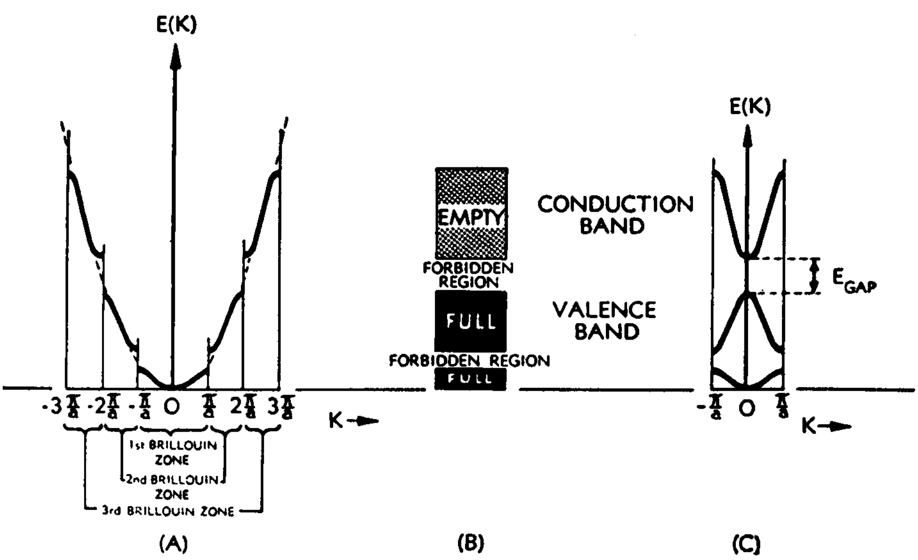


Fig. 5. ***(Right)*** **(A) Energy of an electron as a function of wave number for the periodically varying field of Fig. 3. The gaps in the energy curve give rise to forbidden energy regions which are indicated schematically in (B). By translation of the energy curves into the first zone (C) is obtained from (A).**

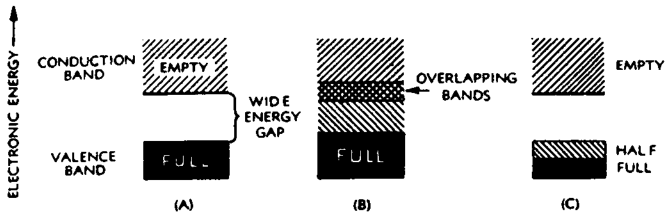


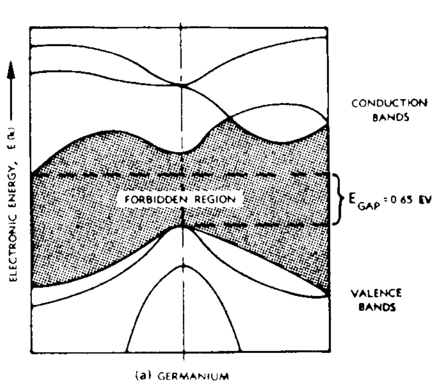
Fig. 6. Energy level diagrams for (A), an insulator; (B) and (C), metals.

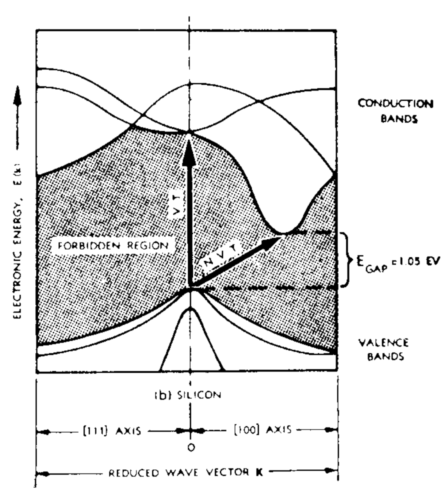
difference between metals and insulators. Thus, as shown in Fig. 6(A), the energy gap between the highest (full) band and the next higher (empty) band in insulators is so large that the electrons cannot be accelerated across the forbidden region. In the case of metals, the bands either overlap as in Fig. 6(B) with essentially no forbidden regions, or else the valence band is only half filled as shown in Fig. 6(C).[1]

It should be noted that the energy contours near the center of Fig. 5(C) are circular. In a three-dimensional plot they would be spherical. In practice, however, it is found that the minimum energy states are not always spherical and do not always occur at the center of the reduced zone. Recent experimental and theoretical studies[2] for instance, indicate that the energy bands for germanium and for silicon are somewhat like that shown in Fig. 7, and it is probable that the energy band structure of many other semiconductors also is quite complicated.[4,5] The conduction bands in Fig. 7 exhibit several minima (which are ellipsoidal rather than spherical), depending on the direction of the wave number *k*. The arrows *VT* and *NVT* indicate a vertical and a nonvertical transition. In the former, the wave number (momentum) remains constant; the energy gap, however, is the smallest energy distance between bands, as indicated by the nonvertical transition.

There is another way of viewing the energy band picture—when the individual atoms (with their permissible discrete energy levels) are brought together to form a solid, each allowed energy level broadens out in a series of levels, so numerous and close together that they are practically continuous within each band. This broadening is due to interaction of the atoms with each other as they come closer together. A similar situation occurs in other mechanical systems (e.g., in coupled oscillators), where the amount of interaction is related to the amount of coupling. Thus, the resonant peaks of inductively coupled tuned circuits are found to

Fig. 7. Schematic diagrams of the energy band structures at room temperature for germanium and for silicon along the 111 and 100 axes.





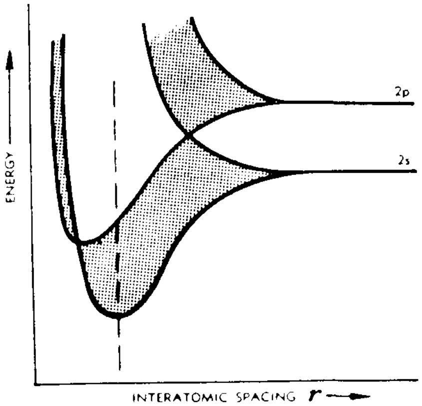


Fig. 8. Broadening of electron energy levels into bands as the atoms of carbon are brought closer together to form the crystal lattice of diamond.[7]

broaden with increased coupling, giving rise to the well-known double hump above a certain value of the coupling coefficient.[6] Fig. 8 shows how the discrete electronic energy levels (far right-hand side) broaden, overlap, and then split apart to form a low-lying band separated from higher bands by a large energy gap. Dashed line shows separation at the actual atomic spacing.[7]

For this discussion, the most important factor is the existence and magnitude of the energy gap between the valence and conduction bands. If the gap is large and the valence band is filled, conduction will not be observed. In metals, the bands usually overlap and the electrons in the valence band can easily be raised to higher, empty levels by the application of an electric field.

Impurity Levels

It is now easier to understand how the electrical properties of semiconductors are explained in terms of their energy bands. If the energy gap is small enough, as seen in Fig. 6(A), so that electrons can be excited thermally from the lower filled valence band to the upper empty conduction band, an intrinsic semiconductor exists.

Now, when an electron moves into the higher band (energetically speaking), not only can this electron carry a current, but so can the vacancy left behind in the valence band as shown in Fig. 9(A). This vacancy, which acts like a positive electronic charge, is called a defect electron, a positive hole or, more simply, a hole. The concept of conduction by holes is basic to the modern theories of semiconductors.

In most semiconductors, however, the value of the energy gap is too large for intrinsic conduction to take place at room temperature, and the observed conductivities are explained on the basis of what is known as impurity conduction. According to this view, impure (or extrinsic) semiconductors owe their conductivity to the presence of additional discrete energy levels located within the forbidden energy region. When the impurity levels lie close to the top of the (full) valence band as shown in Fig. 9(B), they are able to accept electrons from the valence band and, therefore, are called acceptor levels. In this case, the semiconductor is said to be p-type, because most of the current is carried by positive holes. The holes left behind in the valence band are free to move. The electrons that moved up into the acceptor levels do not, as a rule, conduct because these levels are localized and not distributed continuously throughout the crystal.

On the other hand, when the impurity levels lie close to the bottom of the (empty) conduction band shown in

Fig. 9. Electronic energy diagrams for semiconductors. Circles represent positive holes and dots represent electrons.

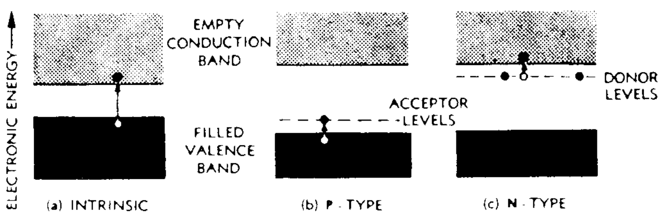


Fig. 9(C), they will donate electrons to the conduction band wherein they will be free to move. The impurity levels are here called donor levels and the semiconductor is termed n-type because most of the current is carried by negative charges.

We thus distinguish two types of semiconductors, p and n type, respectively. To illustrate how n and p type semiconductors can be prepared by suitable doping, consider germanium and silicon, two widely used elements from the fourth group of the periodic table of the elements.

These elements have a chemical valency of four due to their four valence electrons, and their atoms tend to join together by means of "covalent" bonds. In every covalent bond, two electrons are found equally shared by the two atoms. Inasmuch as the covalent bond is very stable, the electrons are not free to conduct and, therefore, under normal conditions the electrical conductivity will be low. (As the temperature is increased, however, the conductivity increases because electrons and holes are produced in equal numbers whenever a bond breaks.)

If additional electrons are now introduced into the crystal lattice by adding elements from Group V (such as arsenic or phosphorus), the additional energy levels will be located somewhat like those shown in Fig. 9(C)

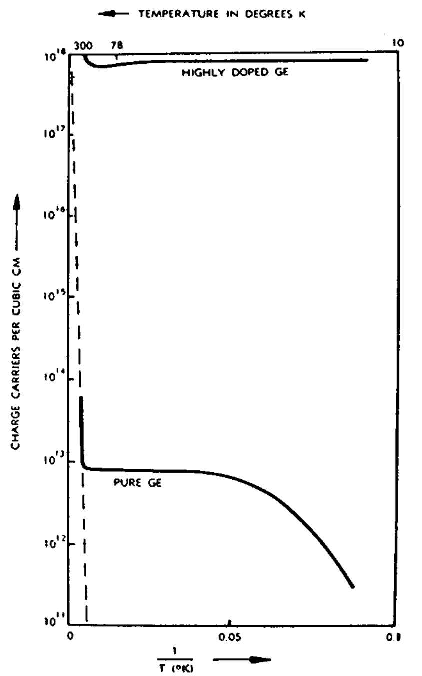


Fig. 11. Density of charge carriers versus temperatures for the same germanium samples of Fig. 10. The dashed line indicates the density of intrinsic carriers.

Greatly enhanced conductivity will be observed because the energy difference between the donor levels and the conduction band is relatively small, of the order of 0.01 electron-volts for germanium and of 0.05 for silicon.[8] These values are small when compared with the room temperature energy gap values of approximately 0.065 for germanium and 1.08 for silicon given in Table I.

The additional electrons come from the donor atoms. Thus, when an arsenic atom is substituted for one of germanium, there is an electron left over which can contribute to the conductivity to an extent dependent on how firmly attached it is to the arsenic atom.

Similar consideration applies to the preparation of p-type germanium or silicon by doping with Group III elements, such as boron or aluminum. These atoms, which have only three valence electrons, will create holes (lack of electrons) in the valence band, introduc-

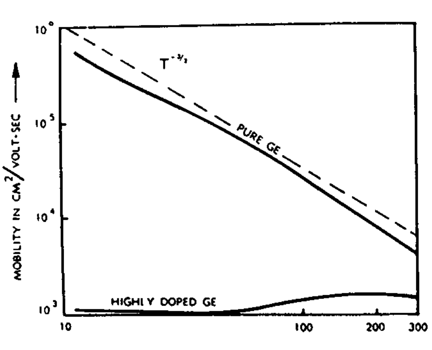


Fig. 10. Variation of mobility with temperature for two samples of germanium.

ing acceptor levels within the forbidden region, as indicated in Fig. 9(B).

When the concentration of impurities in the semiconductor becomes very large, we find the semiconductor becoming metallic in character. It is then said to be degenerate. Under such conditions, the number of charge carriers is practically independent of temperature as indicated in Fig. 11.

Recombination, Lifetime and Minority Carriers

As discussed in connection with Fig. 9, carriers are created by either intrinsic or extrinsic excitation. But at the same time that carriers are being generated (through absorption of radiation or by injection through a suitable contact, as in a transistor), they also are being destroyed through recombination. Under conditions of equilibrium, the rates of generation and of recombination are equal, and the number of charge carriers will be given in equation 5.

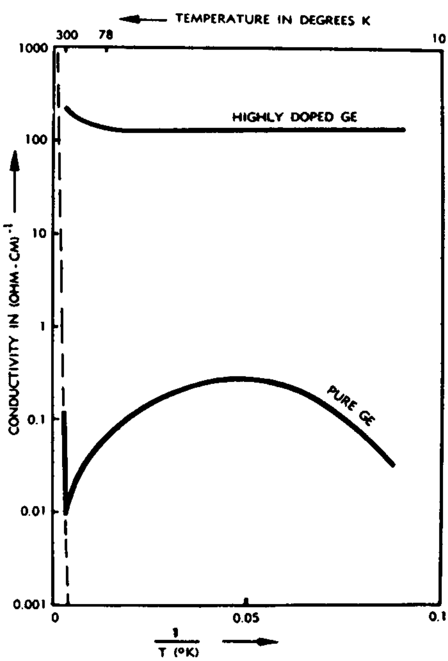


Fig. 12. Conductivity versus temperature for the same two germanium samples of Figs. 10 and 11.

It has been found that these generation and recombination rates are related to the so-called mean lifetime of the minority carriers. For our purpose, the latter can be considered as the average length of time that the minority carrier exists between generation and recombination. Lifetimes in semiconductors depend on the state of perfection and of the purity of the crystal. Values as high as 0.001 to 0.01 seconds have been obtained in high purity germanium; the values in silicon and in other semiconductors are lower.

Although direct recombination of holes and electrons has been observed in germanium and in silicon, the most important recombinations processes in most semiconductors appear to be those occurring at the surface and in the bulk by means of recombination centers, or energy levels within the forbidden region. These centers may consist of lattice imperfections, vacant lattice sites, interstitial atoms, and impurities. In many cases, a carrier that has dropped into such an intermediate energy level will be thermally re-excited and released before it recombines with a carrier of opposite sign. In such cases, the recombination center is often called a trap.

Conductivity, Mobility, and Concentration

The electrical conductivity of a semiconductor is determined both by the number of mobile charge carriers and the facility with which these carriers move under an applied field. The latter property is called the mobility and is defined as the drift velocity per unit field.

The actual expression for conductivity, σ, is given by

$$\sigma = \sigma_n + \sigma_p = ne\mu_n + pe\mu_p \qquad (4)$$

where n and p are the electron and hole concentrations, e is the electronic charge, and μ_n and μ_p are the electron and hole mobilities, respectively.

From equation 4 one can see that in order for the conductivity to increase with temperature, the product of concentration and mobility must increase.

In practice, it is found that the conductivity at first tends to increase with rise in temperature, and then at higher temperatures it tends to decrease (illustrated by the sample labelled "pure" in Fig. 12).

The variation in mobility with temperature for two samples of *n*-type germanium is shown in Fig. 10, while the temperature variation of the carrier concentration for the same two samples is shown in Fig. 11. The sample marked "pure" contained less than 10^{13} charge carriers per cm^3 at room temperature, or about one conduction electron for every 5½ billion germanium atoms! The other sample was highly doped with arsenic[9,10] to about 8 x 10^{18} carriers per cm.[3]

Fig. 12 illustrates how the conductivity varies with temperature, for the same two samples of Figs. 10 and 11. Because the number of carriers and the mobility are relatively constant for the impure sample, the conductivity is also a constant as a function of temperature.

With respect to the concentration of electrons and holes at any given temperature, equation 5 states that the product of these two quantities is a constant, regardless of the purity of the semiconductor:

$$pn = n_i^2 = \text{constant } T^3 \left[\exp \left(\frac{-E_g}{kT} \right) \right] \quad (5)$$

TABLE I. ENERGY GAPS AND MOBILITIES IN SEMICONDUCTORS AT ROOM TEMPERATURE

	E electron volts	μ_n, cm^2 per volt-second	μ_p, cm^2 per volt-second
Si	1.08	1200	500
Ge	0.65	3900	1900
Grey Sn	0.09	~ 2000*	~1000*
Boron	~1.1	—	—
Hexagonal Se	~1.7	—	< 10
Te	0.32	830	540
Black P	0.33	220	350
Grey As	1.20	—	—
Iodine	~1.3	—	—
CdS	2.4	210	—
CdSe	1.7	~ 100	—
CdTe	1.5	600	50
Cd_3As_2	0.6	—	—
PbS	0.30	600	~ 250
PbSe	0.22	1175	868
PbTe	0.27	1200	475
ZnS	3.60	—	—
ZnSe	2.58	—	—
ZnTe	2.2	—	—
ZnSb	0.55	—	—
Mg_2Si	0.77†	—	—
Mg_2Ge	0.74†	530	106
Mg_2Sn	0.33†	320	260
Mg_3Sb_2	0.8	—	—
InP	1.25	3400	650
InAs	0.35	30000	~ 200
InSb	0.18	77000	~1250
GaP	2.3	—	—
GaAs	1.3	4000	> 250
GaSb	0.7	4000	850
AlSb	1.6	1200	200
$CuInS_2$	1.2	—	—
$AgInSe_2$	1.18	—	—
$CuInSe_2$	0.92	300	26
$AgInTe_2$	0.96	—	—
$CuInTe_2$	0.95	—	—
$CuFeS_2$	0.53	—	—

* At 0 degrees centigrade
† At 0 degrees Kelvin

where p and n are the hole and electron concentrations, n_i the intrinsic concentration, T the absolute temperature, k Boltzmann's constant, and E_g the thermal energy gap of the forbidden region. The cubed term indicates why the number of carriers increases so rapidly with temperature.

The conductivity of a semiconductor is given in equation 4. By means of separate measurements of the conductivity and of the mobilities one obtains values for the concentrations n and p. In most semiconductors, the electron mobility is greater than the hole mobility. Some typical values for a number of semiconductors are given in Table I. The very high electron mobility of indium antimonide, in particular, leads to pronounced magnetic effects and a number of technological applications have already been proposed for this material.[11,12]

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This article originally appeared in ELECTRICAL ENGINEERING

Arc Suppression with Semiconductor Devices

by F. W. Parrish, BEE
Chief Engineer, International Rectifier Corporation
Member AIEE, NACE

Contact protection circuit design using germanium or selenium rectifiers reduces contact erosion from inductive kickback voltage. Design procedure is given together with curves from which unknowns may be derived to specify the rating of the rectifier.

Wherever electric power to inductive devices must be controlled by contacts which initiate and interrupt the flow of current, the problem of protecting the contacts from erosion becomes important. This protection is more important in d-c circuits, although it is often necessary in a-c circuits, and commands greater attention at higher supply voltages.

When the switch in the inductive circuit illustrated in Fig. 1 is opened, the magnetic field in the coil collapses and a voltage is generated equal to $L\ di/dt$, where $L =$ coil inductance and $di/dt =$ time rate of change of decay current. This voltage is frequently many times the supply voltage, enough to maintain an arc across the contacts. The arc may be a glow discharge, or even a small metallic bridge which becomes hot enough to vaporize a small portion of the contact metal. Repeated arcing causes erosion, pitting, and general deterioration of the contacts and results in high contact resistance and increased maintenance.

Several methods of contact protection have been employed with varying results. These methods have used various components such as arc blowout coils, permanent magnets, fixed resistors, capacitors and semiconductor devices. Semiconductor devices have proved to be most effective and are

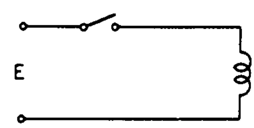


Fig. 1. Inductive circuit requiring arc suppression.

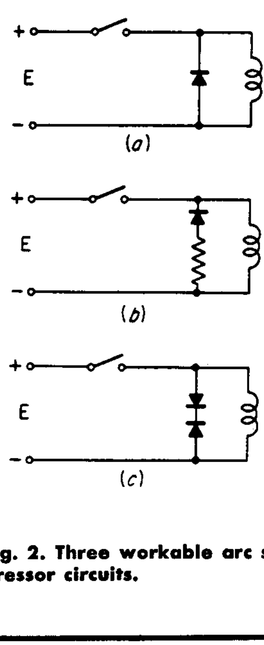


Fig. 2. Three workable arc suppressor circuits.

able to overcome some of the inherent disadvantages of other methods as noted below:

1. Blow-out coils or magnets, while reducing arcing, tend to increase the voltage generated by the coils, sometimes to values that will puncture the coil or circuit insulation. Semiconductors both reduce the arcing and control peak voltages.

2. Fixed resistors can reduce the arcing and control coil peak voltages, but consume power while the coil is energized and sometimes increase drop-out time excessively.

3. Capacitors also provide arc reduction, but sometimes draw excessive charging currents (causing contact heating) and may also increase drop-out time.

Proper design and application of semiconductor arc suppressors can minimize or eliminate the above disadvantages, and may be applied to many types of magnetic devices.

To obtain maximum contact protection concurrent with optimum circuit operation, it is necessary to select the proper suppressor circuit (See Fig. 2) and to specify the proper type and rating of the semi-conductor device. The choice of the most suitable circuit usually is governed by the following three circuit conditions, any one of which may assume the determining role under various modes of operation: (1) supply voltage, (2) maximum permissible induced voltage, and (3) maximum allowable time delay in de-energizing the coil.

On many magnetic loads such as lifting magnets, magnetizer coils; large contactors, or motor fields, the time delay in voltage decay is of minor or no importance. Here items 1 or 2 above will be the controlling factor, and the circuit Fig. 2a will usually be used, with an alternate choice of Fig. 2b. In other applications, such as magnetic brakes or high-speed relays, time delay becomes of prime importance, and the circuit of either Fig. 2b or 2c will be prescribed to minimize the delay in voltage decay. On all a-c circuits, the suppressor arrangement of Fig. 2c is necessary, since the suppressor must block voltages of both polarities. In some applications, a delay in drop-out time of a relay or contactor may be an advantage. The duration of this delay can be controlled by selecting the correct suppressor, or made adjustable by the circuit of Fig. 2b with a variable resistor.

Design Procedure

To design a semiconductor suppressor for a specific magnetic circuit, the following parameters must be known or determined by measurement.

Supply voltage	E
Steady-state coil current	I
Coil resistance	$R_L = \frac{E}{I}$
Coil inductance	L (in millihenrys)
or Ratio $\frac{\text{inductance}}{\text{resistance}}$	L/R_L (from tests & chart Fig. 6)
Suppressor resistance	R_S = resistance of suppressor plus added series resistance if any
Total circuit resistance	$R = R_L + R_S$

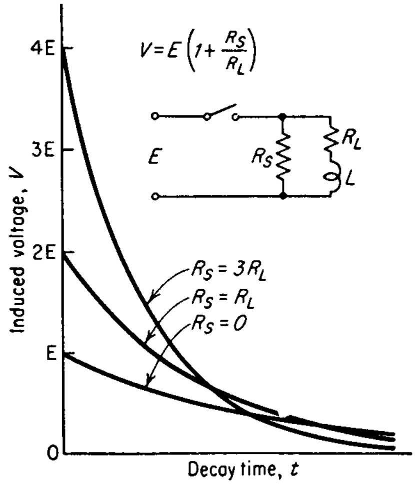


Fig. 3. Induced voltage and decay time for typical magnetic circuit.

Max. allowable induced voltage	V_o
Max. or min. decay time	t (if important)
Relay drop-out voltage	E_d (if drop-out time is important)
Decay voltage	V (at time t after contacts open)

The voltage induced in the coil after the contacts are open decays along an exponential curve similar to those of Fig. 3, and may be expressed by:

$$V = IR\varepsilon^{\frac{-t}{L/R}}$$

at time of opening contact

$$t = 0,\ \varepsilon^{\frac{-t}{L/R}} = 1 \text{ and } I = E\frac{1}{R_L}$$

therefore the peak induced voltage

$$V = E\left(1 + \frac{R_S}{R_L}\right) \qquad (2)$$

From equation (2) it is found that the peak voltage is dependent only on the supply voltage and the ratio of the suppressor resistance to coil resistance (see Fig. 3). Therefore, if drop-out-time is unimportant, the correct value of R_S may be chosen to limit the peak induced voltage to acceptable values

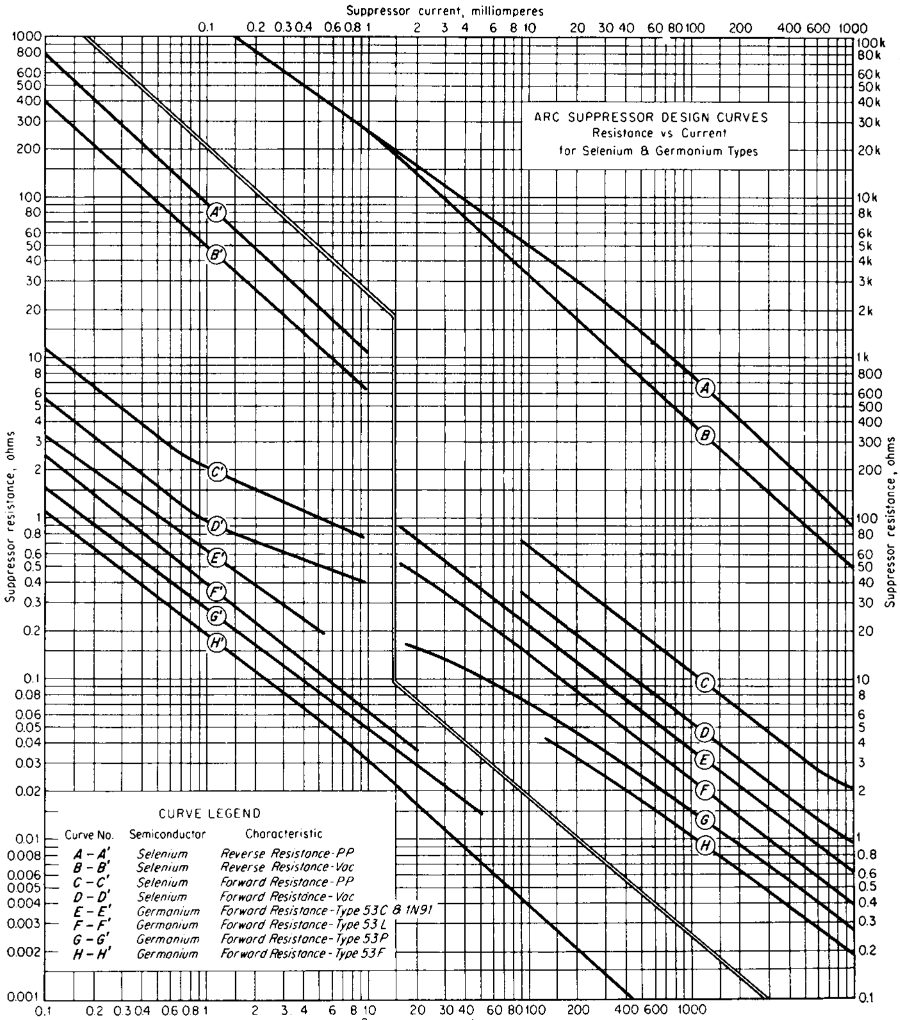


Fig. 4. Resistance vs current curves for selenium and germanium rectifiers.

and the correct suppressor designed from Fig. 4, the semiconductor rating (see table) and the steady-state values of E and I as described below. However, if drop-out time is critical, equation (1) may be rewritten:

$$\varepsilon^{\frac{-t}{L/R}} = \frac{E_d}{IR}$$

where E_d = relay drop-out voltage, and R has been tentatively selected by referring to equation (2). Then, by using the value found for $\varepsilon^{\frac{-t}{L/R}}$ and t, the L/R ratio may be found from Fig. 5.

Then, since $R = R_L + R_S$

$$R_S = \frac{L}{L/R} = R_L \qquad (4)$$

If L is not known, it can be estimated from Fig. 6. Since the original value of R was assumed, the answer is approximate and the new value of R_S should be substituted and the answer rechecked.

By further examining equation (1), it can be seen that as R_S is made smaller to reduce the peak generated voltage, the delay time becomes longer. Therefore, where dropped-out time as well as peak voltage is critical, a compromise between these two parameters must be reached to achieve optimum delay and minimum generated voltage.

Now, let us examine in detail the curves of Figs. 4, 5, and 6.

Figure 4 shows typical resistance *vs* current curves for selenium cells (based on 1 sq. in. of active area) and some commonly available diffused junction germanium rectifiers. Inspection of these curves illustrate the principal reason for the superior per-

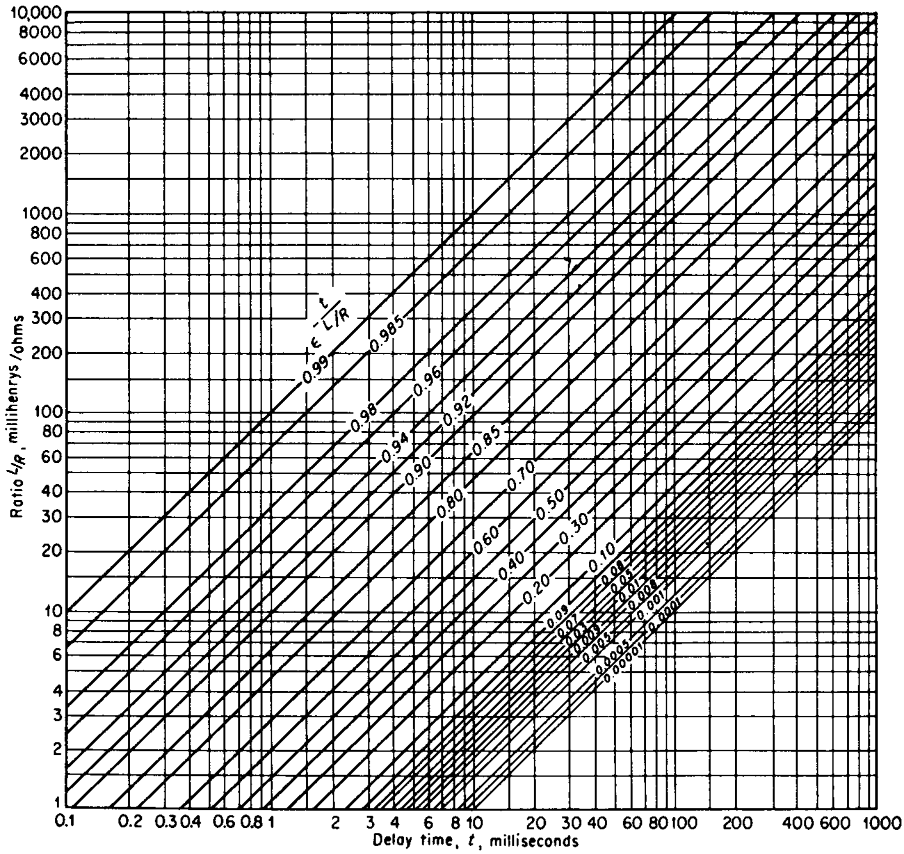


Fig. 5. Graphical solution of exponential term.

formance of semi-conductor suppressors over other types, explained as follows: The maximum current flowing through the suppressor occurs at the instant the switch is opened and is equal to but never greater than the steady-state coil current, I. The current then decays in an exponential manner similar to the voltage decay curves of Fig. 3.

In Fig. 4, note that as the current decays, the resistance of the semiconductor becomes greater. This action accelerates the rate of voltage decay so that the actual ratio is faster than that illustrated in Fig. 3 when resistance of fixed value was used to calculate the decay curve.

The nonlinear resistance of the semiconductor prevents accurate calculation of drop-out time t_1, but assures that the drop-out time will always be less than the value calculated for an equivalent linear resistance, or less than the assumed value used to calculate the required suppressor resistance Rs. Thus, the semiconductor suppressor not only consumes less power but also provides faster drop-out than that obtainable from a fixed resistor.

Figure 5 has been prepared to facilitate solution of the exponential equations (1) or (3). After the tentative suppressor resistance Rs has been estimated from equation (2), and the exponential function calculated from equation (3) the value of L/R can be read from Fig. 5. The required drop-out time t_1 is known from circuit operation.

Figure 6 is useful in determining the L/R ratio of the coil and in turn the coil inductance L from tests which may be made using readily available instruments. The necessary instruments include an a-c and d-c voltmeter and ammeter, a variable a-c voltage supply, and a well filtered variable d-c voltage supply. Coil inductance can be esti-

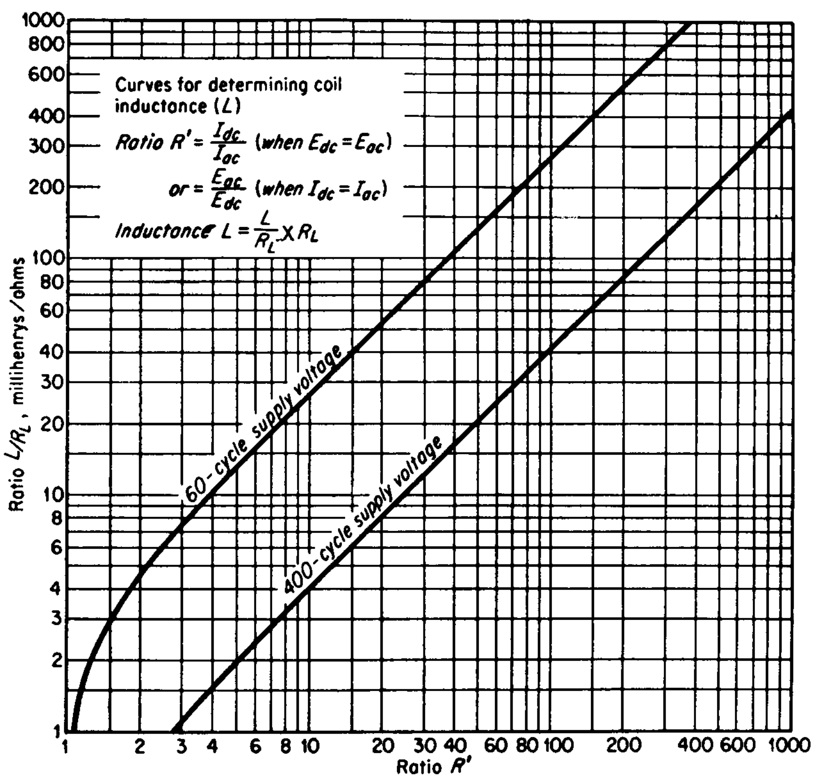


Fig. 6. Curves for determining coil inductance.

mated from the following relationships:

$$\text{Ratio } R' = \frac{I_{dc}}{I_{ac}} \text{ when } E_{dc} = E_{ac}$$

or $$R' = \frac{E_{ac}}{E_{dc}} \text{ when } I_{dc} = I_{ac}$$

and, of course

$$R_L = \frac{E_{dc}}{I_{dc}}$$

In Fig. 6, curves are shown for both 60-cycle and 400-cycle voltages, since these are the principal frequencies found in test laboratories.

Typical semiconductor assemblies are pictured in Fig. 7. For most suppressor applications, selenium assemblies will prove most economical. Germanium assemblies will normally be specified only when an intentional time delay is desirable which in turn requires the lowest possible resistance. Selenium rectifier cells will normally block approximately 20 volts d-c per cell in series.

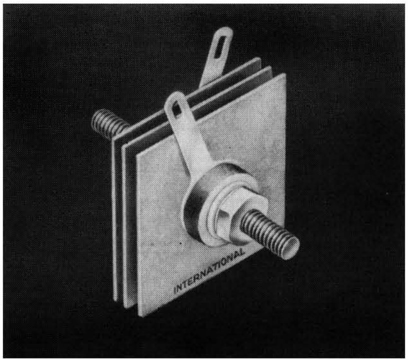
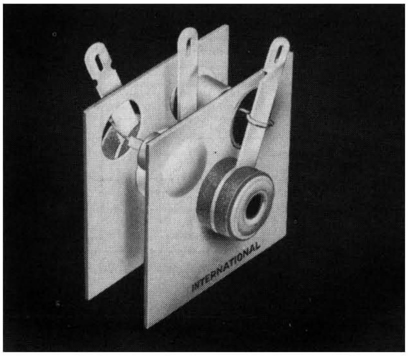


Fig. 7. Typical arc suppression semiconductor assemblies. Above, selenium; below, germanium.



To find the suppressor resistance for the circuit of Fig. 2a, choose the cell size according to current capacity from the rating table. Then divide the current I by the cell active area, and using this value of current density, refer to Fig. 4 to find the corresponding resistance per cell in ohms. Multiply this value of resistance by the number of cells in series as required by the applied voltage and the answer will be R_S. The same method is applicable to the suppressor of Fig. 2c by using the selenium "reverse" curve and the "reverse" ratings from Fig. 4, and the rating table. The germanium curves are plotted in ohms *vs* amperes for specific junction sizes, and no area calculation is necessary. International Rectifier types 53-0150 to 0153 and 53-0106 to 0109 will block voltages of 26, 36, 52 and 66-volts d-c respectively. The IN91 and IN92 types are available in blocking ratings of 70 and 140-volts d-c, respectively.

Typical Design Problem

As an example of the determination of the proper suppressor for use with a d-c coil, a 50-amp single-pole aircraft type contactor with a 24-volt rated coil was selected.

1. Tests were made to determine the coil resistance, inductance, and "drop-out" voltage.

(a.) With 16.5 volts d-c applied to the coil the measured current is 2.6 amp, therefore $R_L = 6.35$ ohms.

(b.) With 16.5 volts at 60 cycles applied, current is 0.51 amp,

$$\text{Ratio } R' = \frac{I_{dc}}{I_{ac}} = \frac{2.6}{0.51} = 5.1$$

from Fig. 6,

$$\text{ratio } L/R_L = 13.3/\text{mh}/\text{ohm}$$

$$L = L/R_L \times R_L = 13.3 \times 6.35 = 84.5\text{mh}$$

(c.) Using a variable d-c voltage supply, the contactor drop-out voltage E_d is found to be approximately 2 volts.

2. Assuming that the generated voltage at the time the contactor is de-energized should not exceed 100 volts,

from equation (2)

$$Rs = \left(\frac{V}{E} - 1\right) R_L = \left(\frac{100-1}{24}\right)$$

6.35=20.1 ohms.

Coil current with 24 volts d-c

$$\text{applied} = \frac{24}{6.35} = 3.78 \text{ amp.}$$

3. To obtain a short drop-out time use the circuit of Fig. 2c.

(a.) From the rating table it is observed that a size "B" cell (1¼ in. sq.) with 1 sq.-in. of active area is rated up to 4 amp peak reverse pulse current.

(b.) Since selenium cells are rated for 20 volts per cell blocking voltage, it is necessary to use a total of three cells, two to block the 24 volts while the switch is closed, and one to suppress the arc after the switch is opened.

4. From curve A^1, Fig. 4, at 3.78 amp, the resistance Rs is approximately 26 ohms. The calculated value of generated voltage will be

$$E\left(\frac{Rs}{R_L}+1\right)=24\left(\frac{26}{6.35}+1\right)$$

=122 volts

5. To determine the maximum drop-out time, refer to equation (3) and calculate:

$$\frac{\varepsilon^{-t}}{\varepsilon^{L/R}} = \frac{E_d}{IR} = \frac{2}{3.78 \times 6.35} = 0.0835$$

and

$$L/R = \frac{84.5}{Rs + R_L} = \frac{84.5}{26 + 6.35} = 2.6$$

from Fig. 4, drop-out time t = 8 millisec.

Values of 122 volts peak and 8 millisec drop-out time should be acceptable for most applications. However, if a shorter drop-out time is required, Rs can be increased. Conversely, if a lower peak voltage is mandatory, Rs can be decreased. However, it is not possible to decrease both peak voltage and drop-out time simultaneously.

Curves sketched from an oscilloscope test are shown in Fig. 8. With 24 volts d-c applied to the contactor coil, the generated voltage without a suppressor is about 300 volts peak. However, addition of the selenium suppressor designed above limits this

Selenium and Germanium Suppressor Current Ratings

Selenium Cell		Active Area (in.²)	Avg. current, amp		Peak pulse (amp)		Blocking voltage (per cell)
Cell*	Size (in.)		Forward	Reverse	Forward	Reverse	
U	⅛ D	0.012	0.005	0.00034	0.15	0.048	20
V	¼ D	0.05	0.020	0.0014	0.6	0.20	20
Y	⅜ D	0.11	0.03	0.0031	0.9	0.44	20
Z	½ D	0.20	0.04	0.0056	1.2	0.80	20
X	¾ D	0.40	0.08	0.011	2.4	1.6	20
A	1 sq	0.62	0.19	0.017	5.7	2.5	20
B	1¼ sq	1.0	0.28	0.028	8.4	4.0	20
C	1½ sq	1.63	0.50	0.045	15.0	6.5	20
L	2 sq	3.0	1.1	0.084	33.0	11.0	20
D	3 sq	7.0	2.2	0.20	44.0	28.0	20
E	4⅜ sq	16.5	4.9	0.46	147.	66.	20
J	4¼ x 6	22.5	6.5	0.63	195	90.	20
F	5 x 6	26.5	7.4	0.74	222	106.	20
H	6 x 6	41.5	12.0	1.16	360.	166.	20

Germanium junctions*	Junction size (in.)	Suppressor current ratings		Blocking voltage
		Average (amp)	Peak pulse (amp)	
1N91	D	0.10	1.0	70
1N92	D	0.10	1.0	140
1N93	D	0.10	1.0	210
53C	1½ sq	2.0	20	70
53L	2 sq	4.0	40	up to 66
53P	4 sq	10.0	100	up to 66
53F	2 D x 2⅛ H	150 (fan cooled)	450	up to 66

* International Rectifier Type Numbers

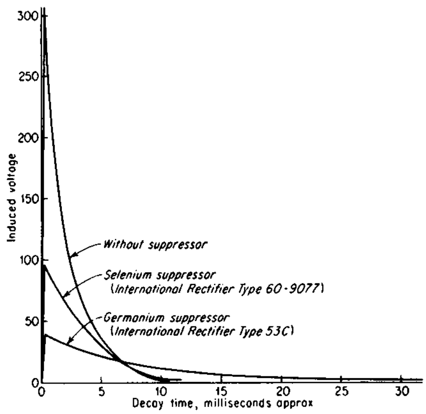


Fig. 8. Induced voltage and decay time with and without arc suppressors for a 24-volt aircraft type contactor coil with 50-amp contacts.

voltage to about 90 volts and with negligible change in drop-out time. It is also evident that when the type 53C germanium suppressor is used, the peak voltage is reduced to about 40 volts peak, but the drop-out time is greatly increased (to an estimated 200 millisec from oscilloscope observation).

In conclusion, it may be stated that with the proper design of a semiconductor suppressor for a specific inductive load, the following advantages may be realized over and above those obtained by other types of suppressors.

1. Reduced erosion and pitting of contacts, and hence longer contact life.
2. Reduced power consumed by the suppressor.
3. Lower generated peak voltage, and hence less chance of insulation damage.
4. Faster drop-out time for a given peak voltage, or
5. Longer time delay (when desired) consistent with adequate contact protection and low suppressor power drain.
6. Decreased number of circuit failures due to high contact resistance (or eroded contacts) or "sticking" contacts.

The wide variety of cell sizes and ratings makes it possible to design suppressors for almost any combination of coil voltage, current, and inductance values.

References

"Investigation of the Selenium Rectifier for Contact Protection," H. F. Herbig and J. D. Winders, *AIEE Transactions, 1951.*

"Introduction to Electrical Engineering," George V. Mueller, McGraw-Hill Book Co., New York, 1948.

"Protecting Relay Contacts Against Arcing," H. N. Sachar, ELECTRICAL MANUFACTURING, Feb. 1954, p. 138.

This article originally appeared in ELECTRICAL MANUFACTURING

International Rectifier Selenium A.C. and D.C. Contact Protectors

The contact protectors listed in the Tables are suitable for a large number of circuits. They are available in three physical configurations; encapsulated diode types, fibre tube cartridges and hermetically sealed cartridges. The hermetically sealed units are of particular importance when severe environmental conditions are encountered. Encapsulated diode types are extremely small in size, for application in limited space; occupying only 0.01 cu. in. of space — slightly larger than a match-head.

All units listed are assembled with selenium cells in a back-to-back configuration. This affords the best protection to the contacts, with the least effect on the operation of the circuit. In specifying contact protectors it is important that the maximum voltage rating of the protector exceeds the maximum value of the supply voltage.

Current ratings given are for intermittent operation with a maximum of 30 to 40 operations per second. As the steady state coil current is the maximum current encountered, the type of cell should be selected whose rating is larger. If the frequency of operation exceeds 40 operations per second, it may be necessary to use larger cells than those listed, and full information will be required in order to analyze the heating effect produced in the rectifier, and so determine the size required. The ratings are based upon maximum ambient temperature of 35°C. When higher ambient temperatures are encountered some derating will be necessary.

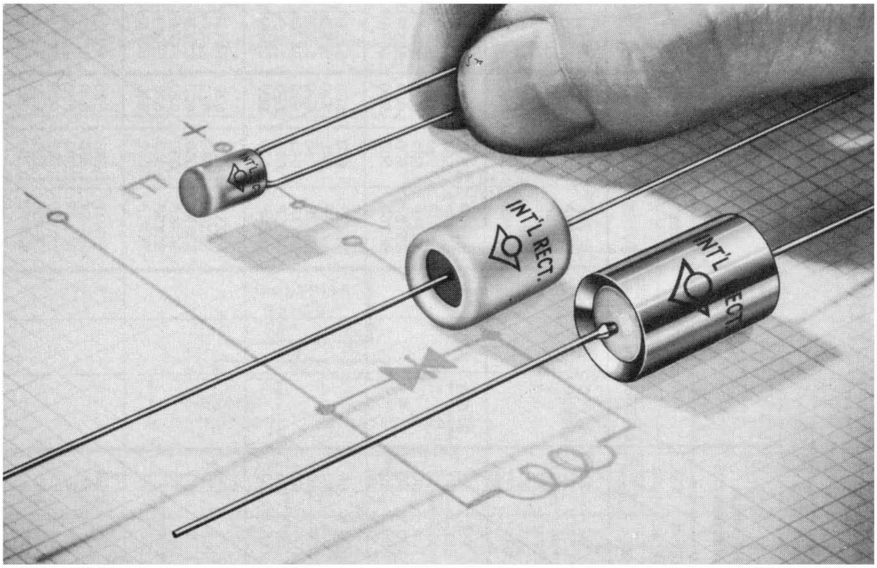
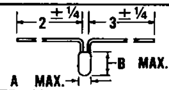
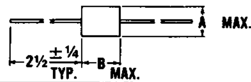


Fig. 1. Pictured here are the three basic types of Contact Protectors produced by International Rectifier Corporation.

Table 1. International Rectifier Contact Protector Types and Specifications.

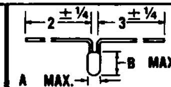
A.C. TYPES

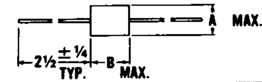




Electrical Characteristics: Working Volts AC Max.	Electrical Characteristics: Max. Coil Current (amp)	Diode Type: Code No.	Diode Type: Dimension A (Max.)	Diode Type: Dimension B	Fibre Cartridge Type: Code No.	Fibre Cartridge Type: Dimension A (Max.)	Fibre Cartridge Type: Dimension B	Hermetic Seal Cartridge Type: Code No.	Hermetic Seal Cartridge Type: Dimension A (Max.)	Hermetic Seal Cartridge Type: Dimension B
26	.20	S1V1D	.310	.470	S1V1P	.380	.620	S1V1H	.440	.860
52	.20	S2V2D	.360	.470	S2V2P	.380	.620	S2V2H	.440	.860
78	.20				S3V3P	.380	.620	S3V3H	.440	.860
104	.20				S4V4P	.380	.620	S4V4H	.440	.860
130	.20				S5V5P	.380	.620	S5V5H	.440	.860
156	.20				S6V6P	.380	.990	S6V6H	.440	1.190
26	.40	S1Y1D	.470	.550	S1Y1P	.500	.620	S1Y1H	.535	.860
52	.40				S2Y2P	.500	.620	S2Y2H	.535	.860
78	.40				S3Y3P	.500	.620	S3Y3H	.535	.860
104	.40				S4Y4P	.500	.620	S4Y4H	.535	.860
130	.40				S5Y5P	.500	.620	S5Y5H	.535	.860
156	.40				S6Y6P	.500	.990	S6Y6H	.535	1.190
26	.60				S1Z1P	.640	.620	S1Z1H	.700	.860
52	.60				S2Z2P	.640	.620	S2Z2H	.700	.860
78	.60				S3Z3P	.640	.620	S3Z3H	.700	.860
104	.60				S4Z4P	.640	.620	S4Z4H	.700	.860
130	.60				S5Z5P	.640	.620	S5Z5H	.700	.860
156	.60				S6Z6P	.640	.990	S6Z6H	.700	1.190
26	.90				S1X1P	1.060	.620	S1X1H	1.090	.860
52	.90				S2X2P	1.060	.620	S2X2H	1.090	.860
78	.90				S3X3P	1.060	.620	S3X3H	1.090	.860
104	.90				S4X4P	1.060	.620	S4X4H	1.090	.860
130	.90				S5X5P	1.060	.620	S5X5H	1.090	.860
156	.90				S6X6P	1.060	.990	S6X6H	1.090	1.192
26	1.2				S1W1P	1.380	.620	S1W1H	1.420	.860
52	1.2				S2W2P	1.380	.620	S2W2H	1.420	.860
78	1.2				S3W3P	1.380	.620	S3W3H	1.420	.860
104	1.2				S4W4P	1.380	.620	S4W4H	1.420	.860
130	1.2				S5W5P	1.380	.620	S5W5H	1.420	.860
156	1.2				S6W6P	1.380	.990	S6W6H	1.420	1.192

D.C. TYPES





Working Volts DC Min.	Working Volts DC Max.	Max. Coil Current (amp)	Diode Type: Code No.	Diode Type: Dimension A (Max.)	Diode Type: Dimension B	Fibre Cartridge Type: Code No.	Fibre Cartridge Type: Dimension A (Max.)	Fibre Cartridge Type: Dimension B	Hermetic Seal Cartridge Type: Code No.	Hermetic Seal Cartridge Type: Dimension A (Max.)	Hermetic Seal Cartridge Type: Dimension B
15	22	.25	S1V1D	.310	.470	S1V1P	.380	.620	S1V1H	.440	.860
23	44	.25	S2V1D	.350	.470	S2V1P	.380	.620	S2V1H	.440	.860
45	66	.25	S3V1D	.400	.470	S3V2P	.380	.620	S3V2H	.440	.860
67	88	.25				S4V2P	.380	.620	S4V2H	.440	.860
89	110	.25				S5V2P	.380	.620	S5V2H	.440	.860
111	132	.25				S6V2P	.380	.620	S6V2H	.440	.860
133	154	.25				S7V2P	.380	.620	S7V2H	.440	.860
15	22	.60	S1Y1D	.470	.550	S1Y1P	.500	.620	S1Y1H	.535	.860
23	44	.60	S2Y1D	.470	.550	S2Y1P	.500	.620	S2Y1H	.535	.860
45	66	.60				S3Y2P	.500	.620	S3Y2H	.535	.860
67	88	.60				S4Y2P	.500	.620	S4Y2H	.535	.860
89	110	.60				S5Y2P	.500	.620	S5Y2H	.535	.860
111	132	.60				S6Y2P	.500	.620	S6Y2H	.535	.860
133	154	.60				S7Y2P	.500	.620	S7Y2H	.535	.860
15	22	.90				S1Z1P	.640	.620	S1Z1H	.700	.860
23	44	.90				S2Z1P	.640	.620	S2Z1H	.700	.860
45	66	.90				S3Z2P	.640	.620	S3Z2H	.700	.860
67	88	.90				S4Z2P	.640	.620	S4Z2H	.700	.860
89	110	.90				S5Z2P	.640	.620	S5Z2H	.700	.860
111	132	.90				S6Z2P	.640	.620	S6Z2H	.700	.860
133	154	.90				S7Z2P	.640	.620	S7Z2H	.700	.860
15	22	1.4				S1X1P	1.060	.620	S1X1H	1.090	.860
23	44	1.4				S2X1P	1.060	.620	S2X1H	1.090	.860
45	66	1.4				S3X2P	1.060	.620	S3X2H	1.090	.860
67	88	1.4				S4X2P	1.060	.620	S4X2H	1.090	.860
89	110	1.4				S5X2P	1.060	.620	S5X2H	1.090	.860
111	132	1.4				S6X2P	1.060	.620	S6X2H	1.090	.860
133	154	1.4				S7X2P	1.060	.620	S7X2H	1.090	.860
15	22	2.				S1W1P	1.380	.620	S1W1H	1.420	.860
23	44	2.				S2W1P	1.380	.620	S2W1H	1.420	.860
45	66	2.				S3W2P	1.380	.620	S3W2H	1.420	.860
67	88	2.				S4W2P	1.380	.620	S4W2H	1.420	.860
89	110	2.				S5W2P	1.380	.620	S5W2H	1.420	.860
111	132	2.				S6W2P	1.380	.620	S6W2H	1.420	.860
133	154	2.				S7W2P	1.380	.620	S7W2H	1.420	.860

The Selenium Rectifier
A Survey

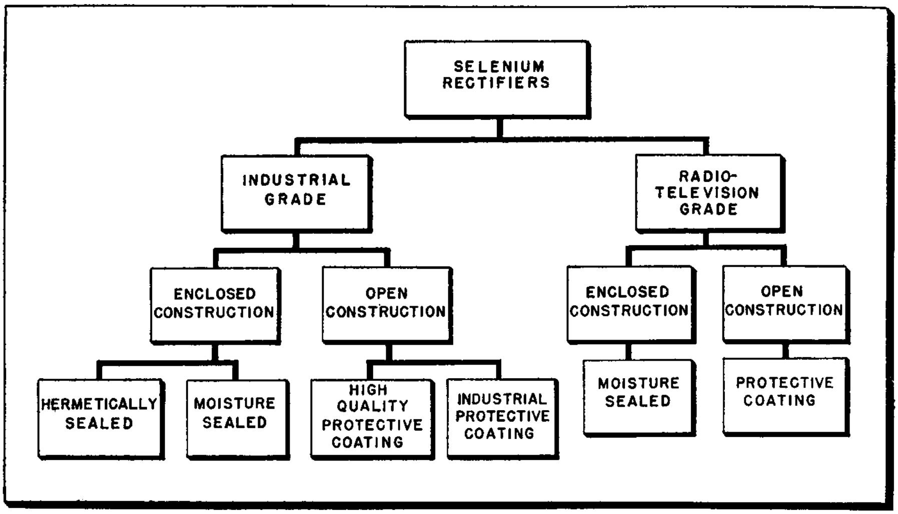
by J. T. Cataldo, BME, BEE
International Rectifier Corporation
Member IRE

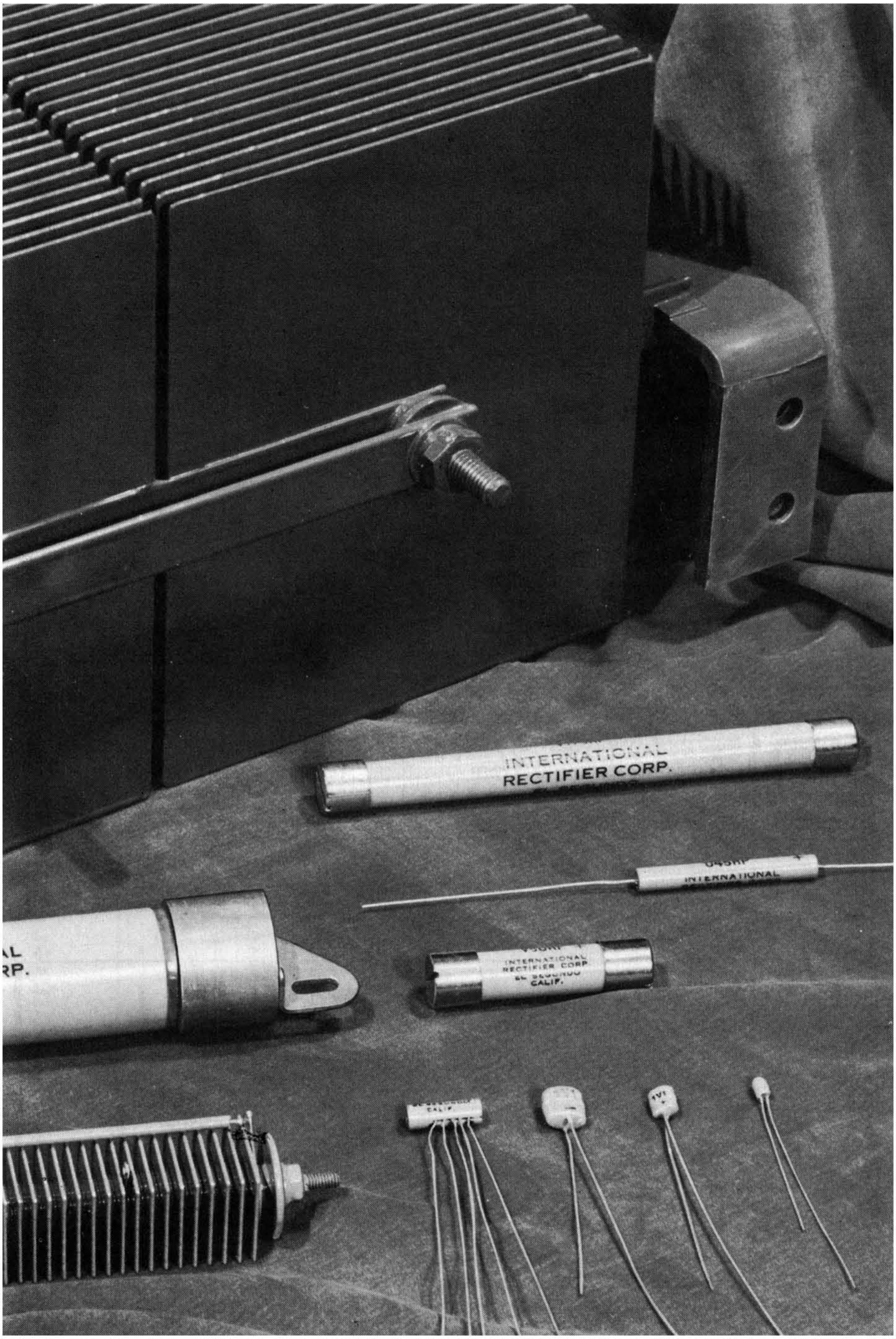
Although the newer semi-conductors, silicon and germanium, are attracting a good deal of attention nowadays, selenium still remains in its apparently secure niche as the most versatile, least expensive semi-conductor for scores of rectifier applications.

In the twenty years since its advent, the selenium rectifier has come a long way. Better understanding of production processes, a multiplicity of new applications, and increasing demands from industry for this semi-conductor resulted in considerable improvement and development. Basic improvement, dictated primarily by the need for miniaturization and increased reliability in military and commercial electronic applications, was directed towards the following phases:[1]

(1) Increasing voltage ratings of selenium plates;
(2) Developing techniques for the punching of small plates;
(3) Increasing ambient operating temperatures of completed units;
(4) Increasing life expectancy.

Fig. 1: Flow chart shows different construction and coating for industrial and radio-TV grades





Few semiconductors demonstrate the extreme versatility of selenium . . . here shown ranging from low-rated diodes to heavy power cartridges and stacks, as manufactured by International Rectifier Corporation.

Fulfillment of this development programme has made possible the production of selenium rectifiers rated from 100 μA to 1,200 amperes, depending on their size, with a material reduction in the size and weight of units for given voltage and current ratings. Ambient temperature ratings as high as 125°C are not uncommon, and life expectancy of today's selenium rectifiers is of the order of 100,000 hours.

Early selenium plates were limited to a maximum reverse voltage rating of 14 to 16 volts r.m.s. New production techniques developed from 1949 to 1951 made possible the mass production of 26, 33, 36 and 40 volt plates, now considered standard by the industry.[2] Selenium rectifiers rated at 52 volts per plate are currently in production.

Industrial and Radio-T.V. Grades

The selenium industry today produces two distinct grades of rectifiers: industrial grade and radio or T.V. grade. Although the processes and techniques employed in their manufacture are essentially the same (see figure 1), the radio-T.V. rectifiers are manufactured at a lower production cost per unit. This lowered cost of production is made possible by producing thousands of certain standard units on a mechanized production line. The rectifier is then adapted to the receiver application. It is obvious that this system eliminates set-up and engineering time necessary for the production of industrial stacks, for example, which are usually designed to meet customer's specifications. The end result is that the useful life expectancy of the radio or T.V. stack is from 1.000 to 3,000 hours, as compared with the industrial stacks with a life expectancy of 20,000 to 100,000 hours or more, if properly designed into the circuit.

Selenium Diodes

For applications requiring small currents (milliamps or less) germanium diodes were used almost exclusively originally. These diodes were limited, however, because of low voltage ratings and low maximum operating temperatures. In some applications it became necessary to connect a number of germanium diodes in series – an undesirable factor in most cases, since voltage across the series string was not necessarily distributed equally due to variations in reverse resistance. This often resulted in circuit or component failure. Early efforts to produce small rectifier cells were not encouraging because the complex production processes were not fully understood. With gradual improvement in these techniques, some manufacturers began the production of miniature selenium rectifier cells. These units although satisfactory for many applications, were limited in so far as frequency response was concerned. Unlike silicon or germanium diodes, selenium diodes are area-type semiconductors. As such, they have a self-

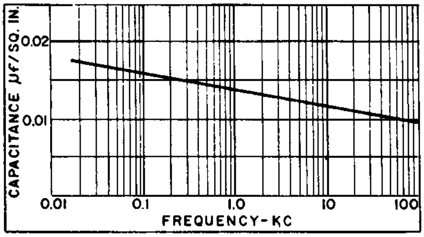


Fig. 2. Self-capacitance of a selenium cell 0.250 inch in diameter with respect to frequency.

capacitance on the order of 0.018 μF per square inch at 60 c/s. In figure 2 are plotted capacitance test data for a selenium cell 0.250 inches in diameter, in μF-per-square-inch vs frequency. From this curve it can be seen that the self-capacitance is 500 μF at 100 Kc/s, and 900 μF at 60 c/s. It is obvious that reducing area of the cell will in turn decrease this self-capacitance. Continued research has made it possible to produce cells with an area of 0.003 square inch, compared with previous units with a cell area of 0.05 square inch. A decrease in capacitance of up to 16 to 1 has been achieved by this reduction. These new units can be used in circuits operating from 100 to 200 αc/s.

Selenium diodes are now available for low currents and voltage ratings up to 208 volt r.m.s. input.[3] This series ranges in output from 100 μA to 11 mA. The small size and light weight of these units makes them ideal for use in limited-space electronic equipment. Their light weight eliminates the need for special supports, and no insulation is required, as they are completely encapsulated in the thermosetting plastic.

Forward voltage drop with ambient temperature for various loads on a basic bridge is shown in figure 3. The bridge has four diodes, one in each arm. Voltage drop was recorded for half-rated, full-rated and four-times-rated loads, with ambients from zero to 100°C. As selenium has a negative temperature coefficient, a lower voltage drop exists at elevated temperatures. Also note that the slope of the curves decreases with decreasing load.

Cartridge Rectifiers

A wide range of cartridge rectifiers is also available today, manufactured in any circuit configuration required for outputs of 200 μA to 200 mA, depending upon voltage rating. Two classes of the enclosed types are the moisture sealed and the hermetically sealed construction cartridges. Radio and T.V. grade rectifiers are also produced in moisture sealed enclosures. For this type, rectangular selenium rectifier plates are secured within a specially processed fibre tube and a plastic compound is used to seal the ends. Electrical connection is made to a "pigtail" lead located at each end. In this type, a quantity of circular cells are assembled in intimate contact within a phenolic tube.

Sealed Rectifiers

Hermetically sealed units are divided into two distinct types. One type is assembled in much the same manner as the above moisture sealed units, except that a glass tube is used instead of phenolic tubing. Glass-to-metal sealing techniques secure the ferules to the glass tubing, thus assuring a true hermetic seal. Hermetic sealing is achieved by securing the metal container to a glass-to-metal or ceramic-to-metal header which is provided with a pigtail lead. A hermetic header, in general, consists of a metal unit through which

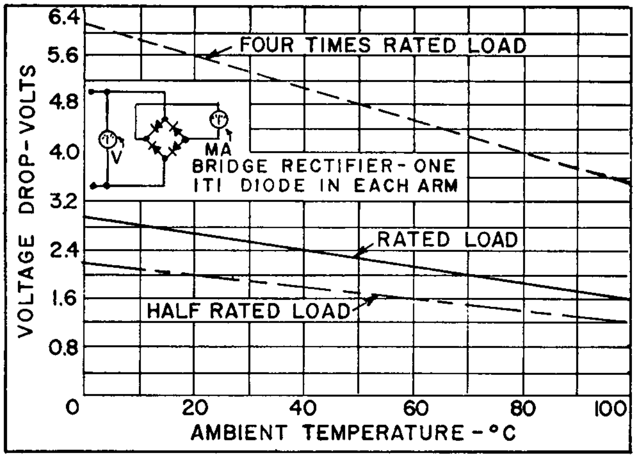


Fig. 3. Forward voltage drop with temperature variations of a typical bridge using 4 selenium diodes.

a glass-to-metal seal is accomplished. The metal enclosure is electrically "hot" since the second terminal is affixed to it. When insulation from chassis is required, a piece of flexible plastic tubing is used.

"Packaged" Rectifiers

Highly developed refinements of this type of hermetically sealed rectifier are being manufactured today. A representative group of these "packaged unit" rectifiers are shown in figure 4. These units are by far the most flexible of those previously described, since they are not restricted to half-wave elements. Individual units are available in half-wave, doubler, or any of the conventional rectifier configurations.

The rectifiers illustrated are high voltage units packaged to provide ratings from 1 milliampere to 1 ampere, and voltages as high as 100,000 volts. They may also be connected in any circuit configuration for even higher voltage ratings. The units are assembled with selenium rectifiers in hermetically sealed oil-filled housings and are operable in temperature ranges to 75°C.

Contact Protectors

Another recent development in the field has been the production of selenium a.c. and d.c. contact protectors—inexpensive devices (illustrated in figure 5) for

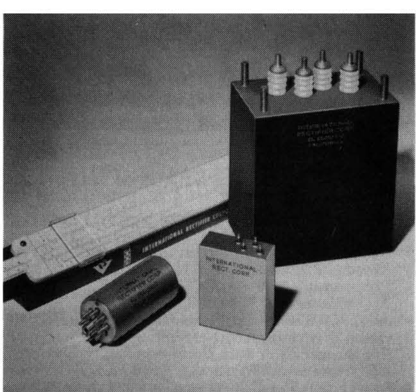


Fig. 4. Representative selection of "packaged" high voltage rectifiers.

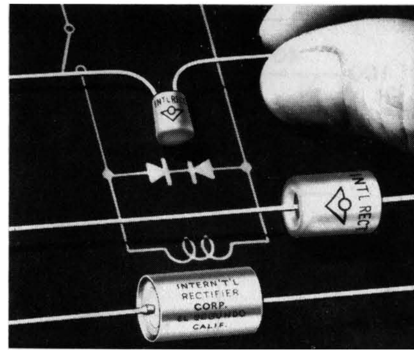
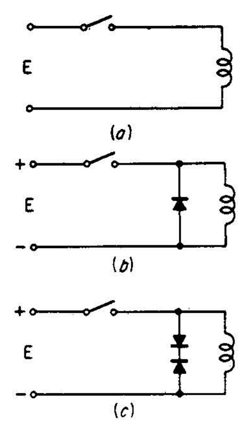


Fig. 5. Contact protector types.

eliminating arcing and erosion across relay, switch and other component contacts.

When the switch in the inductive circuit illustrated in figure 6 (*a*) is opened, the magnetic field in the coil collapses and a voltage is generated equal to $L di/dt$, where L=coil inductance and di/dt=time rate of change of decay current. This voltage is frequently many times the supply voltage, enough to maintain an arc across the contacts, with consequent damage.

Fig. 6.



Several methods are in use to reduce the generated voltage below a value at which arcing will not occur. These include such components as fixed resistors, capacitors, permanent magnets and arc blowout coils. Semi-conductor de-

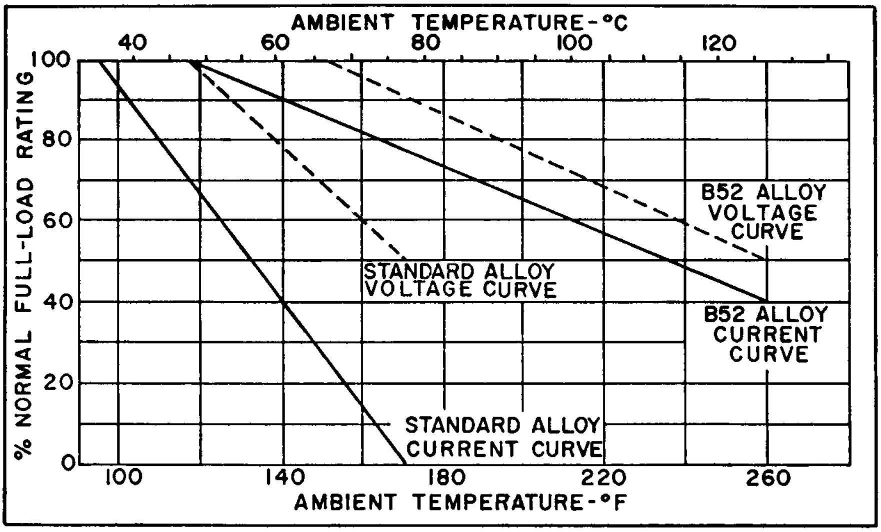


Fig. 7. Derating curves for high-temperature operation of selenium rectifiers.

vices have proved to be most effective, however, and have the additional advantages of small size, long life, low cost and ease of installation. Typical circuits illustrating the use of selenium in contact protection are shown in figure 6 (*b*) and (*c*). The choice of which circuit to use will depend on three factors:

(1) supply voltage;
(2) maximum permissible induced voltage; and
(3) maximum allowable time delay in de-energizing the coil.[4]

High Temperature

Counter-electrodes, in selenium rectifiers are commonly made from a eutectic alloy. This material formerly was compounded of tin, cadmium, and bismuth, and had a melting point of 103°C. This was one factor in limiting operating temperature of selenium rectifiers, necessitating the derating of current above 35°C and of voltage above 45°C. A new alloy, B-52, requires derating for current at 45°C, and for voltage at 65°C, as shown in figure 7. Additional research has resulted in the development of a new counter-electrode alloy which permits rectifiers to be operated up to 125°C for short-life applications, or to 100°C for longer life.

Life Expectancy

Life expectancy of selenium rectifiers has improved immeasurably in recent years. Manufacturers have extended life of selenium units to better than 100,000 hours (when used at rated voltage, current and ambient temperatures), by tightening quality control standards and improving processing methods.

The obvious advantage of selenium rectifiers is their surprising versatility . . . their applicability in circuits requiring as little as 100 μa, or as much as thousands of amps. A recent article by Dr. Stritzl in Direct Current (Vol. 3, page 215, December, 1957) underlines this point by giving details of large-scale applications.

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4 "Arc Suppression with Semi-conductor Devices", *Electrical Manufacturing*, June, 1956.
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This Article originally appeared in the publication "DIRECT CURRENT"

Selenium Diode Applications

by J. T. Cataldo, BME, BEE
International Rectifier Corporation
Member IRE

THE development of the selenium diode offers the electronic design engineer a series of semi-conducting components heretofore not available. These units were developed, in part, to help fill the ever increasing demand for miniature diodes of the metallic family which was created with the advent of electronic computers and miniaturized equipment of all types. Germanium and silicon diodes were used almost exclusively in computers as well as in other electronic equipment such as hearing aids, electronic organs, bias supplies, sensitive d.c. relays, TV and radio receivers. Manufacturers have been sponsoring research and development activities since the first commercial production of selenium rectifiers. The development of the selenium diode, shown in Fig. 1, is the result of the progress made to date in the effort to miniaturize selenium rectifiers.

Initial efforts to produce small rectifier cells were not very encouraging because the many intricate and complex production processes were not well understood. However, with the gradual and continued improvement and control of production techniques and processes, a few selenium rectifier manufacturers started producing miniature rectifier cells. These small cells were assembled into various types of enclosures. These units, although exceedingly satisfactory for many applications, were limited insofar as their frequency response is concerned. Unlike the silicon or germanium diode, the selenium rectifier is an area type semi-conductor. As such, the selenium rectifier possesses a self-capacitance which is on the order of 0.018 microfarad per-square-inch at a frequency of 60 cycles-per-second. In Fig. 2 are plotted capacitance test data of an 0.250 inch diameter selenium rectifier cell in microfarads per-square-inch *versus* frequency. From this curve, the self-capacitance of an 0.250 inch diameter cell is calculated to be 500 μμfd. at 100 kc. and 900 μμfd. at 60 cycles. Since the capacitance of a selenium rectifier is a function of its area,

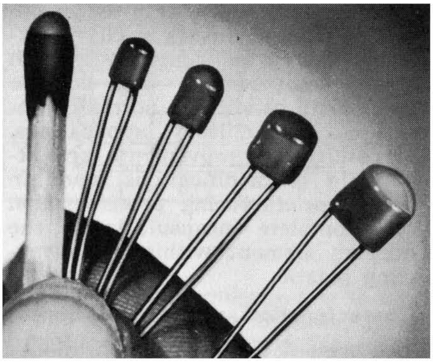


Fig. 1. International Rectifier Selenium Diode Types.

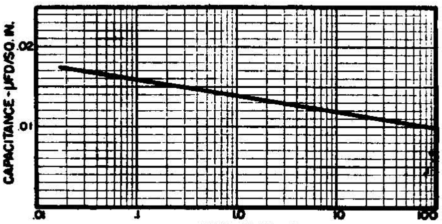


Fig. 2. Capacitance versus frequency curve.

it is obvious that reducing the area of the cell would, in turn, decrease the self-capacitance. Large scale production of smaller diameter cells was accomplished after continued research resulted in resolving the many difficulties previously encountered. Consequently, it is now possible to produce rectifier cells having an area of 0.003 square inch as compared to previous small cells having an area of 0.05 square inch. A decrease of capacitance of as much as 16 to 1 has been achieved by this reduction in rectifier cell size. The decrease of self-capacitance permits the use of these selenium diodes in circuits operating in a frequency range of 100 kc. to 200 kc. These research and development activities also resulted in operational improvements such as extreme stability and long life in high ambient temperatures and adverse environment conditions normally encountered in military applications. The resulting improvements are attributable to modifications made in several manufacturing processes and to the complete encapsulation of the rectifying element within a thermosetting plastic.

Characteristics and Specifications

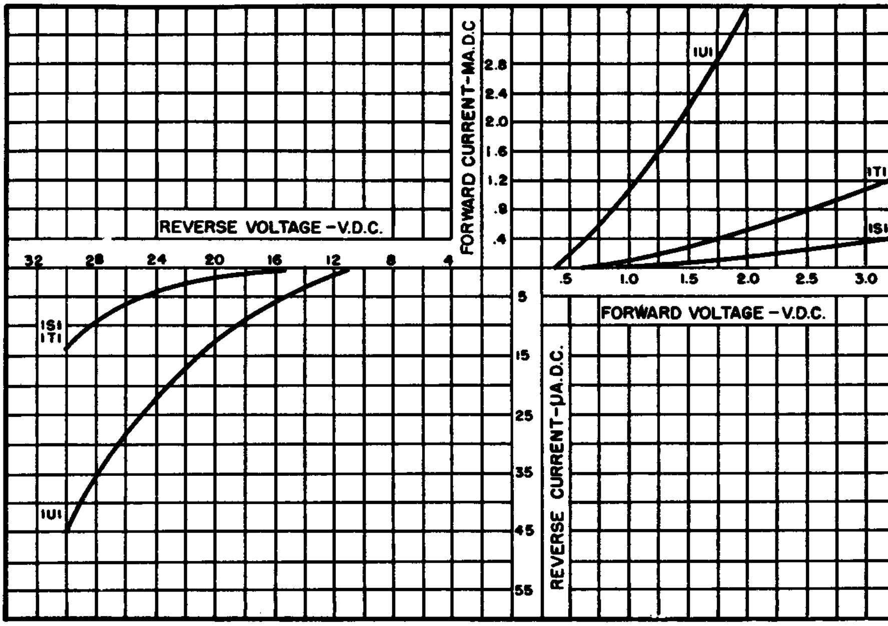
The present line of selenium diodes consists of three series: Series S, Series T, and Series U. The units are provided with pigtail leads to facilitate wiring into crowded chassis. Their small size (see Table 1 for dimensions) makes them ideal for use in electronic equipment where space is limited. They do not require any additional support because of their light weight.

The d.c. output current rating is 100 microamperes, 200 microamperes, and 1.5 milliamperes for the Series S, T, and U respectively. The Series S and T are produced for output voltages of 20 and 40 volts, while the Series U is available for output voltages of 20, 40, 60, 80, and 100 volts at rated output current. Higher output voltages are attainable with these selenium diodes at reduced output current. Static forward and reverse characteristics for the three available series are shown in Fig. 6. The characteristics shown are for the Type 1S1, Type 1T1, and Type 1U1. However, these curves are also applicable to the other diodes if the forward voltage and reverse voltage scales are multiplied by 2, 3, 4, or 5. For example, the Type 5U1 would have a maximum forward voltage drop of 6.0 volts when it is delivering an output current of 1.5 milliamperes. The characteristics in Fig. 6 are the minimum acceptable quality level for these diodes. Units in production all have characteristics well within the limits

Table 1. Specifications on the Series S, Series T, and Series U selenium diodes.

	1S1	2S1	1T1	2T1	1U1	2U1	3U1	4U1	5U1
Rated Forward Current	100 μa.	100 μa.	200 μa.	200 μa.	1.5ma.	1.5ma.	1.5ma.	1.5ma.	1.5ma.
Max. Applied Voltage (r.m.s.)	26 v.	52 v.	26 v.	52 v.	26 v.	52 v.	78 v.	104 v.	130 v.
Max. d.c. Output Voltage	20 v.	40 v.	20 v.	40 v.	20 v.	40 v.	60 v.	80 v.	100 v.
Peak Inverse Voltage	60 v.	120 v.	60 v.	120 v.	60 v.	120 v.	180 v.	240 v.	300 v.
Max. Surge Current (in ma.—1 sec.)	5	5	10	10	80	80	80	80	80
Voltage Drop at Full Load	1 v.	2 v.	1 v.	2 v.	1 v.	2 v.	3 v.	4 v.	5 v.
Max. r.m.s. Input Current	250 μa.		500 μa.		3.75 ma.				
Peak Rectified Current (in ma.)	1.3		2.6		20				
Reverse Current at Max. Applied Voltage	6 μa.		6 μa.		27 μa.				
Reverse Current at	—10 v.	—20 v.	—10 v.	—20 v.	—10 v.	—20 v.	—30 v.	—40 v.	—50 v.
	.6 μa.		.6 μa.		2.4 μa.				
Shunt Capacity at Max. Frequency	57 μμfd.	29 μμfd.	57 μμfd.	29 μμfd.	140 μμfd.	70 μμfd.	50 μμfd.	35 μμfd.	28 μμfd.
Max. Frequency	200 kc.		200 kc.		100 kc.				
Ambient Temperature Range: —40 to 100 degrees C.									

Fig. 5. Static forward and reverse characteristics of Types 1S1, 1T1, and 1U1 diodes.



shown in Fig. 5. In others words, lower forward voltage drop and lower reverse currents can be expected of selenium diodes from regular production runs. Examination of this figure will disclose that a minimum forward-to-reverse resistance ratio of 5000 to 1 is obtainable when the reverse voltage on the unit is not more than 20 volts for the single cell units. This ratio is also attainable with a reverse voltage of 100 volts on the Type 5U1.

Forward voltage drop *versus* ambient temperature characteristics for various loads on a basic bridge are shown in Fig. 3. The bridge consisted of four Type 1T1 selenium diodes, one in each arm. The input voltage or voltage drop across the bridge was recorded for loads of half-, one-, and four-times rated for ambient temperatures of 0 to 100° C. Since selenium has a negative-temperature coefficient, a lower voltage drop exists at elevated temperatures. It will also be noted that the slope of the curves decrease with decreasing load.

These selenium diodes are being used in many novel circuits. An interesting application is as a clamping diode in a telemetering circuit, shown in Fig. 4. The purpose of this circuit in the telemetering equipment is to convert a signal voltage of fixed phase with the reference voltage into a d.c. voltage of 0-5 volts that is proportional to the amplitude of the signal voltage. In operation, the rectifier SR_1 rectifies the a.c. voltage existing at the cathode of the tube, V_1. Since there is no control on the magnitude of the input signal, the output voltage can exceed 5 volts thereby causing

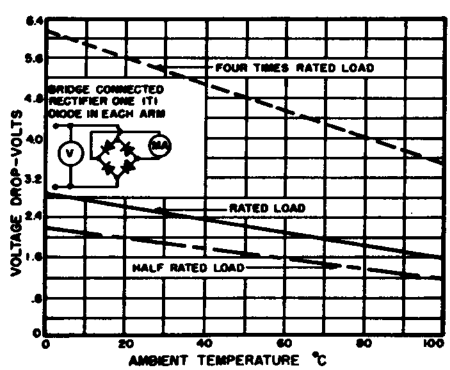


Fig. 3. Forward voltage drop vs ambient temperature characteristics for basic bridge.

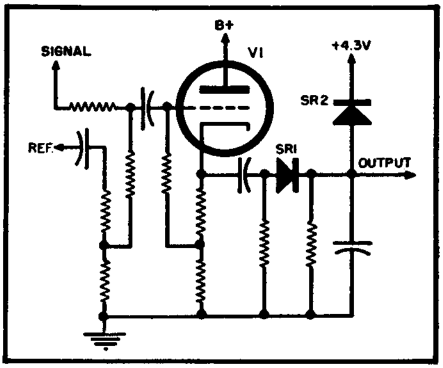


Fig. 4. Telemetering circuit showing selenium diode used for the clamping action.

malfunctioning of the telemetering circuit. To preclude this condition, a Type 1U1 selenium diode is incorporated into the circuit as a clamper. With a clamping potential of 4.3 volts, clamping occurs when the output reaches 5 volts. In Fig. 4, SR_1 is an *International Rectifier Corp.* #V1HM rectifier and SR_2 is a 1U1 type. The circuit was supplied by the *Raymond-Lindsey Co.* of Gardena, Calif.

There are many other applications for these units. For example, the diodes have been designed into hearing aids, electronic organs, and numerous electronic instruments. The circuits of these applications cannot be disclosed at this time, since their disclosure may jeopardize certain patentable features. The most popular usage for these diodes is to provide bias voltage in electronic equipment. Fig. 6 shows a typical application for providing fixed bias for the push-pull stage of an audio system. It is well to note that fixed bias offers several advantages over the conventional cathode bias provided that the cathode resistor is not intended to obtain degeneration. It should be noted that the greatest advantage of fixed bias is for class AB_1 push-pull amplifiers. When used in this type of circuit, fixed bias provides higher power output, increased stability, and reduced distortion for a given output tube plate current. A good example is a push-pull circuit for 2A3, 6A3, or 6B4 tubes. When fixed bias is used, the power output is increased by about 50% and the distortion is decreased by 50% for the same current rating. The fixed bias (Fig. 6) for the output tubes is obtained from the high voltage winding of the power transformer with a voltage divider, a selenium diode, and a filter network. There is no need to consider the loading effect on the high voltage transformer winding, since the additional current drawn by the grids of the tubes or the voltage divider is negligible.

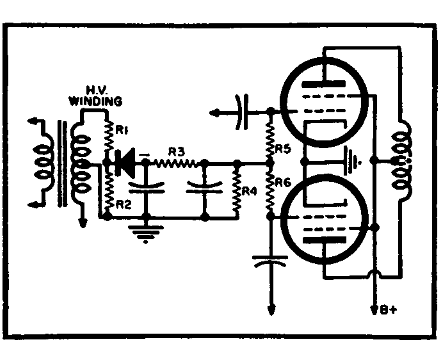
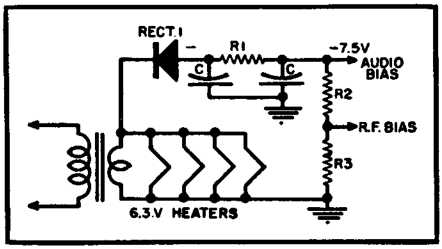


Fig. 6. Push-pull stage with fixed bias.

Fig. 7. Fixed bias supply circuit for audio stage and r.f. stages of an a.c. receiver.



Fixed bias for the output and r.f. stages of an a.c. radio receiver can be simply accomplished by the use of a selenium diode and associated resistors and condensers. A typical example of such a circuit is shown in Fig. 7. The a.c. input to the rectifier network may be obtained from the 6.3 volt filament winding on the power transformer.

Because selenium diodes range in input voltages from 26 to 130 volts r.m.s., the number of bias voltages that can be provided is practically unlimited when proper voltage dividers are used. For another example, it may be well to note that the power supply of TV receivers can be simplified by supplying individual bias for the audio, synchronization, r.f., and i.f. stages. This is also desirable since it eliminates the possibility of load changes in one circuit affecting the other circuits which was often the case in earlier TV receivers. The circuits shown in Fig. 8 are two possibilities. On the other hand, they may be combined as shown in Fig. 9, depending upon the choice of the design engineer.

It is believed that the Type 5U1 selenium diode is the most versatile of the line. This unit is rated for a

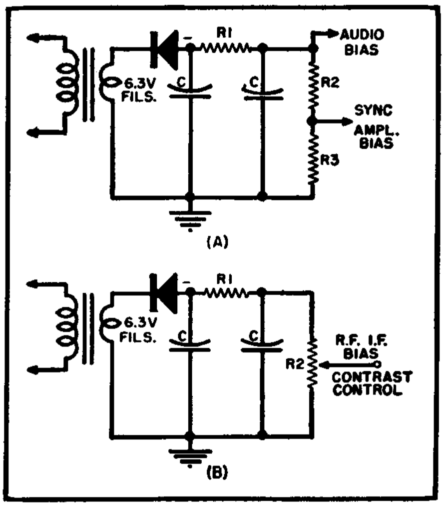


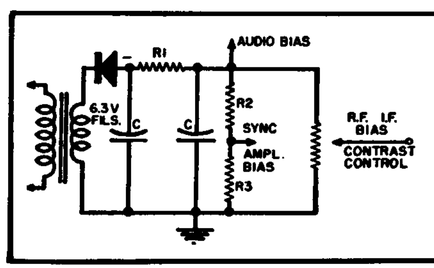
Fig. 8. Two TV circuits illustrating selenium diode applications. (A) In audio and sync amplifier bias circuits, and (B) in the r.f. and i.f. bias circuits of set.

maximum input voltage of 130 volts r.m.s. and can consequently be connected directly to a 117-volt line for its source of voltage. It is obvious that this unit is ideal for use in equipment that does not have any transformer winding such as an a.c.-d.c. radio set. The circuit would be similar to Fig. 6. The resistance of R_1 plus R_2 should be on the order of 150,000 ohms or more.

For higher output voltages, several of these selenium diodes may be connected in series. For example, three Type 5U1 diodes connected in series can be used to deliver 300 volts d.c.

It is believed that the selenium diodes thus far developed have made available a series of new components to the design engineer for consideration in his future circuit designs. The examples given are merely intended as illustrations of a few such possibilities and it is hoped that they may stimulate the imagination and ingenuity of the circuit design engineer.

Fig. 9. Biasing for four stages in TV set.

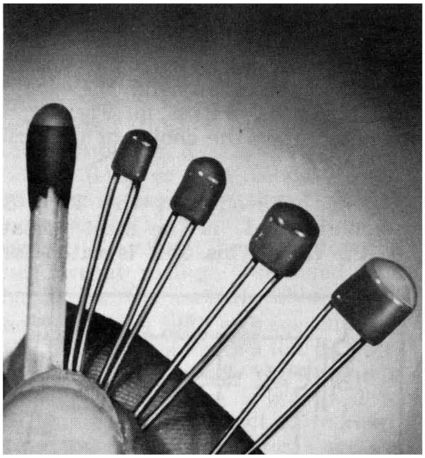


This article originally appeared in RADIO & TELEVISION NEWS.

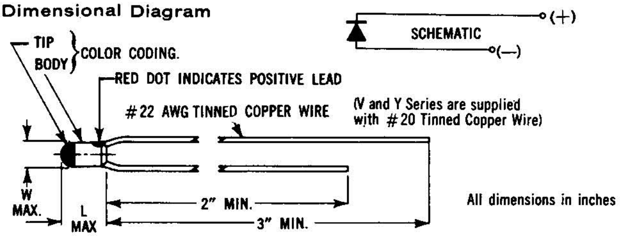
Subminiature Selenium Diodes

These subminiature selenium diodes have been developed specifically for applications where ambient temperature is high and savings in space and weight are prime considerations. They are small and compact in size with pigtail leads to facilitate wiring into crowded chassis. The units are designed for stable operation in an ambient temperature range of —50°C to +100°C.

The rectifying elements are potted in a rugged thermosetting compound to protect them against corrosive atmospheres, moisture, salt spray and fungus. High stability and reliability along with extreme miniaturization make these units ideal for such applications as bias supplies, sensitive relays, digital and analog computers, hearing aids, electronic organs and compact airborne electronic equipments.



Dimensional Diagram



Typical Ratings, and Characteristics at 25° C

JETEC TYPE	INT'L TYPE	MAXIMUM RATINGS: RMS INPUT AC VOLTAGE (VOLTS) RES. LOAD	CAP. LOAD	RECTIFIED DC OUTPUT	SURGE, Ma (1 SEC.)	PIV VOLTS	FREQ. (KC.)	MAXIMUM DIMENSIONS (INCHES) W	L	ELECTRICAL CHARACTERISTICS (DC) FORWARD VOLTS	I ma MIN	REVERSE VOLTS	I μa MAX.	COLOR CODING BODY	TIP
1N1625	1S1	33	20	250μa	5	48	200	.165	.225	1	0.1	26	15	Yellow	Brown
1N1626	2S1	66	40	250μa	5	96	200	.165	.225	2	0.1	52	15	Yellow	Red
1N1625A	1T1	33	20	500μa	10	48	200	.165	.225	1	0.2	26	15	Green	Brown
1N1626A	2T1	66	40	500μa	10	96	200	.165	.225	2	0.2	52	15	Green	Red
1N1627	1U1	33	20	3.75ma	80	48	100	.190	.265	1	1.5	26	27	Gray	Brown
1N1628	2U1	66	40	3.75ma	80	96	100	.190	.265	2	1.5	52	27	Gray	Red
1N1629	3U1	99	60	3.75ma	80	144	100	.190	.265	3	1.5	78	27	Gray	Orange
1N1630	4U1	132	80	3.75ma	80	192	100	.265	.265	4	1.5	104	27	Gray	Yellow
1N1631	5U1	165	100	3.75ma	80	240	100	.265	.265	5	1.5	130	27	Gray	Green
1N1632	6U1	198	120	3.75ma	80	288	100	.345	.265	6	1.5	156	27	Gray	Blue
1N1633	7U1	231	140	3.75ma	80	336	100	.345	.265	7	1.5	182	27	Gray	Violet
1N1634	8U1	264	160	3.75ma	80	384	100	.345	.265	8	1.5	208	27	Gray	Gray
1N1635	1V1	33	20	12.5 ma	250	48	25	.320	.395	1	5.0	26	108	Gray	*
1N1636	2V1	66	40	12.5 ma	250	96	25	.320	.395	2	5.0	52	108	Gray	*
1N1637	3V1	99	60	12.5 ma	250	144	25	.320	.395	3	5.0	78	108	Gray	*
1N1638	4V1	132	80	12.5 ma	250	192	25	.395	.395	4	5.0	104	108	Gray	*
1N1639	5V1	165	100	12.5 ma	250	240	25	.395	.395	5	5.0	130	108	Gray	*
1N1640	1Y1	33	20	28 ma	550	48	10	.430	.475	1	11.0	26	240	Gray	*
1N1641	2Y1	66	40	28 ma	550	96	10	.465	.475	2	11.0	52	240	Gray	*
1N1642	3Y1	99	60	28 ma	550	144	10	.465	.475	3	11.0	78	240	Gray	*

* International Rectifier Part Number is stamped on body.

Applications of High-Voltage Selenium Cartridge Rectifiers

by John Vickrey, BEE
International Rectifier Corporation
Member AIEE, Eta Kappa Nu

Cartridge-type selenium rectifiers have brought simplicity and compactness to the design of high-voltage supplies. Tubeless operation results in freedom from warm-up time filament circuit complications, reduced heat radiation, increased ruggedness, unlimited life, and reduction of space requirements.

International Rectifier Corporation's high voltage, cartridge-type selenium rectifiers are obtainable with ratings up to 9.9 kilovolts r.m.s. input for single units. These single rectifiers may be employed in conventional and special voltage doubler, tripler, and quadrupler circuits, as well as in simple half-wave and full-wave circuits. Polyphase operation is also possible, as with lower-voltage rectifiers. Besides half-wave units, standard cartridges are available in full-wave center tap, voltage doubler, and single-phase bridge types.

Typical applications of these rectifiers include insulation test equipment, capacitor breakdown testers, magnetic amplifiers, bias supplies, oscilloscope high-voltage d.c. supplies, television high-voltage supplies, radiation detecting instruments (Geiger and scintillation counters), electrostatic dust and smoke precipitation, electrostatic spray painting, photoflash high-voltage supplies, photomultiplier tube supply, arc suppression in contact protection circuits and many similar uses.

The accompanying illustrations show practical circuits for several small-sized devices employing selenium rectifiers to obtain high d. c. voltages. The simplicity of these devices, resulting from tubeless rectification, is evident. While each circuit is intended for a specified application, other uses will suggest themselves.

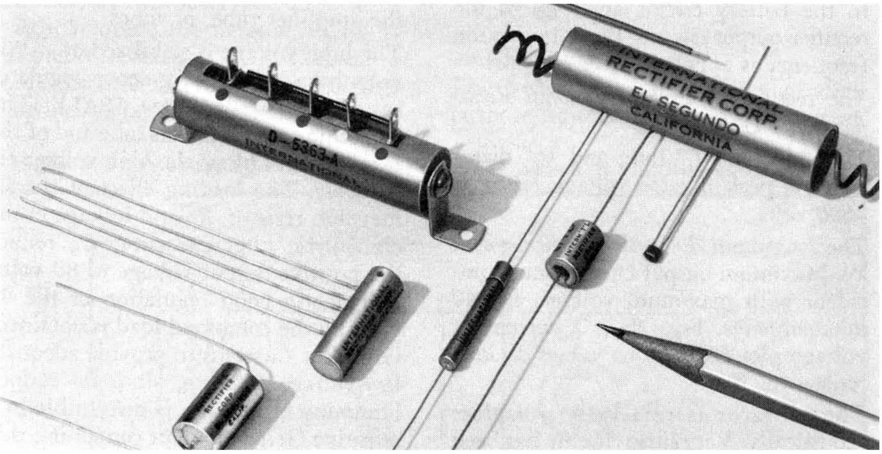


Fig. 1. Typical cartridge-type selenium rectifiers as made by International Rectifier.

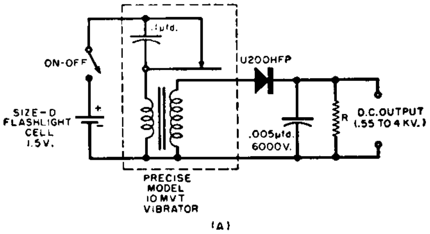
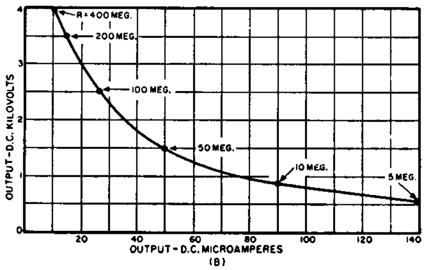


Fig. 2. (A) Schematic diagram of a midget, low-current, high-voltage supply which is completely portable and self-contained. It operates from a 1½ volt flashlight cell. (B) A current versus voltage plot for various values of load resistance, R.



Portable High-Voltage Supply

Fig. 2A shows the circuit of a midget, low-current, high-voltage supply. Operated from a single Size-D 1½-volt flashlight cell, this unit is completely portable and self-contained.

The high a.c. voltage is supplied by a small vibrator transformer, Model 10MVT (*Precise Measurements Company,* Brooklyn 23, New York). This component is completely encapsulated and requires only four connections, two to the battery circuit and two to the rectifier-output circuit. The interruption frequency is approximately 250 cps.

The rectifier is an *International Rectifier* Type U200HFP.

This unit, is 7¼" long and ¼" diameter. Its peak inverse voltage rating is 9600 volts.

The maximum d.c. output voltage is 4 kv. Maximum output current, not coincident with maximum voltage, is 140 microamperes. Fig. 2B is a current *vs* voltage plot for various values of load resistance, *R*.

The vibrator is relatively noiseless acoustically. Very little trouble has been experienced with electrical hash from the contacts. If hash is observed in a particular installation, however, it can be eliminated or minimized by means of a 0.005 to 0.01 microfarad buffer capacitor shunting the high-voltage secondary winding.

At the low values of current drain indicated in Fig. 2B, the 0.005 μfd. output capacitor will furnish sufficient filter action.

The high-voltage supply may be built into other equipment, such as radiation detectors, vacuum system leak detectors, dielectric breakdown testers, etc.

Geiger Counter Supplies

Vibrator Type: The circuit shown in Fig. 3 will supply –900 volts of regulated d.c. to a 1B85, or equivalent, Geiger tube and plus 80 volts at 0.2 ma. to one or two amplifier tubes in the counter circuit.

As in the preceding circuit, initial driving power is derived from a single 1½ volt Size-D flashlight cell. The cell operates a Model 10MVT miniature vibrator transformer, previously described. This feature provides simplicity and compactness, as well as economy and convenience of battery replacement. Two Type U50HFP cartridge selenium rectifiers are employed. The first, SR_1, is "reverse-connected" to supply a negative potential of 900 volts to polarize the 1B85 Geiger tube. The second, SR_2, is "forward-connected" to supply the positive plate and screen voltage to the amplifier tube, or tubes.

The high voltage is stabilized at —900 volts by a miniature gaseous regulator tube (*Victoreen* Type 5841). The smoothing action of this tube and of the R_2C_2 network filters the high voltage effectively. The loading effect of the ½ megohm resistor, R_1, and leakage in the electrolytic filter capacitor, C_1, reduce the positive output voltage to 80 volts. Sufficiently good regulation of the 80 volts by the combined load is obtained. Capacitor C_1 seems to provide adequate low-voltage filtering, since no serious humming or buzzing is discernible in a sensitive Geiger counter containing this power supply.

In addition to operating the vibrator, the 1½ volt cell can also heat the filaments of the amplifier tubes in the counter circuit.

Transistor Type: In Fig. 4, a transistor takes the place of the vibrator in the primary circuit of a battery-operated step-up transformer. The transistor functions as a low-frequency oscillator with clipped-peak wave-form. The high a.c. voltage is presented to a selenium voltage doubler circuit consisting of two Type U75HFP, cartridge rectifiers and the 0.002 μfd. capacitors, C_3 and C_4. This circuit is adapted from the original arrangement by Chambers and Coleman[1].

The d.c. output is 2000 volts at 20 microamperes. This is adequate for a sensitive scintillation counter. The high turns-ratio midget transformer, T_1, is a special component, Type TC-673 (*Cam-Co Engineering Company,* Culver City, California). The transistor oscillator is powered by a medium-sized 22½ volt "B"-battery (*Burgess* Z30NX, or equivalent). The low d.c. drain of 7½ to 10 milliamperes insures long battery life. Efficient voltage doubling in the full-wave circuit is afforded by the two rectifier cartridges. However, a dual rectifier unit, like the *International Rectifier* Cartridge Type U50DP may be used, if desired. For small over-all size, the electrolytic capacitors, C_1 and C_2, may be of the subminiature tantalum variety.

In adjusting the unit, the following steps should be observed. (1) With switch S_1 open, set rheostat R_1 to its maximum resistance. (2) Connect a high-resistance d.c. voltmeter (20,000 ohms-per-volt or higher) to the d.c. out-

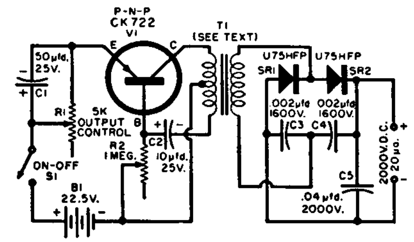


Fig. 4. Transistorized high-voltage supply for Geiger and scintillation counters.

put terminals and close switch S_1. (3) Adjust rheostat R_2 for maximum voltage. (4) Lock R_2 in this position and do not subsequently disturb its setting. Make all later output voltage adjustments with rheostat R_1.

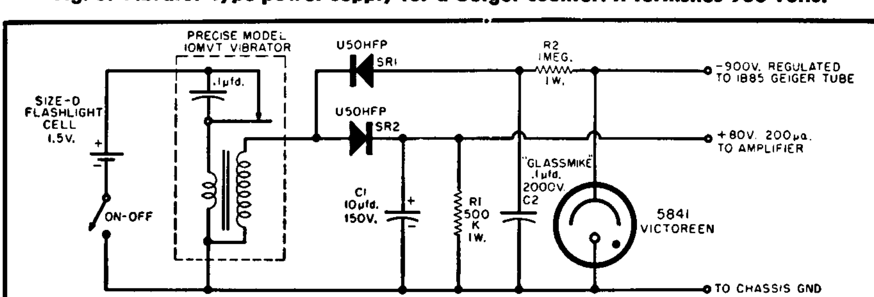
This transistor oscillator is stable and is a good starter if the R_1 and R_2 adjustments have been made correctly. With the d.c. voltmeter connected to the d.c. output terminals, the starting action may be checked by throwing switch S_1 rapidly back and forth several times. The voltage should rise and fall quickly in response, within the limitations set by the meter damping.

Beside its specific use as the high-voltage d. c. supply for Geiger and scintillation counters, this unit may be employed in other applications requiring a totally quiet, battery-operated, portable source of 2 kv. or less. Such uses include photomultiplier tube supply, volt-meter calibration, klystron electrode supply, portable oscilloscope supply, etc.

Variable-Voltage Supply

Fig. 5 shows the circuit of a general-purpose, adjustable-output, low-current,

Fig. 3. Vibrator-type power supply for a Geiger counter. It furnishes 900 volts.



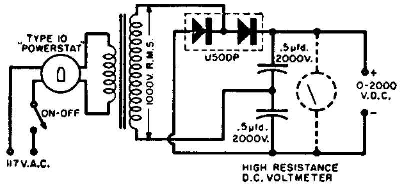


Fig. 5. A general-purpose, variable, high-voltage, low-current type power supply.

high-voltage supply which may be made as small as some test meters. The d.c. output voltage is 0 to 2000 volts at a maximum current of 3 ma.

In this arrangement, the a.c. input voltage to the transformer may be varied by means of a *Superior Electric* Type 10 "Powerstat." A *General Radio* 200B "Variac" also may be used for this purpose. A full-wave voltage doubler is operated from the high-voltage secondary of the transformer. The doubler consists of a Type U50DP doubler type high-voltage selenium cartridge and the two 0.5 μfd., 2000 volt capacitors.

Any convenient transformer having a 1000 volt r.m.s. secondary may be used. For convenience and economy, the entire secondary winding of a small replacement type transformer may be employed, neglecting the center tap of this winding.

At the low values of current drain specified, storage action of the two 0.5 μfd. capacitors and the full-wave operation of the rectifier unit will smooth the d.c. output well enough to permit use of the high-voltage output for the calibration of d.c. voltmeters, polarization of cathode-ray and photo-multiplier tubes, dielectric studies, radiation detector operation, and polarizing capacitors. However, additional filter circuitry may be added externally or internally for discriminating applications.

A continuously variable supply of this type will find sundry uses in the laboratory and shop. A prosaic application is the flash-burning of particles from between the plates of variable capacitors. An optional output-voltage indicating meter may be included in the completed unit, as shown dotted in Fig. 5. This must be a high-resistance d.c. voltmeter of at least 20,000 ohms-per-volt sensitivity.

Scope High-Voltage Supply

A selenium voltage multiplier circuit can simplify the high-voltage section of a 5- or 7-inch oscilloscope power supply. Fig. 6 shows a circuit of this type complete with focus and intensity controls. A half-wave doubler is used so that a common ground may be employed throughout. A Type U50DP doubler type cartridge is used. The voltage multiplier capacitors are C_1 and C_2. Capacitor C_3 provides additional filtering action, operating in conjunction with the 2000 ohm filter resistor, since this circuit is not as easily filtered as the full-wave doublers described previously.

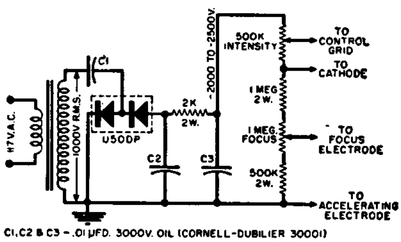


Fig. 6. High-voltage supply for a scope.

The transformer may be a special half-wave unit having a 1000 volt, low-current secondary. The entire secondary (both sides of center tap) of a low-voltage transformer supplying the amplifier and sweep tubes in the oscilloscope may be employed under some circumstances.

Insulation Tester

Another type of continuously variable, high-voltage d.c. supply is shown in Fig. 7. This setup has been designed primarily for insulation testing and other dielectric breakdown measurements but may be used in any other application requiring an adjustable low-current output up to 5500 volts d.c. Smooth variation of the output voltage is obtained by adjusting the input voltage to the transformer by means of a small (Type 10) *Superior Electric* "Powerstat." A *General Radio* 200B "Variac" may also be employed for this purpose.

The transformer has a 1000 volt secondary. Its output voltage is presented to a voltage quadrupler circuit composed of two U50DP doubler type selenium cartridges and capacitors C_1, C_2, C_3, and C_4. The d.c. output voltage is four times the peak value of the secondary r.m.s. voltage, minus the drop in the rectifiers.

The 50-megohm resistor in series with the positive output terminal limits the output current to 100 microamperes on external short circuit. The 8AG, 1/500 ampere fuse has a blow point of 3 ma. and protects the rectifiers in the event of a sustained external short circuit or overload.

A high-resistance d.c. voltmeter may be operated in parallel with the d.c. output terminals to monitor the output voltage. Where the use of such a meter is not feasible, however, the output voltage may be approximated from the measured value of a.c. voltage at the transformer primary. The following expression may be used: $E_{dc} = 5.65 E_1 N$. Here, E_{dc} is the approximate output voltage, E_1 is the r.m.s primary voltage, and N is the turns-ratio of the transformer.

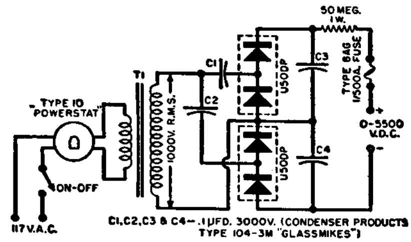


Fig. 7. Schematic of an insulation tester.

Conclusion

Possible uses of high-voltage selenium cartridges are multitudinous. We have selected those applications about which information is constantly requested. These are small-sized devices in which the elimination of tubes contributes lighter weight, cooler operation, smaller size, simplicity of construction, and ease of servicing.

Reference

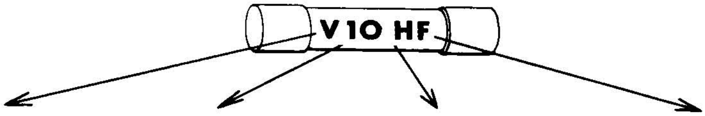
1. *Chambers, R. W. & Coleman, L. G.: "A High-Voltage Transistor Power Supply," Radio & Television News, October 1955.*

This article originally appeared in RADIO & TELEVISION NEWS

Editor's Note: Where small unit size and operation in temperatures exceeding 100° C are required, the silicon rectifiers listed on the following pages are recommended and in most cases are interchangeable with the selenium units indicated in this article.

High Voltage Selenium Cartridge Rectifiers
Partial Listing, Ratings and Sizes

The coding system for International cartridge rectifiers is indicated in the rectifier number. For example V10HF indicates a cartridge rectifier using "V" size selenium cells, 10 cells in series, half wave circuit and having ferrule type terminals.



CELL SIZE
T – 1/16"
U – 1/8"
V – 1/4"
Y – 3/8"
Z – 1/2"
X – 3/4"
W – 1"

NUMBER OF CELLS IN SERIES
AS REQUIRED FOR YOUR SPECIFIC APPLICATION

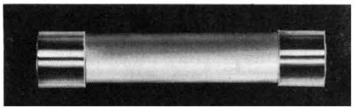
TYPE OF CIRCUIT
Single Phase: H = Halfwave
B = Bridge
C = Center Tap
D = Doubler
M = Mag Amp Bridge
Three Phase: S = Halfwave
T = Bridge

TERMINALS
P = Pigtail
S = Stud
L = Solder Lug
F = Ferrule
FP = Ferrule Pigtail
G = Ferrule on glass tube

This construction applies to single phase half wave units only except for special applications. (When letter S follows P or L terminal designations, it indicates insulated studs for mounting only and is available on special request and certain sizes. Consult manufacturer.)

Color Coding System — Red: Positive Black: Negative Yellow: AC

HALF-WAVE CARTRIDGE RECTIFIERS

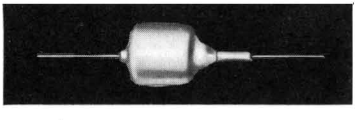


Current ratings for these units are given in Fig. 1

Cells Per Cartridge In Series	Max. AC Input Volts RMS		Nominal DC Output Voltage		Peak Inverse Voltage	T–*HP	U–*HF	U–*HFP	U–*HP	V–*HP	V–*HF	V–*HG	Y–*HP	Y–*HF	Z–*HP	Z–*HF	X–*HS	W–*HS
	Resistive Load	Capacitive Load	Resis. Load	Capac. Load		Outside Diameter 5/32"	O.D. 1/4"	O.D. 1/4"	O.D. 1/4"	O.D. 3/8"	O.D. 9/16"	O.D. 37/64"	O.D. 9/16"	O.D. 9/16"	O.D. 11/16"	O.D. 13/16"	O.D. 1"	O.D. 1 1/4"
						Length	L."	L."	L."	L."	L."	L."	L."	L."	L."	L."	L."	L."
1	33	20	13	20	48		5/8	5/8	1/2	1/2	1 1/8	1 13/16	1/2	1 1/8	5/8	1 3/8	1 1/8	1 1/8
3	99	60	39	60	144		5/8	5/8	5/8	5/8	1 1/8	1 13/16	5/8	1 1/8	3/4	1 3/8	1 1/8	1 1/4
5	165	100	65	100	240	3/4	5/8	5/8	5/8	5/8	1 1/8	1 13/16	3/4	1 1/8	7/8	1 3/8	1 1/8	1 1/4
10	330	200	130	200	480	3/4	3/4	3/4	3/4	7/8	1 1/8	1 13/16	7/8	1 1/8	1	1 3/8	1 3/8	1 3/8
20	660	400	260	400	960	7/8	7/8	7/8	1 1/4	1 1/4	1 1/8	1 13/16	1 1/4	1 1/8	1 5/16	1 5/8	1 3/4	1 3/4
30	990	600	390	600	1,440	1 1/4	1 3/16	1 3/16	1 1/2	1 1/2	1 3/8	1 13/16	1 5/8	1 3/8	1 3/4	1 5/8	1 7/8	2 1/8
40	1320	800	520	800	1,920	1 11/16	1 1/2	1 1/2	2	1 7/8	1 3/4	1 13/16	2 3/8	1 3/4	2 1/2	2	2 1/4	2 3/8
50	1650	1000	650	1000	2,400	2	1 15/16	1 15/16	2 1/8	2 5/16	2 5/16	2 1/2	2 3/8	2 5/16	2 1/2	2 3/8	2 3/4	2 7/8
75	2475	1500	975	1500	3,600	2 3/4	2 11/16	2 11/16	3	3 1/8	3	3 5/16	3 1/8	3	3 1/8	3 1/8	3 1/2	3 3/4
100	3300	2000	1300	2000	4,800	3 1/2	3 5/16	3 5/16	3 7/8	4 1/8	4	3 13/16	4 1/8	4	4 1/4	4	4 1/2	4 5/8

*Number of cells in series – refer to first column of table.

HERMETICALLY SEALED CARTRIDGE RECTIFIERS



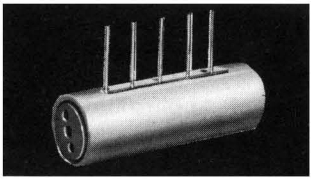
Current ratings for these units are given in Fig. 1

Cells Per Cartridge	Max. AC Input Volts RMS		Nominal DC Output Voltage		Peak Inverse Voltage	T–*HM	U–*HM	V–*HM	Y–*HM	Z–*HM	X–*HM	W–*HM
	Resistive Load	Capacitive Load	Resistive Load	Capacitive Load		O.D. = 3/16"	O.D. = 3/16"	O.D. = 3/8"	O.D. = 1/2"	O.D. = 9/16"	O.D. = 1"	O.D. = 1 5/16"
						Length "	Length "	Length "	Length "	Length "	Length "	Length "
1	33	20	13	20	48	17/32	17/32	1/2	11/16	11/16	1 1/4	1 1/4
5	165	100	65	100	240	17/32	17/32	1/2	13/16	13/16	1 1/2	1 1/2
10	330	200	130	200	480		23/32	7/8	15/16	15/16		
15	495	300	195	300	720			7/8	1 3/16	1 3/16		
20	660	400	260	400	960			1 1/4	1 3/16	1 3/16		

*Number of cells per cartridge – refer to 1st column of this table.

VOLTAGE DOUBLER CARTRIDGE RECTIFIERS

For cell current ratings refer to Figure 1. When these voltage doublers are used as individual sections of single or three-phase bridges, they should be rated in accordance with the applicable bridge ratings.

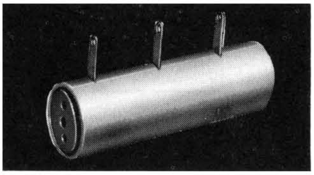


Cells In Series (per leg)	Cells Per Cartridge	Max. AC Input Volts RMS**	Nominal DC Output Voltage		Peak Inverse Voltage	U-*CP	V-*CP	Y-*CP	Z-*CP	X-*CP	W-*CP
		Resistive OR Capacitive Loads	Resistive Load	Capacitive Load		O.D.=¼" Length"	O.D.=⅜" Length"	O.D.=9/16" Length"	O.D.=11/16" Length"	O.D.=1" Length"	O.D.=1¼" Length"
1	2	33	13	16	48	¾	⅞	⅞	⅞	1⅛	1⅜
5	10	165	65	80	240	⅞	1	1	1⅛	1⅜	1½
10	20	330	136	160	480	1⅛	1¼	1¼	1¾	2	2
15	30	495	204	240	720	1¾	1½	1⅝	2	2¼	2¼
20	40	660	271	320	960	2	2	2⅛	2⅛	2¾	2¾
30	60	990	406	480	1440	2⅝	2½	2⅞	2¾	3¼	3¼
50	100	1650	680	800	2400	4	4⅛	4¼	4½	4½	4¾

*Cells in series per leg – refer to first column of table. **Line to line voltage.

FULL-WAVE CENTER TAP CARTRIDGE RECTIFIERS

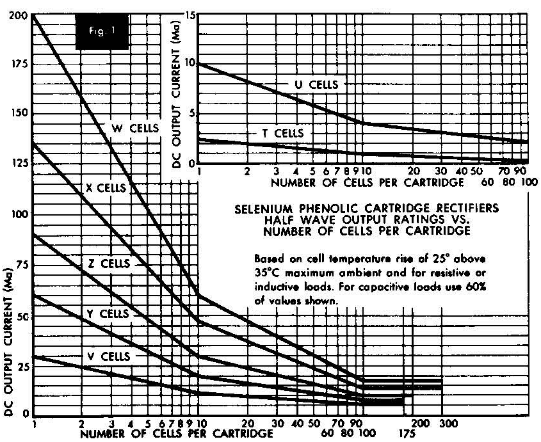
For cell current information, refer to ratings for single phase bridge cartridge rectifiers in Fig. 1 below.



Cells In Series (per leg)	Cells Per Cartridge	Max. AC Input Volts RMS	Nominal DC Output Voltage		Peak Inverse Voltage	U-*BP	V-*BP	Y-*BP	Z-*BP	X-*BP	W-*BP
		Resistive OR Capacitive Load	Resistive Load	Capacitive Load (Nominal)		O.D.=¼" Length"	O.D.=⅜" Length"	O.D.=9/16" Length"	O.D.=11/16" Length"	O.D.=1" Length"	O.D.=1¼" Length"
1	4	33	25	33	48	¾	⅞	1	1	1⅛	1⅜
5	20	165	125	165	240	1¼	1¼	1¼	1¾	2	2¼
10	40	330	250	330	480	2	2	2⅛	2⅛	2¾	2¾
15	60	495	375	495	720	2⅝	2½	2⅞	2¾	3⅜	3⅜
20	80	660	500	660	960	3⅜	3¼	3½	3½	4⅛	4⅛
25	100	825	635	825	1200	4	4⅛	4¼	4¼	5⅛	5⅛

*Number of cells in series per leg – refer to first column of table.

Also available are hundreds of Bridge Rectifier Cartridges not listed. For complete data on all cartridge types available ask for Bulletin H-2.



CURRENT RATINGS

Current ratings for International selenium cartridge rectifiers in phenolic tubing. Curves indicate half-wave DC output current ratings vs. number of cells per cartridge for resistive or inductive load.

(For half-wave capacitive loads, use 60% of values shown.)

RERATINGS FOR OTHER CIRCUITS
MULTIPLY CHART RATING BY:

Single Phase	Resistive-Inductive Load	Capacitive Load
Half Wave	1	.6
Full Wave Center Tap	2	1.6
Full Wave Bridge	2	1.6
Three Phase		
Half Wave	2.6	2.6
Center Tap	3.6	3.6
Bridge	3	3.

High Voltage Silicon Power Diodes

600 to 1000 PIV at 125 ma.

Typical Applications

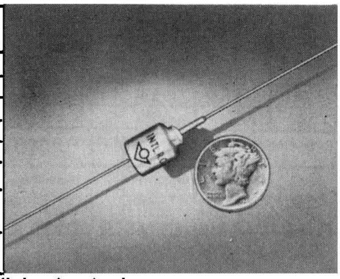
- **Radar Power Supplies**
- **High Voltage Bias Supplies**
- **Airborne & Guided Missile Application**
- **Replacement of Vacuum Rectifier Tubes**

Offering:

- **High Operating PIV Ratings**
- **High Temperature Operation**
- **High Rectification Efficiency**
- **Optimum Reliability at elevated and sub-zero temperatures**

ABSOLUTE MAXIMUM RATINGS AT 75°C AMBIENT

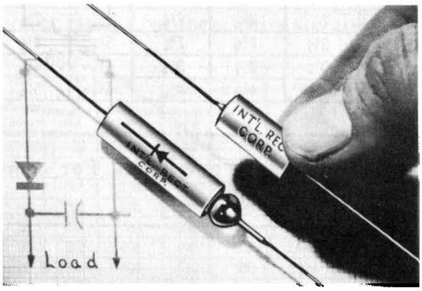
DIODE TYPES	IN596 (EM1J2)	IN597 (FM1J2)	IN598 (GM1J2)
Peak Inverse Voltage, volts	600	800	1000
RMS Input Voltage, volts	420	560	700
Rectified DC. Output Current, ma.	125	125	125
Continuous DC. Current, ma.	150	150	150
Max. Surge Current (0.1 sec.) ma.	1000	1000	1000
ELECTRICAL CHARACTERISTICS AT 25°C			
Max. DC. forward volt drop at rated DC. current—volts	3.0	3.0	3.0
Max. DC. reverse current at rated PIV—ma.	0.025	0.025	0.025



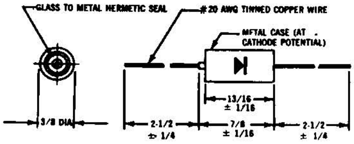
For more detailed engineering data, request Bulletin SR-138-E

600 TO 2400 PIV at 100 MA.

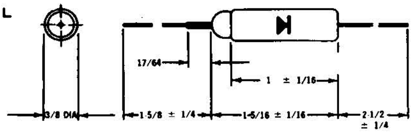
High temperature operation and optimum reliability at elevated and sub-zero temperatures are provided by this series of high voltage silicon cartridge rectifiers. Available in two physical configurations, their characteristics ideally suit them for application to radar power supplies, high voltage bias supplies, and airborne and guided missile instrumentation.



Style K



Style L

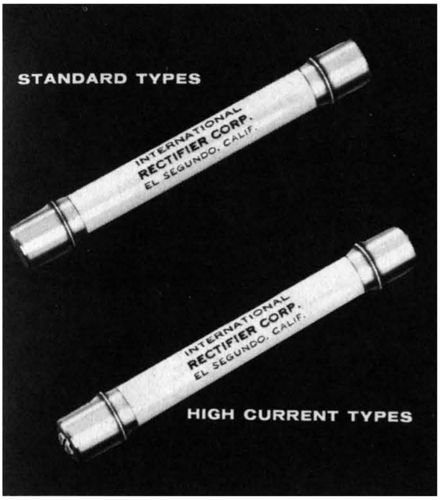


Absolute Maximum Ratings at 75° C Ambient

DIODE STYLE AND TYPES	STYLE K			STYLE L				
JETEC DESIGNATION ▶ INT'L RECT. NUMBER ▶	1N1406 66-0706	1N1407 66-0708	1N1408 66-0710	1N1409 EM1L4	1N1410 EM1L5	1N1411 EM1L6	1N1412 FM1L5	1N1413 FM1L6
Rated Peak Inverse Voltage (Volts)	600	800	1000	1200	1500	1800	2000	2400
Continuous dc voltage (Volts)	600	800	1000	1200	1500	1800	2000	2400
RMS Input Voltage (Volts)	420	560	700	840	1050	1260	1400	1680
Rectified dc Output Current ma.	100	100	100	100	100	100	100	100
Continuous dc current ma.	125	125	125	125	125	125	125	125
Max. Surge Current (1m sec.) ma.	4000	4000	4000	4000	4000	4000	4000	4000
Electrical Characteristics at 25°C								
Max. dc forward volt drop at rated dc current (volts)	5.0	5.0	5.0	5.0	6.25	7.5	6.25	7.5
Max. dc reverse current at rated PIV (ma.)	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Typical dc reverse current at rated PIV (ma)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Typical reverse current at full load at 75°C ambient (full-cycle average) ma.	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

For more detailed engineering data, request Bulletin SR-157.

High Voltage Silicon Cartridge Type Rectifiers
1000 to 20,000 Volts PIV—45 to 440 ma



These rectifiers will provide high temperature operation, high efficiency and miniaturization to a wide range of high voltage applications. Designed to meet the most rigorous military requirements, they provide optimum reliability over a temperature range from —55°C to +150°C.

MECHANICAL FEATURES:

Construction: Silicon diodes in series, hermetically sealed within a metalized ceramic housing.

Mounting: Ferrule terminals for clip-in mounting into standard 30 amp fuse clips.

ELECTRICAL CHARACTERISTICS:

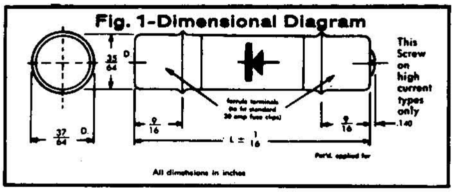
Forward Voltage Drop: See table below.

Maximum Reverse Current: 0.025 ma at rated inverse voltage at 25°-C.

Operating Temperature: —55°C to 150°C.

Storage Temperature: —55°C to 170°C.

Fig. 1-Dimensional Diagram



STANDARD TYPES
Designed for Normal Convection Cooling

ABSOLUTE MAXIMUM RATINGS AT 75°C AMBIENT
(Normal Convection Cooling — Horizontal Mounting)
Half-Wave Resistive Load — 60 CPS

JETEC Type	Int'l Type	"L" Length Inches	Peak Inverse Voltage Volts	Note 1 Max. Rectified DC Output Current MA	Forward DC Volt Drop at Rated DC Current Volts
IN1133	CF1B10	2½	1500	75	15.0
IN1134	EF1A5	1 13/16	1500	100	7.5
IN1135	CF1B12	2½	1800	65	18.0
IN1136	EF1A6	1 13/16	1800	85	9.0
IN1137	CF1B16	2½	2400	50	24.0
IN1138	EF1A8	1 13/16	2400	60	12.0
IN1139	DF1C18	4 5/16	3600	65	27.0
IN1140	EF1B12	2½	3600	65	18.0
IN1141	DF1C24	4 5/16	4800	60	36.0
IN1142	EF1B16	2½	4800	50	24.0
IN1143	DF1C30	4 5/16	6000	50	45.0
IN1143A	EF1C20	4 5/16	6000	65	30.0
IN1144	DF1D36	6 1/16	7200	50	54.0
IN1145	EF1C24	4 5/16	7200	60	36.0
IN1146	DF1D40	6 1/16	8000	45	60.0
IN1147	EF1D40	6 1/16	12000	45	60.0
IN1148	FF1D35	6 1/16	14000	50	52.0
IN1149	FF1D40	6 1/16	16000	45	60.0

NOTE: 1. Rerating of Output Current
Capacitive Load Rerating to 75% of Resistive Load Rating

HIGH CURRENT TYPES
Designed for Forced Convection or Oil Cooling

ABSOLUTE MAXIMUM RATINGS AT 75°C AMBIENT
Half-Wave Resistive Load — 60 CPS

JETEC Type	Int'l Type	"L" Length Inches	Peak Inverse Voltage Volts	Note 1: Max. Rectified DC Output Current (MA) — Oil Immersed Oil Temp.: @75°C	Note 1: Max. Rectified DC Output Current (MA) — Forced Convection 2000 LFM @75°C	Forward DC Volt Drop at Rated DC Current Volts
IN1745	CF1B10M	2½	1500	380	300	15.0
IN1746	EF1A5M	1 13/16	1500	440	360	7.5
IN1747	CF1B12M	2½	1800	360	270	18.0
IN1748	EF1A6M	1 13/16	1800	420	330	9.0
IN1749	CF1B16M	2½	2400	320	220	24.0
IN1750	EF1A8M	1 13/16	2400	380	270	12.0
IN1751	DF1C18M	4 5/16	3600	370	290	27.0
IN1752	EF1B12M	2½	3600	360	280	18.0
IN1753	DF1C24M	4 5/16	4800	330	230	36.0
IN1754	EF1B16M	2½	4800	320	220	24.0
IN1755	DF1C30M	4 5/16	6000	290	210	45.0
IN1756	EF1C20M	4 5/16	6000	360	280	30.0
IN1757	DF1D36M	6 1/16	7200	290	240	54.0
IN1758	EF1C24M	4 5/16	7200	330	230	36.0
IN1759	DF1D40M	6 1/16	8000	250	220	60.0
IN1760	EF1D40M	6 1/16	12000	250	220	60.0
IN1761	FF1D35M	6 1/16	14000	300	240	52.0
IN1762	FF1D40M	6 1/16	16000	250	220	60.0

Rerating of Output Current
Capacitive Load Rerating to 75% of Resistive Load Rating

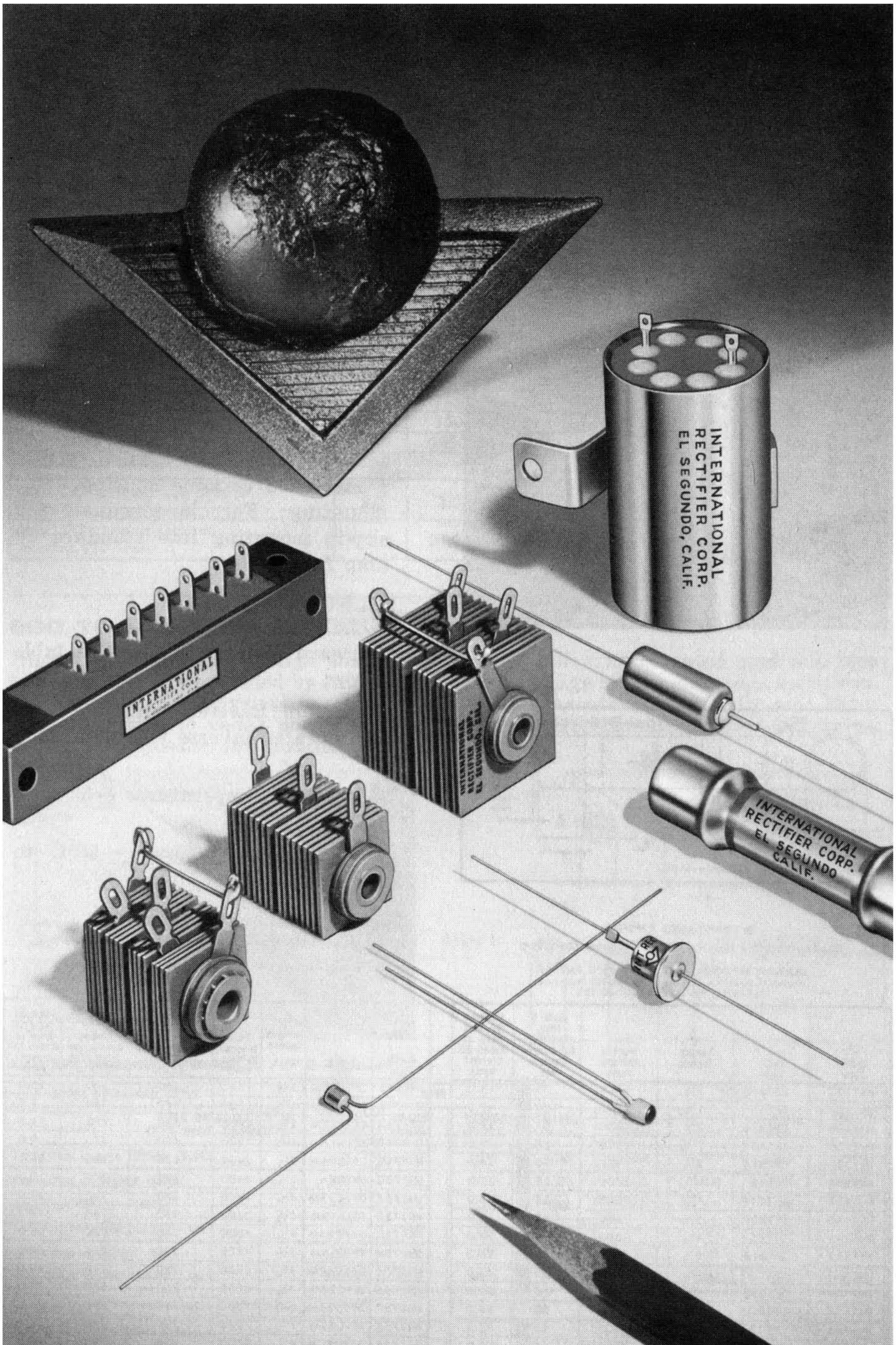


Fig. 1. Typical rectifiers used in opening dc. relay coils from ac supply sources.

Rectifiers and Circuits for DC Relays

by F. W. Parrish, BEE
Chief Engineer, International Rectifier Corporation
Member AIEE, NACE

This article deals with rectifiers for relay applications including some of the less well known circuits and applications.

Semiconductor rectifiers of all types have been used in power supplies for relays and contactors for many years. At present selenium rectifiers, either in cartridge form, diode form, or in small sized open stacks are the most widely used. However, germanium and silicon power diodes are fast receiving acceptance and wide usage in relay circuits. Copper oxide rectifiers are still used also, especially in the meter-movement type contact-making relays.

The largest single use of relay rectifiers is to supply power to the operating coils of relays. Available types of selenium and silicon rectifiers for this purpose are shown in Fig. 1. Where only ac is available as in many applications, ac relays would normally be used if possible. However, the life of an ac relay is much less than that of a dc type. The ratio has been estimated at about 5 to 1. Moreover, dc relays close less violently than ac relays (resulting from the presence of the high current surge in ac relays prior to the closing of the magnetic circuit) and are therefore quieter and maintain accurate adjustment for longer periods of time. Accordingly, there is often considerable advantage gained by using dc relays; in which case, rectifiers must convert the ac line current to dc.

Semiconductor rectifiers are inherently well adapted to relay applications for the following reasons: (1) For a given coil current, they are smaller than most tube rectifiers; (2) They provide efficient long life service when properly applied to the individual relay coils; (3) No filament supply is required as would be necessary for most vacuum tube rectifiers; (4) They are available for all voltage ratings; and (5) They are more rugged and less susceptible to shock and vibration than are vacuum tube rectifiers.

Preventing Chatter

Half-wave rectifiers can sometimes be used to supply dc power to relay coils. The simple half-wave rectifier, shown in Fig. 2a, was probably the first type of rectifier used in this service and is still used occasionally. However, most dc relays will chatter or buzz considerably when used on half-wave rectified power (unless specifically designed for that duty) unless some

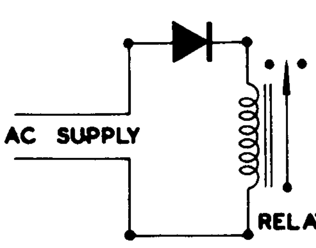


Fig. 2A. Simple half-wave circuit for relays using copper ring to prevent chatter.

auxiliaries are used to prevent it. A large copper ring is often mounted on the relay core beside the coil when a relay is to be operated from a half-wave voltage supply. As the magnetic field in the relay coil collapses during the non-conducting half cycle, transformer action generates a current in this copper ring (which performs as a single turn secondary winding) and holds the relay armature closed until the next conducting half cycle.

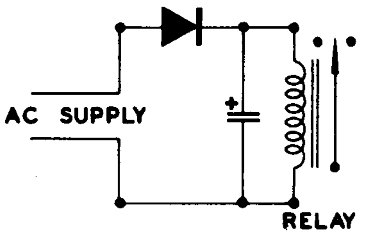


Fig. 2B. Half-wave circuit with smoothing capacitor for coils without copper ring.

Another method of preventing chattering has been to place a capacitor across the relay coil (Fig. 2b). In this way, the capacitor will be charged approximately to its point of maximum energy storage during the conducting half cycle and will discharge this energy to the relay coil during the non-conducting half cycle, and in that way, prevent chatter of the relay armature.

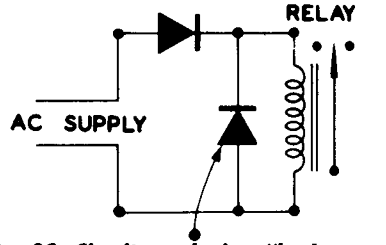


Fig. 2C. Circuit employing "back-wave" rectifier to give steady current through coil.

The third method, which is gaining increasing acceptance to accomplish the same results, is the use of what has been termed a "back-wave" rectifier (Fig. 2c). This rectifier, similar to the one which supplies power to the relay coil is connected across the coil as shown. No current will flow through this "back-wave" rectifier during the conducting half cycle; but, during the blocking half cycle, it provides a low resistance path for flow of current generated by collapsing magnetic field of relay coil. The relay armature is thus held closed without

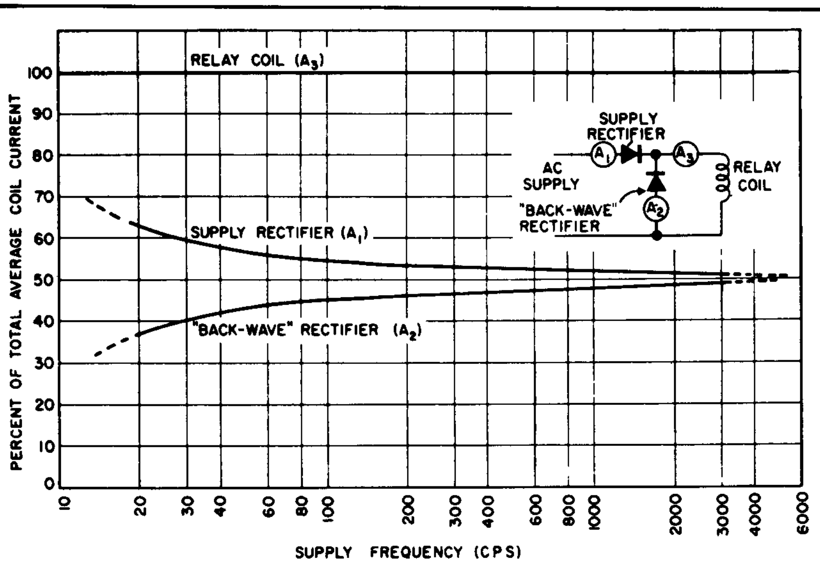


Fig. 3. Rectifier and relay coil current — frequency characteristics — "Back-wave" rectifier connection.

buzzing or chattering. Advantages of the "back-wave" rectifier over the copper ring and the capacitor are as follows: (1) time constant of the relay is not altered as much as with the copper ring; (2) weight is generally less; (3) current drawn through the main rectifier during the conducting half cycle is considerably less than when a capacitor is used across the relay, because it is not necessary to supply energy to charge the capacitor in addition to operating the relay; and (4) the main rectifier may have a current capacity approximately 60 per cent of the coil current, and the "back-wave" rectifier about 40 per cent (Fig. 3).

Coil Voltage

When the simple half-wave rectifier is used, the relay coils should be designed to operate at approximately 40 per cent of the ac line voltage. With

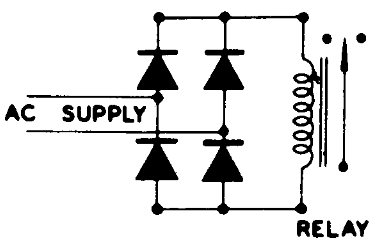


Fig. 4. Single-phase full-wave bridge relay supply.

a capacitor across the coil, the coil should be designed to operate at approximately full line voltage. With a "back-wave" rectifier, the coil should be designed for 40 per cent line voltage.

Other Circuits

To minimize the smoothing problem a full-wave bridge type rectifier (Fig. 4) is commonly employed. If additional smoothing is required, a small capacitor can be used as a filter, connected across the relay coil; however, without the capacitor, the bridge acts as its own "back-wave" rectifier to help maintain a smooth flow of current through the relay coil, even during the time the waveform dips to zero.

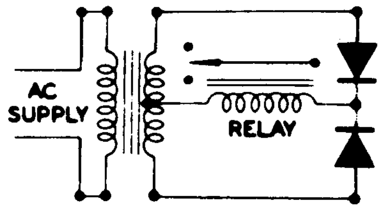


Fig. 5. Single-phase full-wave relay supply.

A full-wave rectifier (Fig. 5) could also be used; however, a center-tapped ac supply is generally not available. Therefore, the bridge type is more popular. It is to be noted the current smoothing action of the "back-wave" current path is not obtained with the full-wave circuit. Where polyphase ac power is available, polyphase rectifiers similar to those shown in Fig. 6 can be used.

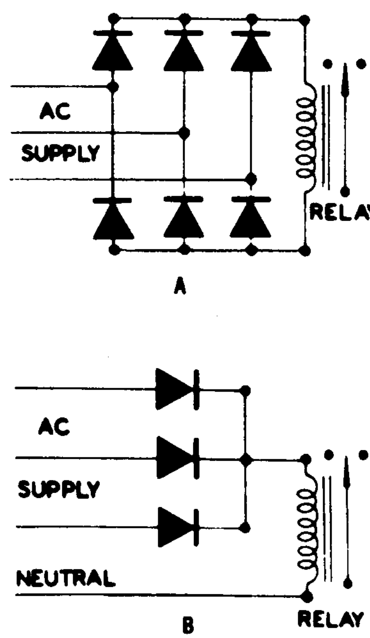


Fig. 6. Polyphase relay supply circuits. (A) Three phase bridge circuit. (B) Three phase half-wave circuit.

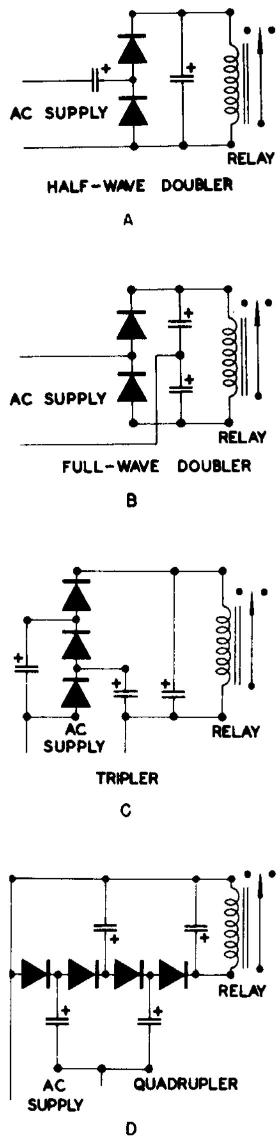


Fig. 7. Voltage-multiplier circuits for relay applications. (A) Half-wave doubler. (B) Full-wave doubler. (C) Tripler. (D) Quadrupler.

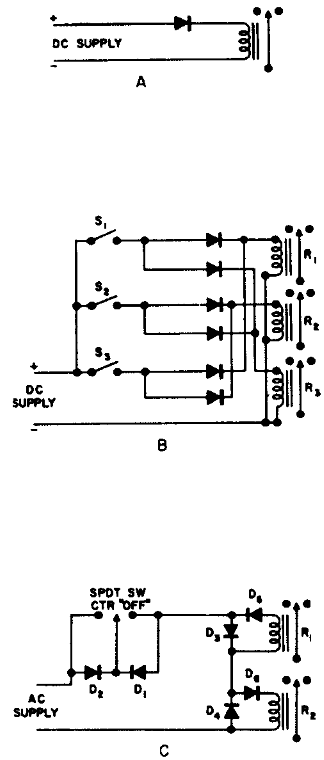


Fig. 8. Selective relay operating circuits.

A. **Simple blocking valve to prevent relay operation if polarity is reversed.**

B. **Selective relaying from dc supply where**

S_1 operates R_1 & R_3 only

S_2 operates R_2 & R_3 only

S_3 operates R_1 & R_2 only

C. **Selective relaying from an ac supply where**

(1) Shorting diode D_1 permits D_2 to rectify the supply and operate R_2;

(2) Shorting diode D_2 operates R_1 similarly.

If impedance of relay coils is high compared to forward resistance of D_3 and D_4, D_5 and D_6 may be omitted.

Voltage multiplier circuits to obtain power for relay operation can also be used where only low voltage ac is available and where it is necessary to operate a higher voltage relay coil. Common voltage multiplier circuits are shown in (Fig. 7).

Special Rectifier Applications

There are some other uses for rectifiers in relay applications, which are not as commonly known as those just described. One such use is as blocking valves. While these have sometimes been used to replace reverse-current protection relays, their principal use is in selective relaying and to provide a simple means of polarizing a relay. Some examples of the uses of blocking valves for selective relaying and polarity sensitive relays are shown in Fig. 8.

Relay rectifiers are also used in timing circuits where a time delay is required in the pickup and drop out of relay coils. Fig. 9a shows the circuit of a time-delay pickup dc relay. The relay picks up when the charge on the capacitor equals the minimum pickup voltage of the relay. A similar arrangement is shown in Fig. 9b, but in this case the time delay is on drop out. The relay coil is directly across the line in this case, so it will pick up as soon as the energizing contacts are closed. However, the capacitor will charge more slowly through resistor *R*. Then, when the circuit is opened, it will discharge slowly through the resistance of the relay coil and the series resistor to give the required time delay. Another form of the delayed drop-out relay is to use the rectifier in a manner similar to the "back-wave" rectifier, but with a resistor in series as shown at Fig. 9c. In this case the relay coil should be selected to have very high inductance, and the "back-wave" rectifier should be selected for the lowest possible forward resistance. These two parameters will provide the maximum possible delay in drop-out; then, drop-out time is adjusted by varying the resistor in series as shown.

One method of using rectifiers (Fig. 9d) provides a time delay pickup for an ac relay. It utilizes the charging

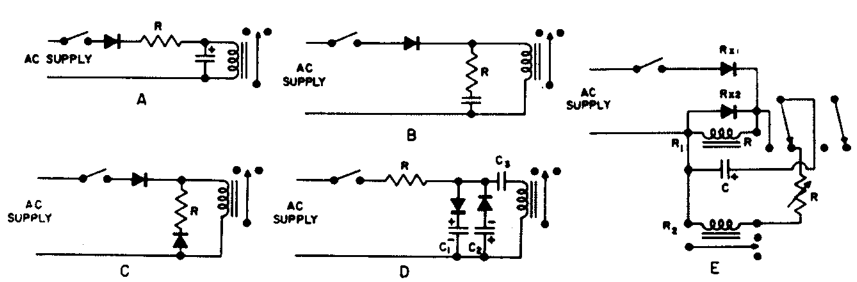


Fig. 9. Circuits for time-delay operation of dc relays.

(A) Time delay pickup of dc relay. A variable resistor will permit varying the delay time.

(B) Time delay drop-out of dc relay. A variable resistor will permit varying the drop-out delay time.

(C) Time delay drop-out of dc relay using "back-wave" rectifier. (Maximum delay is less with this circuit than with capacitor.)

(D) Time delay pickup of ac relay. (May be adjusted by using a variable resistor at R.)

(E) Instantaneous pickup followed by time-delay drop-out of relay R_2 after completion of cycle of Relay R_1.

rates of capacitors to limit the output voltage for the desired pickup time delay.

Still another use of time delay relays is to provide for the initiation of a new circuit function after a pre-determined interval following the completion of a previous function. In Fig. 9e rectifier R_{x1} operates relay R_1 and also charges capacitor C. After relay R_1 is de-energized, the stored energy in capacitor C closes relay R_2 and holds it closed until the charge on the capacitor decays to the drop-out voltage of the relay.

Other important uses of rectifiers with relays involve the protection of relay contacts when used with inductive loads. The three basic circuits for arc suppression and contact protection are illustrated in Fig. 10. Arcing at relay contacts can cause pitting, sticking, or welding, and general deterioration. Propitious use of rectifiers as arc suppressors can minimize or eliminate these conditions and greatly increase relay life. For detail design methods for arc suppressors readers are referred to Ref. 3.

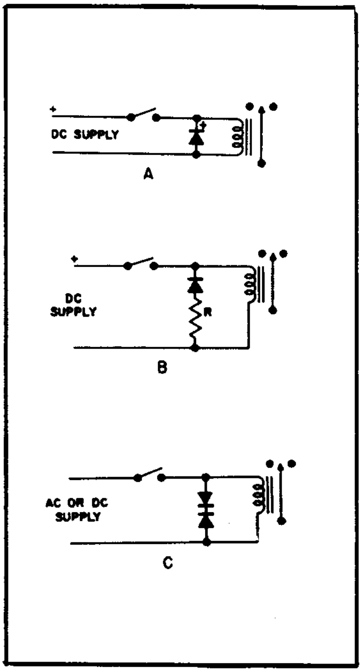


Fig. 10. Relay contact protection circuits for inductive loads. The circuit to use depends upon the load conditions.

This Article originally appeared in ELECTRONIC DESIGN

REFERENCES

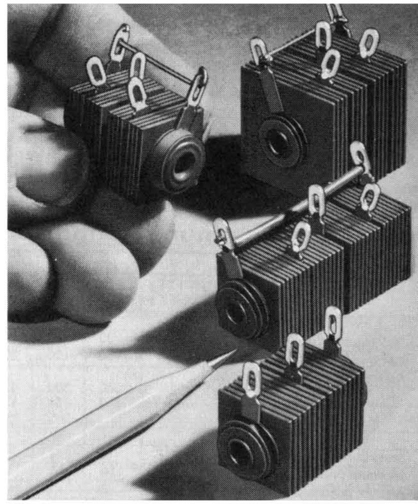
1. Relay Engineering (Handbook) Struthers-Dunn, Inc.

2. "Simplification of Control Circuits," W. H. T. Holden, *Electrical Manufacturing*, April 1956, Vol. 57, No. 4, Page 82.

3. "Arc Suppression With Semiconductor Devices," F. W. Parrish, *Electrical Manufacturing*, June 1956, Vol. 57, No. 6, Page 127.

Miniaturized Selenium Bridge Rectifiers

For use with Relays, Magnetic Amplifiers and other Magnetic Devices



TYPES D-3575F AND D-3575M — These single phase full-wave bridge rectifiers are designed for use directly from 117 volt ac systems. They are rated to deliver an output of 9 watts, continuous duty. With the addition of a 3 mfd, or larger filter capacitor, these rectifiers will deliver 120 volts dc. The overall volume of this rectifier is only 0.875 cu. inches.

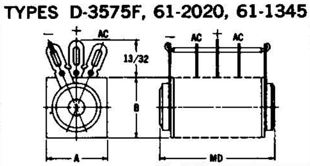
TYPE 61-2020 — This single phase full-wave bridge rectifier will deliver 16 watts at ratings listed in the table below. Overall volume: 1.76 cu. inches.

TYPE 61-1345 — A single phase bridge designed to operate from 260 volts RMS. Will deliver 14 watts. Occupied volume: 1.23 cu. inches.

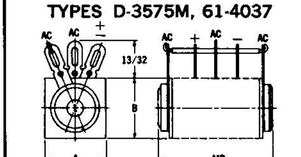
TYPE 61-4037 — This unit is a single phase bridge similar to Type 61-1345, but designed specifically for higher output — 18 watts maximum. Volume: 1.31 cu. inches.

TYPE 60-9150 — This is a voltage doubler unit. Two connected as a full wave bridge will deliver 18 watts. It may also be connected as a half-wave rectifier (by not using the center terminal) to operate from a 520 volt RMS input to supply 50 ma to a resistive load, or to operate from a 360 volt RMS supply to deliver 38 ma to a capacitive load. In a voltage doubling circuit it will deliver 350 volts dc at 38 ma from a 175 volt RMS supply.

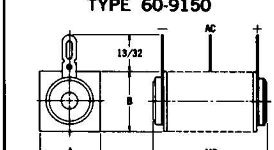
TYPES D-3575F, 61-2020, 61-1345



TYPES D-3575M, 61-4037



TYPE 60-9150



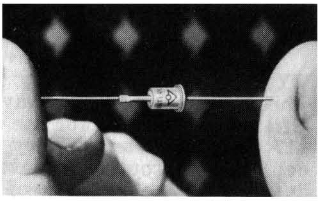
Rectifier Ratings and Dimensions

TYPE	INPUT VOLTS		OUTPUT			DIMENSIONS (INCHES)			CLEAR. hole dia.
	RMS (MAX.)	PIV	VOLTS DC	RES. LOAD ma	CAP. load DC	A	B	MD	
D-3575F	130	200	90 120	100	75	21/32	21/32	1¼	0.164
D-3575M	130	200	90 120	100	75	21/32	21/32	1¼	0.164
61-2020	130	200	90 120	175	130	1	1	1¼	0.164
60-9150*	260	400	180 240	100	75	21/32	21/32	1¼	0.164
61-1345	260	400	180 240	70	55	21/32	21/32	1¾	0.164
61-4037	260	400	180 240	100	75	21/32	21/32	1⅞	0.164

*60-9150 is a doubler stack. Ratings are for 2 stacks connected as a full wave bridge. Half wave and doubler ratings are one-half of those shown in rating table.

Miniature Silicon Power Diodes-50 TO 500 PIV

These twin series of highly reliable silicon diodes are designed to meet the needs of extreme miniaturization, while providing optimum power dissipation in an all-welded, hermetically sealed package. The entire housing of this unit acts as a heat exchanger to permit maximum power dissipation . . . making these diodes especially suitable for missile and airborne equipment applications.



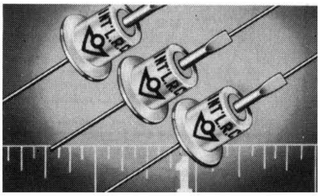
Absolute Maximum Ratings (at 60 cps. Resistive or Inductive Load)

DIODE STYLE AND TYPES	3MS SERIES						5MS SERIES					
JETEC DESIGNATION ▶ INT'L RECT. NUMBER ▶	1N1701 3MS5	1N1702 3MS10	1N1703 3MS20	1N1704 3MS30	1N1705 3MS40	1N1706 3MS50	1N1707 5MS5	1N1708 5MS10	1N1709 5MS20	1N1710 5MS30	1N1711 5MS40	1N1712 5MS50
Peak Inverse Voltage (Volts)	50	100	200	300	400	500	50	100	200	300	400	500
RMS Input Voltage (Volts)	35	70	140	210	280	350	35	70	140	210	280	350
Continuous DC Voltage (Volts)	50	100	200	300	400	500	50	100	200	300	400	500
Rectified DC Output Current (Ma.) @ 50°C Ambient @ 100°C Ambient	300 150	300 150	300 150	300 150	300 150	300 150	500 —	500 —	500 —	500 —	500 —	500 —
@ 150°C Ambient	—	—	—	—	—	—	175	175	175	175	175	125
Surge Current (One Cycle)	8	8	8	8	8	8	10	10	10	10	10	10
Maximum Operating Frequency (Kc)	50	50	50	50	50	50	50	50	50	50	50	50
Ambient Operating Temperature, °C	—65°C to +125°C (All Types)						—65°C to +165°C (All Types)					
Storage Temperature, °C	—65°C to +175°C (All Types)						—65°C to +175°C (All Types)					
Electrical Characteristics												
Max. Forward Voltage Drop (Volts) @ 1 Amp. DC	1.7	1.7	1.7	1.7	1.7	1.7	1.3	1.3	1.3	1.3	1.3	1.3
Max. Leakage Current (Ma.) (Full Cycle Average @ 100°C Ambient) @ 150°C Ambient)	0.4 —	0.4 —	0.3 —	0.3 —	0.3 —	0.3 —	— 0.4	— 0.4	— 0.3	— 0.3	— 0.3	— 0.3

For more detailed engineering data, request Bulletin SR-203

Industrial Silicon Power Diodes-100 TO 500 PIV

Specifically designed for industrial power applications, these hermetically sealed silicon power diodes provide high reliability along with high power capabilities. Rectified d.c. output current ratings to 750 ma. at 50°C are obtained over a PIV voltage range of 100 to 500 volts. All welded, hermetically sealed, shock proof housing.



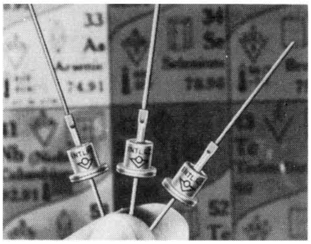
Absolute Maximum Ratings (at 60 cps. Resistive or Inductive Load)

DIODE TYPES	SD-91	SD-92	SD-93	SD-94	SD-95	SD-91A	SD-92A	SD-93A	SD-94A	SD-95A
Peak Inverse Voltage, Volts	100	200	300	400	500	100	200	300	400	500
RMS Input Voltage, Volts	70	140	210	280	350	70	140	210	280	350
Continuous D.C. Voltage, Volts	100	200	300	400	500	100	200	300	400	500
Rectified D.C. Output Current, ma. at 50° C Ambient	550	550	550	550	550	750	750	750	750	750
at 100° C Ambient	300	300	300	300	300	500	500	500	500	400
Max. Surge Current (1 cycle), Amps.	10	10	10	10	10	15	15	15	15	15
Max. Operating Frequency, Kilocycles	50	50	50	50	50	50	50	50	50	50
Ambient Operating Temperature, °C	–65°C to +125°C					–65°C to +125°C				
ELECTRICAL CHARACTERISTICS										
Max. D.C. Forward Voltage Drop at 25°C	1.5 volts @ 550 ma dc (all types)					1.3 volts @ 750 ma dc (all types)				
Min. Series Resistance (Capacitive Load) (ohms)	6.8	6.8	6.8	6.8	6.8	4.7	4.7	4.7	4.7	4.7
Max. Leakage Current (mA.) at Rated Continuous D.C. Voltage at 100°C	1.0	1.0	1.0	.80	.65	0.5	0.5	0.5	0.4	0.3

For more detailed engineering data, request Bulletin SR-201

High Temperature Silicon Diodes-50 TO 600 PIV

Optimum reliability, high efficiency, a reduction in space requirements and installation ease result from the application of diodes in this series. They are designed to provide maximum forward conductance under elevated temperature conditions without an additional heat sink which would require space — increase assembly time and costs. Excellent forward and reverse characteristics result in high rectification efficiency.



Absolute Maximum Ratings 60 cps RESISTIVE OR INDUCTIVE LOAD

	1N536	1N537	1N538	1N539	1N540	1N1095	1N1096
PEAK INV. VOLT. (VOLTS)	50	100	200	300	400	500	600
RMS INPUT VOLT. (VOLTS)	35	70	140	210	280	350	420
CONTINUOUS DC VOLT. (VOLTS)	50	100	200	300	400	500	600
RECTIFIED DC OUTPUT CURRENT, (ma) @ 150°C AMBIENT	250	250	250	250	250	250*	250‡
@ 50°C AMBIENT	750	750	750	750	750	750*	750‡
SURGE CURRENT (ONE CYCLE) MAX.(amps)	15	15	15	15	15	15	15
MAX. OPERATING FREQUENCY, Kc	50	50	50	50	50	50	50
AMB. OPERATING TEMP.	−65°C TO +165°C (ALL TYPES)						
STORAGE TEMP.	−65°C TO +175°C (ALL TYPES)						
Electrical Characteristics							
MAX. FULL-LOAD FORWARD VOLTAGE DROP (VOLTS) (FULL CYCLE AVERAGE @ 150°C)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
MAX. LEAKAGE CURRENT (ma) (FULL CYCLE AVERAGE @ 150°C)	0.4	0.4	0.3	0.3	0.3	0.3	0.3

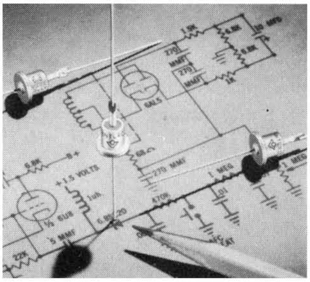
* 1N1095 Current Ratings: 250 ma at 135°C; 750 ma at 35°C.
‡ 1N1096 Current Ratings: 250 ma at 130°C; 750 ma at 30°C.

For more detailed engineering data, request Bulletin SR-202

Semicap—Voltage Variable Capacitor

Q of 1000+ at 1 Megacycle

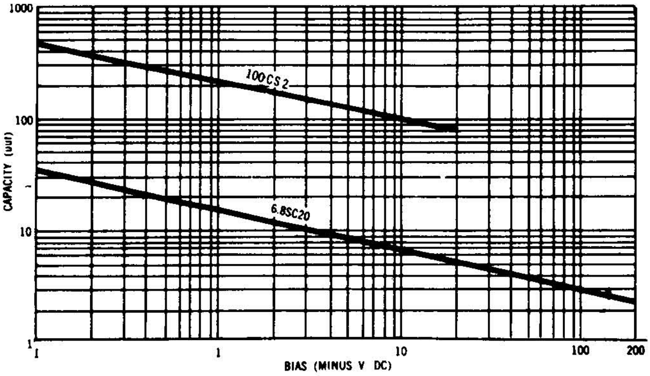
Semicap . . . a voltage-sensitive variable capacitor . . . opens up new design possibilities never before practical in oscillator control circuits. *Semicap's* small size and weight, along with its high reliability and negligible power requirements, make it ideal for automatic frequency control, frequency modulation oscillators and band-pass, and filter networks where precision capacity control is an essential design parameter.



Typical Capacity VS. Bias Voltage

TYPE	CAPACITY AT −10 VOLTS ±20%	MAX. BIAS VOLTS DC
6.8SC20	6.8 uuf	200
100SC2	100 uuf	20

Units of intermediate capacitance ratings will be available at a later date.



For more detailed engineering data, request Bulletin SR-205

Fine grain selenium layer, keyed plates and lugs to prevent rotation and the patented "Bellows Spring" contact spring make International Rectifier's extensive Selenium Power Rectifier line the most dependable in the industry. See Pages 63 and 64 for listings of standard types available through distributors.

Forced Air Cooling Requirements for Selenium Power Rectifiers

by F. W. Parrish, BEE
Chief Engineer, International Rectifier Corporation
Member AIEE, NACE

When forced convection cooling is applied to selenium rectifier stacks, appreciable economies may be realized as a result of the increased current ratings allowed. However, the amount of cooling air necessary to effectively cool and safely operate selenium rectifiers at this rating, has not received universal accord. In fact, general statements as to required air velocity vary from 250 to 1000 lineal feet per minute, based usually on a nominal plate size of 5″x6″ (5″ length parallel to air flow).

The basis for current ratings for selenium rectifiers has been formulated to allow a 20 to 25°C temperature rise above ambient air when the rectifier stack is free convection cooled in air, with the plane of the rectifier cells vertical. This degree of temperature rise above possible industrial ambient air conditions of 40 to 50°C results in a cell temperature of 60 to 70°C; 75°C considered to be about the maximum continuous cell temperature consistent with optimum rectifier life.

It is well known that the rate of heat transfer from parallel, flat fins with a fixed velocity and density of cooling air varies with the length of the fin parallel to the direction of air flow.[1] For turbulent flow this heat transfer coefficient varies approximately as the fourth root ($L^{(.25)}$) of the fin length (velocity constant). If the length is held constant, the coefficient varies as the 4/3 root ($V^{(.75)}$) of the velocity. It has been found that the actual rates of heat transfer do not strictly obey these conditions, although results obtained by use of these factors are sufficiently accurate for practical industrial designs.

There are several reasons for these

> ## Good Design Steps
> **In Forced Convection Cooling of Selenium Rectifiers:**
>
> 1. Since the rectifiers usually have the lowest thermal storage capacity of any power supply components, the cooling air should pass over the rectifiers prior to any of the other components.
> 2. Best design requires an exhaust type circulatory system, where the fan or blower exhausts the hot air from the power supply, and cool air is drawn in (over the rectifiers) by the reduction in pressure.
> 3. Never cool rectifier stacks by blowing directly against the stack by a propeller-type fan. Air flow in front of this type fan is very non-uniform. It is better to use either an exhaust system or a plenum chamber to smooth out the air flow.

variations, which will be discussed as follows:

Refer to Figure 1, and note the location of the International Rectifier Rating "Curve A (L=5″)" and "Curve B (L=5″)" (from other rectifier literature). The basic curve and competitive curve are both located quite conservatively with respect to the Region of actual test data. Reasons for this conservative position are as follows:

1. As a selenium rectifier is operated over an extended period of time, the cell losses increase due to natural aging. It is therefore necessary to supply more air initially, to insure an adequate supply after partial aging has taken place.
2. Tests are made on new, clean rectifiers. An accumulation of dirt and deposits on rectifiers after extended use will reduce the rate of heat transfer.
3. Actual installations may not be baffeled as carefully as the test stacks, to insure that all of the air flow is between the cells, and not in surrounding void spaces.
4. Uniformity of air distribution over the stack area may vary from the test stacks resulting from the type and location of the fan or blower.

Referring again to Figure 1, note that less air is required to cool the smaller cell (L=2″) than for the International Rectifier "Curve A (L=5″)." The reduction in air velocity is determined from Figure 2, which is based on the fourth root of fin length ($L^{(.25)}$) as mentioned above, which shows for L=2″ the required air is about 79% of that necessary for a cell of 5″ length. Note that the "Curve B (L=2″)" indicates air requirements far below those recommended by International Rectifier Corporation, and far below those indicated by actual test data. It is believed that these excessively low air requirements are erroneous for the following reasons:

1. At the low velocities indicated by "Curve B (L=2″)" the air flow would tend to be "Laminar" rather than "Turbulent" and the corresponding rate of heat transfer would be very substantially reduced.
2. In the normal assembly of selenium rectifiers, the center stud and spacers cause a dead spot in the air flow path. Since in small cells the center stud is a larger percentage of the total cell width, the masking effect is greater on small cells and can result in greater temperature gradients over the cell area.
3. It is usually more difficult to adequately baffle small rectifier stacks to insure all the air will flow between the cells.

Accordingly, it is believed more consistent with actual rectifier practice and performance to vary the rate of air flow by adjusting the International Rectifier "Curve A (L=5″)" by amounts as indicated by Fig. 2 for other cell lengths.

However, since the aging of selenium rectifiers is primarily influenced by (1) cell temperature and cooling efficiency; (2) current density, and (3) inverse voltage; a recommended limit has been quite uniformly established by the several manufacturers as the optimum current density consistent with moderate acceleration of aging and the economics of forced cooling. This optimum up-rating factor is 2.5 times the free convection-cooled current density, which is 160 ma/in^2, for half-wave resistive load, (NEMA). (Longer life will be realized if smaller up-rating factors are used.)

The ultimate test of cooling effectiveness is the actual temperature rise of the cell, above ambient air. At air velocities between cells comparable to those indicated by the International Rectifier Curve of Fig. 1 and by Fig. 2, the temperature rise should not exceed 15°C and probably will be more nearly 12°C for new rectifiers. These values of temperature rise have been found consistent with rectifier thermal storage capacity, optimum aging rates, and reliable industrial performance of selenium rectifiers.

REFERENCE:
1. Heat Transmission (Book) by McAdams, (McGraw-Hill) 3rd Edition

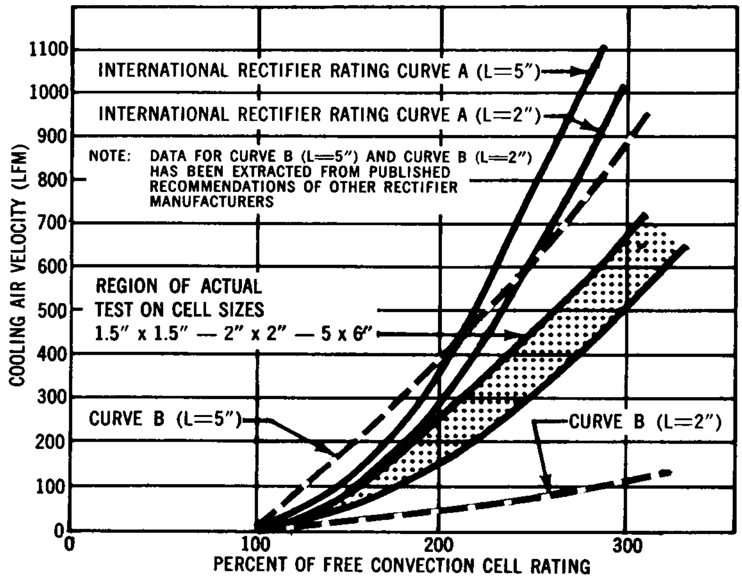


Fig. 1. Basic Re-Rating Curve for Forced Air Cooling of Selenium Cell 5" long.

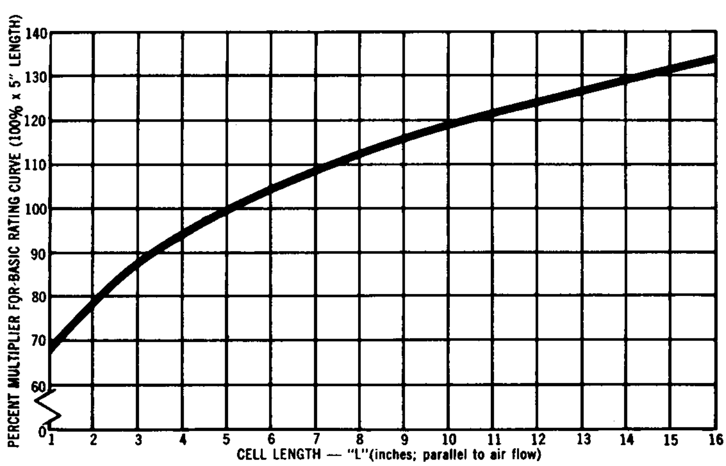
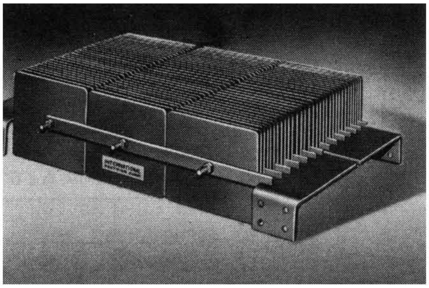


Fig. 2. Influence of Cell Size on Forced Air Cooling.

International Rectifier Corporation
Standard Selenium Power Rectifiers

For all DC power needs from microwatts to kilowatts. Features: long life; compact, light weight and low initial cost. Ratings: to 250 KW, 50 ma to 2,300 amperes and up. 6 volts to 30,000 volts and up. Efficiency to 87%. Power factor to 95%. For complete information write for Bulletin C-349.



Circuit and Connecting Diagrams

FIG. 1

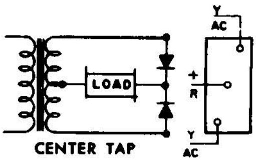


FIG. 1A

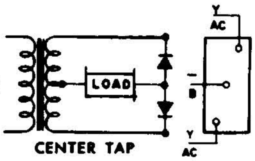


FIG. 2

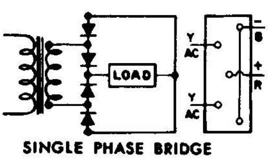
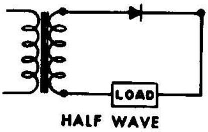


FIG. 3



Diagrams of Dimensions

FIG. A

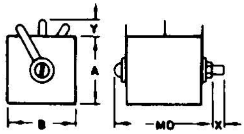
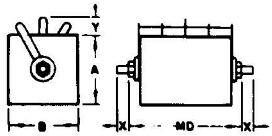
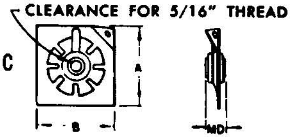


FIG. B



Battery Charging Types

FIG. C



Type	Code Number	Output		Max. Input AC Volts	Circuit & Connecting Diag. Fig.	Dimensions (Inches)						
		DC Volts	DC Amp.			Fig.	A	B	MD *	X	Y	Stud
JD-500G	B1C1SDAGX		0.4	13/26	1	A	1 1/4	1 1/4	1 1/8	3/8	3/8	8-32
JD-501G	C1C1SDAGX		0.7	13/26	1	A	1 1/2	1 1/2	1 1/8	3/8	5/16	8-32
JD-3011	L1C1SDAGX		1.5	13/26	1	A	2	2	1 3/8	3/8	5/8	1/4-20
JD-503G	D1C1SDAGX	0-10	3.0	13/26	1	A	3	3	2	3/4	5/8	3/8-16
JD-504P	P1C1SDAGX		5.5	13/26	1	A	4	4	2	3/4	13/16	3/8-16
JD-505G	F1C1SDAGX		9.5	13/26	1	A	6	5	2 1/8	3/4	1 1/8	3/8-16
JD-506G	H1C1SDAGX		15.0	13/26	1	A	7 1/4	6 1/4	2 1/8	3/4	1 1/8	3/8-16
JD-4346B	F1J3NDBKX	0-13	30.0†	16.5/33	1A	B	6	5	4 1/8	3/4	1 1/8	3/8-16
JD-507G	B1B1SDAGX		0.4	26	2	A	1 1/4	1 1/4	1 1/2	3/8	3/8	8-32
JD-508G	C1B1SDAGX		0.7	26	2	A	1 1/2	1 1/2	1 1/2	3/8	5/16	8-32
JD-3022	L1B1SDAGX		1.5	26	2	A	2	2	1 7/8	3/8	5/8	1/4-20
JD-510G	D1B1SDAGX	0-20	3.0	26	2	A	3	3	2 5/8	3/4	5/8	3/8-16
JD-511P	P1B1SDAGX		5.5	26	2	A	4	4	2 5/8	3/4	13/16	3/8-16
JD-512G	F1B1SDAGX		9.5	26	2	A	6	5	3 1/4	3/4	1 1/8	3/16-16
JD-513G	H1B1SDAGX		15.0	26	2	A	7 1/4	6 1/4	3 1/4	3/4	1 1/8	3/8-16
JD-514G	B2B1SDBGX		0.4	52	2	B	1 1/4	1 1/4	2 5/16	3/8	3/8	8-32
JD-515G	C2B1SDBGX		0.7	52	2	B	1 1/2	1 1/2	2 5/16	3/8	5/16	8-32
JD-3023	L2B1SDBGX		1.5	52	2	B	2	2	3	3/8	5/8	1/4-20
JD-517G	D2B1SDBGX	0-40	3.0	52	2	B	3	3	4 1/16	3/4	5/8	3/8-16
JD-518P	P2B1SDBGX		5.5	52	2	B	4	4	4 1/16	3/4	13/16	3/8-16
JD-519G	F2B1SDBGX		9.5	52	2	B	6	5	5 5/8	3/4	1 1/8	3/8-16
JD-520G	H2B1SDBGX		15.0	52	2	B	7 1/4	6 1/4	5 5/8	3/4	1 1/8	3/8-16
JD-9317	D3B1SDBGX		2.4	78	2	B	3	3	5 11/16	3/4	5/8	3/8-16
JD-9318P	P3B1SDBGX	0-60	4.2	78	2	B	4	4	5 11/16	3/4	13/16	3/8-16
JD-9319	F3B1SDBGX		8.5	78	2	B	6	5	7 15/16	3/4	1 1/4	3/8-16
JD-9320	D4B1SDBGX		2.4	104	2	B	3	3	7 3/16	3/4	5/8	3/8-16
JD-9321P	P4B1SDBGX	0-80	4.2	104	2	B	4	4	7 3/16	3/4	13/16	3/8-16
JD-9322	F4B1SDBGX		8.5	104	2	B	6	5	10 1/4	3/4	1 1/4	3/16-16
JD-3012	B5B1SDBGX		0.3	130	2	B	1 1/4	1 1/4	4 9/16	3/8	3/8	8-32
JD-3007	C5B1SDBGX		0.6	130	2	B	1 1/2	1 1/2	4 9/16	3/8	5/16	8-32
JD-3008	L5B1SDBGX		1.2	130	2	B	2	2	6 1/4	3/8	5/8	1/4-20
JD-3009	D5B1SDBGX	0-100	2.4	130	2	B	3	3	8 9/16	3/4	5/8	3/8-16
JD-3010P	P5B1SDBGX		4.2	130	2	B	4	4	8 9/16	3/4	13/16	3/8-16
JD-3013	F5B1SDBGX		8.5	130	2	B	6	5	12 5/8	3/4	1 1/8	3/8-16
JD-3014	H5B1SDBGX		13.0	130	2	B	7 1/4	6 1/4	12 5/8	3/4	1 1/8	3/8-16
JD-3015	B6B1SDBGX		0.3	156	2	B	1 1/4	1 1/4	5 3/8	3/8	3/8	8-32
JD-3016	C6B1SDBGX		0.6	156	2	B	1 1/2	1 1/2	5 3/8	3/8	5/16	8-32
JD-3017	L6B1SDBGX		1.2	156	2	B	2	2	7 5/16	3/8	5/8	1/4-20
JD-3018	D6B1SDBGX	0-120	2.4	156	2	B	3	3	10 1/4	3/4	5/8	3/8-16
JD-3019P	P6B1SDBGX		4.2	156	2	B	4	4	10 1/4	3/4	13/16	3/8-16
JD-3020	F6B1SDBGX		8.5	156	2	B	6	5	15	3/4	1 1/8	3/8-16
JD-3021	H6B1SDBGX		13.0	156	2	B	7 1/4	6 1/4	15	3/4	1 1/8	3/8-16
JD-116G	D-116G		2	26	3	C	3	3	1/2	Eyelet type		
JD-116G**	D-116G**		4	13/26	1	C	3	3	1/2	Eyelet type		
JD-117P	D-117P		2.7	26	3	C	4	4	1/2	Eyelet type		
JD-117P**	D-117P**	0-10	5.5	13/26	1	C	4	4	1/2	Eyelet type		
JD-241G	D-241G		6	26	3	C	6	5	1/2	Eyelet type		
JD-241G**	D-241G**		12	13/26	1	C	6	5	1/2	Eyelet type		
JD-240G	D-240G		9	26	3	C	7 1/4	6 1/4	1/2	Eyelet type		
JD-240G**	D-240G**		18	13/26	1	C	7 1/4	6 1/4	1/2	Eyelet type		

† Rated 100 amp DC for fast battery charging when fan cooled at 800 linear feet/min.
All ratings for Ambient Temperature of 35°C * Tolerance: ±1/32"
** Two stacks of this type number required.

High Current Density Selenium Rectifiers

Where space and weight considerations are paramount, International Rectifier High Current Density Rectifiers will deliver approximately twice the rectified direct current output of standard selenium rectifiers. Thus, a saving of 50% in volume for a given rating may be expected. In addition, these units feature low forward voltage drop and high inverse voltage ratings.

Circuit and Connecting Diagrams

FIG. 1

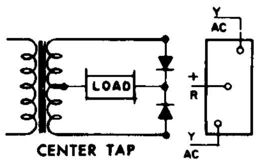
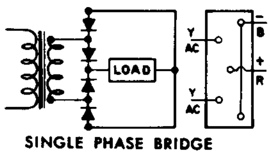


FIG. 2



Diagrams of Dimensions

FIG. A

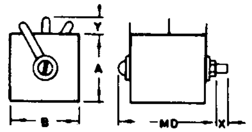
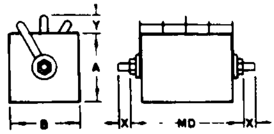


FIG. B



Type	Code Number	Output		Max. Input AC Volts	Circuit & Connecting Diag. Fig.	Dimensions (Inches)						
		DC Volts	DC Amp			Fig.	A	B	MD *	X	Y	Stud
J14C04	A1C1SDALD	0	0.4	36	1	A	1	1	1⅛	⅛	¼	8-32
J14C1	C1C1SDALD		1.5	36	1	A	1½	1½	1⅛	⅜	5/16	8-32
J14C5	D1C1SDALD	to	4.8	36	1	A	3	3	1⅛	¾	⅝	⅜-16
J14C8	P1C1SDALD		8.4	36	1	A	4	4	1⅞	¾	1⅛	⅜-16
J14C17	F1C1SDALD	14	17.0	36	1	A	6	5	2⅛	¾	1¼	⅜-16
J29B04	A1B1SDALD	0	0.4	36	2	B	1	1	1½	⅜	¼	8-32
J29B1	C1B1SDALD		1.5	36	2	B	1½	1½	1½	⅜	5/16	8-32
J29B5	D1B1SDALD	to	4.8	36	2	B	3	3	2⅝	¾	⅝	⅜-16
J29B8	P1B1SDALD		8.4	36	2	B	4	4	2⅝	¾	1⅛	⅜-16
J29B17	F1B1SDALD	29	17.0	36	2	B	6	5	3¼	¾	1¼	⅜-16
J58B04	A2B1SDBLD	0	0.4	72	2	B	1	1	2¼	⅜	¼	8-32
J58B1	C2B1SDBLD		1.5	72	2	B	1½	1½	2¼	⅜	5/16	8-32
J58B5	D2B1SDBLD	to	4.8	72	2	B	3	3	4 3/16	¾	⅝	⅜-16
J58B8	P2B1SDBLD		8.4	72	2	B	4	4	4 3/16	¾	1⅛	⅜-16
J58B17	F2B1SDBLD	58	17.0	72	2	B	6	5	5⅝	¾	1¼	⅜-16
J116B04	A4B1SDBLD	0	0.4	144	2	B	1	1	3 13/16	⅜	¼	8-32
J116B1	C4B1SDBLD		1.5	144	2	B	1½	1½	3 13/16	⅜	5/16	8-32
J116B5	D4B1SDBLD	to	4.8	144	2	B	3	3	7 3/16	¾	⅝	⅜-16
J116B8	P4B1SDBLD		8.4	144	2	B	4	4	7 3/16	¾	1⅛	⅜-16
J116B17	F4B1SDBLD	116	17.0	122	2	B	6	5	10¼	¾	1¼	3/16-16
J135B04	A5B1SDBLD	0	0.4	180	2	B	1	1	4 9/16	⅜	¼	8-32
J135B1	C5B1SDBLD		1.5	180	2	B	1½	1½	4 9/16	⅜	5/16	8-32
J135B5	D5B1SDBLD	to	4.8	180	2	B	3	3	8 11/16	¾	⅝	⅜-16
J135B8	P5B1SDBLD		8.4	180	2	B	4	4	8 11/16	¾	1⅛	⅜-16
J135B17	F5B1SDBLD	135	17.0	180	2	B	6	5	12 9/16	¾	1¼	-3/10-16

For more detailed engineering data, request Bulletin SR-152

How to Determine the Equivalent Continuous Current of Periodically Varying Loads

by L. W. Phinney, BEE
International Rectifier Corporation
Member AIEE

Occasionally a metallic rectifier will be called upon to supply a load current which varies over a fixed and repetitive time cycle. It is then desirable to obtain an equivalent continuous current which can be used as a basis for the choice of the minimum size rectifier plate required to give equivalent expected life. It is intended in this article to discuss the type of reasoning and analysis which will produce this result.

The useful life obtained from a Selenium rectifier is determined by several factors, the most important of which is the operating temperature of the plate (or cell). This assumes there are no extreme overload or surge conditions and that the rectifier has been made by a reputable manufacturer with close supervision of quality and ample experience to be fully cognizant of the many manufacturing variables which affect the resulting rectifier characteristics.

Design Considerations

It is customary to design Selenium rectifier stacks, which are to be cooled by self-induced convection currents, for a rise over the ambient temperature of about 25°C. In the case of forced air cooling, designs are usually based upon a rise above the ambient temperature of from 10° to 15° C. It is upon these temperature rise figures that published current ratings are based (See International Rectifier Corporation Bulletin C-349). There must also be noted the maximum ambient temperature specified in the bulletins which, in effect, limits the maximum temperature at which the plate may be operated. Incidentally, some conception of the rate at which anticipated life falls with increased plate operating temperature, for convection cooled applications can be obtained from page three of bulletin C-349 (rev. Jan. '55.)

Under rated load conditions the temperature rise of a Selenium rectifier is largely determined by the forward (or load) current. This current produces heat in the plate due to the forward resistance of the plate. This heat will be proportional to the square of the current. Where the load current is periodically varying it is necessary to find the continuous current value which would produce the same average rectifier plate heating as the actual load current. This is illustrated in Fig. 1, wherein i is some function of t expressed as $i = f(t)$. The average heat produced by the actual load current will be proportional to the average of the square of each instantaneous load current, taken in time sequence during one load cycle.

This would be expressed as follows:

Equation 1 $\text{Average heat} = k\frac{1}{t}\int_{t_o}^{t} F^2(t)\,dt$ –

Where k is a factor of proportionality.

The heating produced by the continuous current (I_o) which we are seeking is proportional to the square of this current.

Equation 2 $\text{Average heat} = k\, I_o^2$ – Where k is the same k as in equation 1.

Editor's Note: Due to the non-linearity of selenium rectifiers, the exponent is usually less than 2.

Since it is the basis of these whole discussions that these two heating values be the same we can equate these two expressions:

Equation 3 $k\, I_o^2 = k\frac{1}{t}\int_{t_o}^{t} F^2(t)\,dt$

or;

Equation 4 $I_o = \sqrt{\frac{1}{t}\int_{t_o}^{t} F^2(t)\,dt}$

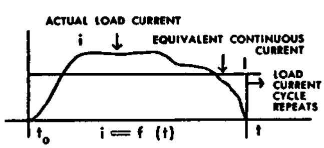


FIGURE 1

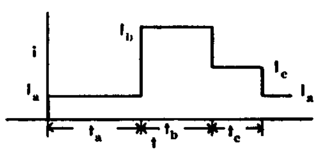


FIGURE 2

This equation 4 is recognized as the root-mean-square (or r.m.s.) value of the load current which is the standard in alternating current circuits.

Equation 4 can be useful in Selenium rectifier applications with two major exceptions. First, the equation for the load current [f (t)] is seldom known, and secondly the load usually varies in steps so a more graphical type of analysis can be used.

Assume that the load current varies cyclically according to Fig 2. Using graphical methods which are amply described in standard text books and which involve taking ordinates spaced at equal intervals, and manipulating in general accordance to equation 4, we obtain the following:

Equation 5 $I_o = \sqrt{\frac{I^2 a\, t_a + I^2 b\, t_b + I^2 c\, t_c}{t_a + t_b + t_c}}$

Additional load steps merely require adding more terms involving I_d, t_d, I_e, t_e etc.

AN EXAMPLE

As an example, let us assume a load occurring in the following steps: 0.8 Ampere for 30 seconds, 0.1 Ampere for 10 seconds, 0.25 Ampere for 20 seconds, this load cycle then repeats.

Using equation 5:

$$I_o = \sqrt{\frac{(0.8)^2 \times 30 + (0.1)^2 \times 10 + (0.25)^2 \times 20}{30 + 10 + 20}} = 0.584 \text{ Amp.}$$

If the circuit to be used is a single phase bridge, the size C plate (1½″ sq.) or larger may be used since it is rated at 0.6 amperes in such a circuit. If the load involves a single valued "on" time and an "off" time, repeatedly occurring, Fig. 1 can be more quickly used.

PRECAUTIONS

This method of evaluating a periodically varying load must be used with discretion. Each portion of the load cycle must be appreciably less than the time required for the rectifier to attain a stable temperature condition. This "thermal time" ranges from 5 to 20 minutes for self-convection cooled stacks and from 2½ to 5 minutes for fan cooled stacks.

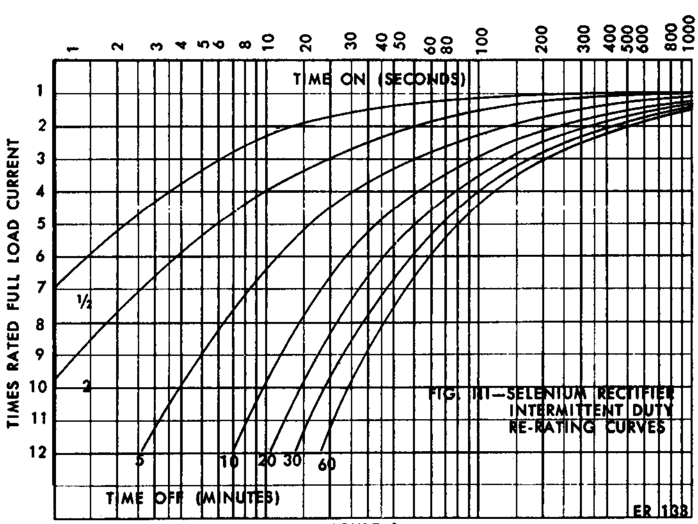
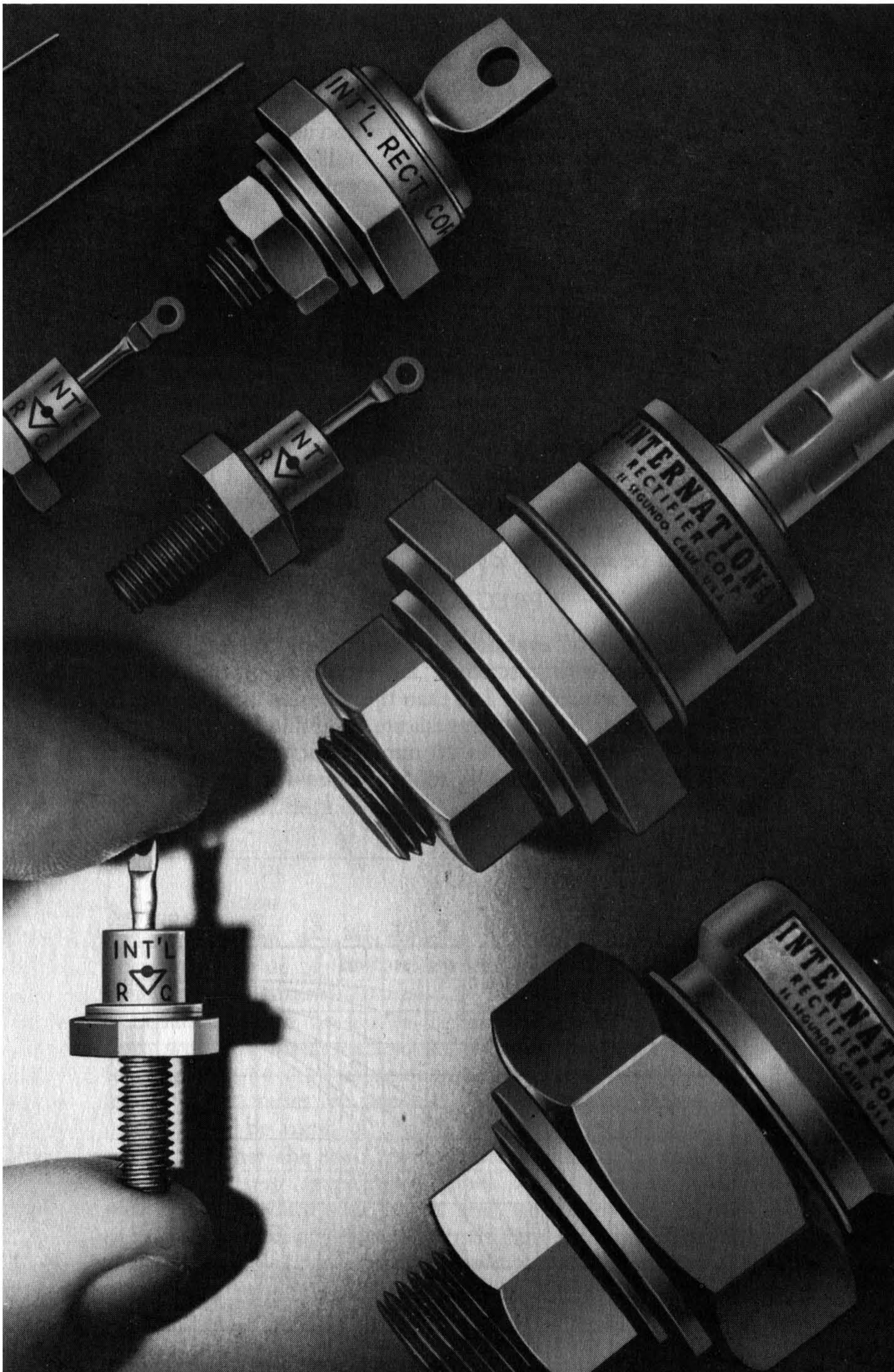


FIGURE 3



International Rectifier Corporation Stud Mounted Silicon Power Diode Types cover a Current Range of from 400 ma to 250 amperes per junction at PIV ratings to 800 volts.

Design of Fins for Cooling of Semiconductors

by Werner Luft, BME
International Rectifier Corporation

Since operating temperature of materials is a general limitation in the application of components and equipment, quantitative methods of analysis of heat dissipation have become essential. For many types of component, fins may be used to increase surface area for heat removal. Semiconductors are typical components in which temperature control is a problem, and are used here to illustrate the engineering approach to the design of fins for cooling.

The choice of proper fin size for heat dissipation from semiconductors depends upon many variables. By making certain simplifying assumptions a method has been evolved which permits numerical solution of fin design problems.

The output current from semiconductor devices such as silicon or germanium diodes is limited by the temperature of the rectifying junction. This temperature depends on the heat losses within the junction and the temperature of the environment. The question arises as to how to dissipate a certain amount of heat from the device within a limited temperature rise of the junction above ambient and by a prescribed method of cooling.

Semiconductor devices are usually mounted on fins of rectangular section. The problem becomes then to determine the necessary fin dimensions. The heat is dissipated by conduction, convection and radiation. Optimum fin design is desirable as it permits maximum cooling with minimum material. Optimum design here signifies maximum heat dissipation for minimum fin volume of rectangular profile, for given material and heat transfer coefficient.

The heat flow from the junction of a semiconductor device mounted on a fin to the environment can be illustrated by

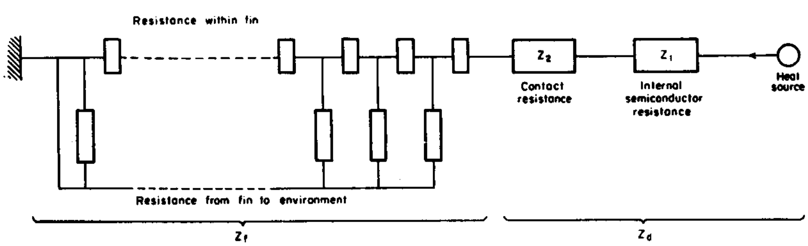


Fig. 1. Electrical circuit analogous to the distribution of thermal resistances between heat source and sink for a semiconductor device mounted on a fin.

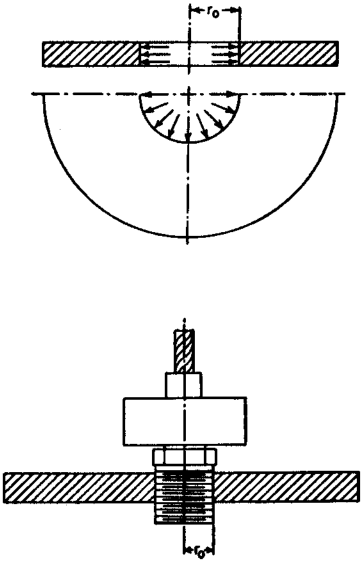


Fig. 2. (Upper) assumed radial heat penetration into an annular fin at the inner radius r_0, and (lower) tapered-thread assembly of semiconductor and fin.

an analogous electrical circuit containing an arrangement of resistances as shown in Fig. 1. The thermal resistances are the internal resistance of the device, contact resistance between the device and the fin, internal resistance of the fin, and the resistance between the fin and the environment, which is regarded as the final heat sink. The last two are each composed of an infinite number of paths and are series-parallel connected over the entire fin area. Each part of the fin internal resistance is infinitely low, and each part of the fin-to-environment resistance is infinitely high.

The resultant of internal fin resistance and the fin-to-environment resistance is called thermal fin resistance and is designated as Z_f. These two resistances must be treated simultaneously rather than as a series-parallel connection of resistances. Some simplifications have been made in order to set up the necessary equations. The fin is assumed to be circular and of rectangular section with the semiconductor in its center, and the heat flow as entering the fin in a radial direction, uniformly distributed, at a certain distance from the geometrical center of the fin, Fig. 2 upper. The distance from the center where the heat enters the fin is called the inner radius of the fin. The thermal conductivity of the fin material is assumed not to change with temperature, the heat transfer coefficient is considered to be constant over the whole fin area and the heat dissipation from the fin edges is neglected. Furthermore, only the heat dissipated from the fin is treated, while in reality heat is also dissipated from the housing of the device and through the electrical contact leads.

The assumption of circular shapes imposes the problem of finding an equivalent diameter if fin forms other than circular are used. For a square fin the side of the square can be chosen as equivalent diameter. The resultant fin resistance will be approximately 10 per cent high and must be reduced accordingly. Rectangular fins with their longest side not exceeding twice the shorter side may be reduced to an equivalent square, and the side of this square can be taken as equivalent diameter. In order to remain on the safe side, the resulting resistance in such a case must not be reduced.

The inner fin radius must be chosen in accordance with the figuration of the semiconductor device. If the device has tapered threads and is assembled to the

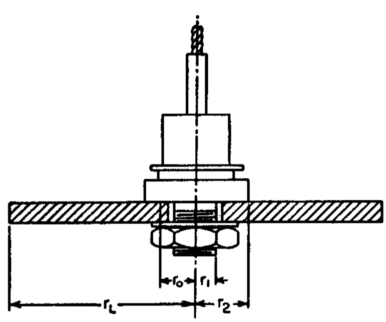


Fig. 3. Type of semiconductor and fin assembly requiring the concept of mean radius in fin design.

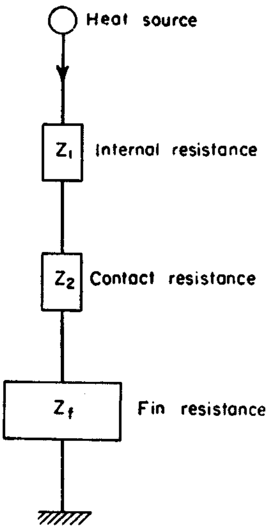


Fig. 4. Simplified electrical circuit analogue.

fin as shown in Fig. 2, lower, half the pitch diameter gives the inner fin radius. When the device is mounted as in Fig. 3, the heat will enter the fin at neither a fixed distance from the center nor in a radial direction. In this case some mean value must be taken as inner fin radius, such as the arithmetic mean of the radii r_1 and r_2.

The errors caused by the further assumptions are negligible in practical cases where the air velocity is not too high. The heat losses from the fin edges can be accounted for by reducing the diameter used in the calculations by the calculated thickness of the fin.

The solution of the differential equations which result from the thermal circuit analysis shows that the thermal fin resistance is a complex function of the heat transfer coefficient, the thermal conductivity of the fin, the thickness of the fin and the inner and outer radii of the fin. Numerical values of the fin resistance can be obtained from the nomograms.

Having obtained values for the fin resistance, the circuit of Fig. 1 can now be reduced to a simple series connection of thermal resistances: the internal semiconductor resistance, the contact resistance and the fin resistance, as shown in Fig. 4. The total thermal resistance for the heat flow from the junction is then obtained by adding the three resistances together. Thus we have obtained an expression of the temperature rise of the junction above the environment per unit of effect loss in the semiconductor device. Obviously, efforts to reduce the fin resistance by altering the fin dimensions are only profitable if the fin resistance is of the same order or larger than the internal semiconductor resistance and the contact resistance together.

Optimum Fin Design.

By calculation and graphical trial and error methods it is found that for given heat transfer coefficient, fin material, inner radius of fin and volume of fin material, the fin resistance yields a minimum in cases met in actual fin design for values of $(r_L - r_0)/R$ between 0.8

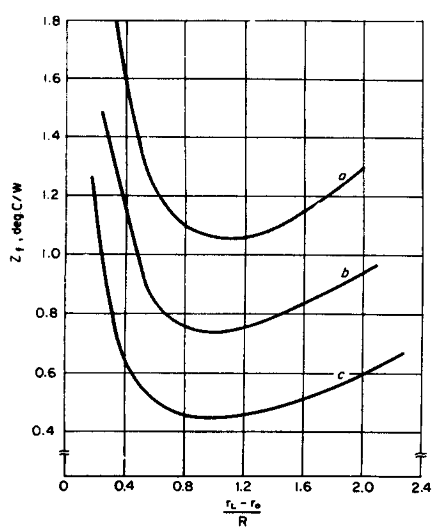


Fig. 5. Thermal fin resistance for circular fins of rectangular section as a function of $(r_L - r_0)/R$, for fixed values of inner fin radius, heat transfer coefficient, thermal conductivity and fin volume.

and 1.2. Figure 5 gives a clear illustration of this correlation. In this figure the fin resistance is plotted against the ratio $(r_L - r_o)/R$ for given values of fin volume, inner fin radius, thermal conductivity of fin material and heat transfer coefficient. Curve (a) is calculated for a fin with a thermal conductivity of 220 Btu/ft-hr-deg F, an inner fin radius of 0.5 in. and a volume of 0.87 cu. in. The heat transfer coefficient is 10 Btu/sq ft-hr-deg F. In curve (b) all variables are the same as for curve (a) except the fin volume which is 2.0 cu. in. Curve (c) differs from (b) in that the inner fin radius has been changed to 0.3 in. and the heat transfer coefficient to 30 Btu/sq ft-hr-deg F.

It is seen that for small values of $(r_L - r_o)/R$ the fin resistance is very high. For increasing $(r_L - r_o)/R$ values the fin resistance decreases rapidly and reaches a minimum; for the three cases shown the minimum lies between 0.95 and 1.09. In the vicinity of the minimum the curves are rather flat and as an approximation it can be said that the minimum occurs at $(r_L - r_o)/R = 1$. For still higher values of $(r_L - r_o)/R$ the fin resistance increases again, but less rapidly than on the opposite side of the minimum point.

The sharp rise of the fin resistance for small values of $(r_L - r_o)/R$ in the figure is to some part due to the simplification of neglecting the heat transfer from the fin edges. The error caused by the simplification is evidently greater for small values of $(r_L - r_o)/R$ than for large ones. We can draw the conclusion that for each value of fin volume the optimum fin dimensions are obtained by choosing the thickness and outer fin radius in such relation that the quotient of the outer fin radius minus the inner radius to the "natural" radius gives a value of 0.8 to 1.2. In practical work with semiconductors where the

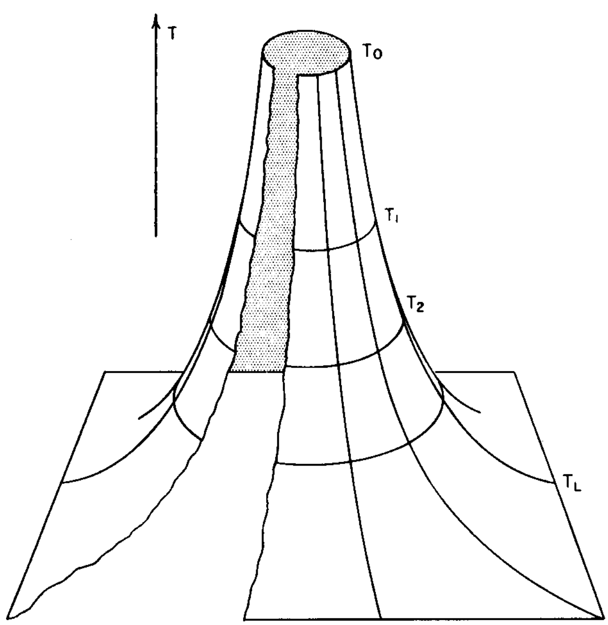


Fig. 6. Surface representing the temperature drop within a square fin of rectangular section.

inner fin radius is small compared with the outer radius, the thumb rule can be used to take the outer fin radius equal to the "natural" radius.

The "natural" fin radius, R, is a function of the thermal conductivity of the fin, the fin thickness and the heat transfer coefficient:

$$R = \sqrt{\frac{ks}{2h}}$$

Thus, if a certain fin diameter is given, the optimum thickness depends on the fin material and the manner of cooling. When choosing materials with better heat conductivity, the thickness can be reduced proportionally, while a higher heat transfer coefficient will require a thicker fin.

Fin Efficiency.

Owing to space limitations the problem frequently arises of dissipating a certain amount of heat from a limited fin area. The optimum fin thickness may then yield a value of the fin resistance which is too high to allow the desired heat dissipation within the given temperature limits. In such a case the fin efficiency can be increased by increasing the fin thickness. Efficiency of a fin is the ratio of the amount of heat actually dissipated by the fin surface per unit temperature rise to that which would be dissipated if, without change of heat transfer coefficient, the whole fin surface were held at the temperature of the fin base.

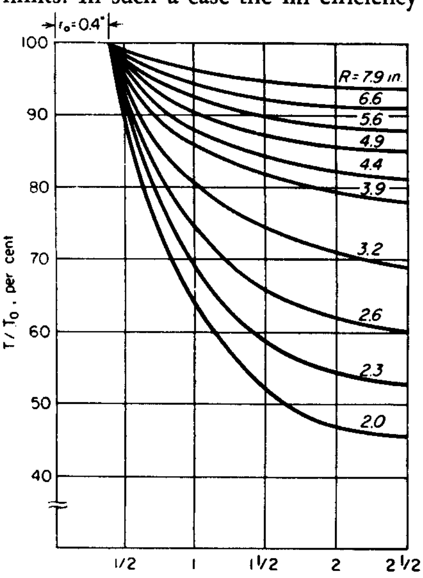


Fig. 7. Temperature drop within a fin, with $r_o = 0.4$ in., $r_L = 2.5$ in. and for various values of the "natural" radius R.

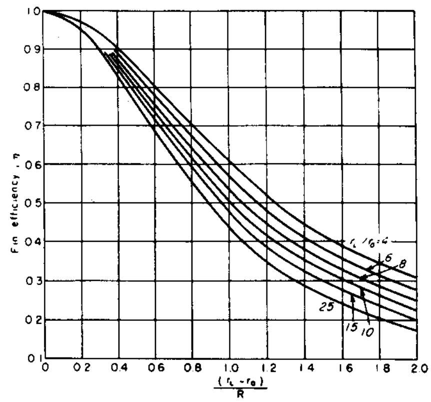


Fig. 8. Relative efficiency of annular fins of constant thickness.

Figure 6 shows a three-dimensional plot of the temperature drop within a square fin from the inner fin radius to the edges of the fin. The Y-axis represents the temperature, and the fin is in the X-Z plane. At the inner fin radius the temperature rise above the environment is T_o and at the edges this temperature difference has dropped to T_L. The temperature drop within the optimal fin is approximately 50 per cent of the total temperature difference between the fin base and the ambient. The amount of temperature drop depends on the fin diameter. The fin efficiency is then about 55 per cent to 60 per cent. By increasing the fin thickness sufficiently, the efficiency can be raised to more than 90 per cent, with a gain in heat dissipation of 50 per cent to 60 per cent.

Figure 7 gives a clear illustration of this statement. The figure shows the temperature distribution in a 5 x 5 in. fin with an inner radius of 0.4 in. for values of the "natural" radius from 2.0 to 7.9 in. The X-axis represents the distance from the fin center, and the Y-axis is the ratio of the temperature difference above the ambient at each point of the fin to the temperature difference at the inner fin radius. The optimal design for this fin would be for a value of $R=2.1$, for $(r_L - r_o)/R = 1$. The efficiency of the fin for this value of R is only approximately 60 per cent of the efficiency the fin would have if R were 8 in.

Figure 8 gives a dimensionless representation of the fin efficiency for annular fins of constant thickness*. It is seen that the fin efficiency decreases with increasing $(r_L - r_o)/R$ and depends on the ratio of the outer and inner fin radius.

From Figs. 6 and 7 it is seen that the temperature gradient is steepest at the center of the fin and becomes zero at the edge. This indicates that the effectiveness of a fin can be greatly improved by making the fin thicker in the center than at the edges. This would save material compared to a fin of uniform thickness. In practice this improvement can be obtained by brazing thick washers of suitable diameter to the center of a fin.

Table of Symbols

Table of Symbols

A	=	Heat transfer area, sq. in.
h	=	Heat transfer coefficient, watts/sq in-deg C
k	=	Thermal conductivity, watts/in-deg C
q_o	=	Heat dissipation per unit time, watts
r	=	Radius of circular fin, in.
r_o	=	Inner radius of fin, in.
r_L	=	Outer radius of fin, in.
R	=	"Natural" radius of fin $= \sqrt{\frac{ks}{2h}}$ in.
s	=	Thickness of fin with rectangular profile, in.
T	=	Temperature rise above the environment at $r = r_o$, deg C
T_L	=	Temperature rise above the environment at $r = r_L$, deg C
V	=	Volume of fin, cu in.
Z_d	=	Thermal resistance of semiconductor, deg C/watt
Z_f	=	Thermal resistance of fin, deg C/watt, $= T_o/q_o$
Z_t	=	Total thermal resistance $= Z_d + Z$ deg C/watt

A numerical example will show how a typical problem can be solved with the aid of nomograms. An output current of 82 amp is desired from a silicon diode shown in Fig. 3. The diode is mounted on a copper fin and is immersed in transformer oil with an average temperature of 80°C. The junction temperature of the diode shall not exceed 140 C. Fin thickness is to be found if outside dimensions are to be a maximum of 4 in. x 4 in. and with known constants as follows:

Heat losses in the diode $q_o = 106$ watts
Dimensions of diode stud $r_1 = 0.25$ in.
(see Fig. 3) $r_2 = 0.55$ in.

Heat transfer coefficient from fin to transformer oil $h = 0.13$ watts/sq in-deg C

Thermal conductivity of copper $k = 9.6$ watts/in-deg C

Internal diode resistance $Z_1 = 0.25$ deg C/watt

Contact resistance diode to fin (if diode is soldered to fin) $Z_2 = 0$

r_o = arithmetic mean of r_1 and r_2 = 0.40 in.
T = maximum temperature rise = 140—80 = 60 C
$Z_t = 60/106 = 0.565$ deg C/watt
$Z_f = Z_t - Z_d = 0.565 - 0.25 = 0.315$ deg C/watt

For the equivalent circular fin we can thus allow a fin resistance of 0.315/0.9 =0.35 deg C/watt

$$rL = \frac{4}{2} = 2 \text{ in.}$$

We assume a value of $R = 4$ in.

$$r_o/R = 0.1$$

$$\frac{rL - r_o}{R} = 0.4$$

From Nomogram I we obtain $Z_f = 0.35$ deg C/watt, which is the desired value.

From Nomogram II we obtain $s = 0.42$ in. The volume of material is 6.7 cu. in.

Nomogram 1 ▶

Fin resistance Z_f for given values of r_o, r_L, h and R. The first step is to derive the ratio r_o/R and $(r_L - r_o)/R$. Enter with the first ratio at the left hand side of the chart, and with the second ratio at the bottom of the chart. From the point of intersection of these ratio values, draw a horizontal line to the first "pivot line," which is the right hand limit of the curve chart (the vertical line representing $(r_L - r_o)/R = 0.1$). A line is then drawn from this point through r_o to the pivot line A, then through h to pivot line B and through R to Z_f.

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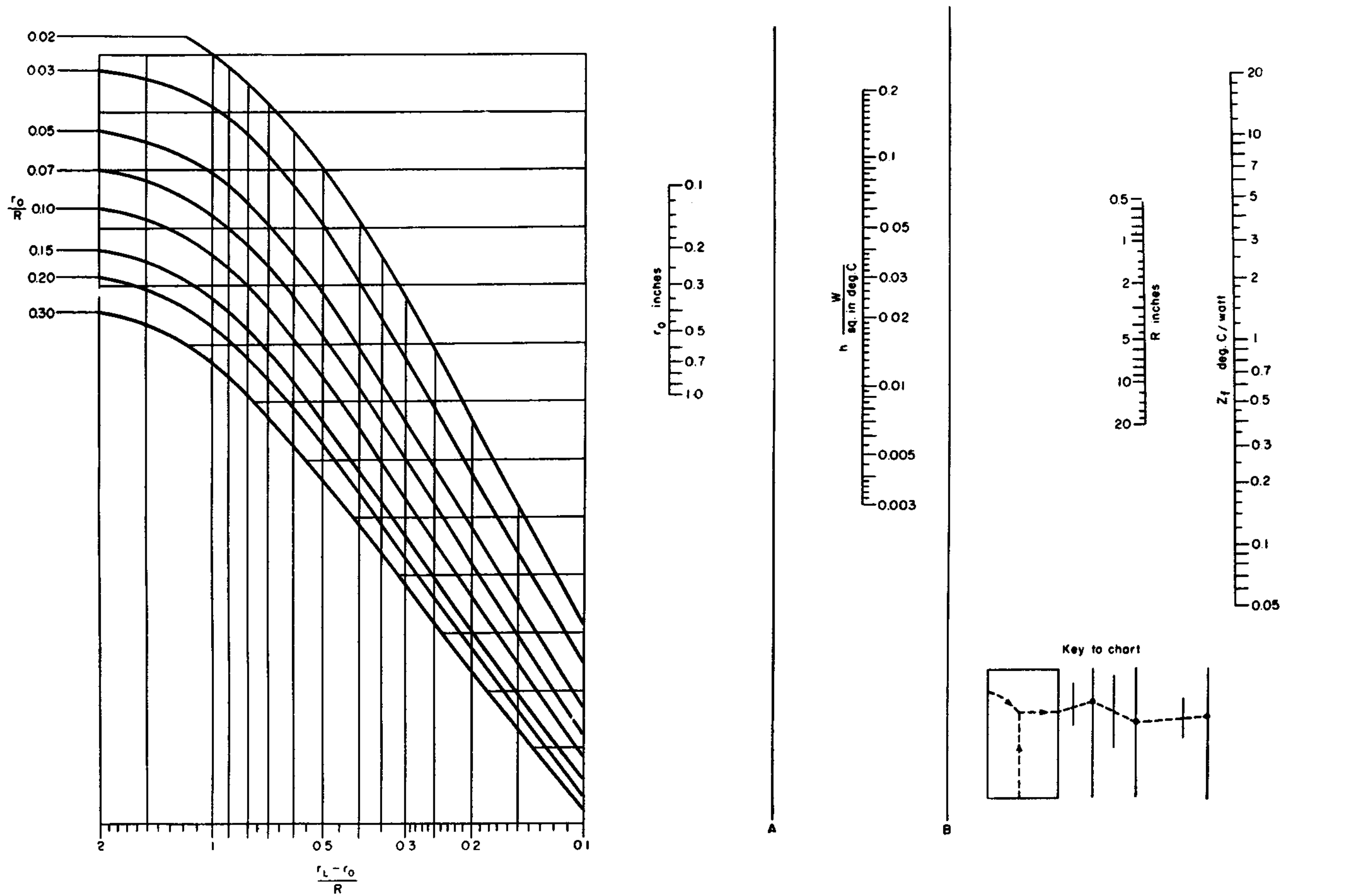
*See "Efficiency of Extended Surfaces", K. A. Gardner, Transactions ASME, Vol. 67, No. 8, Nov. 1945


r_o/R
0.02
0.03
0.05
0.07
0.10
0.15
0.20
0.30
2
1
0.5
0.3
0.2
0.1
$(r_L - r_o)/R$
r_o inches
0.1
0.2
0.3
0.5
0.7
1.0
A
h W/sq. in deg. C
0.2
0.1
0.05
0.03
0.02
0.01
0.005
0.003
B
R inches
0.5
1
2
5
10
20
Z_f deg. C / watt
20
10
7
5
3
2
1
0.7
0.5
0.3
0.2
0.1
0.05
Key to chart

Nomogram 1

If the first trial gives a too high value of Z_f a new trial must be made with a higher value of R and vice versa. To find the optimum dimensions the trial and error method must be used again.

Assume $rL = 3$ in.

$$\frac{rL - r_o}{R} = 1 ; R = 2.6$$

$$r_o/R = 0.15$$

From Nomogram I, $Z_f = 0.24$ deg C/watt. We can thus take a smaller rL

Assume $rL = 2.5$ in.

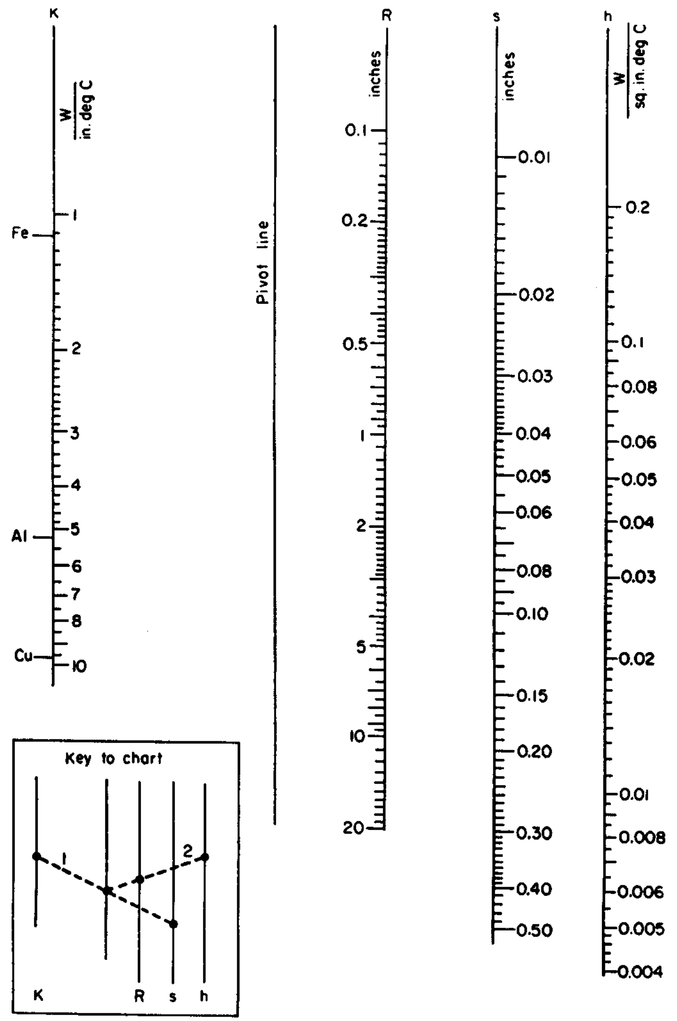
$$\frac{2.5 - 0.4}{R} = 1 ; R = 2.1$$

$$r_o/R = 0.19$$

$$Z_f = 0.35 \text{ deg C/W}$$

From Nomogram II $s = 0.12$ in.
Volume of material = 3.0 cu. in.

The optimum dimensions result in 55 per cent less material but 56 per cent more space than the first trial.

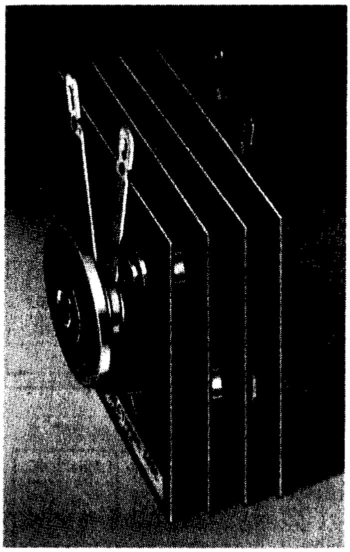


NOMOGRAM II **The function** $R = \sqrt{\frac{ks}{2h}}$

In order to find *R* when the three other variables are known, line (1) is first drawn, as indicated in the chart key, then line (2) from the intersection on the pivot line, to *h*. When *s* is desired, and the other variables are known, line (2) is drawn from *h* to *R* and extended to the pivot line. *This article originally appeared in ELECTRICAL MANUFACTURING*

Silicon Rectifier Stacks
1.5 to 14.4 Amperes 31 to 1500 Volts

International Rectifier Silicon Stacks are designed primarily for high temperature operation over the range from —65°C to 170°C. This table provides a partial listing of standard assemblies now available. Other configurations, including half-wave, three phase half-wave, six phase star and single phase magnetic amplifier bridge assemblies are available in a variety of voltage and current ranges. For more detailed information on this complete line of silicon rectifier stacks, request bulletin SR-206.



Hermetically Sealed Silicon Junctions

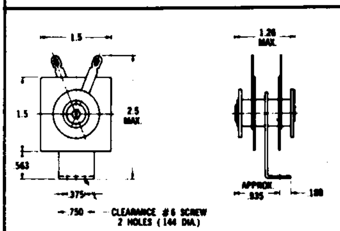


Fig. A

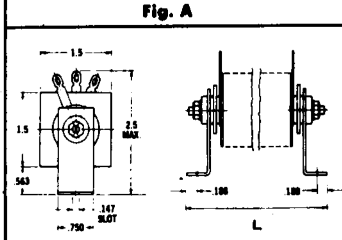


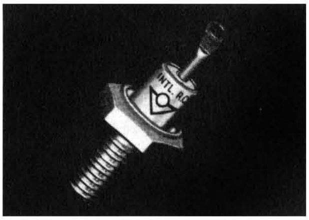
Fig. B

Standard Types and Ratings
(Partial Listing)

Type	Max. A.C. RMS. Volts	D.C. Output Voltage Volts	D.C. Output Current at 25°C Amps	Fig.	Dimension L
Single-Phase Center Tap					
66B1C1S2CS4	70	31	3.0	A	–
66B1C2S2DS4	70	31	6.0	B	3.50
66B1C3S2DS4	70	31	9.0	B	4.48
66B1C1S2CU4	140	62	3.0	A	–
66B1C2S2DU4	140	62	6.0	B	3.50
66B1C3S2DU4	140	62	9.0	B	4.48
66B1C1S2CV4	210	94	3.0	A	–
66B1C2S2DV4	210	94	6.0	B	3.50
66B1C3S2DV4	210	94	9.0	B	4.48
66B1C1SCW4	280	125	3.0	A	–
66B1C2SDW4	280	125	6.0	B	3.50
66B1C3SDW4	280	125	9.0	B	4.48
66B2C1S2DV4	420	188	3.0	B	3.51
66B2C2S2DV4	420	188	6.0	B	5.02
66B2C3S2DV4	420	188	9.0	B	7.00
66B2C1S2DW4	560	250	3.0	B	3.51
66B2C2S2DW4	560	250	6.0	B	5.02
66B2C3S2DW4	560	250	9.0	B	7.00
66B3C1S2DW4	840	376	3.0	B	4.49
66B3C2S2DW4	840	376	6.0	B	7.00
66B4C1S2DW4	1120	500	3.0	B	6.01
66B5C1S2DW4	1400	625	3 0	B	6.54
66B6C1S2DW4	1680	750	3.0	B	7.53
Single-Phase Bridge					
66B1B1S2DS4	70	62	3.0	B	3.51
66B1B2S2DS4	70	62	6.0	B	5.49
66B1B3S2DS4	70	62	9.0	B	6.99
66B1B1S2DU4	140	125	3.0	B	3.51
66B1B2S2DU4	140	125	6 0	B	5.49
66B1B3S2DU4	140	125	9.0	B	6.99
65B1B1S2DV4	210	188	3.0	B	3.51
66B1B2S2DV4	210	188	6.0	B	5.49
66B1B3S2DV4	210	188	9.0	B	6.99
66B1B1S2DW4	280	250	3.0	B	3.51
66B1B2S2DW4	280	250	6.0	B	5.49
66B1B3S2DW4	280	250	9.0	B	6.99
66B2B1S2DV4	420	376	3.0	B	5.00
66B2B1S2DW4	420	376	3.0	B	5.00
66B3B1S2DW4	840	750	3.0	B	6.48
Three-Phase Bridge					
66B1T1S2DS4	70	93	3 6	B	4.48
66B1T2S2DS4	70	93	7.2	B	7.00
66B1T1S2DU4	140	188	3.6	B	4.48
66B1T2S2DU4	140	188	7.2	B	7.00
66B1T1S2DV4	210	283	3.6	B	4.48
66B1T2S2DV4	210	283	7.2	B	7.00
66B1T1S2DW4	280	376	3.6	B	4.48
66B1T2S2DW4	280	376	7.2	B	7.00
66B2T1S2DV4	420	575	3.6	B	6.54
66B2T1S2DW4	560	750	3.6	B	6 54

Stud Mounted Silicon Power Diodes
50 TO 600 PIV

These silicon diodes are designed primarily for high temperature applications. They may be operated at temperatures up to 150°C and can withstand exposure to temperatures from —65°C to +170°C. Exhaustive tests on these diodes at high ambient temperatures have shown no detectable aging in their characteristics.



POWER SUPPLY TYPES

Absolute Maximum Ratings at 100° C ambient — **Characteristics at 25° C**

JETEC Type	Int'l Diode Type	Peak Inverse Voltage volts	Max. RMS Input Voltage volts	Max. Rectified DC Output Current ma.	Max. Continuous D.C. Current ma.	Max. Surge Current (0.1 Sec.) ma.	Max. D.C. Volt Drop at 200 ma. DC Output Current volts	Max. D.C. Reverse Current at Rated P.I.V. ma.
1N607	3AT1	50	35	800	1000	2000	1.5	.025
1N608	3BT1	100	70	800	1000	2000	1.5	.025
1N609	3CT1	150	105	800	1000	2000	1.5	.025
1N610	3DT1	200	140	800	1000	2000	1.5	.025
1N611	3ET1	300	210	800	1000	2000	1.5	.025
1N612	3FT1	400	280	800	1000	2000	1.5	.025
1N613	3GT1	500	350	800	1000	2000	1.5	.025
1N614	3HT1	600	420	800	1000	2000	1.5	.025

MAGNETIC AMPLIFIER TYPES

Absolute Maximum Ratings at 100° C ambient — **Characteristics at 25° C**

JETEC Type	Int'l Diode Type	Peak Inverse Voltage volts	Max. RMS Input Voltage volts	Max. Rectified DC Output Current ma.	Max. Continuous D.C. Current ma.	Max. Surge Current (0.1 Sec.) ma.	Max. D.C. Volt Drop at 400 ma. DC Output Current volts	Max. D.C. Reverse Current at Rated P.I.V. ma.
1N607A	3AT2	50	35	800	1000	2000	1.5	.001
1N608A	3BT2	100	70	800	1000	2000	1.5	.001
1N609A	3CT2	150	105	800	1000	2000	1.5	.001
1N610A	3DT2	200	140	800	1000	2000	1.5	.001
1N611A	3ET2	300	210	800	1000	2000	1.5	.001
1N612A	3FT2	400	280	800	1000	2000	1.5	.0015
1N613A	3GT2	500	350	800	1000	2000	1.5	.002
1N614A	3HT2	600	420	800	1000	2000	1.5	.0025

MILITARY TYPES

Ratings and Characteristics at 135°C ambient

JETEC* Types	Peak Inverse Voltage, Volts	Max. RMS Input Voltage, Volts	Max. Rectified DC Output Current, ma.	Max. Surge Current, Amps	Max. DC Voltage Drop, Volts (at 25°C)	Max. Reverse Current, 135°C Average Over One Cycle
1N253	95	65	1000	4.0	1.5V @ 1000 ma.	100 μa. @ 70V
1N254	190	135	400	1.5	1.5V @ 500 ma.	100 μa. @ 140V
1N255	380	270	400	1.5	1.5V @ 500 ma.	150 μa. @ 280V
1N256	570	400	200	1.0	2.0V @ 500 ma.	250 μa. @ 420V

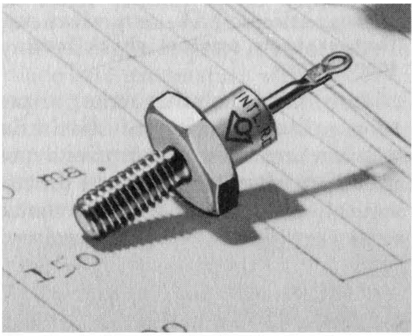
* JAN Types

Mounting Methods and Cooling Considerations - Silicon Stud Mounted Diodes

by F. W. Parrish, BEE
Chief Engineer, International Rectifier Corporation
Member AIEE, NACE

Silicon stud mounted diodes are manufactured with a large variety of base and stud sizes, each having its own particular mounting requirements to obtain optimum performance.

The use of a mounting stud accomplishes two functions; i.e., electrical connection to rectifier cathode (or anode if diode is reversed polarity), and transfer of thermal losses from the diode to the heat exchanger and cooling media. The electrical connections are easily made by any of several common methods and will not be considered here. However, proper mounting to achieve low thermal resistance is not so readily accomplished. Consequently, more emphasis will be placed on means to obtain good thermal transfer of diode losses.



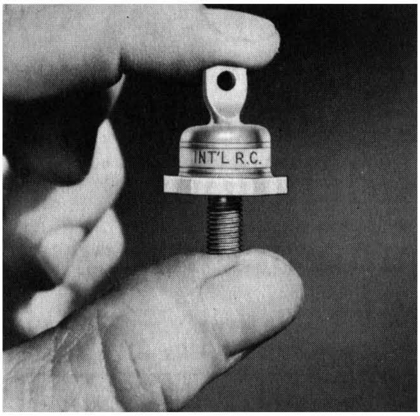
Typical configuration of International Rectifier stud mounted power diode rated 50 to 600 V PIV up to 800 ma.

Steps to Obtain Low Thermal Resistance

1. Diode base material must be a good conductor of heat. Copper is usually used.
2. Diode contact surface must be flat and smooth.
3. Surface to which diode is fastened must be flat and smooth. (Ideally the two surfaces should be lapped to obtain maximum contact area, but this is excessively expensive for usual applications.)
4. The two mating surfaces should be chemically compatible to prevent formation of high resistance films by galvanic action of dissimilar metals.
5. The two mating surfaces must be clamped together as tightly as practicable consistent with the structural rigidity of the device. Clamping is usually accomplished by means of the threaded stud.
6. Apply a thermally conductive, lubricating film between the two mating surfaces to exclude the partial stagnant air thermal insulating film.

The first two of the above items are inherent in good diode manufacturing practice. Item three may be the responsibility of the diode manufacturer, (if diodes are sold as fin-mounted assemblies) or of the user if purchased as components and mounted in his equipment.

Item 4 requires that the heat exchanger material (or the plated surface on this heat exchanger) be near to the diode base material or plated surface



25 ampere silicon rectifier series featuring advanced ceramic technology that protects against shock loads of temperature.

coating in the galvanic series, to prevent galvanic action of dissimilar metals where moist or corrosive atmospheres are present, to eliminate the consequent increase of thermal contact resistance. Table 1 lists the galvanic series of metals to assist in selecting compatible materials. Normally, the copper diode base and stud has an electroplated finish of nickel, tin or silver; indicating that heat exchanger or fin materials or surfaces should be close to one of these in the galvanic table. Note that an "active" nickel surface on a diode may safely be used against a tin plated fin. Also, a "passive" nickel surface on a fin is compatible with a silver plated diode.

Note that bases with tin, nickel or silver plating should not be used directly against aluminum fins where moisture or corrosive atmospheres exist unless the aluminum contact surface is treated in some manner to make it chemically compatible. Aluminum fins may be electroplated with nickel, silver, or tin; or an irridite surface (chromate treatment) often provides a smooth and passive surface against which the diode may be clamped.

Item 5 requires that the nut on the diode stud be tightened within the tolerances specified by the manufacturer, to obtain maximum pressure of the two mating surfaces, and yet not cause mechanical distortion of the diode base, which can stress the crystal wafer and cause changes in electrical characteristics or actual cracks in the crystal. Suggested limits are listed in Table 2.

A TORQUE WRENCH (ACCURATE IN THE LISTED TORQUE RANGE) SHOULD *ALWAYS* BE USED WHEN TIGHTENING DIODES.

Item 6 . . . Contact between the diode base and the cooling fin — even when both are machined smooth — is actually a large number of point contacts. Between the points of contact is a thin film of dead air, which is a thermal barrier. To eliminate this thermal barrier, a thin film of a thermally conductive lubricant should be applied to both mating surfaces before tightening. A silicone grease (similar to DC 200) is recommended for the bases with machine screw studs. For the taper pipe thread bases, a colloidal graphite suspension is recommended.

TABLE 1 GALVANIC SERIES OF METALS

ANODIC END

1	Magnesium
2	Zinc
3	Aluminum
4	Cadmium
5	Steel
6	Cast Iron
7	Stainless Steels (A)
8	Lead-Tin Solders
9	Lead
10	Tin
11	Nickel (A)
12	Iconel (A)
13	Nickel-Chromium Alloys
14	Brasses
15	Copper
16	Bronzes
17	Nickel-Silver
18	Copper-Nickel Alloys
19	Monel
20	Silver Solder
21	Nickel (P)
22	Iconel (P)
23	Stainless Steels (P)
24	Silver
25	Graphite
26	Gold
27	Platinum

CATHODIC END:
(A)=Active Metal Surface
(P)=Passive Metal Surface

TABLE 2

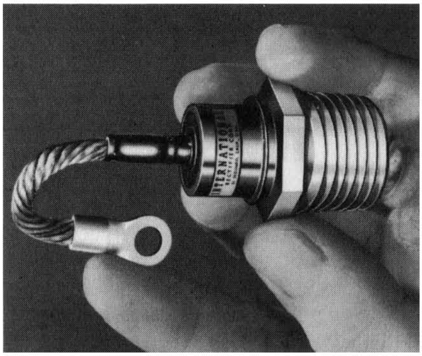
DIODE BASE		Tightening Torque (Lb.-Inches)		Approx. Contact Area (Sq. in.) Diode to Fin	Recommended Minimum Fin or Boss Thickness (Inches)
Stud Size	Hex. Size	Min.	Absolute Max.		
10-32 NF2A	7/16"	12	15	0.138	1/32
1/4-28UNF2A	9/16" 1 1/16" 3/4"	20	25	0.359	3/64
3/8-24NF2A	1"	85	100	0.752	1/16
1/2-20NF2A	1" 1 1/8" 1 1/4"	144	180		
1"-20NEF2A	1 1/8"	200	300	0.904	1/8 1/4
1/4-18 ASA Taper	1 1/8"	150	200	0.738*	1/4
3/4-14 ASA Taper	1 1/8" 1 1/4"	200	300	1.05 *	1/4

(*) When tapped into 1/4" Thick fin or boss.

Note: When tightening taper pipe thread it is also suggested that the fin or boss be heated to a temperature of +150°C before the diode is screwed into the hole, and the diode tightened while the fin is still hot.

When it is necessary to electrically insulate the diode from the cooling fin and yet maintain high thermal conductivity, thin films of high dielectric strength materials are usually employed. Commonly used materials are mica (.003" Tk), Mylar (.001 to .003" Tk) or a mica bonded glass silicone in the form of insulating washers. A light coating of silicone grease is usually applied to all surfaces to maintain the thermal resistance as low as possible. Table 3 lists some typical relative values of thermal resistances for the mounting methods discussed above.

From the above it is evident that adequate derating must be applied when diodes are electrically insulated from the cooling fin. The actual final test to prove design adequacy is to measure the diode base temperature with diodes operating at the maximum expected load and maximum ambient temperature conditions, to assure that operation is within the manufacturer's current and temperature ratings.



International Rectifier 45 amp silicon diode features standard and reverse polarity in machine thread and pipe thread base configuration.

TABLE 3 TYPICAL THERMAL RESISTANCES FOR SELECTED MOUNTING METHODS

STUD SIZE x HEX. SIZE	Metal to Metal with DC200 Grease		Metal to Metal Dry	(.001" Mylar)		(.003" Mylar)		(.003 Mica)	
	°C/watt	%		DC 200	Dry	DC 200	Dry	DC 200	Dry
10-32 x 7/16"	2.0	100%	130%	260%	320%	280%	440%	280%	400%
1/4-28 x 11/16"	0.70								
3/8-24 x 1"	0.35								
1/2-20 x 1 1/8"	0.25								

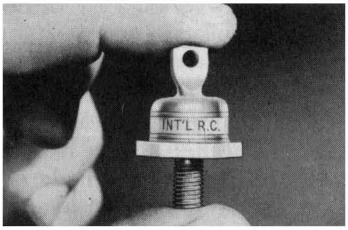
NOTE: All diodes torqued to limits required by Table 2.

Silicon Medium Power Rectifiers

These hermetically sealed silicon rectifiers, utilize the latest ceramic techniques, and are engineered to give long-term reliability on a wide variety of power applications. Designed to meet the most rigid military specifications, they will provide added stability in environmental extremes of temperature (—65°C to 200°C), humidity, shock and vibration.

25 TO 45 AMPERES - 50 TO 500 VOLTS PIV

Part Number	Rated PIV	RMS Max.	Recommended Max. RMS Volts
25H5	50	35	12
25H10	100	70	24
25H15	150	105	36
25H20	200	140	48
25H25	250	175	60
25H30	300	210	72
25H35	350	245	84
25H40	400	280	96
25H45	450	310	108
25H50	500	350	120



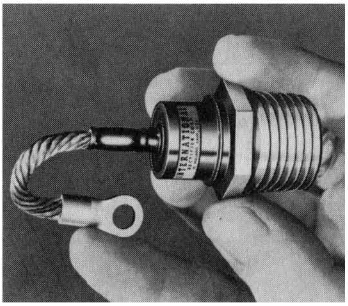
45 TO 150 AMPERES-50 TO 800 VOLTS PIV
MACHINE THREAD TYPES

STYLE L Part Number	STYLE M Part Number	RATED VOLTAGE Rated PIV	RMS Max.	Recommended Max. RMS Volts
45L5	45M5	50	35	12
45L10	45M10	100	70	24
45L15	45M15	150	105	36
45L20	45M20	200	140	48
45L25	45M25	250	175	60
45L30	45M30	300	210	72
45L35	45M35	350	245	84
45L40	45M40	400	280	96
45L45	45M45	450	310	108
45L50	45M50	500	350	120
45L60	45M60	600	420	144
45L70	45M70	700	490	168
45L80	45M80	800	560	192

TO ORDER REVERSE POLARITY TYPES add the letter "R" to the basic part number. For example: 45LR5, 45MR5, etc.

45 TO 150 AMPERES-50 TO 800 VOLTS PIV
PIPE THREAD TYPES

TYPE P Standard Types	Reverse Polarity Types	RATED VOLTAGE Rated PIV	RMS Max.	Recommended Max. RMS Volts
45P5	45PR5	50	35	12
45P10	45PR10	100	70	24
45P15	45PR15	150	105	36
45P20	45PR20	200	140	48
45P25	45PR25	250	175	60
45P30	45PR30	300	210	72
45P35	45PR35	350	245	84
45P40	45PR40	400	280	96
45P45	45PR45	450	310	108
45P50	45PR50	500	350	120
45P60	45PR60	600	420	144
45P70	45PR70	700	490	168
45P80	45PR80	800	560	192



Coordination of Fuses and Semiconductor Rectifiers

by Ed Diebold, MEE
International Rectifier Corporation
Member AIEE

In large rectifier installations containing many semiconductor rectifier elements, the protection of the elements themselves is usually done by means of current limiting fuses. In well designed rectifier equipment, these current limiting fuses are not the only protection. In order to understand the role of the current limiting fuses, it is necessary to differentiate between different types of faults and the means used to protect against them.

At the input of a rectifier unit, there is usually a circuit breaker; a.c. fuses or an a.c. contactor which has a tripping device which is thermally or magnetically operated. This a.c. protection must eliminate the possibility of damage to the transformer or any other component in the unit and furthermore interrupt whenever the unit itself is overloaded.

A second level of protection is usually afforded by the current limiting fuses in series with a rectifier element.

A third level of protection is afforded by a d.c. circuit breaker, d.c. current limiting fuse or similar device. This last protection is usually for fault current, over-currents or overload which are appearing on the rectifier unit output.

Design Trend

The trend of design has tended to use a current limiting fuse or extremely fast circuit breaker with instantaneous trip on the d.c. output side of the rectifier unit. If, then, the rectifier unit is overloaded, this device separates the rectifier unit from the overload and the rectifier elements within the unit are protected. This, particularly, is the case when the rectifier elements are selected conservatively and a substantial overload is necessary on the unit in order to reach the so-called rated load of the rectifier elements in the unit. If, at 100% unit capacity, the rectifier elements are operated at 50% of their rated capacity, then the unit must be overloaded by 200% until the rectifier elements reach the rated load. This type of application has the advantage that it is usually possible to find a fast acting circuit breaker or current limiting fuse which permits to protect the rectifier elements in the unit from d.c. faults.

Coordination

The coordination problem, then, exists only inasmuch as we must know the resistance and inductance of the expected worst short circuit (in order to obtain the rate of rise of the current), the interrupting curve of the current limiting fuse or fast circuit breaker, and the current-time curve of the aggregate of all the rectifier elements which feed into this fault. If the aggregate current capacity of all the rectifier elements feeding into this fault is substantially higher than the current which is let through by the fuse or circuit breaker until the protecting means interrupts the current, then the unit is well-designed and protected on the d.c. side. As the next step of protection, we come to the rectifier elements with their current limiting fuses, which should be deliberately selected to fail to open under a d.c. short circuit which is properly interrupted by the d.c. protective means. Thus the rating of the individual fuses should be selected high enough to permit passage of the short circuit current feeding the short circuit on the d.c. side, until the protective means of the d.c. side interrupts. Thus, the fuses associated with the rectifier elements within the unit are useless for the protection against d.c. faults of the rectifier unit.

Internal Short Circuits

In a unit containing many branches of rectifiers connected in parallel within the unit, the failure of any one rectifier element may entail an internal short circuit of the unit which damages all the rectifier elements. This internal short circuit is not protected by the output protection described above. Furthermore, it is not wise to depend upon an a.c. protective means to cover this internal short circuit, because the a.c. protection must be designed to withstand the inrush current of the transformer. This inrush current is very high, necessitating a circuit breaker setting which protects the transformer, but not the rectifier elements.

Assuming that a large rectifier unit contains ten rectifier elements in parallel per arm, there are ten rectifier elements operating in parallel per arm whenever the current is carried in any one phase. If any one element fails in one of the phases, a fault current flows from the good elements in the other two phases through the failed element in the third phase. The fuse of the failed element must carry a ten times higher current than the individual currents of the ten good elements in the other phases. If this particular fuse is selected in such a way that it interrupts the fault current before the ten elements in the other phases which feed into this fuse are overloaded, the protection is very effective and safe.

This type of protection depends on the number of rectifier elements in parallel per phase. If there are ten elements in parallel per phase, the selection of the fuse is easy. If there are only two rectifier elements in parallel per phase, the selection may be very difficult and a different means of protection may be used. In this latter case, it may be more advantageous to limit the short circuit current by a high impedance transformer and to interrupt the current on the primary side by means of a very fast tripping electrically operated circuit breaker or contactor which is tripped by the current through a relay or current transformer-relay arrangement in the rectifier circuit on the secondary. This arrangement permits almost instantaneous interruption of any fault current within the rectifier itself, without being tripped by the inrush current of the transformer. In addition to the instantaneous interruption, it may be necessary to add a thermal protection of the transformer to interrupt the transformer current whenever it is too high.

It should be noted that the so-called i^2t constand is meaningless for many fuses and completely meaningless for rectifier elements. The only way to coordinate the different means of protection is by comparison of current-time curves.

Protection on the d.c. side depends on the impedance of the d.c. system and the apparent inner impedance of the rectifier unit; see for example: "Extended regulation curves for six-phase double way and double wye rectifiers," by L. K. Dortort, AIEE technical paper 53-36, 1953. Protection for internal faults depends mainly on the transformer impedance, the speed of the protective means, the overload curve of the rectifier elements, their current and derating at rated equipment load, and the number of elements in parallel per arm.

In severe cases of short-circuits it may be necessary to use extremely high speed circuit breakers, high reactance transformers, and radical derating of rectifier elements simultaneously in order to cope with the fault conditions. Furthermore, it may be advantageous to use many small rectifier elements in parallel instead of a few large elements.

Summary

Protection of any type of equipment should be studied in view of its application and the expected availability in service. If the loading is severe and subjected to disturbances and the reliability should be high, the application of the rectifier elements should be extremely conservative and well protected.

Elimination of Surge Voltage Breakdowns of Semiconductor Diodes in Rectifier Units

by Ed Diebold, MEE
International Rectifier Corporation
Member AIEE

A phenomena common to all electric power systems is that of transient surge voltages. Normal switching, opening and closing of circuit breakers, will always result in surges. Most of the electrical equipment currently in use is not sensitive to these surges, and the standard measuring instruments used in the field are not capable of indicating them. Rectifier equipment utilizing semiconductor diodes will subject these diodes to the normally present transient surges unless special precautions are taken in designing the equipment. If the peak voltage of the transient surge exceeds the dielectric breakdown voltage of the diode, the diode will be destroyed. Surge voltages of lesser magnitude will, of course, have no ill effect on the diode in use. This destruction of the diode by the transient surge voltage can be prevented either by the elimination of the transient surges at their source or by providing a by-pass around the diode to neutralize the surge.

Causes of Transient Surge Voltages

The first cause of voltage surges is the release of magnetic energy, stored in the leakage reactance of transformers and other system reactances, when the power is suddenly cut off. These transient voltages are mostly oscillatory and may have very complex wave forms. The magnitude and frequency of the transient voltage are determined by the leakage reactance, the line to line capacity, and the speed of the circuit breaker. The behavior of a given circuit is hard to predict if several reactive and capacitive elements are present and switching may occur on any one of several different points. Figure 1 shows a simple power circuit having transient voltages of this first kind. When the circuit breaker B is closed, a sine wave voltage originating in the generator G is transformed by the transformer T and applied to the diode D. Opening the circuit breaker B causes oscillations between the leakage reactance L of the transformer and the circuit capacitances C.

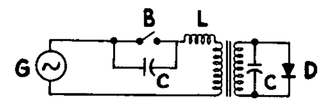


Fig. 1.

Figure 2 shows a transient voltage appearing in one phase of a three phase system when a circuit breaker opens under heavy current. In reality the transient frequency is much higher than shown in the figure and the duration of the transients may be very much shorter than one cycle of the line frequency.

The second cause of transient voltage surges is the sudden interruption of the magnetizing current of a transformer operating without load. Figure 3 shows the flux-current curve of a transformer core and its deforma-

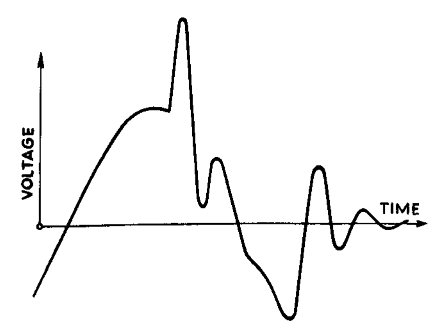


Fig. 2. Diode Voltage-Time Diagram

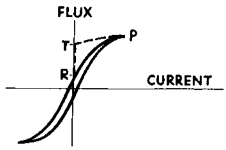


Fig. 3. Transformer Magnetizing Curve

tion (dotted line) when the magnetizing current is suddenly interrupted. From a maximum of current and flux at the point P the current suddenly is forced to zero. Due to eddy currents in the transformer core, the flux does not directly come to the point R but diminishes to the point T in an extremely short time. The flux reduction from T to R occurs at a decreasing rate as the eddy currents are damped by the iron resistance. This sudden change of flux and subsequent relaxation is the cause of an extremely short and high voltage pulse shown in Figure 4. Nature and magnitude of such transients depend intimately on the transformer design (notably the joints of the core and the flux density). They also will depend on the duration of the arc when the magnetizing current alone is interrupted. Surge voltages of this type may be extremely high; they are usually aperi-

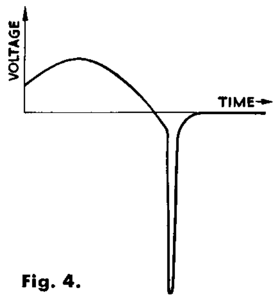


Fig. 4.

odic with one high initial voltage peak. This type of transient may be partially avoided by designing transformer cores without stacked joints and only a very small air gap (e. g. wound cores).

The third cause of surge voltages is the sudden energizing of a step-down transformer. Primary and secondary windings of any transformer are coupled by the coil capacity; when suddenly energized, the capacitive coupling transmits part of the high primary voltage to the secondary low-voltage side. Figure 5 shows the equivalent circuit to a transformer having transient voltages of the third kind. Before the circuit breaker B is closed a high voltage is already present at the generator G. A certain time after closing the circuit breaker B, the transformer T transforms this voltage down to a much lower voltage which then appears on the diode D. At the closing instant, however, the primary and secondary windings of the transformer are coupled through the winding capacity W, thus permitting a short voltage pulse to be transmitted directly from the high voltage side to the low voltage side. The appearance of such a transient voltage is shown in Fig. 6. The nature of this

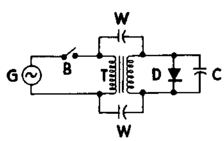


Fig. 5.

transient voltage may be aperiodic or oscillatory; it may not be noticeable in transformers which are always connected to a resistive or capacitive load. Surge voltages of this nature can (theoretically) be avoided by reducing the capacitive coupling of the primary and secondary windings. This, however, works against the normal requirement of a moderate leakage reactance.

Voltage surges, as described before, have various origins. Their common property is that the transient energy which feeds these surges is relatively low. Surges occur on almost any point of the circuit and are present whether diodes are used or not.

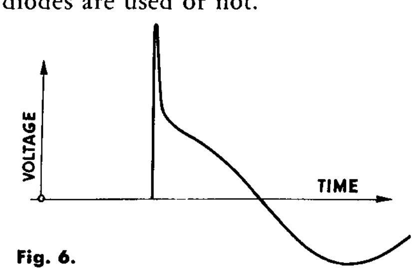


Fig. 6.

Surge Voltages on Diodes

Rectifying elements in rectifier equipment are subjected to all voltages of the circuit, both normal voltage and transients.

Metallic rectifier elements (e. g. selenium, copper oxide, etc.) have a high capacity during the blocking cycle and carry a high reverse current when subjected to an excessive inverse voltage. If such elements are subjected to a low energy transient, excessive voltage build-up will not occur because the capacitive and resistive currents form an effective short circuit.

Germanium diodes have a characteristically low capacity during the blocking cycle and carry only a very low reverse current when subjected to a high inverse voltage (except in the case of break-down). If such elements are subjected to a low energy transient, excessive voltage build-up may occur because there is no short-circuiting effect.

Means to Prevent Surge Voltage Breakdowns

From the previous discussion, it is apparent that voltage surges cannot be predicted easily and that they depend on many variables. Surge voltages as such are unavoidable. They are harmless only if they do not exceed the breakdown voltage of the diodes. The complete suppression of all voltage transients is an impractical and very costly task. If the peak voltage appearing on the diode can be cut down to a harmless value, the problem is solved without difficulty.

Surge voltage arrestors or limiters located at any one point of the system are no warranty that over-voltages may occur at another point. Notably, a surge voltage limiter applied to the primary of the transformer cannot prevent all the surge voltages caused by the transformer itself, i.e., the most dangerous ones.

One extreme solution is to perform all the switching on the transformer when the diodes are not connected to it. This necessitates a special switch for each diode. The system and the transformer are then energized prior to closing the diode switches and applying the load. Similarly, the load and the diodes must be disconnected before the transformer is de-energized. This method is cumbersome, expensive, and is not entirely safe, because unexpected transients may still occur. Surge voltage breakdowns of germanium diodes can be eliminated by partially duplicating the conditions of the dry plate rectifiers. If capacitors or non-linear resistors are connected in parallel with the diodes, the transient power surges are short circuited by the capacitive or resistive currents.

Capacitors

Surge voltages caused by the interwinding capacity of the transformer can be substantially reduced by the use of capacitors connected directly across the secondary transformer terminals. Surge voltages caused by other factors can be limited by this method except that the higher energy may require extremely large capacitors. Capacitors can lead to oscillations and hence to other over-voltages; their use should be checked by oscilloscopic observation. Capacitors also tend to broaden high-voltage, short-duration transients into low-voltage long-duration transients, a condition which is not necessarily safe.

Capacitors do not have an appreciable power loss, they may be large and expensive. Preferably, paper-oil insulated capacitors should be used and conservatively rated because of their high harmonic load in rectifier service. For the limitation of interwinding capacity surges, preference should be given to capacitors.

Non-Linear Resistors

Silicon carbide resistors with non-linear properties are commercially available (trade name Thyrite). These resistors show a decrease of resistance with increasing voltage. When connected in parallel with a diode, a voltage surge causes a proportionally much greater surge current which is

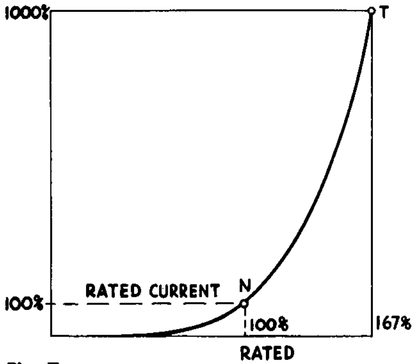


Fig. 7.

in effect a short-circuit for the transient. With increasing magnitude of the voltage surge, the current increases much more, thus a maximum of by-pass effect is available when it is most desirable. Figure 7 shows the current voltage characteristics of such a non-linear resistor. Normally it would operate at the point N or below, carrying a small current at an appreciable voltage. If the voltage increases beyond the point N, the current increases at a much higher rate. At the point T, the voltage is 167% of the rated voltage and the current 1000% of the rated voltage.

Non-linear resistors have a disadvantage due to the inherent power loss which reduces the efficiency of the rectifier. Their application is thus limited by the reduction in overall efficiency which they cause, and the necessity of cooling to dissipate the lost power. It is advantageous to force cool the non-linear resistors as much as possible, e.g., by clamping them between cooling fins and subjecting the assembly to a strong air blast, or cooling them in a liquid. Under these circumstances, the resistors may be operated at an increased capacity where they exhibit the most non-linear properties.

Example

Rectifier, 3-phase bridge circuit, 85 volts, 450 ampere output. One stack of three Thyrite resistors (Catalog #3993060G1, 3" dia., 1/10" thick) connected across the dc terminals of the bridge. Each resistor is clamped with one 4½" square cooling fin on each end and separated by 3" diameter, 1/8" thick metallic spacer, from the next resistor. The stack is located in the same cooling air blast as the germanium diodes. In normal operation, each resistor operates at approximately 28.3 volts and 1.5 amperes, representing a total of power loss of 128 watts, or 1/3% of the rectifier output.

If a transient overvoltage of 50% should appear on the rectifier, the non-linear resistor carries 5 amperes, i.e., the transient must furnish 3.5 amperes at 42.5 volts or 150 watts. This is more power than ordinary transients can deliver, which means that the actual magnitude of the transient voltage will be much less than the 42.5 volts.

Connections of Protective Elements

In a bridge rectifier, one protective element, connected across the dc terminals of the bridge, is sufficient. This is shown in Figures 8 and 9.

A single element may also be used in a single phase center tap rectifier, connecting it directly across the transformer terminals, as shown in Figure 10.

Multi-phase half-wave rectifiers need as many protective elements as there are phases, as shown in Figures 11 and 12. The protective elements in multiphase half wave circuits may be connected directly across the diodes or across the phases from line to line, however, the voltage rating of the elements connected across the diodes is only 90% of the voltage rating of the elements connected from line to line. In order to reduce the power loss, non-linear resistors should be connected across the diodes.

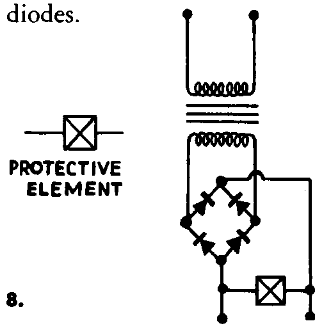


Fig. 8.

Comparison of Protective Elements

Besides capacitors and non-linear resistors, other means may be used, such as ordinary resistors and cold-cathode gas-discharge tubes. Ordinary resistors present a steady power drain and are not very effective. However, they are inexpensive and easy to utilize. Gas discharge tubes limit the voltage peaks effectively, except during the time the tube requires to ignite. This may be long enough to damage the diodes. Tubes must be carefully checked to have their burning voltage above the established voltage of the rectifier, otherwise they are destroyed.

As an overall evaluation, preference is given to non-linear resistors over capacitors. Capacitors are surge voltage limiters, but may lead to oscillations and, although they reduce the peak value of voltage surges, increase their duration, which is not desirable. Experiments show that non-linear resistors effectively cut down the voltage peaks, without increasing the duration of the over-voltage.

For practical application, it may be advantageous to assign a standard non-linear resistor to each standard rectifier and make it available whenever diode failures due to transient over-voltages are found. For a new rectifier unit, it is advisable to connect a cathode ray oscilloscope across the secondary transformer terminals, before the diodes are connected, and operate the circuit-breaker repeatedly to observe if high transient peaks are present during switching. If excessive transients (double or more than the normal voltage) are seen, then the standard non-linear resistor may be connected, together with the diodes. Observation with the oscilloscope should then be repeated.

Conclusion

Surge overvoltages due to transients cannot be accurately predicted because they may have many different origins. If excessive voltage surges are encountered, they can be limited to a safe value by the application of non-linear resistors or capacitors.

Fig. 9.

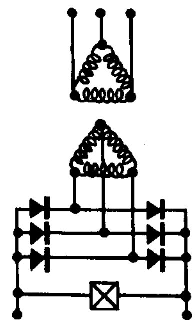


Fig. 10.

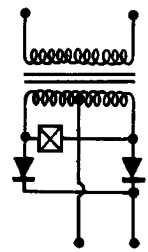


Fig. 11.

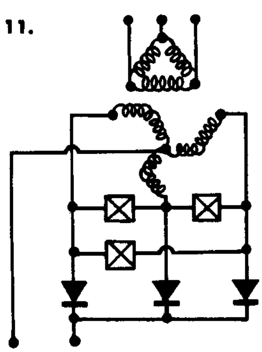


Fig. 12.

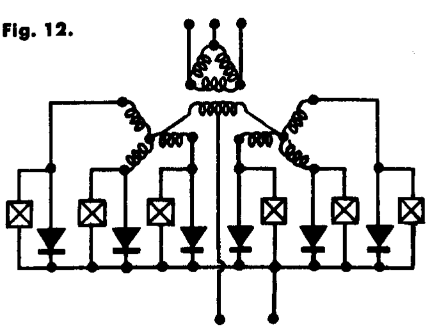


Fig. 2. Representative collection of germanium power rectifiers. Forced air-cooled units shown are rated from 330 amp to 500 amp half wave. The liquid-cooled unit at upper left is rated 667 amp (half wave) up to 66 v r.m.s. input.

Application Data for the Germanium Power Rectifier

by J. T. Cataldo, BME, BEE
International Rectifier Corporation
Member IRE

A NEW concept for power conversion equipment has been made possible with the production and availability of germanium power rectifiers. With the advent of alternating current for electrical power arose the need for conversion equipment. As the years passed, many various types were developed. The principal methods employed in the United States for the conversion of a.c. into d.c. power may be generally grouped into four classes: (1) rotating equipment, which includes the synchronous convertor and the motor generator set; (2) thermionic rectifiers, which include the vacuum, gasfilled or vapour-filled hot-cathode tube, or the pool-cathode tank or tube; (3) mechanical rectifiers; and (4) metallic rectifiers, which include the copper oxide, magnesium copper sulphide and selenium.

The various types of rectifiers each found their own niche in industry, depending on their particular characteristics and advantages for the application.

The Ideal Rectifier

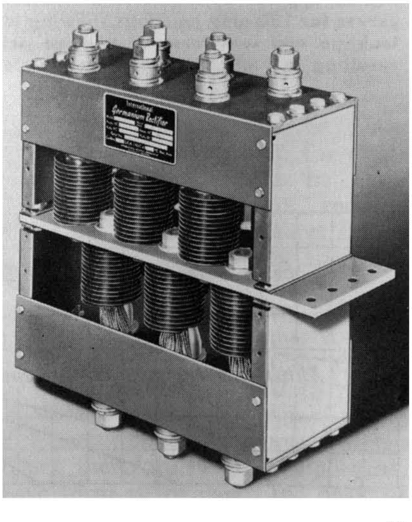
In the development of new rectifiers, attempts were made to develop units approaching the ideal rectifier, *i.e.*, zero forward resistance and infinite reverse resistance. The newest and nearest approach to date for high power conversion is the germanium power rectifier. Although other earlier types of convertors have equivalent efficiencies, certain disadvantages preclude their continued use.

Three years ago fan-cooled germanium power rectifiers were put into mass production. A typical unit of this vintage rated to deliver up to 42 V d.c. at 1,500 amp when connected as a dual three-phase, half-wave unit, with an interphase transformer is shown in figure 1. Newer types of air-cooled and liquid-cooled germanium power junctions are shown in figure 2. The ratings of these units range from 300 amp to 667 amp (half wave). They are available for input voltages of 26, 36, 52 and 66 V r.m.s.

Advantages

Major advantages of germanium rectifiers are their high efficiency,

Fig. 1. Forced air-cooled germanium power rectifier assembly—rated 1,500 amp output in a dual three-phase, half-wave circuit with inter-phase transformer.



which is in the vicinity of 98.5 per cent for the junctions alone. Rectifier circuits using germanium elements, therefore, operate very close to the theoretical values of an ideal rectifier. High efficiency also permits cooling with a small amount of air, allowing use of small blowers, filters and simplified duct work. If recirculation is desired (in areas of high air impurities) the heat exchangers required are very small, for example, much smaller than for mercury-arc rectifiers. Except for the transformer voltage drop, the germanium rectifier has almost no regulation, assuring an unchanging output voltage for varying loads.

Another advantage of germanium rectifiers is the absence of ageing. Rectification is accomplished in a single crystal which does not change with age or storage. A third advantage is the small size and weight of the germanium rectifier junction. Being a small device, the cooling method is much different than for larger rectifying devices of the same capacity. Whereas large devices are convection cooled or cooled by a relatively slow air flow in a large space, germanium rectifiers require a small volume of air flowing in a small duct at high speed.

Characteristics

The germanium power rectifier has superior characteristics over other types of metallic rectifiers for high current and medium voltage range. The low leakage current and low forward voltage drop are illustrated in figure 3. These characteristics explain the high efficiencies attainable with germanium power rectifiers.

Depending on the circuit and voltages required, rectifier efficiencies as high as 98.5 per cent are attainable. Other outstanding features are small size and unlimited life. No measurable increase in forward voltage drop or reverse current has been noted after 24,000 hours of continuous operation at rated current and voltage. This is indicative of the non-ageing properties of germanium power rectifiers and is equivalent to 3,000 working days (approximately ten years) of operation at eight hours per day. Another very important characteristic of germanium power rectifiers

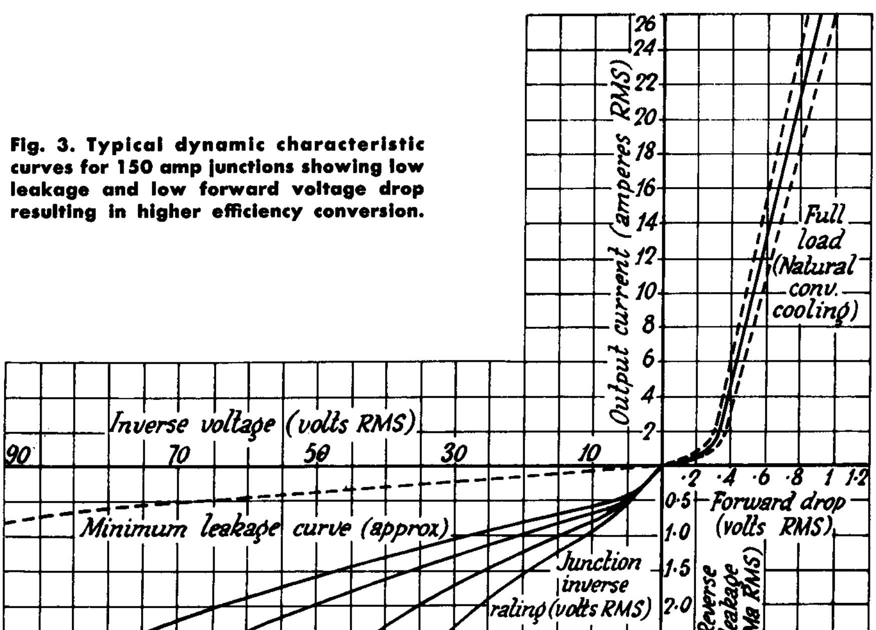


Fig. 3. Typical dynamic characteristic curves for 150 amp junctions showing low leakage and low forward voltage drop resulting in higher efficiency conversion.

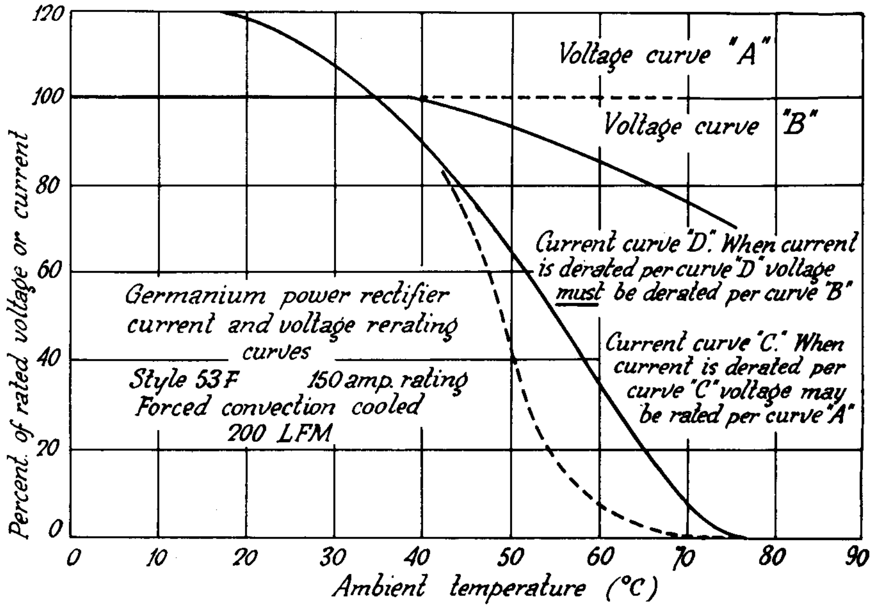


Fig. 4. Typical re-rating curves for various ambient temperature operation.

is that there is no change in characteristics after storage, *i.e.*, no re-forming is required after extended periods of non-operation.

Cooling

Germanium power rectifiers are produced for both air and liquid cooling. As previously mentioned, air-cooled types require a small volume of air flowing at a fast rate. The range of the air volume recommended is 75 to 250 cubic feet per minute at a static pressure drop of 0.75 to 1.0 inches of water. It is obvious that only a small blower is required.

The liquid-cooled germanium rectifier junction is designed to operate with many of the commercial coolants. Liquid cooling should be supplied to the special heat exchanger assemblies at inlet coolant temperatures not exceeding 30 degrees C and at flow rates of approximately three gallons per minute for water. The flow rate for other coolants such as trichlorethylene and butyl alcohol is dependent on the specific heat, thermal conductivity and viscosity. Germanium power rectifiers are thermally rated like most electrical and electronic components. Consequently, if the ambient temperature exceeds 35 degrees C for forced convection-cooled units, the unit must be derated in accordance with figure 4. For liquid-cooled units, when coolant inlet temperatures in excess of 30 degrees C are necessary, the manufacturer should be consulted.

Surge Voltages

The maximum applied a.c. voltage to the germanium rectifier junctions should not exceed the rated r.m.s. voltage of the unit, even for short durations. Care should be exercised in the design of rectifier equipment to prevent voltage surges above this value. It is therefore recommended that input voltages should be approximately 10 per cent below the rated r.m.s. voltage. However, each installation should be investigated in regard to power line fluctuations. The r.m.s. rating is based upon sine wave voltage forms, therefore, when a high peak wave form is involved, the peak of the a.c. voltage applied should not exceed the rated r.m.s. voltage multiplied by $\sqrt{2}$. If the peak voltage of the transient surge exceeds the dielectric breakdown voltage of the junction, the junction will be destroyed. Surge voltages of lesser magnitude will, of course, have no ill effect on the germanium rectifier junction in use. This destruction by transient surge voltages can be prevented either by the elimination of transient voltage surges at their source or by providing a by-pass around the junction to neutralise the surge. Surge voltages caused by interwinding capacity of the transformer can be substantially reduced by the use of capacitors connected directly across the secondary transformer terminals. Transient surges having a higher total energy content than caused by inter-winding capacitance, may be effectively reduced by the use of non-linear resistors. Silicon carbide resistors with non-linear properties are commercially available as thyrites.

Overloads

The forced air-cooled and liquid-cooled germanium power rectifiers are applicable for all types of d.c. load requirements except those requiring heavy surge currents and those subject to heavy intermittent overloads or occasional short circuits. Intermittent overloads on forced air-cooled and liquid-cooled germanium power rectifiers are permitted up to the limiting values indicated by the curves in figure 5, but not in excess of these limiting values. Where the overloads are repetitive they must be thermally evaluated to insure that maximum operating temperatures are not exceeded. Unlimited operating life can be expected over a temperature range of −55 degrees C to 45 degrees C maximum when equipment is designed to operate within specified voltage, current and temperature rise ratings. This temperature range provides ample safety factor for all normal industrial and commercial applications.

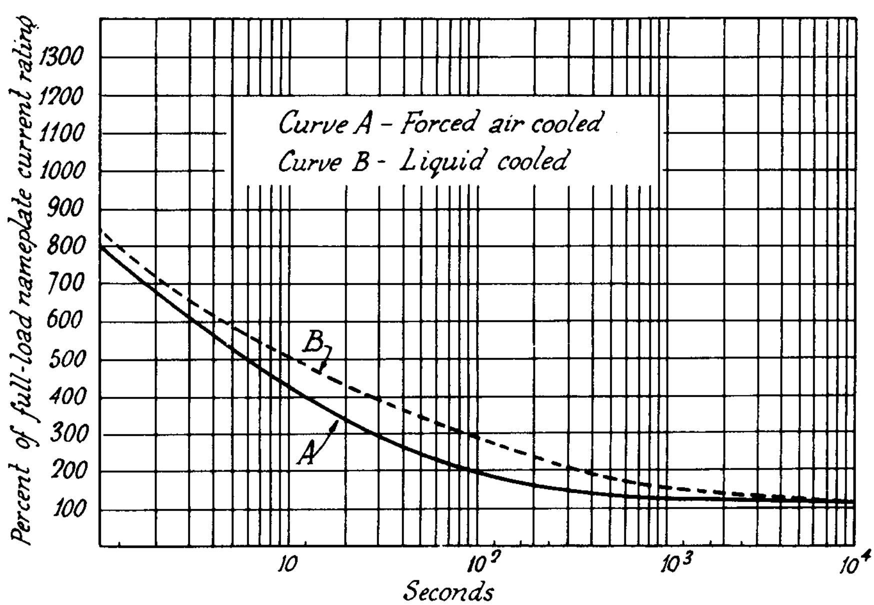


Fig. 5. Intermittent duty and overload curves for both forced air-cooled and liquid-cooled units. Note that protective devices must open the a.c. supply within maximum time shown in curve.

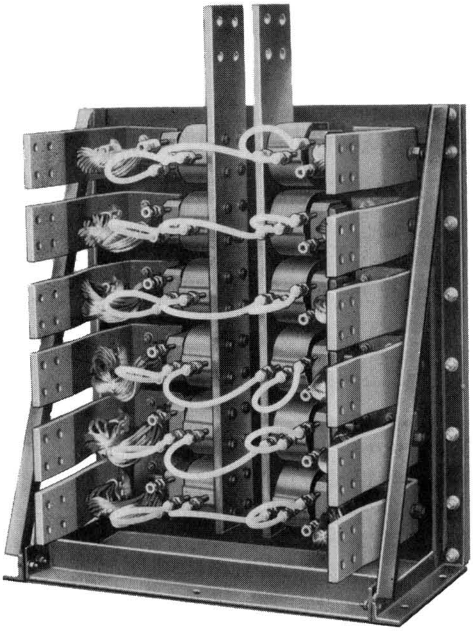


Fig. 6. Typical liquid-cooled germanium rectifier assembly. This unit measures approximately 26½ in. high by 24 in. wide and 13 in. deep. Units of this type are used to supply filament current to large vacuum tubes.

Applications

Contrary to original prediction, the germanium power rectifiers are not necessarily replacing selenium rectifiers. By far the largest volume of germanium is being used to replace M-G sets, mercury arc rectifiers and mechanical rectifiers. A few of the end uses of this d.c. equipment are: vacuum refining of metals, reduction of aluminum and production of such chemicals as hydrogen peroxide, caustic soda and chlorine, to name a few. Germanium is, however, also being used for electroplating and anodising equipment. This equipment has been designed using both the air-cooled and liquid-cooled germanium shown in figure 1.

A typical example of a liquid-cooled germanium rectifier assembly is shown in figure 6. The circuit of this configuration is a triple diametric with two junctions in parallel per arm using paralleling reactors. This assembly is designed to deliver 8,700 amp at 10 V to 25 V, depending on the voltage rating of the junctions used. Ratings for the various germanium junctions connected in various circuits are given in table I.

Analysis of various germanium power installations indicates a material saving in weight of the equipment and volume it occupies over mercury arc rectifiers. For example, a comparison of a 1,000 kW-250 V d.c. germanium unit with a mercury arc unit of the same rating shows approximately a 4 to 1 saving in weight and a better than 16 to 1 saving in cubic space requirements. The germanium unit provided 50 kW per cubic foot of space at only 0.8 lb per cubic foot.

Conclusions

By proper circuit design, germanium power rectifier equipment may be produced to deliver up to 250,000 amp or more at voltages up to 300 V d.c. As will be noted, germanium rectifiers offer many advantages, such as smaller size, high efficiency and lighter weight, among others. This relatively new rectifier has opened new fields for the d.c. power equipment manufacturer heretofore impossible with other types of metallic rectifiers.

This article originally appeared in DIRECT CURRENT

Silicon and Germanium Power Rectifier Circuit Diagrams, Transformer Connections and Rectifier Ratings

HOW TO USE THE TABLE APPEARING ON PAGES 98-99

The Table is Divided Vertically into Three Parts

At the left-hand side appear circuit diagrams of the most commonly used power rectifiers, with the number of phases and generally accepted designations.

The right-hand part of the table shows five International Rectifier Corporation rectifiers. In the columns below the junctions, opposite each circuit, appears the maximum current output of each circuit in amperes d.c., having only one junction in parallel per arm.

The center portion of the table contains twelve columns of general information on rectifier circuits and transformers. A description of the tabular data as it appears in each column of the table is given here by column number.

(Note: Standard circuit designations for Mercury-arc rectifiers and metallic rectifiers are not the same.)

Column 1

Ratio of no-load rms. a.c. voltage [E] to no-load d.c. voltage [E_{do}]. The a.c. voltage [E] is always taken line to line [diametric in the case of 6-phase star.] This a.c. voltage is also the rms. value of the commutating voltage; multiplying it by $\sqrt{2}$ gives the peak inverse voltage appearing on one arm of the rectifier.

The no-load d.c. voltage is approximately given by:

$$E_{do} = [E_d + n\,E_f]\,[1 + \frac{r}{100} + \frac{x}{z}]$$

Wherein

E_d = d.c. voltage

E_f = forward voltage drop [rectified direct voltage]

n = number of cells in series per arm [half-wave] 2 × number of cells in series per arm [bridge]

r = percent resistive drop in transformer

x = percent reactive drop in transformer

z = number, tabulated in column 12

Note: Busbars, primary devices [saturable reactors, tap changers] and system impedance may increase both the resistive and reactive voltage drop.

Column 2

Ratio of d.c. ripple frequency [f_r] over line frequency [f]. For high ripple frequency [e.g. $\frac{f_r}{f}$ higher than 3], small overlap and without phase control, the rate of the minimum rms. ripple voltage to the d.c. voltage is given by:

$$\frac{E_r}{E_d} = 1.5 \quad [\frac{f}{f_r}]^2$$

Example: 3-phase parallel bridge:

$$\frac{f_r}{f} = 12$$

$$\frac{E_r}{E_d} = \frac{1.5}{144} = 1.04\%$$

Note: The overlap [high commutating reactance] increases the ripple voltage. Phase control also increases the ripple voltage substantially.

Column 3
Ratio of average rectified d.c. [I_a] per arm to total output d.c. current [I].

Column 4
Ratio of rms. current [I_r] per arm to total output d.c. current [I].
Note: Fuses must be dimensioned for rms. current.

Column 5
Ratio of secondary rms. current [I_s] in the line from transformer to rectifier, to total output d.c. current [I].
Note: Fuses in the a.c. leads of bridge rectifiers must be dimensioned for this secondary current.

Column 6
Ratio of the primary rated power [P_p] of the rectifier transformer to the ideal output power [P] of the rectifier. This power is determined by $P = I \times E_{do}$, the product of no-load voltage E_{do} times full-load current I. (See for [E_{do}] under Column 1.)

Column 7
Ratio of the secondary rated power [P_s] of the rectifier transformer to the ideal state output power [P] of the rectifier. (See under Column 6.)

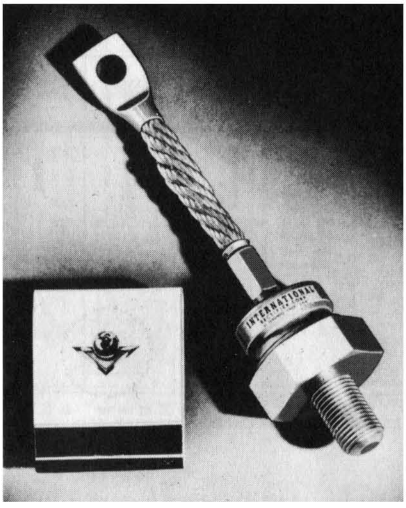
Column 8
Maximum obtainable power factor [distortion factor]. Ratio of apparent power [in kVA] to real power [in kilowatt] in primary of transformer. Overlap and phase control [saturable reactors] reduce the power factor to a value below this maximum.

Column 9
Ratio of the interphase transformer rms. voltage [E_i] to the no-load d.c. voltage [E_{do}]. The interphase transformer voltage [E_i] is measured from line to neutral, except for the triple diametric circuit, where it is given per coil.

Column 10
Ratio of the frequency [f_i] in the iron core of the interphase transformer to the line frequency [f].

Column 11
Ratio of the equivalent power rating [P_i] of the interphase transformer, to the ideal output power [P] of the rectifier (see under Column 6). Equivalent power rating [P_i] means: Power rating of a transformer operating at the frequency [f] of the a.c. line, and having the same size and weight as the interphase transformer. These figures are derived for identical iron losses per pound at the frequency of the interphase transformer and the flux density of the interphase transformer against the line frequency and the normal flux density.

Column 12
Impedance factor needed for calculation of voltage drop.



High current silicon power rectifiers providing d.c. forward currents up to 250 amperes with a maximum peak inverse voltage range from 50 to 500 volts are currently available from International Rectifier Corporation, El Segundo, California. These units are designed for use at high temperatures and are capable of operation at a junction temperature of 190°C.

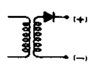
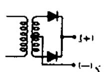
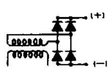
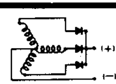
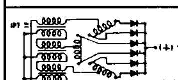
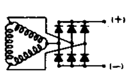
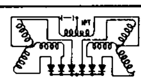
Engineered and manufactured to meet the most rigid military specifications, these rectifiers utilize the latest techniques in hermetic sealing to provide additional reliability in environmental extremes of temperature, vibration and shock. To further increase reliability and assure freedom from contamination, no soft solders or fluxes are used in sealing. Bulletin SR-305, describing these units in detail, is now available.

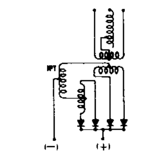
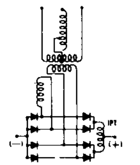
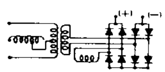
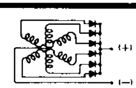
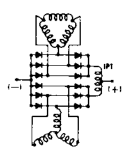
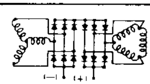
Table of Circuit Diagrams, Transformer Connections and Rectifier Ratings

Rectifier Types and Ratings

Max. Circuit Output Current (Amps, DC), One Junction In Parallel Per Arm

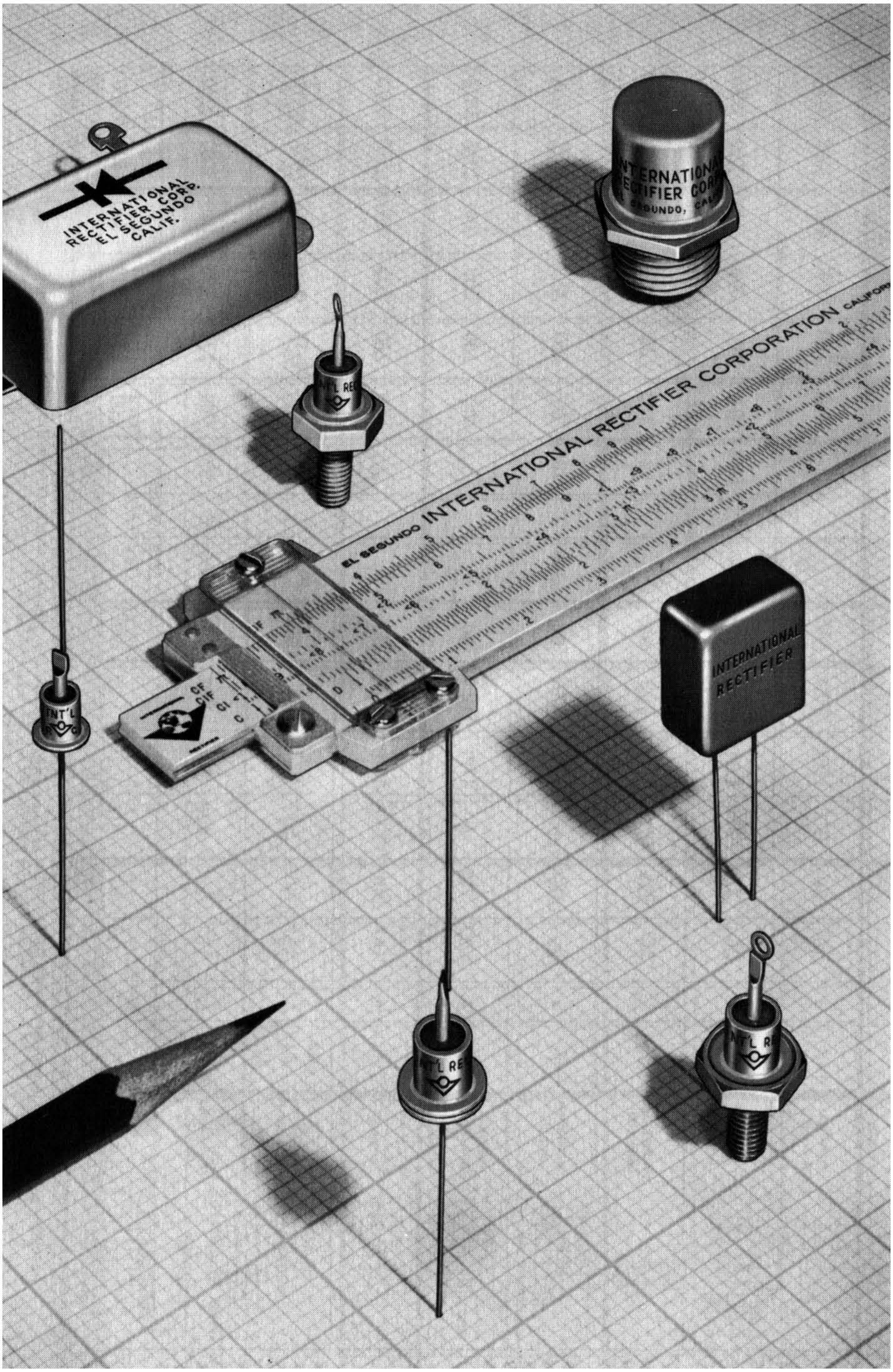
INTERNATIONAL RECTIFIER SILICON AND GERMANIUM POWER RECTIFIERS

	APPLICATION DATA	CIRCUIT INFORMATION				TRANSFORMER INFORMATION			POWER FACTOR	INTERPHASE TRANSFORMER			IMPED. FACTOR	SILICON* See data sheets for specific rating and cooling data.			GERMANIUM (At 35° C)	
	COLUMN REFERENCE NO.	1	2	3	4	5	6	7	8	9	10	11	12	25 SERIES	45 SERIES	70 SERIES	500 AMP.	670 AMP.
	ABBREVIATIONS (See Reverse Side)	E/E_{do}	fr/f	I_a/I	I_r/I	I_s/I	P_p/P	P_s/P	PF	E_i/E_{do}	fi/f	P_i/P	Z	AIR COOLED	AIR COOLED	AIR COOLED	AIR COOLED	LIQUID COOLED
SINGLE PHASE	 Half Wave Resistive or inductive load	2.22	1	1	1.57	1.57	2.47	3.5	.405				200	50	115	195	553	737
	 Full Wave Center Tap	2.22	2	.5	.707	.707	1.11	1.57	.90				200	100	230	390	1106	1473
	 Bridge	1.11	2	.5	.707	1	1.11	1.11	.90				200	100	230	390	1106	1473
THREE PHASE	 Wye	1.48	3	.333	.577	.577	1.21	1.48	.826				191	135	310	520	1500	2000
	 Triple Diametric	2.22	6	.167	.236	.236	1.11	1.57	.955	.325	2	.262	200	300	690	1170	3320	4430
	 Bridge	.74	6	.333	.577	.816	1.05	1.05	.955				200	135	310	520	1500	2000
	 Double Wye	1.71	6	.167	.289	.289	1.05	1.48	.955	.252	3	.162	141	270	620	1040	3000	4000

SCOTT FOUR PHASE		Center Tap (without IPT)	1.57	4	.25	.50	.50	1.11	1.57	.90				100	160	360	640	1860	2410
		Double Diametric (with IPT)	2.22	4	.25	.353	.353	1.11	1.57	.90	.255	2	.206	200	200	460	780	2210	2950
		Parallel Bridge (without IPT)	.785	4	.25	.50	.707	1.11	1.57	.90				100	160	360	640	1860	2410
		Parallel Bridge (with IPT)	1.11	4	.25	.353	.50	1.11	1.57	.90	.255	2	.206	200	200	460	780	2210	2950
		Series Bridge	.555	4	.500	.707	1	1.11	1.57	.90				200	100	230	390	1106	1473
SIX PHASE		Star	1.48	6	.167	.408	.408	1.28	1.81	.955				58	220	535	900	2530	3370
		Parallel Bridge (without IPT)	.715	12	.167	.408	.577	1.01	1.43	.985				200	220	535	900	2530	3370
		Parallel Bridge (with IPT)	.74	12	.167	.289	.408	1.01	1.05	.985	.085	6	.059	200	270	620	1040	3000	4000
		Series Bridge	.37	12	.333	.577	.816	1.01	1.05	.985				200	135	310	520	1500	2000

*Absolute max. ratings, forced air cooled (1000 Lfm) at 25°C ambient temperature. See data sheets on specific units for detailed cooling data.

For complete data on each rectifier type listed, write for these specific bulletins. SILICON: 25 Series, SR-304; 45 Series, SR-300 and SR-301; 70 Series, SR-305. GERMANIUM: 500 Ampere Air Cooled, GPR-2SA; 670 Ampere Liquid Cooled, GPR-3SA.



International Rectifier Corporation manufactures a zener diode type and rating for every voltage regulation and control application.

Silicon Zener Voltage Regulators

by George Porter
International Rectifier Corporation

CHARACTERISTICS, SELECTION AND APPLICATION DATA

Technological advances in the manufacture of silicon junction diodes have made an extremely valuable component available for use in accurate voltage regulator reference design.

The silicon junction diode is a semiconductor device possessing a very high back resistance up to its critical reverse breakdown, or zener, voltage. At this point, the back resistance drops to a very small value. In this region, the current will increase very rapidly, while the voltage drop across the diode remains almost constant. Figure 1 illustrates that over a wide range of current, an essentially constant voltage will be maintained. Zener diodes, therefore, when biased in the reverse direction, can be used as a voltage regulator, or reference element.

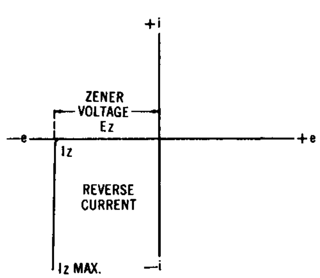


Fig. 1. Typical Reverse Breakdown Characteristics.

Silicon Regulator Advantages

The silicon diode regulator possesses definite advantages over other types of reference elements. It has a longer life expectancy because of mechanical ruggedness and does not suffer from deterioration under storage. There is essentially no aging during its operating life as contrasted to other regulating devices. Small size and light weight make its use especially desirable in airborne or portable equipment. Moreover, the silicon regulator or combinations thereof, can be supplied in values at any desired voltage and can operate over a wide range of current, whereas

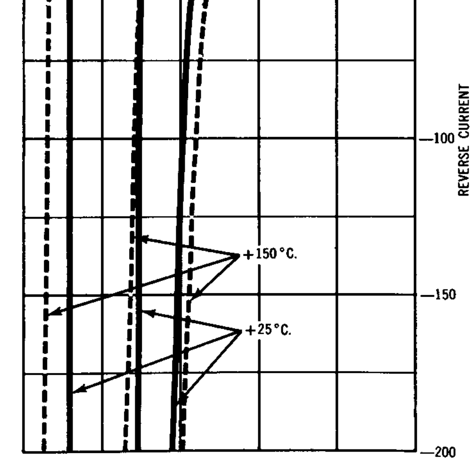


Fig. 2.

other regulators are restricted to specific voltages and very limited current ranges.

ZENER REGULATOR CHARACTERISTICS

The breakdown voltage of a zener diode is dependent on the resistivity of silicon material used and can be controlled to a great degree in the manufacturing process. Figure 2 shows a typical zener characteristic vs. temperature in detail. It can be seen that the voltage is dependent to a degree upon the operating ambient temperature.

Temperature Coefficient

Those diodes for which the zener voltage is high have a positive temperature coefficient of reverse breakdown, where the voltage is low, the temperature coefficient is negative. In the region from about 5 through 6 volts, the temperature coefficient may be made positive or negative by control of the reverse current. In Figure 2, (a) indicates that at a value of 45 ma, the coefficient is zero. It should be understood that the point of exactly zero coefficient for those diodes in the 5 volt region hold true for a specific reverse current only. This is best illustrated in Figure 2 at the intersection point (a). Temperature coefficient for zener regulators is a constant for a given regulator and is related to its breakdown voltage, as shown in Figure 3.

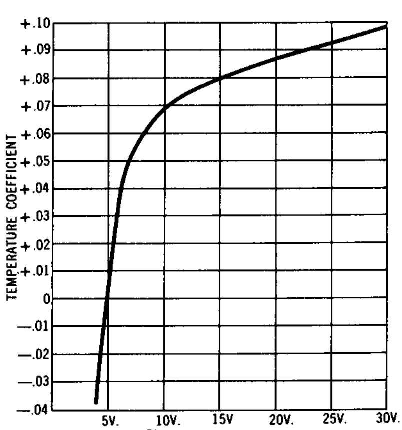


Fig. 3. Zener Diode Temperature Coefficient Curve.

This graph indicates that this coefficient, although approaching 0.1% per degree centigrade at the higher voltages. passes through zero at about 5 volts and then becomes negative for lower voltages, reaching —.04%/°C at about 3.5 volts.

Zero Temperature Coefficient

The zero temperature coefficient characteristic is not limited to diodes of exactly 5 volt breakdown only, but can be found at various operating current points in regulators in the voltage range from 4.5 to 6.5 volts. As shown in Figure 4, points b, c, and d, are points of

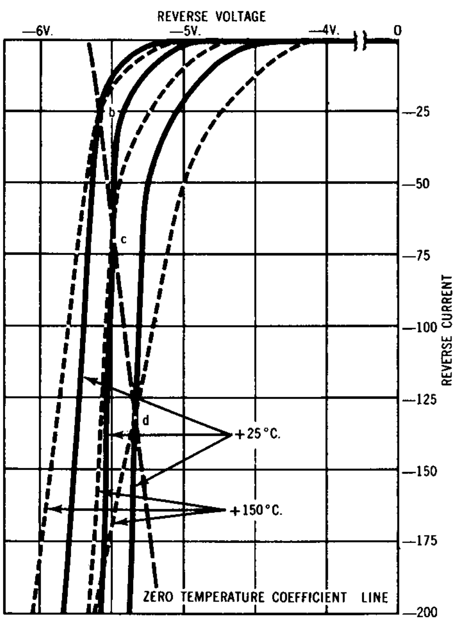


Fig. 4.

intersection that provide zero coefficients at a definite reverse current. Below 4.5 volts, the high current value necessary to achieve the condition of zero coefficient is prohibitive and approaches the maximum I_z of the device. Above 6 volts, the intersection of zero coefficient has reached the zero reverse current line.

Maximum Current Limits

Any silicon zener regulator has a maximum limit of current range over which it can operate. This upper limit is established by the heat dissipation capability of the regulator. The maximum current which can flow through the diode is limited in practice by the heat generated at the junction, the temperature of which must not rise above some critical value. Heat generated internally at the crystal junction contributes, together with the ambient temperature, to the determination of the junction temperature. A typical derating curve for an International one watt zener diode is shown in Figure 5.

Various power classes of regulators are in production ranging from several hundred milliwatts to 10 watts. Silicon regulators for higher power dissipation are currently being developed at International Rectifier Corporation to provide operation at currents up to 10 amperes.

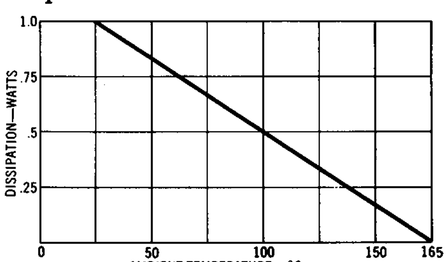


Fig. 5. Typical Temperature Derating Curve.

SELECTION OF ZENER DIODES

The dynamic resistance (R_z) in the zener region is the basic parameter for establishing the regulating ability of the silicon voltage regulator and is one of the most important factors to be considered when selecting a diode to be used in a regulator application. The dynamic resistance is determined by measuring the A-C voltage developed across the regulating diode when operating with a specified A-C current superimposed on the D-C current corresponding to the design center current (I_z) of the reference element.

This dynamic resistance is an expression of the change in voltage for a small change in current about its operating D-C current point. All International Rectifier zener diodes are measured by using a value of A-C current which is 10% of I_z. For a diode having a nominal I_z rating of 30 ma a 3 ma A-C signal is used.

In general, the dynamic resistance is a function of the D-C current flowing through the diode, and under conditions of rated current, is of the order of a fraction of an ohm for low voltage diodes and several hundred ohms for high voltage types. Since R_z is dependent upon the operating current, those diodes capable of high dissipation, hence higher current, offer a much lower resistance. The higher the allowable current through the diode, the lower the resulting dynamic resistance. A change in dynamic resistance can be observed with variations in ambient temperature; the higher the temperature, the greater the resistance. This change is linear with temperature, increasing by approximately 30% for 100°C rise.

Current Selection

It should be noted that although I_z is the recommended operating point, usually 20% of I_z maximum, any current beyond the zener breakdown curvature may be arbitrarily selected. A family of reverse current curves of typical zener diodes is shown in Figure 6. If operation near the knee of the curve is desired, diodes exhibiting an E_z of above approximately 7 volts should be chosen.

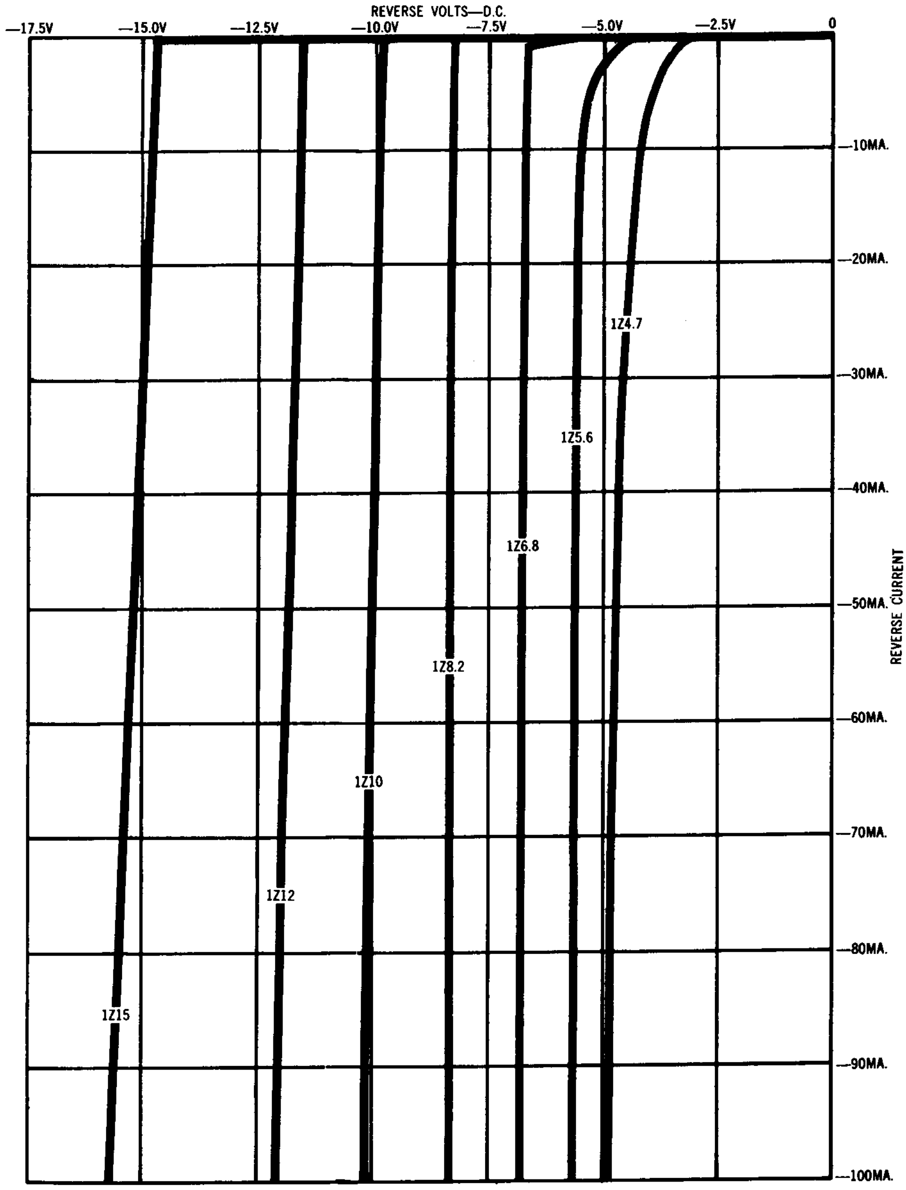


Fig. 6. Reverse Current Curves of Typical Zener Diodes.

APPLICATION DATA

Silicon Zener Voltage Regulators

Beyond breakdown, the characteristics of the silicon diode are almost identical to the gas voltage-regulator tube and may be considered to be the semiconductor equivalent. The effect can be used in exactly the same manner to provide a constant voltage output.

The simple shunt regulator (Figure 7) is a circuit in which a shunt element draws variable current through a resistor, which is also in series with the load.

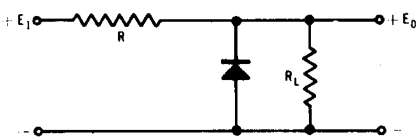


Fig. 7. Shunt Voltage Regulator.

The current through resistor R is dependent upon the load requirements. As the load increases or decreases, the zener shunt element will draw more or less current. The net result is substantially a constant output voltage across R_L.

Thermally Induced Resistance

Resistor R should be so selected that the current in the diode does not exceed I_z max. or exceed the maximum power dissipation rating if the load R_L were removed. In practice I_z is chosen as approximately 20% of I_z max. and as a shunt regulator, will absorb current variations between the I_z and I_z max. limits. Referring to Figure 7, it can be seen that the larger I_z becomes, the lower the dynamic resistance.

Therefore, the greater the permissible current through the shunt diode, the larger the ripple reduction will be and the better the circuit regulation. However, as the diode current is increased, the junction temperature will rise to the point where the dynamic resistance will increase, due to a thermally induced resistance in the element. This thermally induced resistance will therefore, tend to limit regulation at high currents, whereas the dynamic resistance will dominate at lower current levels. For any particular diode, a compromise operating point must be selected. The alternative would be to use a regulator of higher dissipation capabilities possessing lower thermal resistance.

The maximum permissible diode current is limited by the temperature rise of the junction and by the heat sink provided to dissipate the heat. Thus, the use of a zener diode as a voltage regulator element is limited only by its rated current handling capabilities. International Rectifier supplies zener regulators over a wide range of power dissipations.

MULTIPLE JUNCTIONS

In many instances, the circuit design engineer requires regulation at higher voltages. Three alternatives are available. A single junction unit rated for the desired voltage can be used, but suffers from a high positive temperature coefficient and high dynamic resistance.

In order to achieve optimum performance a number of lower voltage units can be used in series. The resultant temperature coefficient, dynamic resistance, and thermal resistance will be much reduced for the series combination.

An example of how a high voltage multiple junction assembly compares with a single high voltage unit can be shown when six 5 volt zeners are connected in series. A single 30 volt zener diode would possess a temperature coefficient of close to +0.1%/°C, a dynamic resistance of 60 ohms and might handle only 30 ma for a particular style diode. The series combination, on the other hand, would have essentially zero coefficient, resistance of only 6 ohms and the ability to handle over 200 ma of reverse current!

Series Advantages

Regulation of such a device will be superior in all respects at any given current. It is also possible to obtain a much closer tolerance by such a series combination. If similar units are used, the series regulator assembly will also have higher current ratings as a result of its increased heat dissipation capability. The higher wattage rating is directly proportional to the number of similar series units used.

Packaged Series Assemblies

The third alternative is the use of packaged series assemblies of the International Rectifier HZ type. Here, six selected zener diodes are assembled in series to provide voltage regulators from 24 through 160 volts. The total dissipation of the package is 5 watts without heat sink, and allows the designer to place the assembly in a convenient location on the chassis without having to provide for mounting of individual diodes.

The power dissipation per diode in such a series combination will be inversely proportional to the number of units used; in this case, six. For a given current, there will be a significant lowering in the operating junction temperatures.

As the junction temperature is lowered life expectancy of each diode will increase.

It is possible, therefore, to achieve an increase in overall reliability, despite the fact that more individual components are involved. In general, multiple junction operation is to be preferred in all ways.

DOUBLE ANODE ZENER DIODES

It is possible, in the 6 to 8 volt region, to compensate for the reverse positive temperature coefficient by taking advantage of the negative coefficient of another diode operating in the forward direction. Two such diodes when connected in series with reversed polarities make possible a stability of ±1% or better over the temperature range of −55°C to +100°C. Optimum compensation and stability will occur at currents of approximately 10 ma.

For this application, the International Rectifier Type ZZ double anode assembly is recommended. Such a device can also be employed to provide a means of simple a-c regulation since the ZZ type diodes are constructed in a symmetrical manner; the reverse voltage of both diodes are matched to within ±5%.

Typical applications involving use of such devices would be: calibration source for oscilloscopes, A-C limiting in servo control systems, speech clipping, etc. The basic A-C regulator circuit is shown in Figure 8.

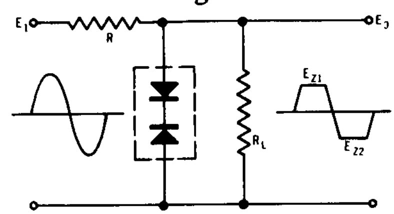


Fig. 8. Basic A.C. Regulator.

Space Savings — Design Freedom

The principal advantage of zener diodes over conventional semiconductor diodes and vacuum tubes for limiting purposes lies in the fact that no D-C bias supplies or heater connections have to be made, thus allowing greater freedom in design and a savings of components.

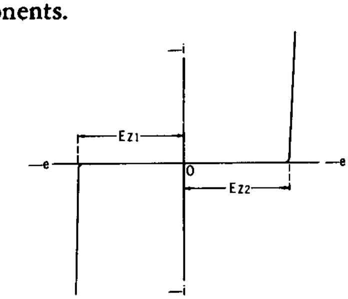


Fig. 9. Typical Reverse Characteristics of Double Anode Type ZZ Diode.

The reverse resistance breakdown in the zener diode is much sharper than the forward conduction break of any other diode and therefore results in a precise and clean limiting action.

The zener diode provides a low impedance cathode bias supply, useful with both vacuum tubes and transistors, illustrated in Figure 10.

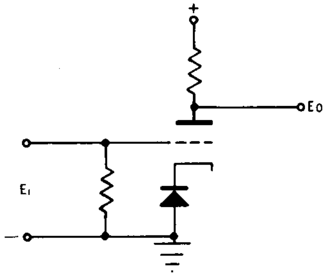


Fig. 10. Zener Diode Cathode Bias Element.

By-Pass Capacitor Unnecessary

The bias for the stages is the zener breakdown voltage of the diode and due to its low impedance requires no by-pass capacitor even at very low frequencies. Where gain is important, the zener unit contributes little or no degenerative effects so that the full gain of the tubes may be realized.

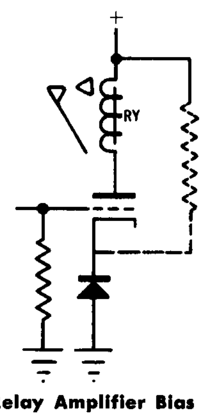


Fig. 11. Relay Amplifier Bias Supply.

Bias Method For Relay Amplifier

Figure 11 illustrates a method of bias for a relay amplifier that can be held in an off condition until a predetermined input level has been reached. The zener diode provides a bias for the amplifier that is close to cut-off, and current through the tube will be insufficient to energize the relay. When the grid is made more positive, it can be seen that the bias will remain constant even though the tube current increases. This is in contrast with a conventional cathode resistor which would result in an ever increasing bias as tube current increases.

The zener diode may be considered as the equivalent of a battery when used for cathode bias purposes. Figure 12 illustrates how a form of fixed bias for two tubes or transistors in a single-ended push-pull servo amplifier may be provided. The result is a simple, highly efficient circuit with a minimum of components.

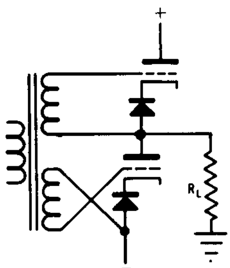


Fig. 12. Zener Diode as Fixed Bias.

Zener Diode as Coupling Device

A silicon zener diode may be used as a coupling device between two amplifier stages in much the same manner as a capacitor, illustrated in Figure 13.

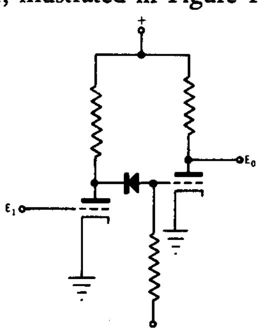


Fig. 13. Zener Diode as D.C. Coupling Device.

The D-C level will be reduced only by an amount equal to the zener voltage drop. The zener element permits frequency response down to D-C due to its extremely low resistance. Although the diode may be replaced by a resistor to achieve the required change.in level, there could be a loss in signal due to the voltage-divider action of the resistors.

Reference Element Application

Fortunately, the zener diode is basically a low voltage device. This fact makes it particularly attractive in the design of transistorized equipment. Of particular interest is its application as the reference element in a series-regulated power supply, as shown in Figure 14.

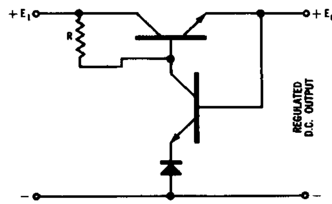


Fig. 14. Zener Reference Element in Transistor Power Supply.

The small size and rugged construction of the diode is compatible with the other semiconductor circuit components, and lends itself admirably to construction of light weight, durable airborne electronic equipment.

Temperature Sensing Device

The apparent disadvantage of a zener diode's temperature coefficient may be put to a useful purpose in the form of a temperature sensing device. A bridge composed of two resistors and two similar diodes (Figure 15) can be constructed so as to indicate a temperature level when one of the diodes is held at a reference temperature and the other is subjected to the varying environment.

An International Rectifier 1Z10 (10 V. zener) has a temperature coefficient of +.07%/°C which corresponds to 7 millivolts per °C change. The sensing element will, therefore, indicate an imbalance of 0.7 volts when undergoing a 100°C temperature change. The output can be read directly, or fed to a recording galvanometer for permanent records.

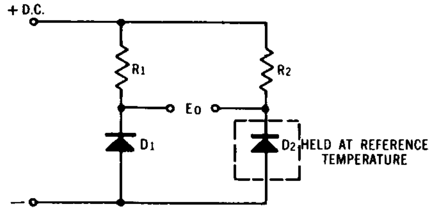


Fig. 15. Temperature Sensitive Bridge.

Selective Signaling Circuit

A precision selective signaling circuit can be made so as to operate a series of relays in a sequential manner corresponding to various values of applied voltage. In Figure 16, as the input voltage reaches the level of each individual zener diode, the diode will conduct through the appropriate relay coil.

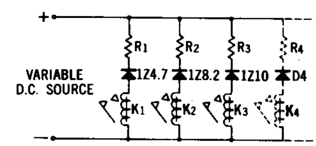


Fig. 16. Selective Relay Signaling Circuit.

The principal advantage over other means is that the pull-in of each relay is virtually independent of coil characteristics and is dependent only on the sharp reverse characteristic of the zener diode. The exact voltage value for relay operation can be set by pre-selection of the proper zener diode, rather than choosing relays of dissimilar characteristics, often times an impossibility.

The applications described are but a few of the many possible uses for the zener regulator diode. As their capabilities become more widely known, numerous other functions will be performed by these versatile components, especially in conjunction with transistors and switching circuitry.

The Zero Temperature Coefficient Zener Diode

by George Porter
International Rectifier Corporation

Without a doubt, the information most often requested by potential users of zener diodes concerns the temperature stability of these voltage-regulating devices; i.e., temperature coefficients.

For those who are to use the zener diode as circuit elements exposed to temperature variations, this characteristic is of extreme importance. Fortunately, zener diodes are obtainable with positive, negative and essentially zero coefficients.

In certain applications, the circuit designer may take advantage of either extreme to provide compensation for another circuit element tending to drift in an opposite direction.

The stability of a zener diode is dependent on several factors, including the value of the zener breakdown voltage, and the operating current. The temperature coefficient tends to be positive at the higher zener voltage ranges, and negative at the lower. Figure 1 illustrates in graphical form this relationship between zener voltage and temperature coefficient.

In many instances the zener diode is to be utilized as an extremely accurate voltage reference element. A reference element of this type must serve, as nearly as possible, as an absolute standard, and voltage deviations with variations in temperature cannot be tolerated. In order to achieve this degree of stability there are three basic courses open to the design engineer:

1. Operation of the Zener Diode in a Crystal Oven: This assures an even temperature (anywhere from ±2°C to ±½°C, depending on oven quality) but only at the expense of increased cost, circuit complexity, larger size and oven operating life. This may be considered as the "brute force" method of achieving stability. On the other hand, there are occasions where conditions demand a reference at a discreet voltage, usually high, where use of the oven is not only justifiable, but sometimes the only solution. Where operation at arbitrary lower voltage values can be used, either of the two following alternatives should be considered:

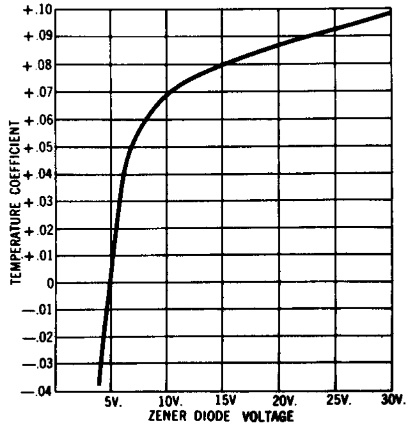


Fig. 1. Zener Diode Temperature Coefficient Curve.

Fig. 2. 1N430 Reference Element.

2. The Diode Compensated Voltage Reference Element: The popular 1N430 (Figure 2) is probably most representative of this type device and at the present time is not only a military standard item, but is nearly the ultimate in stability. Temperature stability better than ±.002% per degree Centigrade is obtainable from the 1N430 and ±.001%/°C may be realized from the 1N430A and 1N430B versions over extremely wide temperature variations. This is accomplished by using diodes operating in their forward direction, (and exhibiting a negative temperature coefficient), being used to nullify the positive coefficient effects of a reverse biased zener diode. If extreme care is taken in coefficient matching, the resultant device is a reference element possessing the aforementioned temperature stability at approximately 8.4 volts.

Although considerably smaller in size than the oven, the 1N430 is considerably larger than a single diode and must be chassis-mounted. Although the necessarily higher cost of this element can be tolerated by producers of military equipment, there are many cases where the simple matter of economics enters the picture and the designer must turn to another answer — the single "zero coefficient" diode.

3. Operation of a Zener Diode of Approximately 5 volts Breakdown, according to Figue 1, provides us with a single diode reference element having essentially zero temperaure coefficient. This should prove especially attractive to engineers who are cost-conscious, and to whom space is a problem.

At first glance the solution seems amazingly simple; install a 5 volt diode and it should follow that we have a stable reference, unaffected by temperature. It is not quite that simple.

In the 5 to 6 volt region, a zener diode exhibits this nearly zero temperature coefficient characteristic only at a specific reverse current. Figure 3 (next page) shows that a 5.3 v. diode will have such a characteristic at approximately 125 ma; a 5.5 v. unit at approximately 60 ma and a 5.6 v. diode at 25 ma.

A high degree of stability is assured by operation of the zener diode at its proper reverse current point.

Zero Coefficient

You may have noticed the use of the terms "nearly" or "essentially" zero coefficient. Although it appears logical from Figure 3 that if we can obtain a negative coefficient at low current values, and a positive coefficient at high current, there *must* be a reverse current at which absolutely zero coefficient can be obtained. This is true only to a limited extent, and is explained graphically in Figure 4.

In order to illustrate more clearly how reverse current is the determining factor in achieving this essentially zero temperature coefficient effect, a diode rated at a zener breakdown voltage of 5.5 v. was selected and its thermal stability measured at a number of different reverse currents. Figure 4 is, in effect, an expansion of the cross-over region at point C in Figure 3, and shows the deviation from an initial voltage drop at +25°C for various amounts of reverse currents. For example, a diode having a drop of 5.500 v. at +25°C at a reverse current of 50 ma d.c. would exhibit a negative change in voltage as the temperature is increased. In this case, a 50° increase in temperature would cause the voltage to drop from its initial value to 5.492 v. at +75°C, or a

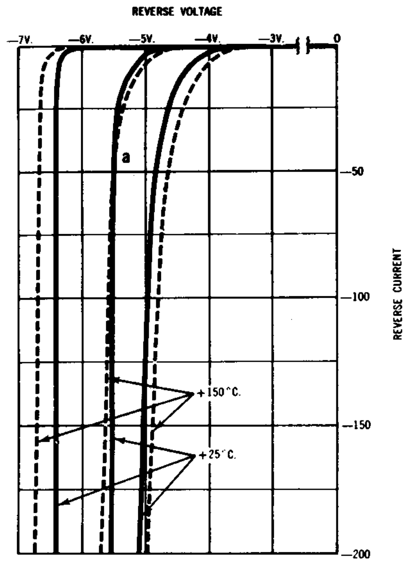


Fig. 3.

net change of —8 millivolts. On the other hand, 80 ma of current would cause the voltage to increase by approximately 9 millivolts for the same temperature rise.

Of interest is the fact that, at this current, the voltage will first change in a positive direction and then at about +75°C will reverse, pass through zero, and then go predominantly negative. At +150°C the net change will be almost exactly equal and opposite to the positive deviation at the lower temperature. This particular diode at 80 ma would therefore leave a stability rating of approximately ±.003%/°C from +25°C through +150°C.

If operation over a limited temperature range is expected; say +25°C through +75°C, it would then be advantageous to operate at an intermediate current value; in this case 57.5 ma where a temperature coefficient of slightly over ±.001%/°C can be expected. This gives a stability that exceeds the 1N430 reference element and approaches the 1N430A.

Current Source

The only problem that remains is to provide a current source for the reference diode. Three methods are normally used. See Figure 5.

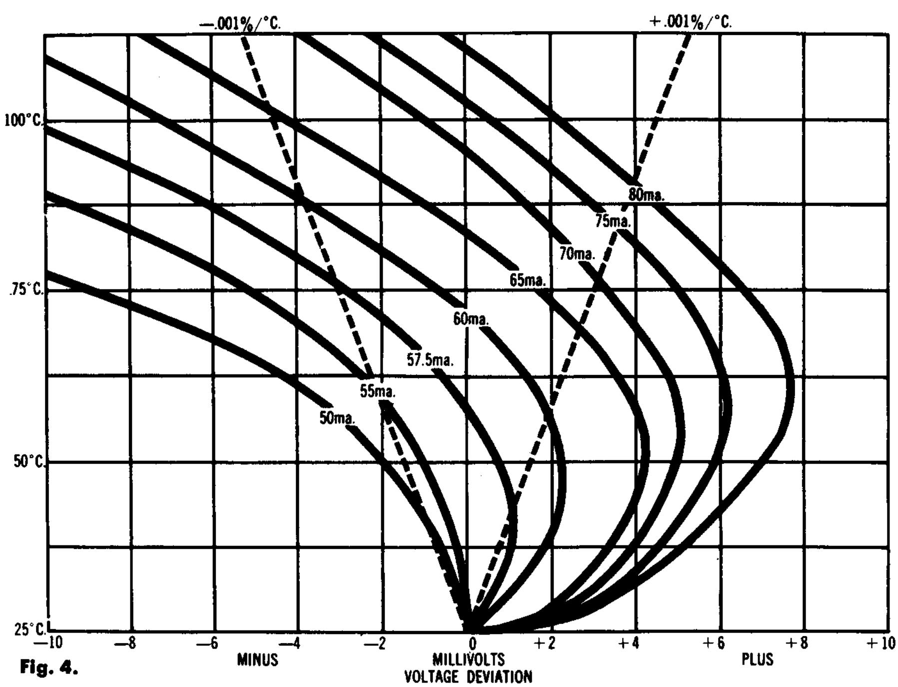


Fig. 4.

(a) makes use of a high voltage as a constant current source.

(b) utilizes a 10 volt zener diode to act as a regulator for the reference diode. The current limiting resistor between the two diodes should have a negative temperature coefficient to compensate for the positive (+.07%/°C) drift of the 10 volt unit.

(c) Two 1Z5.6 diodes, each having nearly zero T.C., in turn act to stabilize the current through the reference element.

In all three cases, R_1 must be assigned a value that insures proper reverse current for the end diode.

Although the data presented is for a particular diode rated by International Rectifier at 5.5 volts, the principle applies to all diodes in the 5 to 6 volt region, and the optimum reverse current will be dependent on the voltage rating of individual diodes; the higher voltage diodes will have their optimum temperature characteristics at lower current values.

As long as this critical current is known for a particular diode, a single junction therefore can be made to perform as an excellent stable reference element at low cost, small size and circuit simplicity.

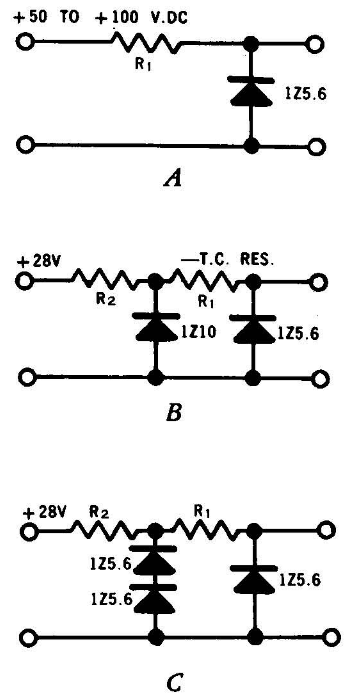


Fig. 5.

Semiconductor equivalents eliminate components and circuitry required by tube counterparts to overcome plasma oscillation and high firing potential.

Voltage regulation circuits can be simplified and the reliability increased by using silicon zener voltage regulators in place of conventional gas tube regulators such as the 0A2, 0A3, 0B2, 0C3, 1B46 and the 991.

The International Rectifier HZ series, provides a substantially lower dynamic resistance than do comparable tube types — and over a much broader temperature range (—65°C to +165°C). This feature, and the unusually high zener reference voltage, stem from the unique construction of these units. Mechanical ruggedness of this package leads to longer term reliability than can be expected from tubes.

Application of Zener Diodes to Industrial Equipment

by George Porter
International Rectifier Corporation

Zener diodes, although a relatively new regulating device, offer the design engineer a versatile component that may be used to good advantage in many electrical industries.

The small size and high current handling capabilities of the zener diode permits design of lightweight, compact equipment, and is particularly attractive when compared to its bulkier counterpart.

In addition to the military, manufacturers of industrial equipment, appliances, and electrically operated machinery represent a large and growing market for this simple semiconductor device. Designers of automatic machinery, communications equipment, aircraft, electronic computers, etc., are constantly finding new applications for the silicon regulator.

The following tabulation indicates, in general, manufacturing groups who at present are making use of the zener diode in new equipment design. The survey includes ten basic industry classifications, type of product manufactured, and a few of the typical applications. This is followed by a breakdown of the particular rating or style of zener regulator normally encountered in such equipment.

These statistics were compiled by the Applications Advisory Group of International Rectifier Corporation, and are fairly representative of the present use of these devices.

Although the industries and products listed represent only a small segment of the total number of electrical equipment manufacturers, the applications and diode types shown are indicative of their present utilization.

It is quite evident that producers of other types of equipment will, in time, incorporate these regulators in new equipment design.

THESE ARE INTERNATIONAL RECTIFIER CORPORATION'S SEVEN BASIC ZENER DIODE STYLES

- **A. STYLE M: 750 MW RATED**
  zener voltage range of 3.6 to 30 volts
- **B. STYLE S: 1 WATT RATED**
  zener voltage range of 3.6 to 30 volts
- **C. STYLE T: 3.5 WATT RATED**
  zener voltage range of 3.6 to 30 volts
- **D. STYLE T: 10 WATT RATED**
  zener voltage range of 3.6 to 30 volts
- **E. STYLE HZ: 5 WATT RATED**
  zener voltage range of 24 to 160 volts
- **F. STYLE ZZ: 600 MW RATED**
  zener voltage range of 4.3 to 30 volts
- **G. REFERENCE ELEMENTS:**
  250 MW RATED *voltage reference range of 8.0 to 8.8 volts*

Zener Diode Application Chart

INDUSTRY AND APPLICATION — USE THESE ZENER DIODES

BASIC INDUSTRY	PRODUCTS	APPLICATIONS	A 750 mw. type	B 1 watt Type	C 3.5 watt Type	D 10 watt Type (and higher)	E Multiple Junction	F Double Anode	G Reference Element
GUIDED MISSILES	Guidance Systems	Regulators, Limiters, Bias	●					●	
	Power Supplies	Regulators, References		●	●	●	●		●
	Missile Launchers	Regulators		●	●	●	●		
	Ground Support	Misc. Regulators	●	●	●	●	●	●	●
ELECT. MEASURING INSTRUMENTS	Inst. Movements	Meter Protection	●					●	
	Digital Voltmeters	Reference, Bias	●	●					●
	Oscilloscopes	Regulators, Bias	●	●			●		
	D.C. Amplifiers	Reference, Limiters						●	●
	Diode Testers	Meter Protection, Regulator	●	●					
	Signal Generators	Limiter, Bias	●					●	
	Transistor Testers	Regulators, Limiters	●	●				●	
	Voltage Calibrators	Regulators, Limiters	●	●			●	●	
	Continuity Checkers	Go-No Go Indicators	●	●					
	Recorders	Reference, Bias	●					●	
	Telemetering Equipt.	Reference					●		●
COMPUTING MACHINES	Aircraft Comp.	Reference, Coupling Elem.	●						●
	Analog-Digital Converter	Bias, Regulators	●	●				●	●
	Data Processing	Reference, Limiters							
	Digital Computers	Regulators, Limiting	●	●	●			●	●
		Gating, Coupling, Reg.	●	●					
COMMUNICATIONS	Comm. Receivers	Noise Limiting						●	
	Radio Transmitters	Bias, Regulators	●	●	●	●	●		
	TV Transmitters	Bias, Regulators	●	●	●	●	●		
	Facsimile	Bias, Regulators	●	●	●	●	●		
	Airborne Comm.	Regulators, Limiters	●	●				●	
	Telephone Systems	Limiting	●					●	
	Alarm Systems	Threshold Control	●						
	Radar Systems	Regulators, References	●	●	●	●	●		●

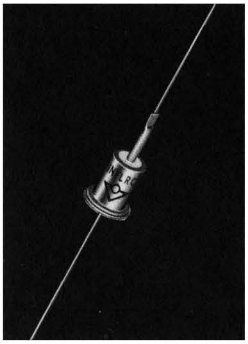
SCIENTIFIC INSTRUMENTS	Nuclear Monitor Systems	Regulators, Limiters	●				●	●	
	Magnetic Locators	Regulators	●						
	Water Purity Testers	Threshold Control							
	Medical Diagnostic Equipt.	M.S.C. Regulators	●	●	●	●	●	●	●
AUTOMATIC MACHINERY	Milling Machinery	References, Regulators	●	●	●	●			●
	Rolling Mills	References, Regulators		●	●	●			●
	Balancing Machines	References							●
	Coil Winders	References							●
	Surface Grinders	References							●
	Positioning Tables	References, Regulators	●	●					●
AIRCRAFT PARTS AND ACCESSORIES	Aircraft Insts.	Meter Protection	●	●					
	Prop. Controllers	Regulators	●	●	●	●			
	Aircraft Temp. Controls	Temp. Sensors	●						
	Fuel Controllers	Regulators	●	●					
	Brake Controllers	Regulators	●	●					
	Navigation Systems	Reference, Regulators	●	●	●				●
	Fire Control Systems	Misc. Reg., References	●	●	●	●	●	●	●
INDUSTRIAL CONTROLS	D.C. Adjustable Voltage Drives	Regulators, References	●	●	●	●			●
	Engine-Generators	Regulators			●	●			
	Alternator Exciters	Regulators		●	●	●			
	Auto Light Control	Regulators	●	●	●				
	Auto. Temp. Control	Temp. Sensors	●						
	Cont. Process Controls	References, Regulators	●	●	●	●	●		●
	Electronic Timers	Threshold Control	●	●					
	Frequency Reg.	References, Bias	●						●
	Furnace Control	Regulators, Temp. Sensors	●			●			
	Mag. Amplifiers	Reference, Regulators	●	●				●	●
	Servo Amplifiers	Bias, References	●	●					●
	Remote Solenoid Control	Regulators	●	●	●	●			
	Quality Control System	References							●
FOOD PROCESSING	Package Filling	Threshold Control	●	●					●
	Package Weighing	References							●
PRINTING TRADES MACHINERY	Auto Typesetters	Regulators	●	●	●	●			
	Paper Cutters	Regulators, References	●	●	●	●			●
SPECIAL INDUSTRY MACHINERY	Battery Chargers	Regulators			●	●	●		
	Elec. Welding	Limiters, Regulators		●	●	●	●		
	Mag. Clutches	Regulators	●	●	●	●			
	Electro-Plating	Regulators			●	●	●		

THE CONTENTS OF THIS ARTICLE AND CHART ORIGINALLY APPEARED IN THE OCTOBER, 1958 ISSUE OF ELECTRONIC INDUSTRIES.

Silicon Zener Voltage Regulator Diodes

International Rectifier's advanced line of Silicon Zener Diodes offer extreme stability and excellent voltage regulation characteristics at high temperatures (up to +165°C ambient). They are designed and process-selected to give exceptionally low dynamic resistance and sharp zener characteristics over the entire operating current range.

Miniature Style M: 750 milliwatts rated

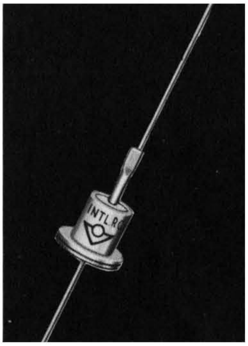


Ratings and Characteristics at 25°C Ambient

JETEC TYPE	INT'L TYPE	ZENER VOLTAGE RANGE	Iz MAX. ma.	DYNAMIC RESISTANCE		NOMINAL TEMP. COEFFICIENT %/°C
				Zz (OHMS)	@ Iz ma.	
1N1507	MZ 3.9	3.6-4.3	180	1.25	35	—.04
1N1508	MZ 4.7	4.3-5.1	150	1.25	30	0
1N1509	MZ 5.6	5.1-6.2	130	2	26	+.03
1N1510	MZ 6.8	6.2-7.5	110	2.5	22	+.05
1N1511	MZ 8.2	7.5-9.1	90	4	18	+.06
1N1512	MZ 10	9.1-11	75	6	15	+.07
1N1513	MZ 12	11-13	60	10	12	+.075
1N1514	MZ 15	13-16	50	20	10	+.08
1N1515	MZ 18	16-20	40	40	8	+.085
1N1516	MZ 22	20-24	33	60	6	+.09
1N1517	MZ 27	24-30	26	75	5	+.095

For more detailed engineering data, request Bulletin SR-251

Style S: 1 watt rated



Ratings and Characteristics at 25°C Ambient

JETEC TYPE	INT'L TYPE	ZENER VOLTAGE RANGE	Iz MAX. ma.	DYNAMIC RESISTANCE		NOMINAL TEMP. COEFFICIENT %/°C
				Zz (OHMS)	@ Iz ma.	
1N1518	1Z 3.9	3.6-4.3	250	1	50	—.04
1N1519	1Z 4.7	4.3-5.1	200	1	40	0
1N1520	1Z 5.6	5.1-6.2	175	1.5	35	+.03
1N1521	1Z 6.8	6.2-7.5	150	2	30	+.05
1N1522	1Z 8.2	7.5-9.1	120	3	25	+.06
1N1523	1Z 10	9.1-11	100	4.5	20	+.07
1N1524	1Z 12	11-13	80	7.5	15	+.075
1N1525	1Z 15	13-16	65	15	13	+.08
1N1526	1Z 18	16-20	55	30	10	+.085
1N1527	1Z 22	20-24	45	45	9	+.09
1N1528	1Z 27	24-30	35	60	7	+.095

For more detailed engineering data, request Bulletin SR-251

Style T-3.5 watt rated

Ratings and typical characteristics

JETEC TYPE	INT'L TYPE	ZENER VOLTAGE RANGE	Iz MAX. ma.	DYNAMIC RESISTANCE		NOMINAL TEMP. COEFFICIENT %/°C
				Zz (OHMS)	@ Iz ma.	
IN1588	3Z 3.9	3.6-4.3	850	.5	150	—.04
IN1589	3Z 4.7	4.3-5.1	700	.5	125	0
IN1590	3Z 5.6	5.1-6.2	625	.75	110	+.03
IN1591	3Z 6.8	6.2-7.5	525	1	100	+.05
IN1592	3Z 8.2	7.5-9.1	425	1.5	80	+.06
IN1593	3Z 10	9.1-11	350	2.5	70	+.07
IN1594	3Z 12	11-13	275	4	50	+.075
IN1595	3Z 15	13-16	225	7.5	40	+.08
IN1596	3Z 18	16-20	200	15	35	+.085
IN1597	3Z 22	20-24	160	22.5	30	+.09
IN1598	3Z 27	24-30	125	30	25	+.095

For more detailed engineering data, request Bulletin SR-252

Silicon Zener Voltage Regulators

Style T-10 watt rated

Ratings and typical characteristics

JETEC TYPE	INT'L TYPE	ZENER VOLTAGE RANGE	Iz MAX. ma.	DYNAMIC RESISTANCE		NOMINAL TEMP. COEFFICIENT %/°C
				Zz (OHMS)	@ Iz ma.	
IN1599	10Z 3.9	3.6-4.3	2500	.25	500	—.04
IN1600	10Z 4.7	4.3-5.1	2000	.25	400	0
IN1601	10Z 5.6	5.1-6.2	1750	.4	350	+.03
IN1602	10Z 6.8	6.2-7.5	1500	.5	300	+.05
IN1603	10Z 8.2	7.5-9.1	1200	.75	250	+.06
IN1604	10Z 10	9.1-11	1000	1.25	200	+.07
IN1605	10Z 12	11-13	850	2	170	+.075
IN1606	10Z 15	13-16	650	4	140	+.08
IN1607	10Z 18	16-20	550	7.5	110	+.085
IN1608	10Z 22	20-24	450	12	90	+.09
IN1609	10Z 27	24-30	350	15	70	+.095

For more detailed engineering data, request Bulletin SR-252

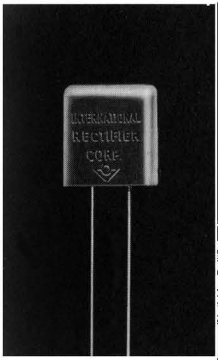
Style HZ: 5 watt rated

Ratings and characteristics at 25°C case temperature

INT'L TYPE	ZENER VOLTAGE RANGE	Iz MAX. ma.	DYNAMIC RESISTANCE		NOMINAL TEMP. COEFFICIENT %/°C
			Zz (OHMS)	@ Iz ma.	
HZ 27	24-30	200	7	40	0
HZ 33	30-36	150	10	30	+0.03
HZ 47	43-51	110	20	22	+0.05
HZ 68	62-75	75	60	14	+0.065
HZ 100	91-110	50	180	10	+0.08
HZ 150	130-160	35	370	7	+0.09

For more detailed engineering data, request Bulletin SR-253

600 MW Rated Type Double Anode



Ratings and Electrical Characteristics at 25°C Ambient

INT'L TYPE	ZENER VOLTAGE RANGE	Iz MAX. ma.	DYNAMIC RESISTANCE		NOMINAL TEMP. COEFFICIENT % /°C
			Zz (OHMS)	@ Iz ma. DC	
ZZ 4.7	4.3-5.1	125	5	25	—.01
ZZ 5.6	5.1-6.2	100	7	20	0
ZZ 6.8	6.2-7.5	80	10	16	+.025
ZZ 8.2	7.5-9.1	70	14	14	+.035
ZZ 10	9.1-11	60	20	12	+.05
ZZ 12	11-13	50	27	10	+.06
ZZ 15	13-16	40	42	8	+.07
ZZ 18	16-20	30	75	6	+.08
ZZ 22	20-24	25	105	5	+.09
ZZ 27	24-30	20	140	4	+.095

For more detailed engineering data, request Bulletin SR-254

Typical of the many configurations International Rectifier offers in standard selenium photocells. Custom cells to any specifications are also available.

Selenium Photoelectric Cells and Sun Batteries

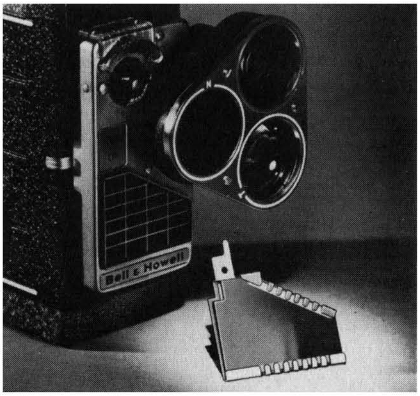
by John Sasuga
International Rectifier Corporation
Manager Photocell Division

Today, three main classes of photoelectric cells are in general use. They are the photoemissive, photoconductive and the photovoltaic or self-generating types. The first of these, the photoemissive type has been the most widely used. Its high impedance has made it most readily adaptable for coupling with the input of vacuum tube amplifiers. Being a vacuum tube itself, it has fitted in with the mass volume production techniques using automatic machinery that has already produced many millions of vacuum tubes at low manufacturing cost. The second of these, the photoconductive cell, is a semiconductor device whose electrical conductivity is a function of the incident illumination. It may be manufactured in compact size and is useful in such specialized applications as those requiring a high infrared sensitivity.

Unlike the other two classes of photoelectric cells, the photovoltaic type, as exemplified by the International photocell, has the characteristic of generating a voltage (up to .58 volt) when light impinges upon its sensitive surface. This self-generated voltage will cause a current to flow in an externally connected circuit; the magnitude of this current is a function of the external circuit resistance and the illumination from the incident light. This type of photocell therefore may be regarded as a primary source of electric power, as much so as an electric galvanic type battery.

The selenium self-generating photocell is a very sensitive and reliable photoelement that offers versatile applications in the infra-red, visible, and ultraviolet spectral range. In the past, the primary application of selenium photocells was in photometric equipment and light measuring devices such as spectral photometers, colorimeters, and photographic light meters. With the advent of automation, and the availability of transistors, many new applications for selenium photocells have evolved; typical examples are in control and safety devices, counters, tape reading mechanisms, and monitoring equipment.

With a response faster than the human eye, an International Rectifier selenium photocell reacts to changing light levels and sets the lens opening on an automatic 8 mm motion picture camera manufactured by Bell and Howell Company. No batteries, motors or springs are required in the operation, said to be the first commercial use of direct light energy in performing a mechanical task without intermediate conversion.



International Rectifier Selenium Photocell activates Bell and Howell "Electric Eye" exposure mechanism in 8 mm movie camera.

Cell Structure and Operation

The metallic structure of the International Rectifier selenium photocell is shown in Fig. 1. It consists of a metal base plate on which are deposited multiple coats of selenium compounds and precious metals. The front electrode and barrier layer are of molecular thickness. The selenium layer is 0.002″ to 0.003″ thick.

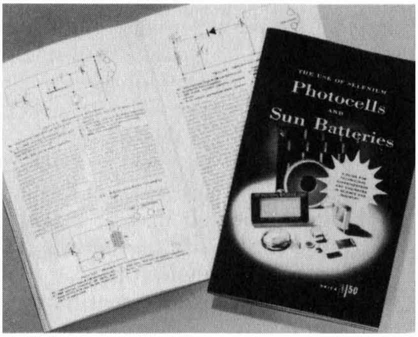
The completed cell is coated with a thermosetting protective resin which provides an extremely rugged, shatterproof finish that is immune to shock and vibration.

Light falling on the cell penetrates the transparent front electrode and causes the selenium to release electrons which travel across the "barrier layer". These electrons are trapped on the front electrode to form a negative charge. They are prevented from returning (except by some small leakage), by the unilateral conductivity of the barrier layer. The collector ring is then the negative and the base plate the positive terminal of the cell.

When these two terminals are connected directly to the actuating device or to an amplifier, a current will flow.

For over ten years, International Rectifier Corporation has been a leading supplier of selenium photocells to the industries of America. During this time, a wealth of data has been developed to assist engineers in the application of these devices to control and measuring instruments. If you require technical assistance in the application of photocells, do not hesitate to call upon our experienced engineering staff. Just completed is an 8-page brochure providing complete technical information and listings on all International Rectifier Photovoltaic devices. Copies may be obtained by writing to International Rectifier Corporation, El Segundo, California on your letterhead. Ask for Bulletin PC-649A.

For those wishing information and actual circuitry involving the use of photocells in radios, relay circuits and many other light powered devices, an 84 page booklet entitled "The Use of Selenium Photocells and Sun Batteries" has been prepared and is available either from your local electronics distributor or by writing directly to the factory. Price: $1.50.



84 page Application Handbook contains theory and circuitry for light powered devices.

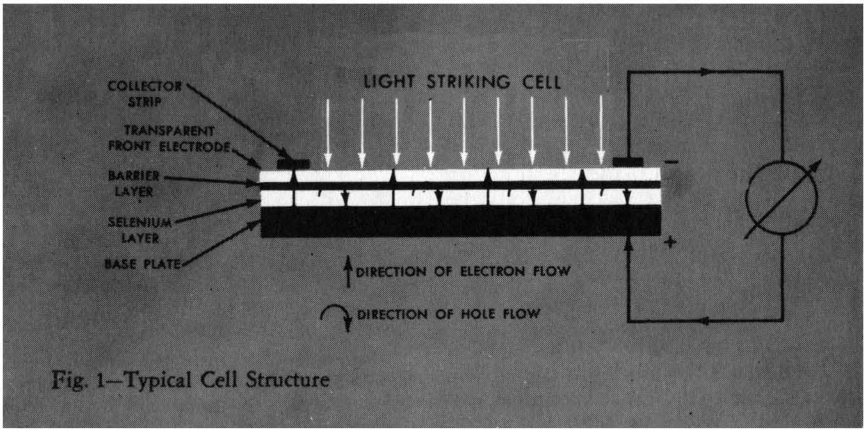


Fig. 1—Typical Cell Structure

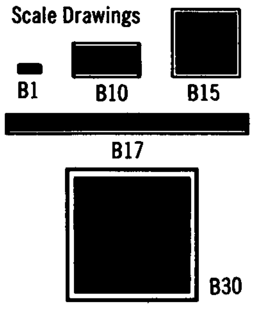
INTERNATIONAL SELENIUM SELF-GENERATING PHOTOELECTRIC CELLS

PHOTOELECTRIC CELL...RATINGS	
Maximum Operating Temperature:	Continuous duty .... 85°C Intermittent duty ....100°C
Spectral Response:	Overall response ....220 to 780 millimicrons Response peak ....550 millimicrons
Speed of Response:	The response of these cells is limited only by their shunt capacitance, and therefore decreases with increasing frequency and load resistance. For optimum frequency response in the range of 1000-10,000 cycles per sec. small area photocells are recommended.
Fatigue:	No measurable aging or irreversible fatigue at illumination levels up to 1000 foot candles.
Life:	The life of these cells is practically unlimited when operating under normal conditions, and within their ratings.

PHOTOELECTRIC CELL...ELECTRICAL CHARACTERISTICS	
Standard electrical characteristics and performance data are measured at ambient temperatures of 25°C using a tungsten lamp source at 2700 K.	
Output Voltage:	The self-generated open circuit voltage of International selenium photocells varies approximately logarithmically with illumination, and approaches a maximum value of 0.6 volts at high light intensities. The output voltage across a load is a function of illumination and load resistance, and is independent of cell area.
Output Current:	The self-generated short circuit current of the International selenium photocell is nominally 3.5 ma. per square inch of active cell area at 1000 footcandles illumination; it is a linear function of illumination intensity over the range from 0 to 1000 foot candles. The output current into a load is a function of load resistance, photosensitive cell area, and illumination intensity.
Matching:	Standard match specification–two or more cells may be matched to within ±5% over the range of 0-100 foot candles, and for any load resistance from 0-10,000 ohms. Special match specifications–cells may be matched for special requirements and applications to a minimum tolerance of ±2%.
Visibility Corrections Filters:	Mounted Photocells are available with visual correction filters to correct the photocell response to that of the human eye. The transmission factor of such a filter is in the order of 50%.

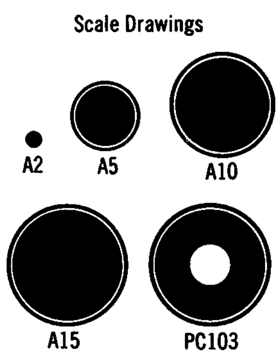
INTERNATIONAL STANDARD UNMOUNTED PHOTOCELLS

RECTANGULAR TYPES



Cell Type	Overall Dimensions length inches	width inches	thickness inches	Typical Photosensitive Area inches²	Output Current 100fc 100 ohms microamperes
B1	0.59	0.24	0.047	0.12	32
B2	0.72	0.44	0.021	0.26	77
B4	0.88	0.54	0.047	0.39	120
B5	1.44	0.64	0.047	0.78	250
B10	1.69	0.88	0.058	1.26	380
B15	1.69	1.69	0.058	2.25	640
B17	6.0	0.50	0.021	2.6	710
B20	2.0	2.0	0.021	3.3	900
B30	3.25	3.25	0.021	9.41	2200

ROUND TYPES



Cell Type	Overall Dimensions diameter inches	thickness inches	Photosensitive Area inches²	Output Current 100fc 100 ohms microamperes
A2	0.25	0.047	0.045	12
A3	0.38	0.047	0.06	20
A5	1.13	0.047	0.78	250
A7	1.50	0.058	1.40	440
A10	1.75	0.058	2.04	600
A15	2.0	0.058	2.58	770
A 30	2.75	0.058	5.10	1400
PC103	O.D. 2.0 I.D. 0.69	0.058	2.20	600

UNMOUNTED CELLS — These cells are offered for convenience of mounting in a user's installation where spring contacts for cell terminals are provided.

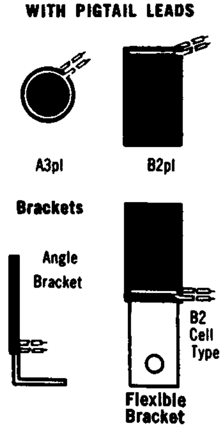
PIGTAIL LEAD CELLS — All unmounted cells are available with pigtail leads attached to the contacts. This mounting is designed to provide "positive contact" connection to the cell terminals. The pigtail leads are not pressure sensitive nor subject to intermittency. To order Pigtail Lead Types, add the suffix "PL" to the basic part number. For example: A3PL, B2PL.

These "pigtail contact" cells are also available with a flexible bracket to permit adjustment of the cell surface to any desired angle. This bracket is attached to the base plate for mounting to chassis. Specifications for other bracket-mounted cell sizes available on request.

MATCHED CELLS — On request, two or more cells may be matched to within ±5% over the range of 0 to 100 footcandles for a specified load resistance, and to ±2% over the range of 0 to 100 footcandles for a specified load resistance.

SPECIAL CELL SELECTION — Photocells used for transistor biasing must be selected to give optimum performance in this application. This selection may be requested by adding the suffix "T" to the cell type number. For example: B2PLT.

WITH PIGTAIL LEADS



INTERNATIONAL SELENIUM SELF GENERATING MOUNTED PHOTOCELLS

HERMETICALLY SEALED PHOTOCELLS

Hermetically sealed photocells are protected against humidity, corrosive atmospheres, and salt spray. These cells are especially suitable for outdoor applications, where protection from corrosion is required, and may be immersed in non-corrosive liquids.

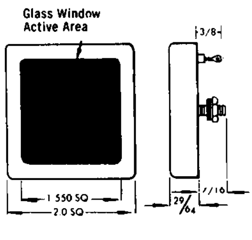


FIG. 1

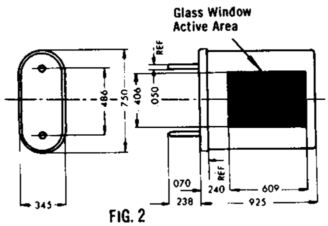


FIG. 2

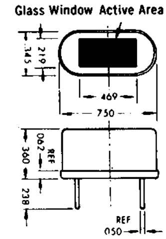


FIG. 3

All Dimensions in Inches

Hermetic Sealed Cell Type	fig	Photosensitive Area inches²	Typical Output Current			Typical Output Voltage	
			100fc 100 ohms microamps	100fc 1000 ohms microamps	1fc 10,000 ohms microamps	100fc RL=1 Megohm volts	1fc RL=100,000 ohms millivolts
DP-5	1	2.25	600	250	3.5	0.30	75
DP-3	2	0.21	66	60	0.6	0.26	34
DP-2	3	0.088	24	20	0.16	0.22	9

MOUNTED PHOTOCELLS IN PLASTIC HOUSINGS

The cells are mounted in a black phenolic or butyrate housing with glass or plastic window. The mounting studs protruding at the rear of the housing also serve as the electrical output terminals.

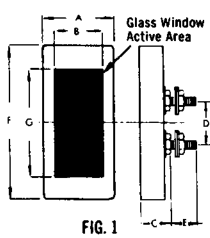


FIG. 1

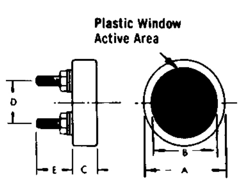


FIG. 2

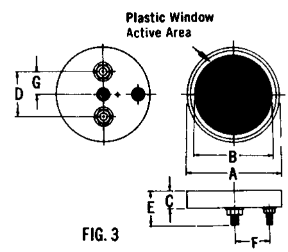


FIG. 3

All Dimensions in Inches

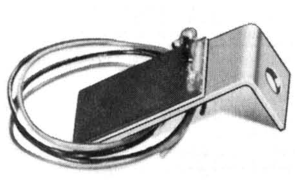
Mounted Cell Type	fig	Dimensions							Typical Output Current			Typical Output Voltage	
		A	B	C	D	E	F	G	100fc 100 ohms microamps	100fc 1000 ohms microamps	1fc 10,000 ohms microamps	100fc 1 Megohm volts	1fc 100,000 ohms millivolts
B10-M	1	1.1	0.7	0.4	0.6	0.3	2.2	2.2	320	210	2.0	0.30	65
A5-M	2	1.2	1.1	0.3	0.6	0.4			220	160	1.5	0.30	60
A7-M	2	1.7	1.4	0.3	0.6	0.4			350	200	2.9	0.31	60
A10-M	2	1.9	1.7	0.3	0.6	0.4			550	240	3.4	0.30	70
A15-M	3	2.1	1.9	0.3	1.0	0.4	0.8	0.5	700	250	3.5	0.31	70

CONTOUR PHOTOCELLS

For applications requiring photocell surfaces in curved, cylindrical or other three-dimensional shapes, "Contour Photocells" are available in the same rectangular dimensions as standard cell types. These cells can be produced to your requirements in three-dimensional shapes with a minimum of 1 inch radius of curvature. A typical application for the units – mounting on a rotating shaft in a position control servo-mechanism. (The current sensitivity of these cells is slightly lower than for standard cell types.)

Very High Current Sensitivity Cells

These selenium photocells offer output current sensitivity 20% higher than for standard cell types. For optimum stability and long life, these cells should not exceed an operating temperature of 60°C.



B2M Sun Battery

Highly popular for experimental use, the B2M selenium photocell and sun battery will generate a current of 2 ma with a 10 ohm load in bright sunlight. These cells may be mounted in series or series-parallel arrangements to convert solar energy into a high power supply for operation of transistorized equipment and portable devices. The mounting bracket is flexible to permit adjustment of the sensitive surface to any desired angle. See the "B2 cell" in the table for additional specifications.

Silicon Solar Cells

by Harry Nash, BEE
International Rectifier Corporation
Member IRE, Assn. for Applied Solar Energy

The silicon solar cells now available from International Rectifier Corporation are practical photovoltaic devices capable of converting radiant or solar energy into electrical power of useful proportions.

Tapping a Resource

When the magnitude of the energy showered upon the earth by the sun each second is considered, it is not surprising that the harnessing of this vast resource has been a constant challenge to man through the centuries.

Although several methods of utilizing solar energy have been in use for many years, with varying degrees of success, the method considered most practical today involves the direct conversion of solar radiation into electrical energy by thermoelectric or photoelectric effects. During the past few years this science has attracted widespread interest, particularly in the branch of science dealing with photovoltaic phenomena. About 1876 the first barrier layer photovoltaic cell was developed, utilizing selenium. Through the development of collateral electrical and electronic technology, the selenium photoelectric cell gained wide application. Recent research in the semiconductor field contributed much basic knowledge which, when applied to the photovoltaic principle, resulted in silicon photocells with efficiency factors far greater than those of selenium forerunner.[1]

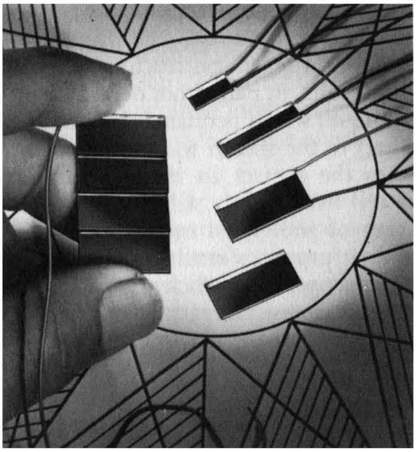


Fig. 1. Ruggedized Silicon Solar Cells designed for high efficiency solar energy conversion.

The Silicon Cell

The International silicon solar cell is of the *p-n* junction type. This *p-n* junction is formed on the surface of the silicon wafer to be exposed to illumination. The junction is composed of two types of semiconductors—the *n*-type and the *p*-type. The *n*-type material is obtained by adding certain impurities to the melt at crystal growing stage. The *p-n* junction is formed when impurities of another type are diffused into the *n*-type silicon wafer.

A cross-section of a silicon solar cell would show the *p*-type and *n*-type silicon to be separated by an extremely thin barrier layer which becomes a built-in, permanent electric field. The movement and displacement of electrons and holes that occurs when light is absorbed by a silicon crystal and the subsequent phenomena that take place at the *p-n* junction cause a voltage difference between the silicon layers of the cell, thus causing an electric current to flow.[2]

Silicon Solar Cell Types

Typical of the silicon solar cells manufactured by International Rectifier are those shown in Figure 1.

This new series of ruggedized silicon photovoltaic cells features extremely high efficiencies, and are capable of converting up to 9% of the radiant energy falling on their surface.

Designed and manufactured to rigorous military specifications, the high efficiency and rugged construction of these units results, in part, from new alloying techniques which permanently bond the contact to the silicon wafer. This bond makes the contact an integral part of the cell itself, while still allowing soldering of individual cells. These new bonding processes result in substantial gains in operating efficiency and minimize series resistance.

Complete engineering data on these cells is contained in Bulletin SR-275A, available on request.

Silicon Solar Cell Modules

To provide engineers with prepackaged solar cells in configurations easily adapted to solar battery requirements, International Rectifier now offers cells in modular forms. See Figure 2.

These silicon solar modules are basic building blocks designed for interconnection in series-parallel configurations to supply from milliwatts up to hundreds of watts of power for a wide variety of power applications. A typical installation can supply a charging current of from 25 ma to greater than 1 amp into a 12-volt nickel cadmium battery in bright sunlight.

Mechanical Construction

Modules are assemblies of series-connected 1 cm × 2 cm silicon solar cells. The cells are embedded in epoxy resin providing a rugged, shockproof, weatherproof housing. Insulated solder terminals for electrical connection extend from the bottom of the module case. For complete data, write for Bulletin SR-276.

REFERENCES

1 D. M. Chapin, C. S. Fuller and G. L. Pearson, *J. Appl. Phys.* 25, 676 (1954); *Bell Record* 33, 241 (1955).

2 C. S. Fuller and J. A. Ditzenberger, *J. Appl. Phys.* 25, 1439 (1954).

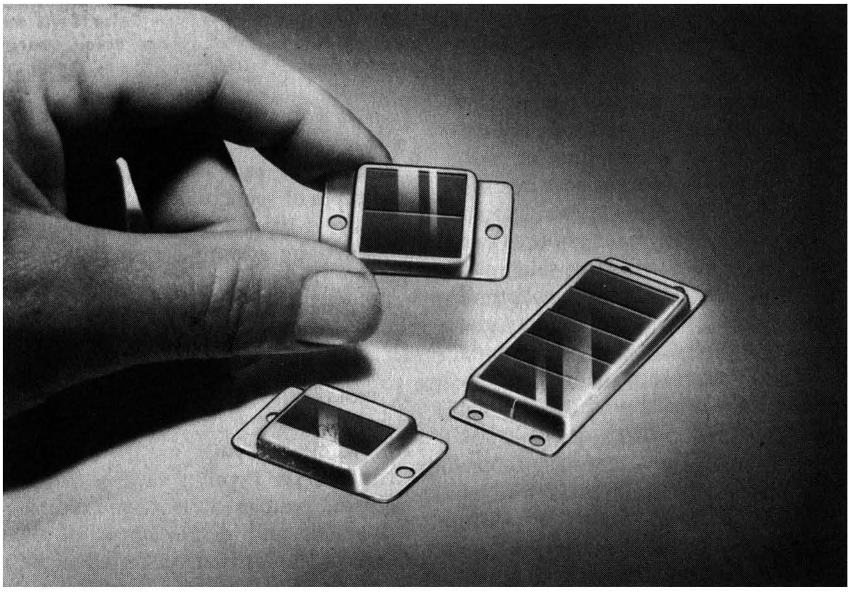


Fig. 2. Silicon Solar Cell modules designed for interconnection to supply any desired power rating.

The Influence of Temperature on Silicon Solar Battery Output

by Werner Luft, BME
International Rectifier Corporation

The power output and the voltage at which this power is supplied is the most important consideration in the application of silicon solar batteries.

When a solar cell is operated at a determined light intensity, the output power can vary from zero to a given maximum. (This maximum value depends on the active cell area and the efficiency of the cell). Within these limits the magnitude of output power depends upon the load resistance connected to the cell, as shown in Fig. 1.

It is, of course, desirable to operate the solar battery at its maximum power output; consequently the load resistance must be matched to this effect. Under identical conditions the load resistance for maximum power output increases with decreasing active cell area.

Limiting the discussion to a cell of given efficiency and active area, operating at a given light intensity, we will only discuss the influence of the cell temperature on the output.

Fig. 2 illustrates the variation in the current-voltage characteristic with temperature. The short circuit current changes but slightly, and increases first somewhat with increasing temperature, to decrease again at still higher temperatures.The open circuit voltage, however, decreases rapidly with increased temperature (approximately 2.25 x 10^{3}-V/°C in figure 2.).

The points for maximum power output on the current-voltage curves are connected by the dashed line. It is seen that the load resistance must be reduced when the temperature increases in order to operate the solar cell at the maximum power point.

Furthermore, the figure illustrates that within normal operation temperatures for earthbound applications (25 to 70°C) the output current is nearly constant along the maximum power line. The voltage at which this current is delivered decreases, however, at increased temperatures, and so does the maximum power output.

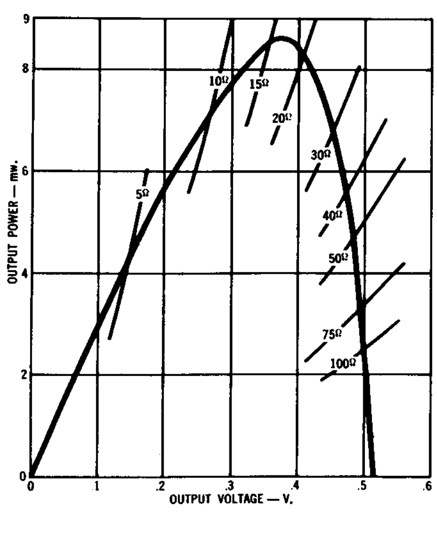


Fig. 1.

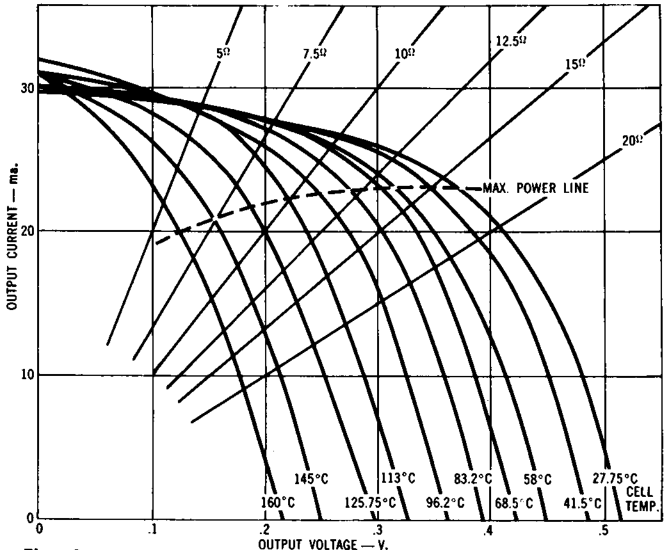


Fig. 2.

In Fig. 3 a comparison is made between the relative change with temperature of the maximum power output, the voltage at which the maximum power is obtained, and the open circuit voltage. A cell temperature of 30°C is taken as reference point.

Above 70°C cell temperature the negative temperature coefficient of the absolute change of the three variables is constant.

The absolute magnitude of the temperature coefficient is lowest for the open circuit voltage; highest for the maximum power output.

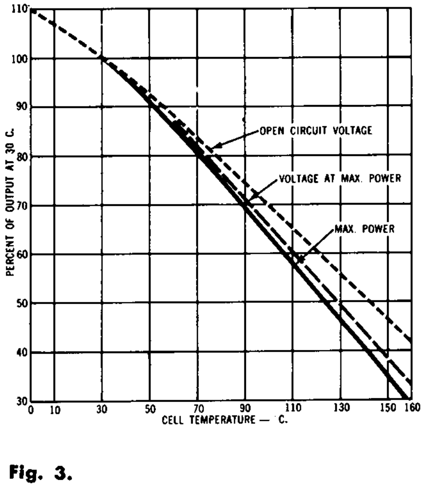


Fig. 3.

Below 70°C the negative temperature coefficient varies and becomes zero at approximately −20°C. Below this temperature the temperature coefficient is positive.

The temperature coefficients will vary somewhat from solar cell to solar cell. The relation between the temperature coefficients of the mentioned three variables will, however, remain approximately the same for any one cell, at least in the region of normal operation temperatures. Therefore the variation in open circuit voltage with temperature (which can easily be measured) can be used to predict the maximum power output and corresponding voltage at any temperature within the normal operating range if the latter are known for a certain temperature.

From Fig. 3 we see that the maximum power output decreases roughly 10% for each 20°C rise in cell temperature. It is, therefore, of considerable interest to the designer of solar battery assemblies to provide adequate cooling for the cells wherever possible. If heat sinks are used for this purpose, efforts must be made to keep the thermal impedance from cell to heat sink to a low value. Direct metallic contact from cell to sink is desirable, but unfortunately not always possible.

For further information on any of the International Rectifier Corporation products listed in this book, write directly to the factory or contact the branch office nearest you. All standard items listed are also carried in stock by International Rectifier Corporation Authorized Industrial Distributors located throughout the United States.

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FOREIGN BRANCH OFFICES:

SWITZERLAND: International Rectifier Corp. 23 Rue du Rhone, Geneva, Switzerland

FOREIGN ASSOCIATES:

ENGLAND: International Rectifier Co. (Great Britain) Ltd., Hurst Green, Oxted, Surrey.

FRANCE: CERAME, 142 Avenue Victor Hugo, Clamart (Seine)

JAPAN: International Rectifier Corp. (Japan) Ltd., 14, 1-Chome, Yuraku-Cho, Chiyoda-Ku, Tokyo

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