APPLICATION NOTES
ON GENERAL ELECTRIC
VAC-U-SEL® RECTIFIERS

ECG-402

SEMICONDUCTOR PRODUCTS DEPARTMENT
GENERAL ELECTRIC COMPANY

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I. BASIC INFORMATION

Semiconductor Junction Rectifiers

A semiconductor, if it were ideal, would only allow current to flow through it in one direction. However, since the rectifying devices being considered here inherently have some losses, the ideal characteristic is only approached.

Basically, a rectifier to be of any practical use must conduct a current substantially greater in one direction than in the other The ratio, therefore, of the reverse resistance of the rectifier to its forward resistance must be high

With progress in the art of manufacture of semiconductors and the introduction of new semiconductor materials, characteristics are more closely approaching the ideal

Junction or "barrier layer" rectifiers such as copper oxide, selenium, germanium and silicon exhibit non-linear resistance characteristics The equivalent circuit of a rectifier cell may be shown to consist of a rectifying junction in series with a fixed resistance The voltage drop across the junction varies logarithmically with the current and the drop across the resistor linearly with the current. The ratio of fixed resistance to the non-linear junction resistance is such that at low current densities the voltage - current characteristic is non-linear and a function of the junction resistance At higher current densities the fixed resistance overshadows the resistance of the junction and the voltage drop across the rectifier is proportional to the first power of current.

The characteristics of the junction and the value of fixed resistance (more commonly known as bulk resistance) vary with methods of processing and are different for cells of different manufacture The basic theory of rectification, however, applies to all.

Rectifier loads are generally cataloged as resistive, capacitive, or inductive In actual practice it seldom, if ever, occurs that the load is composed of pure resistance, capacitance, or inductance The usual load may contain two or all three of these elements The treatment depends on which one predominates

Capacitive Loading

When the load contains a small capacitive component with respect to the load resistance, it may be treated as "resistive loading" without appreciable error in calculations for current and voltage output of the rectifier.

If, however, the capacitance is large with respect to resistance, then special treatment is indicated. This brings up the question as to how large is "large" The best measure in this case is the "RC' or time constant of the load.

RC equals the load resistance in ohms times the capacitance in farads (If the capacitance is given in microfarads, multiply by 10^{-6} to get value in farads) Load resistance can be determined by simply dividing d-c load voltage by d-c load current.

On a 60-cycle circuit, if the RC of the load is less than 001, the capacitive component may be ignored. Larger than this, it begins to affect the d-c to a-c conversion factor (Fig 4), and also affects the current rating of the rectifier due to increased heating

Purposes of Capacitance in Load

If the load contains a large proportion of capacitance, it is usually there for a purpose The purpose may be (1) Boosting the output d-c voltage with respect to the a-c input voltage, (2) To preserve voltage regulation during high momentary current overloads, (3) Filtering, that is, smoothing out the ripple in the d-c output of the rectifier

Boosting Output Voltage

Operating from a sinusoidal a-c supply, the output voltage of a rectifier is uni-directional but pulsating, each pulse being sinusoidal in shape. If this output wave is measured with a d-c voltmeter, the reading will be the average of all the instantaneous values of voltage that occur over a period of one cycle

For instance, in a single-phase full-wave circuit, the average will be 636 x E max. But, the a-c (root-mean-square) value is 707 x E max. Hence, the d-c value is 9 x a-c value In other words, if there were no losses in the rectifier, the d-c output voltage would be nine-tenths of the a-c input voltage to the rectifier in the case of single-phase, full-wave (Similar factors are derived for other rectifier circuits).

If a capacitor is connected across the rectifier output, current will flow into the capacitor until its voltage approaches E max., the peak of the input wave The d-c output voltage is now (theoretically) 1 41 times the a-c input voltage When the capacitor is completely charged, current ceases to flow from the rectifier unless a load is applied across the capacitor to discharge it.

When a load is applied, the voltage of the capacitor falls exponentially until it equals the instantaneous voltage of the rectifier as it rises during the next half cycle Then the rectifier recharges the capacitor. The d-c voltage output wave is now "saw-tooth ' in shape.

The depth of the "teeth" depends on the relationship between the amount of capacitance and the load resistance, i e., the "RC" of the load.

If the capacitor is large, its voltage will drop only a small amount during the interval between peaks and the average voltage will be close to E max. If the RC is low (due to the capacitor being too small or the load too heavy), then the capacitor voltage will drop considerably during the interval between peaks and the average voltage will be low relative to E max.

For a given value of load resistance, it will be seen that the size of the capacitor will depend on the length of the time interval between successive pulses in the rectifier output. This, in turn, is dependent on the ripple frequency which is the fundamental frequency of the a-c supply multiplied by a factor for the particular rectifier circuit. These factors are -

Rectifier Circuit Factor

Circuit	Factor
Single-phase, half-wave	1
Single-phase, full-wave	2
Two-phase, full-wave	4
Three-phase, half-wave	3
Three-phase, full-wave	6
Six-phase star	6

Thus, a single-phase, full-wave rectifier operating from a 60-cycle a-c source would have a ripple frequency of 120 cycles per second The time interval between peaks would be $\frac{1}{120} = .0083$ sec Now, if the supply source were 30 cycles instead of 60 cycles, the time interval would be doubled and the capacitor would have to be twice as big to do the same job Likewise, if we went to a half-wave rectifier instead of full-wave, the time interval would be doubled and the capacitance would have to be increased accordingly

In practice, it is never possible to obtain the maximum theoretical output voltage of 1.41 times the applied a-c voltage, due to a slight voltage drop caused by leakage current in the rectifier and also in the capacitor Under no-load conditions, it is possible to obtain a d-c output voltage 1 35 times the a-c input voltage. Under load, the output voltage depends on the combined regulations of the rectifier and the capacitor

The curves in Fig (4) show the multiplying factors for various values of RC when the a-c input is 60-cycles Two scales of RC are shown on the abscissa, one for single-phase, half-wave, and one for full-wave

The values of "Conversion Factor" shown on the ordinate are the values by which the d-c output voltage may be multiplied to determine the a-c input voltage (To this must be added the r m s voltage drop in the rectifier to obtain total a-c input volts See explanation in rectifier application manual, ECG-344)

It will be noted that as C approaches zero, the value of RC must also approach zero, at which point, the conversion factors are the same as for resistive loading, namely, 1 125 for full-wave and 2 25 for half-wave

We now see that by adding capacitance to the load we can boost the d-c voltage output without changing the a-c input voltage. There are many instances where this is advantageous Probably the most frequent use is in radio and TV applications Here the normal 117-volt a-c supply may be boosted to 130 - 135 volts d-c with a simple, half-wave rectifier and capacitor or by using any of the various "doubler" circuits, 260 to 270 volts d. c may be obtained from a 117-volt, a-c line, thus avoiding the cost of a transformer

The scheme is also applicable in many industrial applications such as operating standard 115-volt d-c relays directly from the a-c line without a transformer

Of course, we don't get this extra power output "for nothing" The rectifier delivers current to the capacitor only during the short intervals when the rectifier voltage is higher than the capacitor voltage This results in a current wave consisting of short pulses with high peaks For this type of wave shape, the r m s value of the current is high compared to the d-c average It is the r m s value that determines the power input to the rectifier Also the r. m. s value determines the heating in the rectifier Hence, for capacitive loading the rectifier must be derated in current as compared to the current rating based on resistive loading.

Effect of Capacitance on Voltage Regulation

Generally speaking, under conditions of continuous load, voltage regulation is poorer with capacitive loading than with resistive loading As the capacitor must supply current to the load during a portion of every cycle, the regulation of the capacitor is added to the regulation of the rectifier

However, there are some applications such as computers and various types of business machines where in addition to a steady load within limits of the rectifier rating there may also be occasional momentary loads of very short duration, but of a magnitude in the order of 10 to 20 times the normal rating of the rectifier As this approaches the short-circuit current of the rectifier, it is obvious that the voltage output would drop to zero during the interval of the high momentary current To avoid this difficulty, it is customary to connect a very high value of capacitance across the output. This may be in the order of thousands of micro-farads Because the peak current pulses are of such short duration, they can be drawn from the capacitor with very little drop in voltage, thus preserving the voltage of the system and preventing any malfunction of other components in the system The capacitor in this case simply acts as a reservoir to store power which may be delivered in large chunks over a short period of time and subsequently replaced by the rectifier over a longer period of time.

Filters

By far the most common reason for using capacitors with rectifiers is for filtering, i e., smoothing out the ripple in the rectifier d-c output

All rectifiers have an inherent ripple in the d-c output. The magnitude of this ripple depends on the circuitry of the particular rectifier For instance, it should be obvious that in a half-wave, single-phase rectifier, the ripple component is very large whereas in a three-phase, full-wave rectifier, the voltage never falls below 86% of peak so the ripple component is small.

A I.E.E. defines ripple voltage as "the alternating component of a substantially uni-directional voltage". Ripple may be expressed as a decimal factor but is more often expressed as a percent. A I.E.E defines Percent Ripple Voltage as "the ratio in percent of the effective (root-mean-square) value of the ripple voltage in the pulsating voltage to the average value of the pulsating voltage".

If we measure the output voltage of a rectifier with a d-c voltmeter, we determine the average voltage. If we measure with an a-c voltmeter, we determine the root-mean-square value of the pulsating voltage, which will be a higher value than the average. For rectifiers having a large ripple component in the output voltage, the ratio of root-mean-square to average is large As the ripple becomes reduced by suitable filters, this ratio decreases and becomes unity when the output is pure d-c with no pulsations

The ratio of the root-mean-square value of output voltage to the average value is defined by A.I.E.E. as the "D-C Form Factor". This is a handy figure to know because, as will be shown, it bears a direct relationship to the amount of ripple in the d-c output

The ripple voltage in percent is given by the formula. -

$$\text{Ripple Voltage Percent} = \frac{Er}{Ed} \times 100$$

where Er is the r m.s. value of the ripple voltage and Ed is the d-c value of output voltage The r.m s. value of the ripple voltage may be measured by various means such as an a-c voltmeter with a capacitor connected in series to hold back the d-c component. It may also be readily calculated from the formula. -

$$Er = \sqrt{Erms^2 - Ed^2}$$

Now we can re-write the formula for ripple as -

$$\text{Ripple Voltage Percent} = \frac{\sqrt{Erms^2 - Ed^2}}{Ed} \times 100$$

$$= \sqrt{\frac{Erms^2}{Ed^2} - 1} \times 100$$

We previously defined the value $\frac{Erms}{Ed}$ as D-c Form Factor so we may express the formula as -

$$\text{Ripple Voltage Percent} - \sqrt{\text{Form Factor}^2 - 1} \times 100$$

In practical applications, the root-mean-square (r m s) value of output voltage and the d-c value may be measured easily and Form Factor determined. The percent ripple may then be calculated from the formula.

Theoretical values of Form Factor for various types of rectifiers operating on sinusoidal a-c may be calculated mathematically, and the theoretical ripple values determined. The following table gives these values for various standard rectifier circuits -

	Ed	Erms	Form Factor	Ripple Percent
Single-phase, half-wave	318xE max.	500xE max.	1 57	121 0
Single-phase, full-wave	636xE max.	707xE max.	1 11	48.3
Two-phase, full-wave	901xE max.	905xE max.	1 005	10 0
Three-phase, half-wave	827xE max.	842xE max.	1 017	18.4
Three-phase, full-wave	955xE max.	956xE max.	1 0009	4 2
Three-phase Star	955xE max.	.956xE max.	1 0009	4.2

It will be seen from the table that the ripple is less for full-wave rectification than for half-wave, and less for poly-phase than for single-phase If ripple is a problem in a particular application, it is desirable to choose a rectifier circuit having minimum inherent ripple However, in many cases the a-c supply is single-phase making filtering necessary if a low value of ripple is required.

There are literally hundreds of different filter circuits and networks used in electronics, but the ones generally employed with metallic rectifiers are simple circuits involving capacitance alone, inductance alone, or a combination of the two

If the first element of a filter circuit is a capacitor, it is generally referred to as a "capacitor input" filter Capacitors are generally used in applications of relatively high voltage and low currents Also where it is desirable to boost the output voltage as well as to filter it.

Where relatively high rectifier current outputs are involved, the size and cost of capacitors for filtering may become prohibitive and inductance is resorted to

A very common type of filter consists of an inductance in series with the d. c followed by a capacitor, generally referred to as a "choke input" filter Such a filter does not have the advantage of boosting the d-c voltage, but its output regulation is much better than that of the capacitor input type of filter

When rectifiers are used for charging telephone batteries, it is customary to employ a simple inductance coil in the d-c charging line for filtering out the objectionable "hum" which would otherwise be audible on the telephone line. In this case, the battery, itself, acts as a large capacitor so the circuit behaves as an IC (inductance-capacitance) filter This explains the reason that there is very little filtering action when an attempt is made to use a "filtered" telephone-type battery charger for some other type of application than battery charging

For a capacitive type filter, the percent ripple from the output of the filter can be calculated from the formula. -

$$\text{Ripple percent} = \frac{\sqrt{2}}{2\pi \ fr \ RLC} \times 100$$

Where RL = Load resistance
C = Capacitance in farads
fr = Frequency of AC supply times the rectifier factor (from table, page 3)

The usual problem is to determine the amount of capacitance necessary to reduce the ripple to a specified ripple percent. In this case, the formula may be written. -

$$C \text{ (in farads)} = \frac{\sqrt{2}}{2\pi \ fr \ RL^{x} \text{ (percent ripple)}} \times 100$$

Working with an a-c supply of 60 cycles, this formula may be written. -

$$C \text{ (farads)} = \frac{375}{r \times RL^{x} \text{ (percent ripple)}}$$

To take an example, suppose we are to design a single-phase, full-wave rectifier and capacitance filter to deliver an output of 100 volts d. c , one ampere with not to exceed 5% ripple Problem Determine value of capacitance

We know the load resistance $= \frac{100 \text{ Volts}}{1 \text{ Amp}} = 100$ ohms

We know from table, page (3) $r = 2$

hence - $$C = \frac{375}{2 \times 100 \times 5} = 000375 \text{ farads}$$
or 375 microfarads

To carry the design a little further -

RC of load = 100 x 000375 = 0375

If we look at the curve, Fig. (4), we see that for a full-wave rectifier and an RC of .0375, the conversion factor is approximately 0 75 from which we can compute the required a-c input voltage

We will see in the foregoing that the factors which determine the values to use in a capacitance filter are simply the ripple frequency of the rectifier output wave and the resistance of the load This type of filter tries to maintain the output at peak level, the capacitor filling in the dips between the peaks.

With a choke input filter, the peaks are cut off by the inductance and the valleys filled in by the capacitor In designing a choke input filter, the percent ripple from the rectifier itself must be taken into consideration. The formula is -

$$LC = \frac{\dfrac{\text{Percent Rectifier Ripple}}{\text{Percent Output Ripple}} + 1}{(2\pi \ fr)^2}$$

This gives us L in Henrys and C in farads

Choke Input filters are generally used with single-phase full-wave rectifiers So, if the a-c supply is 60 cycles, we may reduce the formula to: -

$$LC = \frac{\dfrac{\text{Percent Rectifier Ripple}}{\text{Percent Output Ripple}} + 1}{57 \times 10^6}$$

Now, let's take the same example as before except to design a choke input filter to give 5% ripple We must now consider the rectifier ripple percent. Referring to the table on page 6, we find that the ripple for a single-phase, full-wave rectifier is 48 3% Under actual conditions, it would probably be nearer 50% Using this value in the formula, we have -

$$LC = \frac{\frac{50}{5} \times 1}{.57 \times 10^{6}} = 19\ 3 \times 10^{-6} = .0000193$$

Now we have a value for the product of L and C. We want to know what proportion these values should be For good regulation, L should be not less than 002 x R load at full load. As our load resistance is 100 ohms, L should be . 2 Henrys for optimum performance.

$$\text{Then } C = \frac{.0000193}{2} = .000097 \text{ farads}$$
$$= 97 \text{ microfarads}$$

We would specify our filter as consisting of 200 millihenrys and 100 microfarads

It must be remembered that the above calculations are based on a single-phase, full-wave rectifier operating from a 60-cycle supply and delivering an output having a ripple frequency (fr) of 120 cycles per second. If a half-wave rectifier were used instead of the full-wave rectifier, the value of LC would have to be doubled to obtain the same degree of filtering

The advantage of making the value of the inductance, L, not less than 002 times the resistance of the load lies in the fact that this holds the output voltage down to the average value that would be obtained under normal conditions of resistance loading and no filtering, i.e., nine-tenths of the r.m.s. value of the a-c input to the rectifier. Hence, the heating current is not increased and no de-rating is required.

In determining the a-c input required for a specified d-c output from the system, the IR drop across the choke must be considered in addition to the drop in the rectifier indicated by the "dv" curves The formula becomes -

$$EAC = 1.125 \quad Edc + IR1 + dv$$

where R1 equals the resistance in ohms of the choke and I is the current in r m.s. amperes.

It will be seen that this formula is similar to those shown in the Application Manual (ECG-344) except that the IR drop of the choke has been added.

Where a greater degree of filtering is needed, it may be more economical to add another stage of filtering rather than to increase the values of LC for the first section. The same formula may be used for the second stage by changing Percent Rectifier Ripple to Percent Input Ripple Thus, if we wanted to reduce the 5% ripple to 1%, the second stage would be calculated. -

$$LC = \frac{\frac{5}{1} + 1}{(2\pi\ fr)^2} = \frac{6}{57 \times 10^6} = 10\ 5 \times 10^{-6}$$

When the degree of filtering is such that two stages will be required, it is often desirable to keep the values of LC alike in both stages. In this case, the values for LC can be calculated by the formula: -

$$LC = \frac{\sqrt{\frac{\%\ \text{Input Ripple}}{\%\ \text{Output Ripple}}} + 1}{(2\pi\ fr)^2}$$

If our problem were to reduce the 50% rectifier ripple to 1% using two similar stages, we would proceed as follows -

$$LC = \frac{\sqrt{\frac{50}{1} + 1}}{.57 \times 10^6} = 14\ 2 \times 10^{-6} \text{ for each stage}$$

It would still be desirable to keep the value of each choke equal to . 002 RL so the chokes will each be 2 Henrys if the load resistance is 100 ohms.

$$C = \frac{14.2 \times 10^{-6}}{2} = 71 \times 10^{-6} \text{ farads}$$

or 71 microfarads

As previously stated the choke input filter is desirable because of its inherently better voltage regulation and lower heating current than is obtained with a capacitor input filter However, it may be advantageous to sacrifice voltage regulation to obtain a higher voltage output. In this case, we could make up a filter consisting of a capacitor followed by a choke and another capacitor

The first capacitor would be calculated independently, as before, to determine its output ripple percent. Then the formula for the choke input filter could be applied to further reduce the ripple of the capacitor stage to the desired percent

One final word of caution to be observed in the design of choke input filters is to avoid a combination of L and C in the first stage that will produce resonance effects. For a rectifier ripple frequency of 120 cycles per second, resonance will occur when the product of inductance in Henrys and capacitance in microfarads is equal to 1 77 For safety in this respect, it is desirable to keep the product not less than 3 50 It will be noted that in the previous examples, this figure for LC was much higher than the minimum safe value

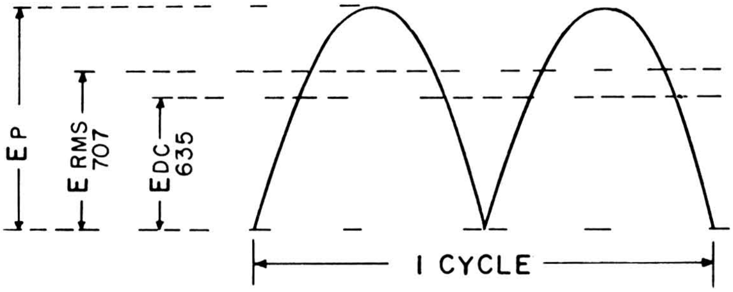


Fig. I D-C VOLTAGE WAVE - RESISTANCE LOAD

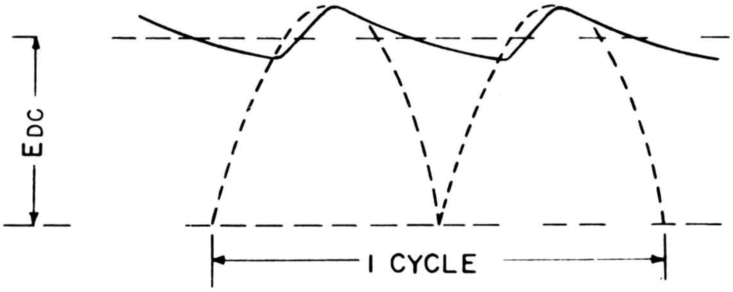


Fig 2 D-C VOLTAGE WAVE - CAPACITIVE LOAD

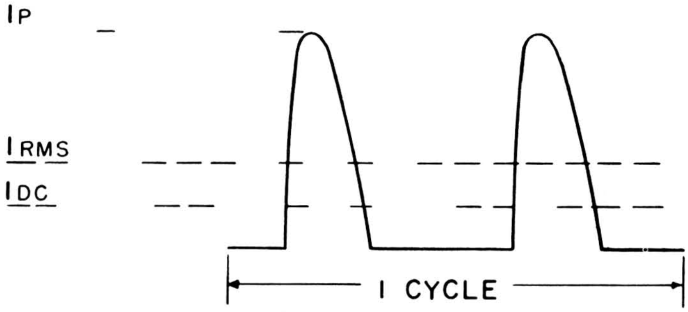
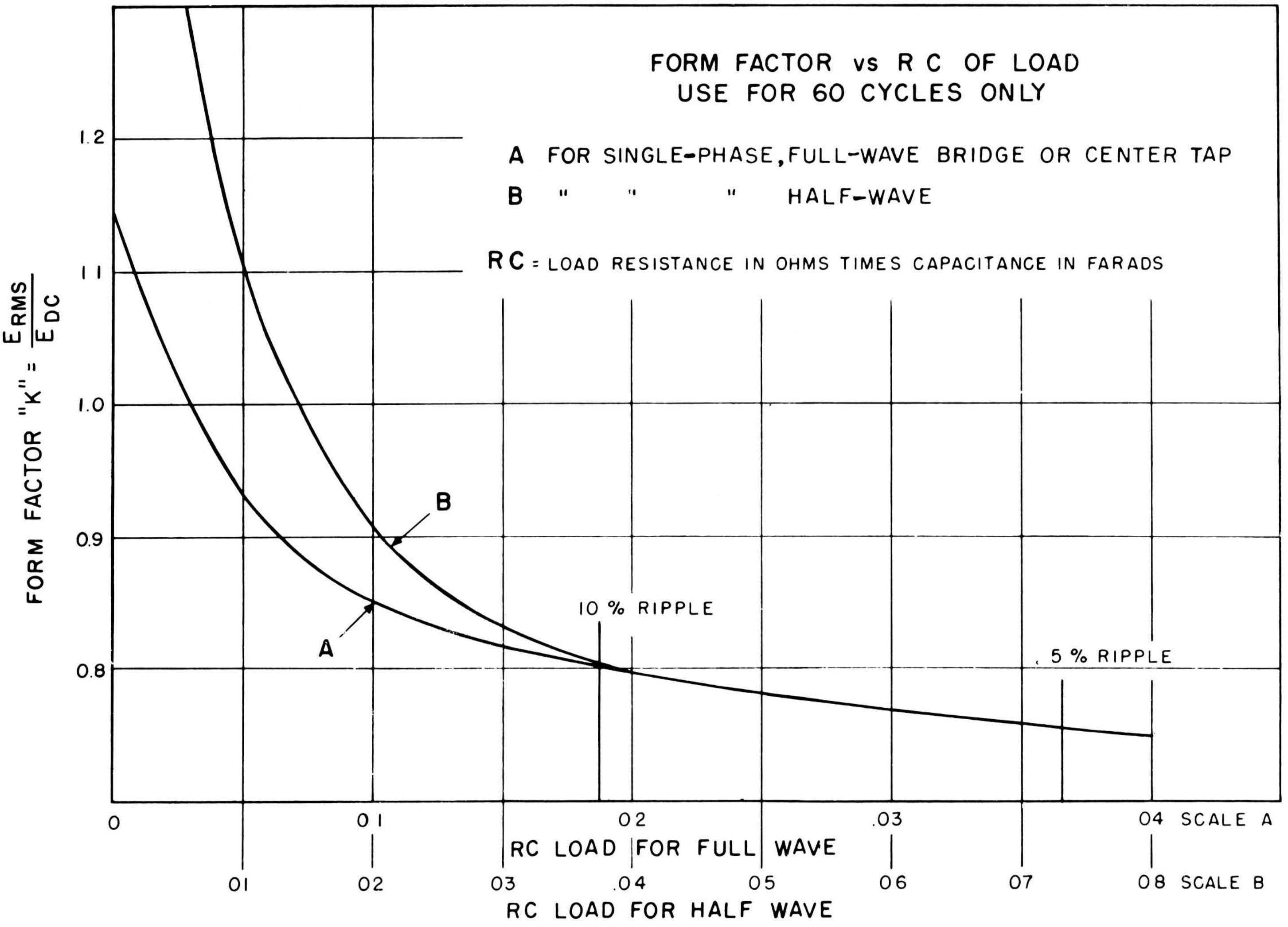


Fig 3 D-C CURRENT WAVE - CAPACITIVE LOAD

Fig. 4


FORM FACTOR vs R C OF LOAD
USE FOR 60 CYCLES ONLY
A FOR SINGLE-PHASE, FULL-WAVE BRIDGE OR CENTER TAP
B " " " HALF-WAVE
RC = LOAD RESISTANCE IN OHMS TIMES CAPACITANCE IN FARADS
FORM FACTOR "K" = $\frac{E_{RMS}}{E_{DC}}$
1.2
1.1
1.0
0.9
0.8
A
B
10 % RIPPLE
5 % RIPPLE
0
.01
.02
.03
.04 SCALE A
RC LOAD FOR FULL WAVE
.01
.02
.03
.04
.05
.06
.07
.08 SCALE B
RC LOAD FOR HALF WAVE

II CUSTOMER INCOMING TEST SPECIFICATIONS FOR SELENIUM RECTIFIERS

A customer often desires to set up an incoming test on material that he receives from vendors. To satisfy such a requirement, the following tabulation is being made for G-E selenium rectifiers.

CIRCUITRY

The recommended test is an a-c or dynamic test, and the data given applies to a basic single-phase, bridge connection. This data, however, may be modified and used for other stack configerations.

The data below include limits for forward-voltage drop, reverse-current, and output voltage when tested under the conditions specified. Test circuits for the tabulated data are given on Fig. 1 (open-circuit, reverse test), Fig 2 (short-circuit, forward test), and Fig. 3 (output-voltage test).

In the open-circuit reverse test, the a-c voltage is increased gradually until the rated stack voltage is applied. The milliampere reading shows the reverse current through the rectifier under these test conditions.

In the short-circuit, forward test, the a-c voltage is raised until the rated current of the stack is shown by the ammeter. The a-c voltage shown by the voltmeter is the forward voltage drop in the stack under these test conditions.

In the output voltage test, rated stack voltage is applied to the a-c terminals of the rectifier stack and the resistance load is adjusted until rated current is obtained. The d-c output voltage is then measured.

If half-wave stacks or half-wave sections of a stack are to be tested, the circuits shown on Fig. 4 and 5 should be used.

Fig. 4 gives the reverse current over a full cycle of a "back-to-back" arrangement of half-wave stacks. The voltage applied will be the rated value as shown in the tabulation and the reverse current will be half that of the bridge value since the reverse currents of the bridge effectively flow through two paths in parallel (equivalent to two back-to back arrangements in parallel)

Fig 5 is the half-wave stack forward test. The forward-test current will be half that of the bridge since conduction only takes place for one-half cycle The maximum ACV input will also be half of the bridge value, since the forward-voltage drop appears across one rectifying-circuit element only whereas in the bridge there are effectively two elements in series during any part of the input cycle. The additional half-wave rectifier across the transformer (Fig. 5) is used to by-pass alternate half cycles of the input wave through the transformer Hence, d-c saturation of the transformer core and distortion of the input-wave form is prevented. The by-pass rectifier should be of the same size, type, and construction as the test rectifier

Each phase of a polyphase stack may be tested in the same way as a single-phase rectifier.

INSTRUMENTATION

Corrections should be made for any current drawn by voltmeter in Fig 1 and 4 (voltmeter should have high input impedance). Also in Fig 2 and 5, corrections should be made for any drop in the ammeters.

The recommended practice is to employ d-c averaging-type ammeters of the moving-coil design which have no more than 50-millivolts drop (Fig. 2 and 5). The drop in the leads also should not exceed 50 millivolts.

The transformer should have a regulation of less than 5%.

In Fig 1 and 4, the ammeter-reading, reverse current may be either of the hot wire-(thermocouple)-dynamometer-or moving-iron type instruments, those in which the deflection is proportional to the mean value of the current squared.

FACTORY TEST

It should be pointed out that the selenium cells are 100% tested and graded for forward and reverse characteristics The cells are then assembled into stacks and the finished stacks themselves 100% tested before shipment to the customer.

To assure uniform voltage distribution across the cells, only cells of the same reverse-characteristic grade are assembled in any one stack

CUSTOMER INCOMING TEST SPECIFICATIONS FOR SELENIUM RECTIFIER STACKS

A-C Tests at 60 Cycles

			Open Circuit Leakage Test per 4-1 1 Bridge (Fig. 1)		Short Circuit Forward Test per 4-1 1 Bridge (Fig. 2)		Output Voltage Test Per 4-1 1 Bridge (Fig 3)		
Cell No.	Cell Size	Cell Designation	ACV Input	Maximum ACMA Leakage after 1 Min.	DCA Load Current	Maximum ACV Input	ACV Input	DCA Load Current	Minimum DCV Output
21	1 x 1	26-Volt Standard Cell	26 x N_s	11 x N_p	0 240 x N_p	2 4 x N_s	26 x N_s	0 240 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	22 x N_p	0 240 x N_p	2.8 x N_s	36 x N_s	0 240 x N_p	29 0 x N_s
		45-Volt Standard Cell	45 x N_s	22 x N_p	0 240 x N_p	2.8 x N_s	45 x N_s	0 240 x N_p	37 0 x N_s
22	1½ x 1½	26-Volt Standard Cell	26 x N_s	22 x N_p	0 720 x N_p	2.4 x N_s	26 x N_s	0.720 x N_p	20 5 x N_s
		36 Volt Standard Cell	36 x N_s	27 x N_p	0 720 x N_p	2.8 x N_s	36 x N_s	0.720 x N_p	29 0 x N_s
		45-Volt Standard Cell	45 x N_s	27 x N_s	0 720 x N_p	2 8 x N_s	45 x N_s	0 720 x N_p	37 0 x N_s
25	2 x 2	26-Volt Standard Cell	26 x N_s	31 x N_p	1 25 x N_p	2.4 x N_s	26 x N_s	1 25 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	38 x N_p	1 25 x N_p	2.8 x N_s	36 x N_s	1 25 x N_p	29 0 x N_s
		45-Volt Standard Cell	45 x N_s	38 x N_p	1 25 x N_p	2.8 x N_s	45 x N_s	1 25 x N_p	37 0 x N_s
14	3-3/8 Rd.	18-Volt Standard Cell	18 x N_s	66 x N_p	3 0 x N_p	2.4 x N_s	18 x N_s	3.0 x N_p	14.0 x N_s
		26-Volt Standard Cell	26 x N_s	66 x N_p	3.0 x N_p	2.4 x N_s	26 x N_s	3.0 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	66 x N_p	3.0 x N_p	2.8 x N_s	36 x N_s	3.0 x N_p	29 0 x N_s
15	4-3/8 Rd.	18-Volt Standard Cell	18 x N_s	110 x N_p	5 2 x N_p	2.4 x N_s	18 x N_s	5.2 x N_p	14.0 x N_s
		26-Volt Standard Cell	26 x N_s	110 x N_p	5 2 x N_p	2.4 x N_s	26 x N_s	5 2 x N_p	20 5 x N_s
		36 Volt Standard Cell	36 x N_s	110 x N_p	5 2 x N_p	2.8 x N_s	36 x N_s	5.2 x N_p	29 0 x N_s
31	4-1/4 x 6	18-Volt Standard Cell	18 x N_s	176 x N_p	8.0 x N_p	2.4 x N_s	18 x N_s	8.0 x N_p	14.0 x N_s
		26-Volt Standard Cell	26 x N_s	176 x N_p	8 0 x N_p	2.4 x N_s	26 x N_s	8.0 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	176 x N_p	8 0 x N_p	2 8 x N_s	36 x N_s	8 0 x N_p	29 0 x N_s
32	5 x 6	18-Volt Standard Cell	18 x N_s	198 x N_p	10 0 x N_p	2.4 x N_s	18 x N_s	10 0 x N_p	14.0 x N_s
		26-Volt Standard Cell	26 x N_s	198 x N_p	10 0 x N_p	2.4 x N_s	26 x N_s	10 0 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	198 x N_p	10 0 x N_p	2.8 x N_s	36 x N_s	10.0 x N_p	29 0 x N_s
6	5/32 Rd.	26-Volt Standard Cell	26 x N_s	0 220xN_p	0 004 x N_p	2.4 x N_s	26 x N_s	0 004 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	0 220xN_p	0 004 x N_p	2.8 x N_s	36 x N_s	0 004 x N_p	29 0 x N_s
		45-Volt Standard Cell	45 x N_s	0.220xN_p	0 004 x N_p	2.8 x N_s	45 x N_s	0 004 x N_p	37 0 x N_s
5	9/32 Rd.	26-Volt Standard Cell	26 x N_s	0.400xN_p	0 016 x N_p	2.4 x N_s	26 x N_s	0 016 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	0.600xN_p	0 016 x N_p	2.8 x N_s	36 x N_s	0 016 x N_p	29 0 x N_s
		45-Volt Standard Cell	45 x N_s	0.600xN_p	0 016 x N_p	2 8 x N_s	45 x N_s	0 016 x N_p	37 0 x N_s
20	15/32 Rd.	26-Volt Standard Cell	26 x N_s	1 760xN_p	0 050 x N_p	2.4 x N_s	26 x N_s	0 050 x N_p	20 5 x N_s
		36-Volt Standard Cell	36 x N_s	1 760xN_p	0 050 x N_p	2.8 x N_s	36 x N_s	0 050 x N_p	29 0 x N_s
		45-Volt Standard Cell	45 x N_s	1 760xN_p	0 050 x N_p	2.8 x N_s	45 x N_s	0 050 x N_p	37 0 x N_s

Where: N_s Number of Cells in series per arm or circuit element.
N_p Number of cells in parallel per arm or circuit element.

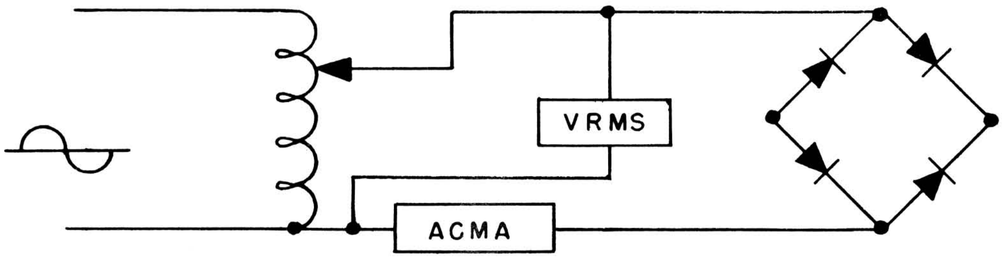


Fig. I OPEN-CIRCUIT LEAKAGE TEST FOR SINGLE-PHASE, FULL-WAVE BRIDGE

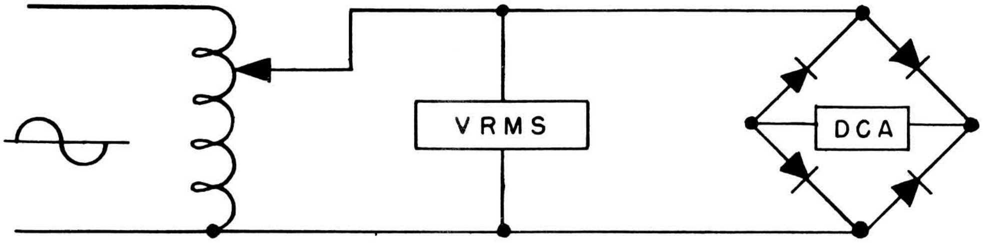


Fig 2 SHORT-CIRCUIT FORWARD TEST FOR SINGLE-PHASE, FULL-WAVE BRIDGE

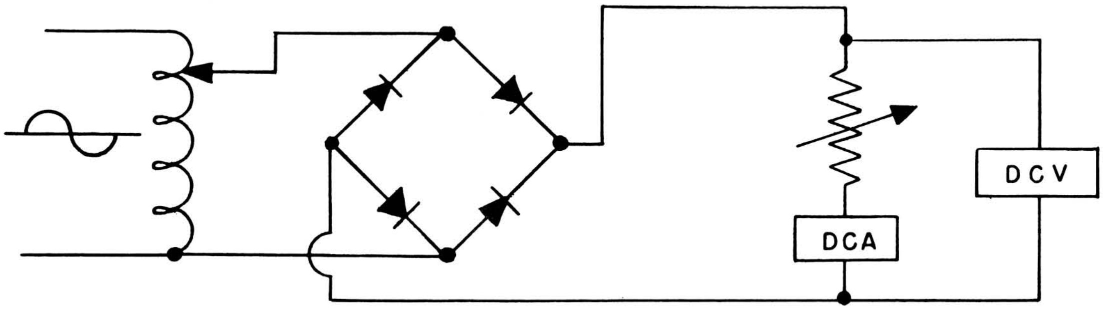


Fig 3 OUTPUT VOLTAGE TEST FOR SINGLE-PHASE, FULL-WAVE BRIDGE

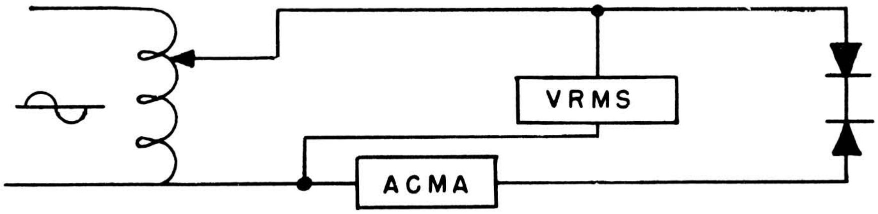
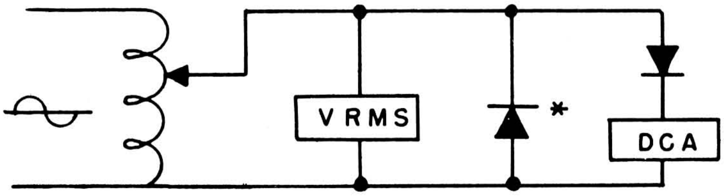


Fig. 4 BACK-TO-BACK LEAKAGE TEST FOR HALF-WAVE RECTIFIERS



* THIS STACK IS NOT UNDER TEST BUT IS USED FOR LOAD BALANCING PURPOSES ON THE TRANSFORMER

Fig. 5 SHORT-CIRCUIT FORWARD TEST FOR HALF-WAVE RECTIFIERS

III FREQUENCY CHARACTERISTICS

In the selection of a selenium rectifier for a given application, two characteristics of the semiconductor are of importance, the forward characteristic and the reverse characteristic.

In power applications, the forward characteristic is of prime importance in that it affects the regulation and efficiency of the circuit. The reverse characteristic in this type of application is of importance only in that it increases the power losses within the selenium cell and indirectly affects the efficiency by establishing the maximum inverse voltage that may be applied to the cell consistent with its heat dissipation capabilities.

Operating of the selenium rectifier at frequencies other than 60 cycles involves a closer study of the reverse characteristic, including the differential capacitance of the cell and its response at higher frequencies.

The selenium cell may be conveniently represented in the reverse direction by a parallel arrangement of a non-linear capacitor and a non-linear resistor From this, it is at once apparent that the leakage of a selenium cell is made up of two components, a resistive leakage component which is in phase with the applied reverse voltage, and an AC or capacitive leakage component which is in quadrature with the voltage The quadrature component of leakage impedance is approximately 75% of the total leakage impedance at 400 cycles.

The total leakage current, therefore, is proportional to the equivalent leakage impedance, and it is this total current, or the variation of same, that bears consideration in critical circuits.

A typical plot of differential capacitance of a selenium cell as a function of voltage is shown on Fig 1, Page 19. It is seen to be higher, at low voltages and, lower at higher inverse voltages The capacitance can, therefore, be said to vary inversely with applied voltage.

Also, the voltage is inversely proportional to the square of the capacitance and this is shown as a straight line on Fig. 1, Page 19

The differential capacitance of a cell does not change appreciable with temperature nor does it change to any great extent with frequency. A typical plot of relative capacitance vs. frequency is shown on Fig 2, Page 19

DIFFERENTIAL CAPACITANCE vs. D-C BIAS VOLTAGE FOR TYPICAL VAC-U-SEL RECTIFIER

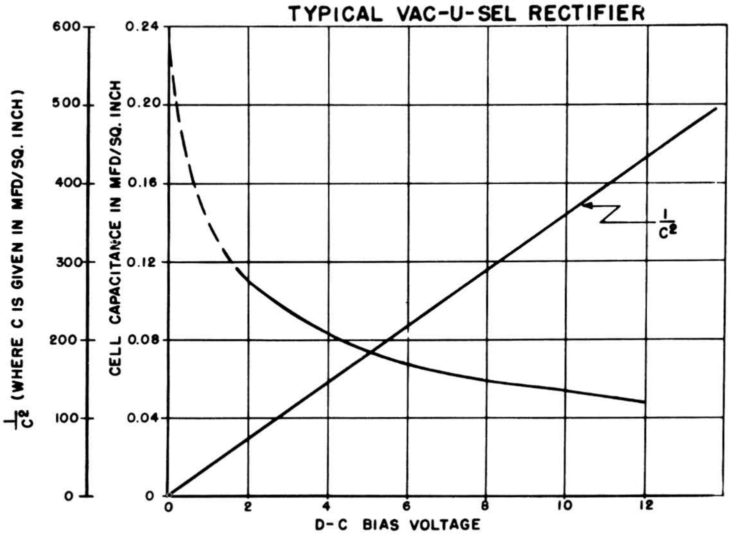
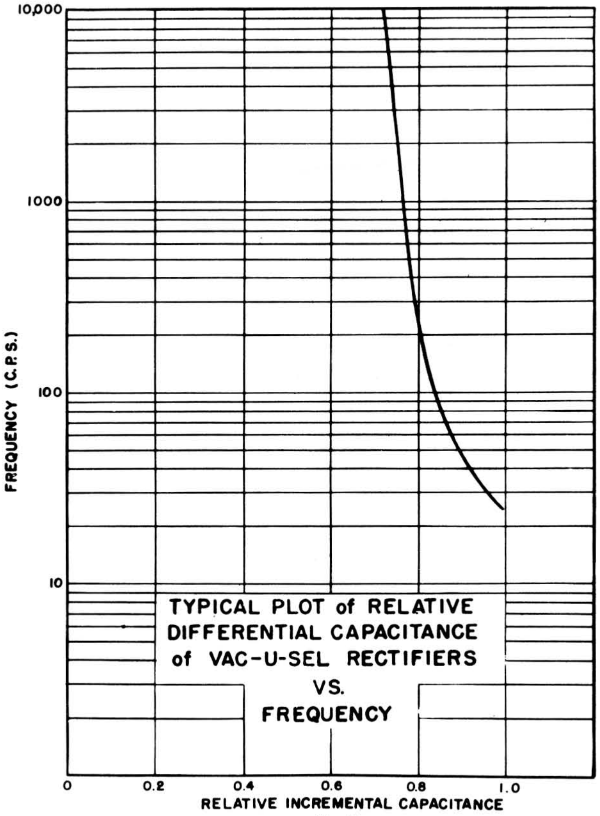


Fig. 1



TYPICAL PLOT of RELATIVE DIFFERENTIAL CAPACITANCE of VAC-U-SEL RECTIFIERS VS. FREQUENCY

Fig. 2

IV PROTECTIVE FINISHES

A selenium rectifier to perform satisfactorily must have in addition to acceptable electrical characteristics and mechanical strength a suitable coating or finish to protect the rectifier against environmental conditions that it is to be exposed to.

The Rectifier Department offers a choice of four types of finishes

I. Standard Commercial Finish

This finish is primarily for use in commercial applications where protection from normal atmospheric corrosion is required.

II. Heavy Duty Commercial Finish

This finish is recommended for protection from high humidity, acid and alkaline atmospheres

III. Military Finish

This finish is used on all open-type selenium rectifier stacks(1) for protection against severe adverse atmospheric conditions generally encountered in military applications

A four-day air-cure time is required between the application of the protective finish and subsequent testing to assure proper curing of the paint

The environmental tests and military specifications that the rectifier stacks in this category meet, follow If a modification in stack construction is required to comply with a certain specification an exception to said specification shall be taken and recommendations made

A Salt Spray Test

(1) All open-type selenium rectifier stacks(1) with military finish are capable of meeting a 100-hour salt spray test.

(2) Specifications met by rectifier stacks of Part 1
  (a) QQ-M-151, Para. 41
  (b) MIL-STD-202, Method 101
  (c) MIL-E-5272, Para 4 6
  (d) MIL-T-5422, Para. 4.5

(3) The stacks shall be considered acceptable if they pass the electrical tests and there is no destructive corrosion, where destructive corrosion is defined as any type of corrosion which interferes with the mechanical or electrical performance of the component.

B Steady State Humidity Test

(1) All open-type selenium stacks (1) with military finish will meet the Steady State Humidity Test of the following applications

- (a) MIL-STD-202, Method 103
- (b) MIL-E-5272A, Para 4 4, Procedure III

(2) All stacks shall be considered satisfactory if they pass the electrical tests (2)

C Cyclic Moisture Resistance Test

(1) Specifications met by stacks finished to Part III
- (a) MIL-STD-202, Method 106
- (b) MIL-R-11050, Para 4.6 6
- (c) MIL-E-5272, Para. 4 4, Procedure I
- (d) MIL-T-5422, Para. 4 4

(2) All stacks shall be considered acceptable if they pass the electrical tests (2)

D Fungus Test

(1) All open-type selenium stacks (1) with military finish will meet the Fungus Test of the following specifications

- (a) MIL-E-5272, Para. 4.8, Procedure I
- (b) MIL-T-5422, Para. 4.8

(2) The stacks shall be considered acceptable if there is no appreciable fungus growth.

E Temperature Cycling or Temperature Shock Test

(1) All open-type selenium stacks (1) with military finish will meet the Temperature Cycling Test of the following specifications

- (a) MIL-STD-202, Method 102
- (b) MIL-E-5272, Para. 4.3, Procedure II

(2) The stacks shall be considered acceptable if there is no cracking or peeling of paint on the selenium cell, and they satisfactorily pass the electrical tests (2)

F Sand & Dust Test

(1) All selenium stacks will pass the Sand & Dust Test of the following specifications

(a) MIL-E-5272A, Para. 4-11, Procedure I
(b) MIL-T-5422, Para 4 7

(2) Stacks shall be considered acceptable if they pass the electrical tests (2) and no apparent damage is evident from the sand and dust particles

G. Light Shock Test

(1) Up to 100 g's is generally considered light shock

(2) All selenium stacks will pass the Light Shock Test of the following specifications

(a) MIL-STD-202, Method 202
(b) MIL-E-5272A, Para. 4 15, Procedure II. (15 g's and a time duration of 11 ± 1 milliseconds in each of three mutually perpendicular planes)

(3) Stacks shall be considered acceptable if their electrical characteristics have not been impaired and they meet the electrical limitations established under electrical tests (2).

H. High Impact Shock

(1) All open-type selenium stacks (1) with double-ended stud-type construction (no cap screw or cantilever type mounting) with the provisions listed below will meet the High Impact Shock Specification MIL-S-901, Type C

(2) Stacks which will meet test:

	Maximum Number of Cells per Stack		Approx. Length between Mounting Brackets*
Cell Size	Convection Cooling	Fan Cooling	
No 21	40	40	6-1/2"
No. 22	40	40	8-1/2"
No 25	40	40	10-1/2"
No 14	24	40	10"
No 15	20	40	10-1/2 '
No. 31	16	40	10-1/2"
No. 32	16	40	11-1/2"

(3) High Shock brackets must be used when brackets are required.

* Dimension varies with circuit and construction.

(4) Glass Rods must be used on the No 31 and No 32 size cells to prevent rotation of cells and terminals

(5) The stacks shall be considered acceptable if they pass the electrical tests (2) and no damage has been done to interfere with their electrical performance.

I. Vibration Test

(1) All open-type selenium stacks (1) will meet the Vibration Test of the following specifications

- (a) MIL-STD-202, Method 201
- (b) MIL-R-18281, Para. 4 4.6
- (c) MIL-T-5422, Para 4.2

(2) Stack construction listed in Section H must be used for Vibration frequencies of from 10 to 2000 cycles

(3) Stacks shall be considered acceptable if their electrical characteristics have not been impaired and they meet the electrical limitations established under electrical tests (2).

J Acceleration Test

(1) All selenium rectifier stacks will meet the Acceleration Test of the following specification.

- (a) MIL-E-5272A, Para. 4.16, Procedure II

(2) Stacks shall be considered acceptable if they pass the electrical tests (2) and no damage has been done to interfere with their electrical performance

K. Low Temperature Exposure

This phase of most military specifications is quite general, and makes further reference to individual customer specifications for exact details

G-E Vac-u-Sel* rectifiers are on the Signal Corps "Acceptable Items Guide" for Specification MIL-R-11050. However, paragraph 3 1.4 of the specification states that "The change in forward voltage drop shall not be greater than 8% at rated current from the initial forward voltage drop, as a result of exposure to -65° C for a period of 2 hours". As shown on Table I, a maximum change of 15% may be expected. The change, however, is not permanent and it has been found that the forward voltage drop returns to normal after approximately one month's operation.

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* Reg. Trademark, General Electric Company

All stacks shall be considered acceptable if they pass the electrical tests (2)

If it is essential that the 8% requirement be met, the factory should be consulted.

L. Dielectric Test

The insulation and spacings used in the construction of the rectifier stack shall be capable of withstanding without breakdown for a period of one minute a 60-cycle alternating - current voltage (as shown in the table below), between current-carrying parts and stud.

Voltage Rating of Stack AC Volts	Test Voltage for 1 Minute
0 - 60	500
61 - 90	900
Over 90	1000 VRMS plus twice rated (Total voltage not to exceed 3000 volts (3))

A one-minute test at 900 volts RMS should not be exceeded for eyelet and tube mounting assemblies

For a shorter one-second test period, it is permissible to increase the one-minute voltage values by 20%.

The above test procedure has been accepted by the NEMA Standard Committee.

V EMBEDDED VAC-U-SEL* RECTIFIERS

A. Embedded stacks are available in 1" sq , 1-1/2" sq., and 2" sq. cell sizes, and are resistant to acids, alkalis, and solvents and will meet all of the specifications listed in Section III (4)

B. The rectifier stack is first assembled on a tube and then embedded in an epoxy resin. It may be furnished in three type constructions

(1) Basic tube design (tube takes an #8-32 stud)
(2) Stud mounting, using an #8-32 stud
(3) Bracket mounting

C. The Salt Spray exposure time may be extended from 100 hours to 500 hours.

* Reg. Trademark, General Electric Company

Table I

Electrical Tests

The maximum changes to be expected as a result of subjecting the Vac-u-Sel* rectifiers to various environmental tests are listed below.

Test	Maximum Increase in Forward Voltage Drop above Factory Passpoint	Maximum Increase in Leakage Current above Factory Passpoint
A Salt Spray Test	20%	20%
B. Steady State Humidity Test	20%	20%
C Cyclic Moisture Resistance Test	20%	20%
D Fungus Test	Not Tested	Not Tested
E Temperature Cycling Test	15%	20%
F. Sand & Dust Test	15%	20%
G. Light Shock Test	15%	20%
H High Impact Shock Test	15%	20%
I Vibration Test	15%	20%
J Acceleration Test	15%	20%
K Low Temperature Exposure Test	15%	20%

* Reg Trademark, General Electric Company

Footnotes (1) With the exception of eyelet and tube construction. This type construction is not recommended for military application.

(2) See electrical tests on Page 15.

(3) The Rectifier Department should be consulted for exact recommendations when the test voltage exceeds 300 Volts.

(4) When ordering specify high temperature embedding compound when ambient temperature exceeds + 75 C.

VI. FORCED AIR COOLING OF SELENIUM RECTIFIERS

When larger amounts of power are required, some type of artificial cooling must be employed to make selenium economically feasible for the application. With forced air cooling the current density per selenium plate may be increased to 2 or 2.5 times its normal rating. For shorter life, even higher values are often permissible.

By operating the selenium rectifier at higher than normal current densities a smaller physical package* is obtained. This means that the cost per watt of output is less, and the space devoted to the housing of the selenium rectifier components is kept to a minimum.

One might feel that the use of artificial cooling would prevent aging and hence render an indefinite life expectancy for selenium rectifier components. For many years aging has been thought to be a result of both temperature and current density. It should suffice to say, however, that aging is a function of junction temperature and that current density is indirectly related in that it has the effect of increasing or decreasing the junction temperature. Life expectancy vs Air Temperature and velocity as a function of current density is shown on nomograph form on Fig. 1, Page 27. Four different parameters are plotted, and by use of a straight edge and knowing at least two of the parameters and unknown parameters may be determined. For example, a selenium rectifier stack operating at 2N (twice short stack rating as given in Table I, below) and being forced cooled at 1000 linear feet per minute with 35°C air would have a life expectancy of 60,000 hours.

It is essential that the air being used to cool the stacks be clean, free of grit, acid fumes and the like. It is preferred the air to be filtered and the selenium components be housed in a location remote from the presence of any adverse environmental conditions.

Also, when installing the selenium stacks it is recommended that they not be stacked more than two deep in the direction of air flow.

Table I

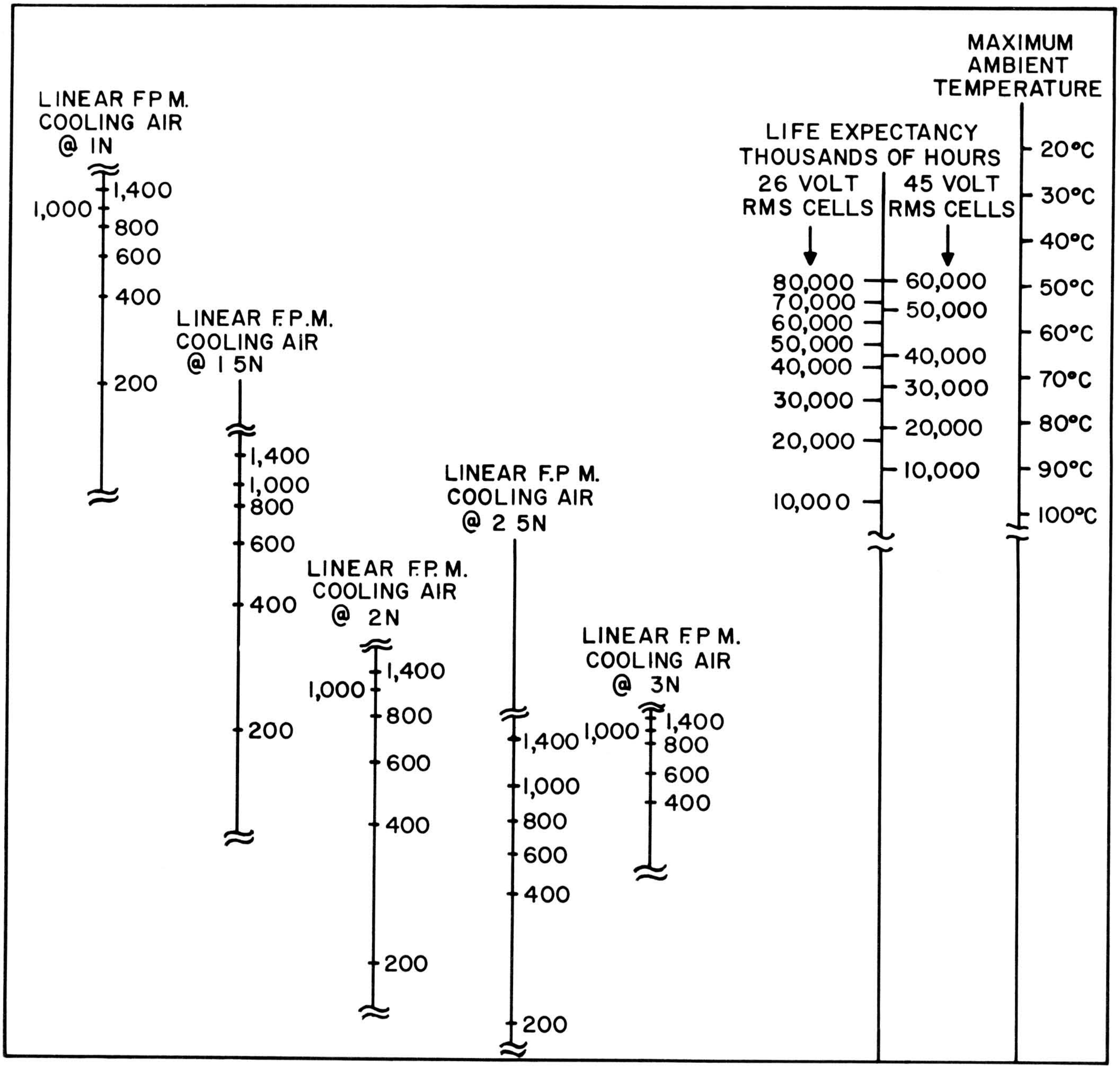
Short Stack Current Rating for Forced Air Cooling

			"N" Rating (In Amperes)	
Cell Type	Cell Size	Half Wave	Single-Phase Bridge	Three-Phase Bridge
21	1 x 1	0.150	0.300	0.450
22	1½ x 1½	0.360	0.720	1.08
25	2 x 2	0.625	1.25	1.87
14	3-3/8 RND	1.50	3.00	4.50
15	4-3/8 RND.	2.60	5.20	7.80
31	4¼ x 6	4.00	8.00	12.00
32	5 x 6	5.00	10.00	15.00

*With artificial cooling, closer than normal spacing may be used.

FORCED-AIR COOLING

Life Expectancy vs Air Temperature and Velocity as a Function of Current Density



(1) **Normal current rating of rectifier (N) for forced air cooling is the short stack rating as given in Table No. 3, Page 22.**

(2) 1400 linear feet per minute is optimum cooling air velocity

(3) To obtain Approximate Life Expectancy when using 36 V-RMS cells, take average at 26 and 45 V-RMS life for same conditions.

Nomograph