Selenium Rectifiers — Factors in Their Application

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Selection of the proper selenium rectifier stacks for best results in the design of dc power supplies involves consideration of characteristics not ordinarily found in published data. This paper describes the data required for the selection of selenium cell sizes and cell combinations, shows typical voltage-current characteristics, and gives the results of extensive life test data necessary for evaluating the life expectancy of the product. The life test data indicate that there are substantial differences in the life expectancy of selenium stacks as manufactured by various companies in this country. Shorter life can be anticipated as the rms cell voltage ratings are increased. In addition, the life is affected by the current density and the temperature at which the selenium cells are operated.

INTRODUCTION

Since their introduction in this country about 1939, selenium rectifier stacks have proved to be a useful means of converting ac power to dc power for Bell System applications. These applications vary from 2 to 2,500 volts and in power sizes from a few watts to 10 kilowatts. Properly designed, the selenium rectifier has a relatively long-life expectancy and requires a minimum amount of maintenance. For these reasons, selenium rectifier stacks are widely used in telephone plants for battery charging, relay operation, plate and filament supply for vacuum-tube amplifiers, bias supplies, telegraph and teletypewriter circuits.

Up to 1952, about 245,000 rectifiers of all types have been manufactured for the Bell System. These include tungar, copper-oxide, vacuum tubes, thyratrons and selenium types. Of this total, about 25 per cent are of the selenium type.

Although Bell Laboratories studies of selenium rectifier stacks date from 1939, rectifiers using such stacks did not enter the telephone plant until 1945. From 1940 to 1945, however, selenium stacks were designed

widely into communication systems for World War II military projects. Since 1945, selenium rectifier power supplies have increased rapidly. For example, in 1945, out of a total of 9,000 rectifiers of all types, about 1,000 or 11 per cent used selenium. In 1951, about 30,000 out of 45,000 rectifiers, or 67 per cent, were of the selenium type.

There are many companies in this country who manufacture selenium stacks but the quality and behavior of the various manufacturers' products show considerable variation, particularly in regard to life expectancy. For many years the Laboratories has carried on an extensive testing program to evaluate properly the various suppliers' rectifiers. As a result of these continuing investigations, the Laboratories is in a position to select cell sizes and combinations of selenium rectifier stacks for use in new power applications. Specifications then are written on one or more suppliers. These specifications have a three fold purpose: (1) They are used as a purchasing and inspection document, (2) they cover the electrical and mechanical requirements necessary for proper electrical design and equipment layout, and (3) they are useful in maintaining records of the electrical and mechanical characteristics.

CELL MANUFACTURE AND STACK ASSEMBLY

A selenium rectifier cell is an elementary rectifying device having one positive electrode, one negative electrode and one rectifying junction. Cells are made by coating a chemically treated base plate, usually aluminum, with a thin layer of purified selenium to which a halogen element (chlorine, iodine or bromine) has been added. This mixture is applied to the base plate by one of the following methods:

1. Sprinkled or dusted on and subjected to heat and pressure.
2. Deposited by an evaporation process in an evacuated chamber.
3. Dipped in molten selenium and spun.

The selenium then is converted to the desired crystalline structure by heat treatments. During the heat treatment, a blocking or barrier layer is formed on the exposed surface of the selenium. This layer is further developed by various chemical means, which are "trade secrets" with each manufacturer. A thin layer of low melting point alloy, the front electrode, is then sprayed on the selenium.

The manufacturing process is completed by electrically "forming" the cells by applying a pulsating dc voltage in the non-rectifying direction for a specified time interval.

Selenium cells are assembled on an insulated bolt or stud, with individual cells separated by metal spacer washers to allow free passage of air for cooling the assembly. Contact terminals are brought out in various

arrangements for series, parallel or series-parallel connection of the cells as required.

The completed assembly is designated as a rectifier stack. A rectifier stack is a single structure of one or more rectifier cells.

Small size cells (less than 1″) have no center hole for mounting. These cells are assembled without spacer washers in glass, metal, phenol fibre or bakelite tubing. Terminal leads extend outside these enclosures.

SYMBOLIC NOTATION

The combination of cells on a stack is described by a sequence of four symbols written a-b-c-d with the following significances:* (a) number of rectifying elements; (b) number of cells in series in each rectifying element; (c) number of cells in parallel in each rectifying element; and (d) symbol designating circuit or stack connections.

The symbols for the more common types of stack assemblies are shown schematically in Fig. 1.

A *basic* selenium stack is defined as a stack having a single selenium cell in each rectifying element. For instance, a 4-1-1B stack is a basic full-wave single-phase bridge rectifier stack with one selenium cell in each of the four rectifying elements.

The total number of selenium cells on any stack is the product of the three numbers indicated. For example, a single-phase full-wave bridge stack with three cells in series and two cells in parallel per rectifying element would be designated as a 4-3-2B stack assembled with 4 × 3 × 2 or 24 cells.
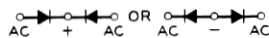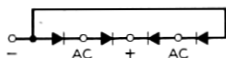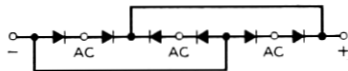

Fig. 1 — Stack assembly symbols. Color coding of terminals (AIEE and NEMA Standard): yellow for ac, red for plus dc output, and black for negative dc output.

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* This method of specifying stack assemblies has been standardized by both the National Electric Manufacturer's Association and the American Institute of Electrical Engineers.

DESIGN CONSIDERATIONS

The proper selection of selenium stacks for use in dc power supplies involves a number of important factors that must be carefully considered.

(1) Circuit requirements must be carefully analyzed so that alllowance may be made for the normal variations in the voltage-current characteristics of each manufacturer's product as well as variations that exist for the same stacks processed by different manufacturers. For a fixed ac input voltage, differences in the forward voltage drop may vary the dc output voltage at least ± 3 per cent from the mean value. If this cannot be tolerated, selenium cells have to be carefully graded and selected to obtain uniformity or other circuit adjustments have to be provided. Special selection of cells, obviously, will increase the cost of the product.

(2) The engineer must take into account the magnitude of the changes in the voltage-current characteristics of the rectifier stacks over the specified temperature range of his project. At very low temperatures, output voltages may be 5 to 10 per cent lower than at normal room temperatures. For high temperature operation, the stacks must be properly derated for both current and voltage to prevent overheating and rapid failure.

(3) Selenium rectifiers age with time. Compensation for this aging should be provided if load requirements warrant. The project engineer should determine what life he expects or requires of the application. For military applications life requirements may vary from minutes to thousands of hours. On other applications, such as telephone and elevator installations, it is desirable to design selenium rectifiers for life expectancies of ten to twenty years or more.

(4) The equipment engineer must anticipate the differences in mechanical details of the same stack assembled by different suppliers. There is no standardization in the selenium industry regarding cell sizes or mechanical details such as the overall length and height of the stack and particularly the type of mounting. However, a committee for the National Electrical Manufacturers' Association is attempting to standardize these mechanical details so that stacks assembled by different suppliers will be mechanically interchangeable.

(5) Unless otherwise specified, rectifying stacks are coated with various types of paints and varnishes for protection against moisture in normal conditions of humidity. For military projects and other applications where selenium rectifiers may be exposed to high humidities, fungus, salt or other corrosive atmospheres, the rectifier stacks must be

provided with a more suitable type of protective coating or finish. These finishes are available from most manufacturers.

(6) When selenium stacks are mounted in cabinets or housing with other heat-generating devices, they should be arranged in such a manner that heat from the other components does not reach the rectifier stacks. The stacks should be mounted below the other components, and in such position that the free flow of air through the rectifier stack is not impeded. The stack should be mounted with the assembly stud in the horizontal, not vertical, position. When two or more stacks are mounted in the same housing, they should be in a horizontal plane with each other, or properly staggered. Cabinets should be provided with louvers to dissipate the heat within the enclosure.

ELECTRICAL RATINGS

The electrical ratings of selenium rectifier stacks are based on their voltage, current and thermal characteristics. All three must be considered carefully for initial design purposes, as any one can affect life expectancy.

Voltage Ratings

The voltage rating usually is expressed as the "reverse voltage rating." It is the maximum rms sinewave voltage above which an excessive reverse current would flow and overheat the cell, causing breakdown. However, the important consideration establishing the rating is the peak voltage applied to the cell. If the applied voltage differs significantly from a sine-wave, it is important that the applied peak voltage shall not exceed 1.41 times the rated rms voltage.

When selenium cells originally were manufactured in this country, their rms reverse voltage ratings ranged from 14 to 18 volts. Ratings later increased to 26 volts. One manufacturer already has successfully produced 33-volt cells for several years; and another supplier announced recently a 40-volt cell. Cells rated at higher voltage have been produced in the laboratory. For non-critical applications, such as low-cost radio and television sets, some selenium manufacturers make cells rated at 45 volts rms. Generally, in such applications, a high reliability product is not required and the units may have a relatively short life.

The nominal dc output voltages obtained from various common *basic* rectifier stacks assembled with cells rated at 18-, 26- and 33-volt rms are listed in Table I. These ratings apply for stacks operating at rated dc output current into a resistance load.

Current Ratings

The current rating of selenium cells is based upon a normal current density of 0.32 ampere for each square inch of active rectifying surface for a single-phase full-wave bridge rectifier stack (4-1-1B) operating into a resistance load. The rating applies to stacks in which the cells are separated by spacer washers so that the cells are cooled by convection air currents. Small size cells mounted without spacer washers are rated at a lower current density.

The dc output current ratings for various selenium cell sizes are listed in Table II.

These ratings are based upon continuous operation in ambient temperatures up to +35°C with unrestricted ventilation for convection cooling of the stacks. For *battery or condenser loads* on single phase circuits, the above current ratings usually are derated to 80 per cent of the above values.

Thermal Ratings

Voltage and current ratings usually are based upon operation of the rectifier stack in a normal ambient temperature of +35°C. It is important to note, however, that for selenium cell application, ambient temperature is defined as the temperature *immediately* surrounding the stack within the equipment enclosure, not the temperature area where equipment is installed. Stacks operating at rated current and voltage into a resistance load have temperature rises ranging from 15 to 30°C when measured with a thermocouple in direct contact with the cell. The temperature rise depends upon the manufacturing techniques used by the various companies as well as the spacing of the selenium cells on the assembled stack. For long life expectancy, the actual cell temperature should not exceed +75°C.

TABLE I — NOMINAL DC OUTPUT VOLTAGES OF RECTIFIER STACKS

	Basic Stack	DC Output Volts		
Cell Rating, Volts rms..		18	26	33
Single Phase				
Half-wave...........................	1-1-1H	6	9	12
Full-wave				
Center tap.........................	2-1-1C	6	9	12
Bridge............................	4-1-1B	12	18	24
Three-Phase				
Full-wave bridge.....................	6-1-1B	19	30	38

For operation in ambient temperatures above +35°C, the voltage or current ratings, or both must be reduced to limit the cell temperature (ambient plus heat rise) to +75°C. The de-rating factors for voltage and current vary somewhat from supplier to supplier, but Fig. 2 shows typical de-rating curves for operation of selenium stacks above a +35°C ambient.

Selenium rectifiers can be operated at cell temperatures above 75°C, but aging accelerates with temperature and excessive temperatures will result in rapid failure.

A special problem today is the application of selenium rectifiers for high temperature military uses. Many military projects are requesting designs to operate at ambient temperatures of +70 to +90°C. Unfortunately very little data about rectifier operation and life expectancy under these conditions have been obtained up to now.

VOLTAGE — CURRENT CHARACTERISTICS

To demonstrate the non-linear characteristics of selenium rectifier cells, Fig. 3 illustrates representative dynamic voltage-current curves showing the open circuit and short circuit characteristics of bridge connected stacks composed of various cell sizes rated at 26 volts, rms. This rating was chosen since all manufacturers presently are producing cells of this type.

Cells with higher voltage ratings generally have a slightly greater forward voltage drop.

TABLE II — DC OUTPUT RATINGS

Cell Size	Area Square Inches*	Continuous DC Amps at +35°C		
		Single-Phase		Three-Phase
		Half wave	Bridge & C.T.	Bridge
¼" Dia.	0.049	0.006	0.012	0.018
½" Dia.	0.196	0.025	0.050	0.075
1" x 1"	0.56	0.090	0.18	0.270
1¼" x 1¼"	1.1	0.175	0.35	0.525
1½" x 1½"	1.7	0.270	0.54	0.810
2" x 2"	3.1	0.500	1.0	1.50
3" x 3"	7.0	1.10	2.2	3.30
4⅜" Dia.	12.5	2.00	4.0	6.00
5" x 5"	21.2	3.40	6.8	10.2
4¼" x 6"	21.2	3.40	6.8	10.2
5" x 6"	26.2	4.20	8.4	12.6

* Approximate active rectifying area (varies with suppliers)

The data shown in Fig. 3 and subsequent data are plotted for *basic* 4-1-1B stacks. Tests were made with 60-cycle sinusoidal supply voltage. The "forward voltage drop" is expressed as the rms volts required to produce a specified current in a moving coil dc ammeter connected directly to (short circuiting) the output terminals of the rectifier stack. For stacks with more than one cell per element, the voltage drop is obtained by multiplying the observed drop in Fig. 3 by the number of cells in series per rectifying element.

The reverse current is measured by applying a specified rms voltage to the ac terminals with the dc terminals open circuited and noting the rms input current after the current has stabilized. When selenium stacks have been "off voltage" for some time, a relatively high reverse current is obtained for the first few seconds. The current then decays approximately exponentially. Usually, the current will stabilize after voltage has been applied for 5 to 10 minutes.

It should be emphasized that these curves are only typical characteristics. Selenium cell manufacture requires individual testing of each cell before assembling into a stack. Cells are graded by their electrical characteristics. Large variations exist between the lowest and highest grade. Each manufacturer sets up his own standards regarding the variations
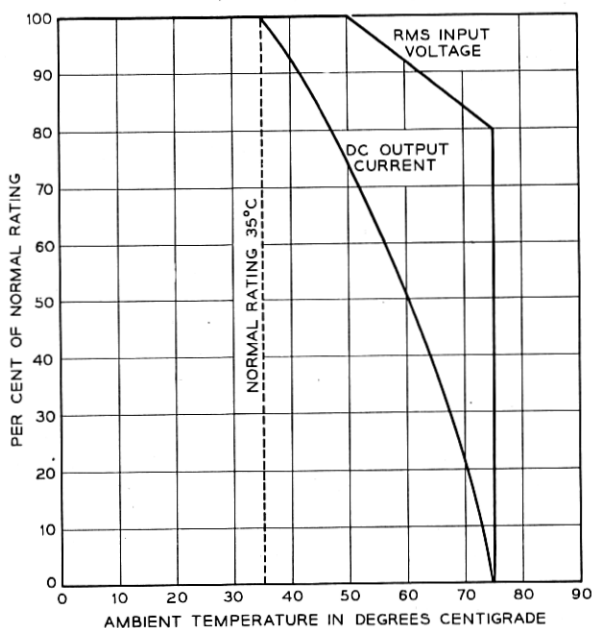

Fig. 2 — Temperature de-rating curves for long-life expectancy.

of characteristics in a given grade. More than one grade of cell may be assembled in a rectifier stack. The art of manufacturing selenium cells is such that, considering production over a yearly period, differences in the forward voltage drop at rated current may vary as much as ±30 to 50 per cent from the mean value. In the reverse direction, a larger per cent spread exists in the reverse current, particularly in cells or stacks made by different suppliers.

Fig. 4 shows dynamic characteristics plotted on a linear scale to illustrate variations of the forward voltage and reverse current characteristics of selenium rectifier stacks that are processed by two different suppliers. Variation of this magnitude exist, not only from supplier to supplier, but also may occur in a particular suppliers' product.

Selenium rectifier stacks in common with other semi-conductor rectifiers, have a negative temperature coefficient of resistance in the forward direction. The forward voltage drop at a specified current decreases as the ambient temperature increases (see Fig. 5). In the reverse direction, the reverse current decreases as the temperature is lowered to approximately −20°C. Below this temperature, there is no apparent change in the current except at the higher voltages. At the higher voltages, the current again tends to increase.

STACK DESIGN

The dc output voltage-current characteristics for various ac input voltages of *basic* rectifier stacks (one cell per rectifying element) are represented in Figs. 6, 7 and 8. The data were obtained by maintaining a constant 60-cycle rms voltage at the stack input terminals and do not take into account transformer regulation or other regulating devices that may be used.

Fig. 6 shows the single phase full-wave bridge characteristics for *resistance* loads.

Fig. 7 shows the single-phase full-wave bridge characteristics for *battery* loads. It will be observed that, with single-phase circuits for a given dc output voltage, lower ac input voltage is required for a battery load than for a resistance load. Capacitor loading is somewhat similar in output characteristics to battery loading, but the value of output voltage is dependent upon the magnitude of the capacity, the quality of the capacitor, and the current drawn by the load. For battery loading, the output voltage is dependent upon the type of battery, the condition of the battery, the battery voltage and the charging current rate required.

For these reasons, it is difficult to accurately predict the exact input-
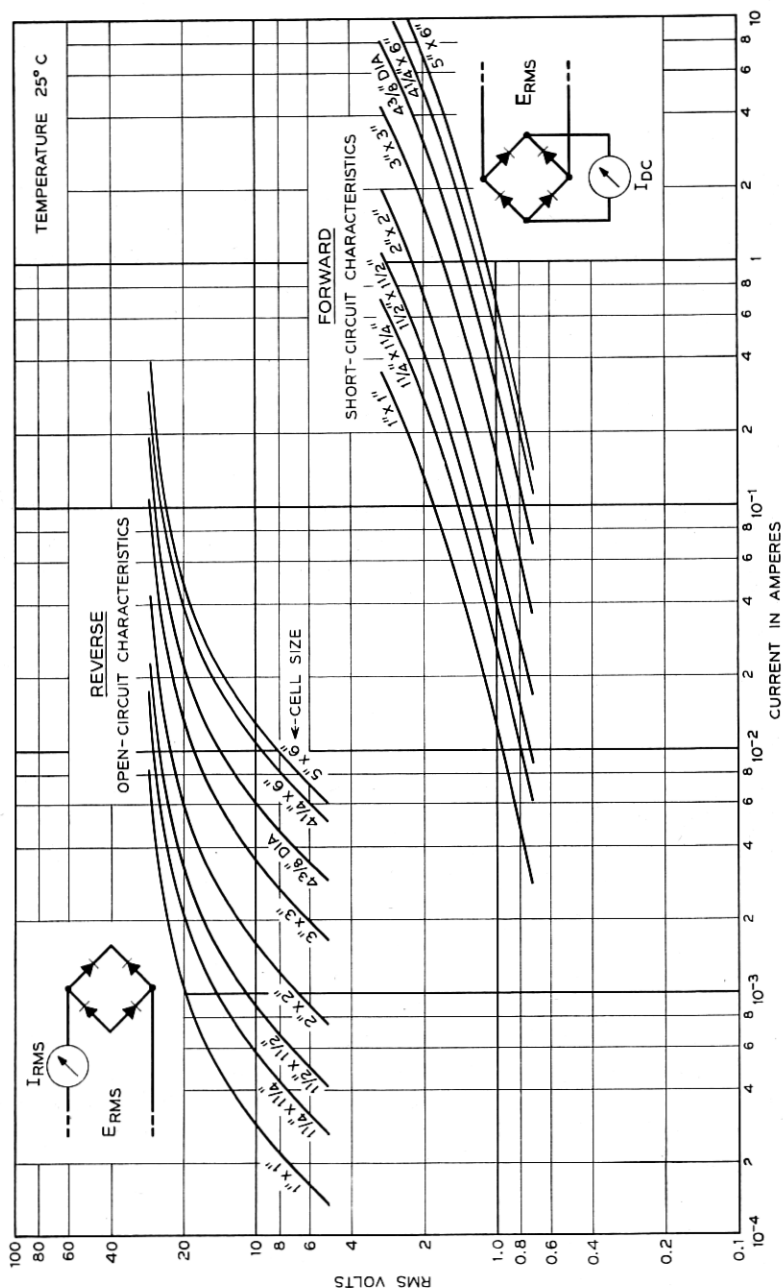
Fig. 3 — Typical dynamic voltage-current characteristics of 4-1-1B stacks with 26-volt cells.

output characteristics of stacks on capacity or battery loads. For precise design information, laboratory tests under the specified conditions should be made to determine the actual slope of these characteristics.

Fig. 8 shows the characteristics for a three-phase full-wave bridge circuit. These characteristics apply to both resistance and battery loads.

To design a selenium rectifier stack, the following procedure may be used:

1. Refer to Table I for the dc output voltage rating for the particular circuit application.

2. For the specified dc output current select the proper cell size from Table II. (If the current exceeds that of a single cell, additional cells may be connected in parallel.)

3. The ac input voltage to the stack for the required dc output voltage and current is then obtained from Figs. 6, 7 or 8.

The following example illustrates this method of stack design.

Example: To design a single-phase full-wave bridge rectifier stack to supply 1.0 ampere dc at 48 volts into a resistance load. From Table I, the highest dc output voltage for a basic stack is 24 volts for cells rated
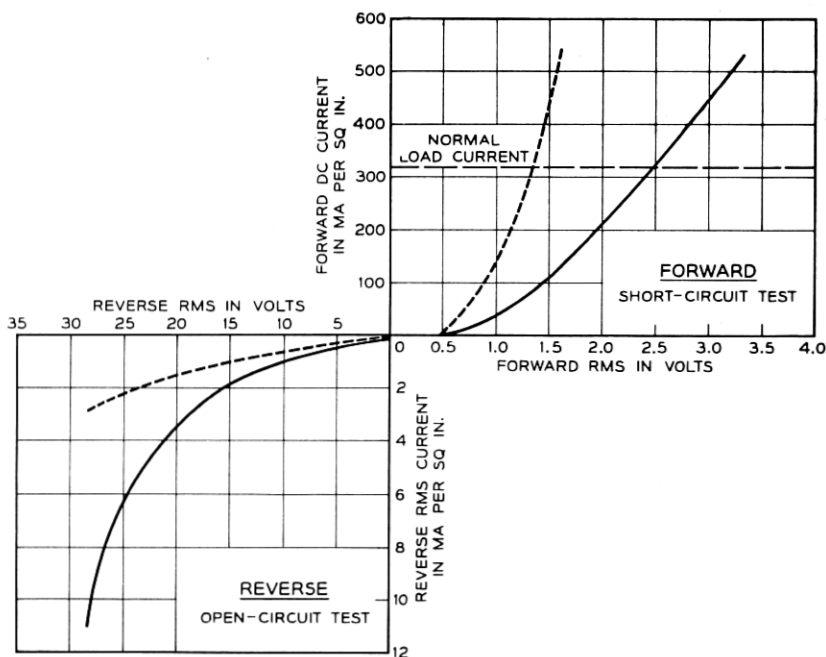

Fig. 4 — Typical dynamic voltage-current characteristics of 4-1-1B stacks with 26-volt cells processed by two different suppliers.

at 33 volts, rms. Therefore, $48\!/\!24$ or 2 cells in series in each of the four rectifying elements of the full wave bridge circuit will be required. From Table II, a 2-inch square cell is needed to carry the specified load of 1 ampere dc. As previously described under "Symbolic Notation," the rectifier stack would be designated as 4-2-1B combination using 8 cells.

Selenium cells rated at 18 or 26 volts rms also could be used, but the total number of cells in the stack would be increased as shown in Table III.

Obviously, the higher the cell voltage rating, the less total cells and consequently a smaller and lighter stack is obtained. However, other factors, particularly life expectancy, must be evaluated as described later in the text.

After the stack cell combination has been established, the required ac input voltage is obtained from Fig. 6. At 100 per cent normal load current (1 ampere dc from Table II) and 24 volts dc, the ac voltage for a *basic* stack is about 30 volts, rms. Since there are two cells in series in each rectifying element, 2×30 or 60 volts rms input voltage would be required for a new stack.

If cells rated at 26 volts rms are selected, three cells in series would be required. For the specified 48 volts dc output, $48\!/\!3$ or 16 volts dc per series cell, is obtained. Again referring to Fig. 6, an input voltage of 20.5 volts per cell or 61.5 volts total is required. This compares to 60 volts for the previous illustration. The higher input voltage results from the added voltage drop of the additional cells in the rectifier stack.

This stack design is satisfactory for operation in ambient temperatures not exceeding $+35°C$. For operation at higher ambients, the stack should be de-rated as shown in Fig. 2. For example, if the stack is required to operate in an ambient of $+60°C$, the dc output current rating would be 50 per cent of the normal rating. The 2″ square cell previously
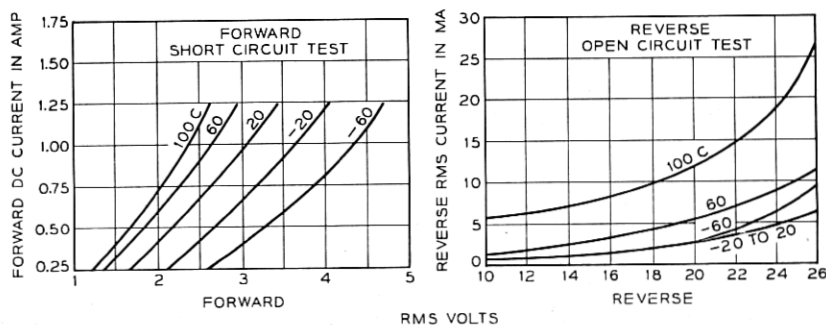

Fig. 5 — Temperature characteristics of 4-1-1B stacks with 2″ x 2″ cells rated at 26 volts rms and 1.0 ampere dc.
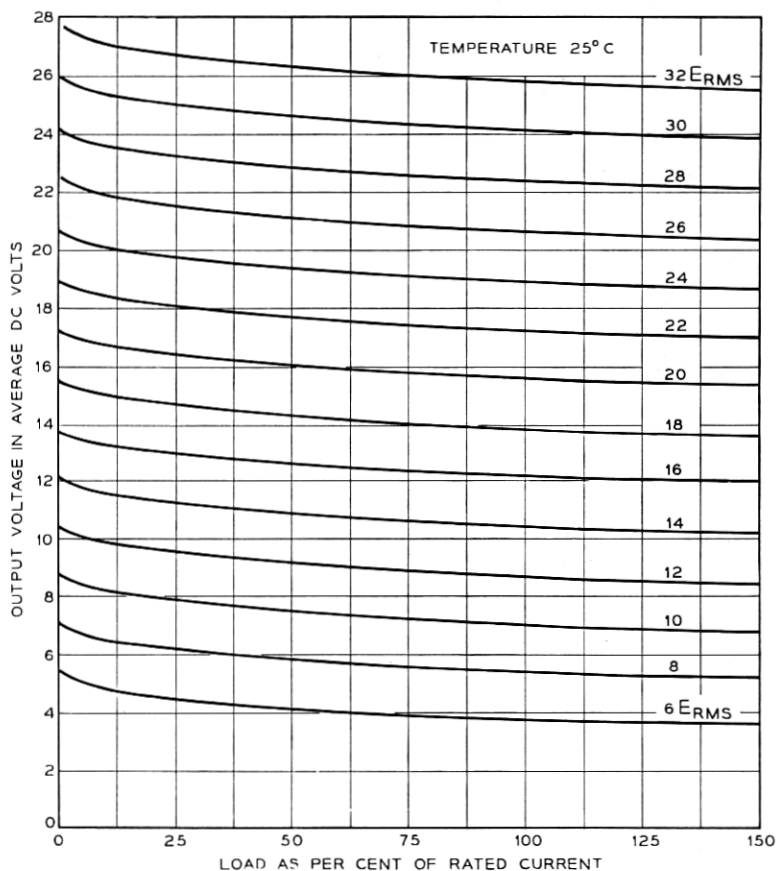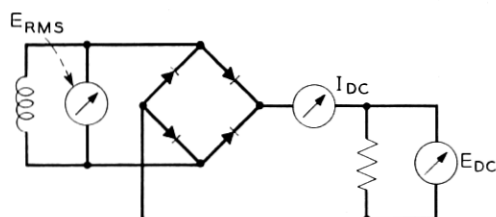
Fig. 6 — Typical output voltage-current characteristics. 60-cycle single-phase full-wave bridge circuit. Basic stack 4-1-1B. Resistance load.
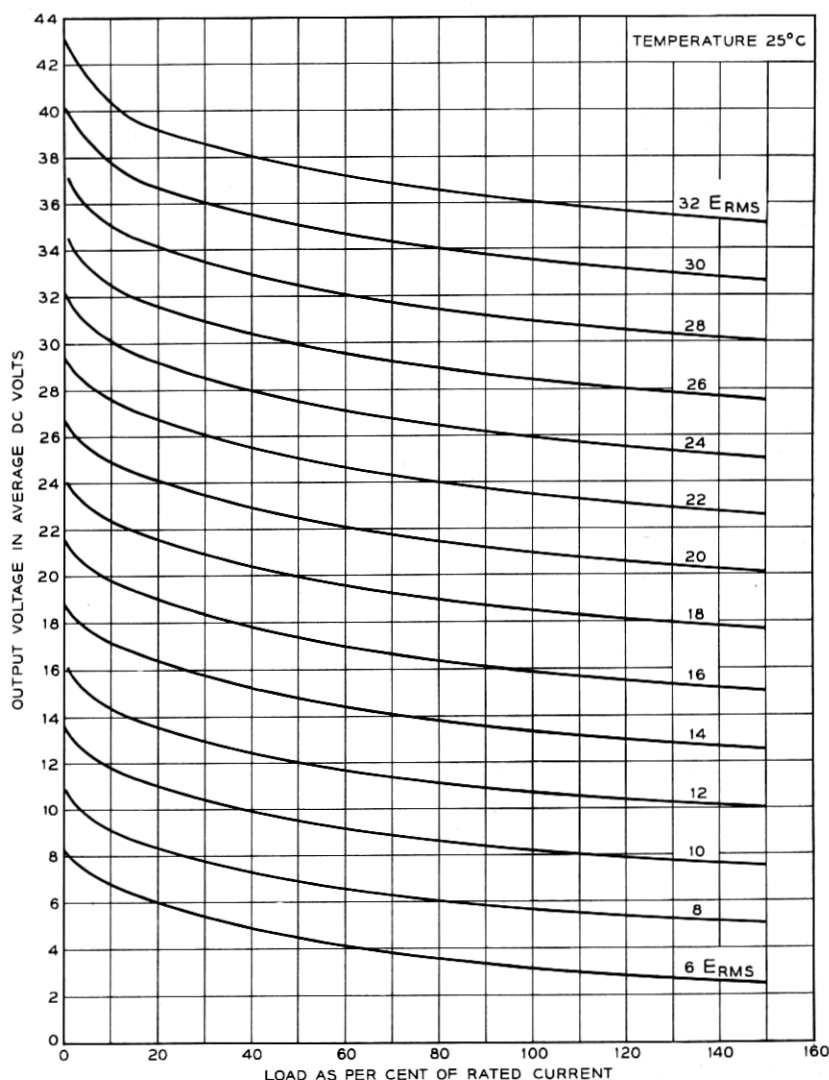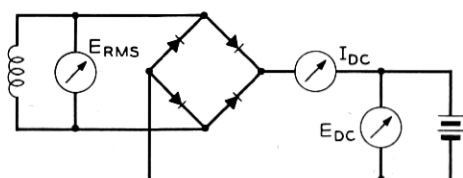
Fig. 7 — Typical output voltage-current characteristics. 60-cycle single-phase full-wave bridge circuit. Basic stack 4-1-1B. Battery load.
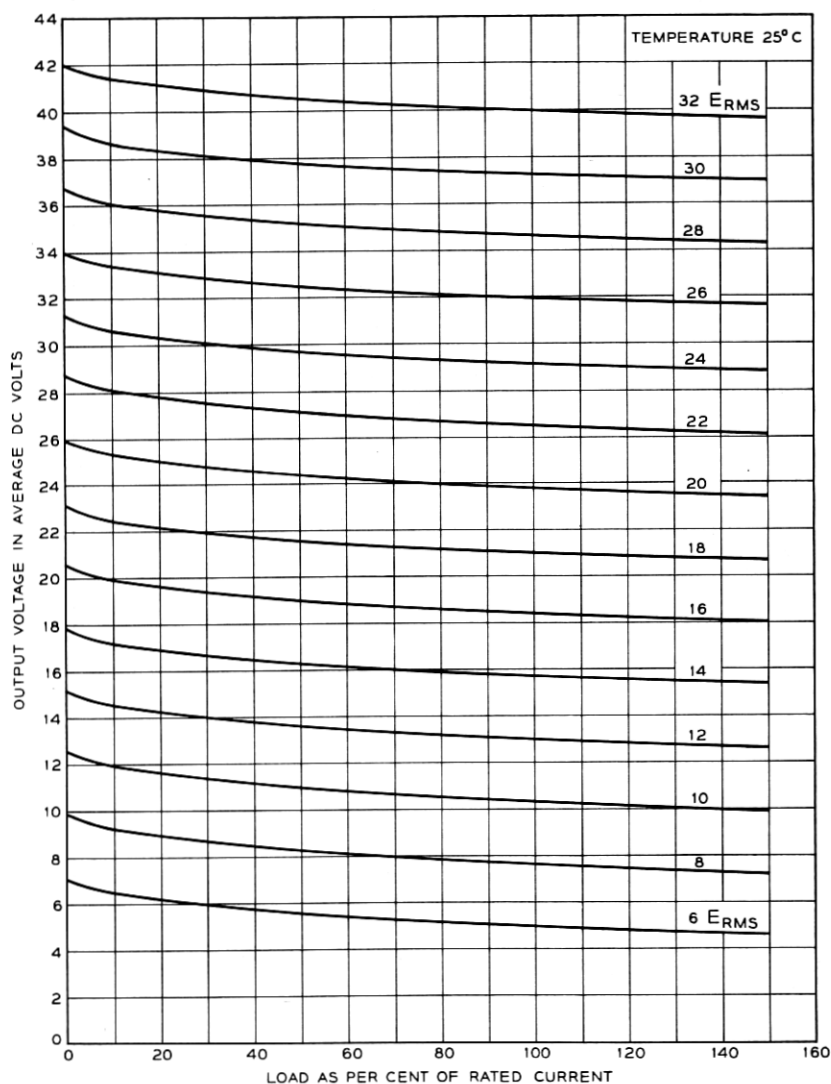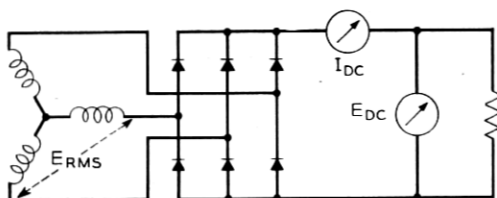
Fig. 8 — Typical output voltage-current characteristics. 60-cycle three-phase full-wave circuit. Basic stack 6-1-1B. Resistance and battery loads.

selected would now be rated at 0.50 × 1 or 0.5 ampere. Therefore, for the specified 1.0 ampere load, two cells in parallel are required or the next larger cell size, (3″ square) could be selected. The 3″ square cell would be rated at 0.50 × 2.2 or 1.1 ampere.

At 60°C ambient, the input voltage for new or aged stacks should not exceed 92 per cent of the normal rms voltage rating.

An alternative method of calculating the input voltage required for any stack cell combination may be obtained by the use of the formulas shown in Table IV.

Since the selenium rectifier stack is a non-linear device whose characteristics vary depending upon the circuit and operating conditions, the values given in Table IV are not precise but they are reasonably accurate for most design purposes.

To illustrate the formulas method, let us determine the input voltage for the previous example, that is, a single-phase full-wave bridge stack to supply 1.0 ampere dc at 48 volts into a resistance load. As previously determined, the stack cell combination would be a 4-2-1B circuit. The

TABLE III — STACK DESIGN

Cell Rating Volts rms.	Cell Combination	Total Cells
33	4-2-1B	8
26	4-3-1B	12
18	4-4-1B	16

TABLE IV — CALCULATING THE INPUT VOLTAGE REQUIRED FOR ANY STACK CELL COMBINATION

Rectifier Circuit	Formulae	K	
		Resistance Load	Battery or Capacity Load
Single-phase Half-Wave.....	$Eac = KEdc + nDV$	2.3	1.0
Single-phase Full-Wave, Center TAP*.................	$Eac = KEdc + nDV$	1.15	0.80
Single-phase Full-Wave Bridge...................	$Eac = KEdc + 2nDV$	1.15	0.80
Three-phase Full-Wave Bridge...................	$Eac = KEdc + 2nDV$	0.74	0.74

Eac = Stack input volts, rms.
Edc = Average dc output volts.
K = Circuit form factor.
n = Number of cells in series in each rectifying element.
DV = RMS forward voltage drop at specified dc output current (see Fig. 9).
* For center tap circuits, Eac is the voltage to the mid-tap on the transformer.
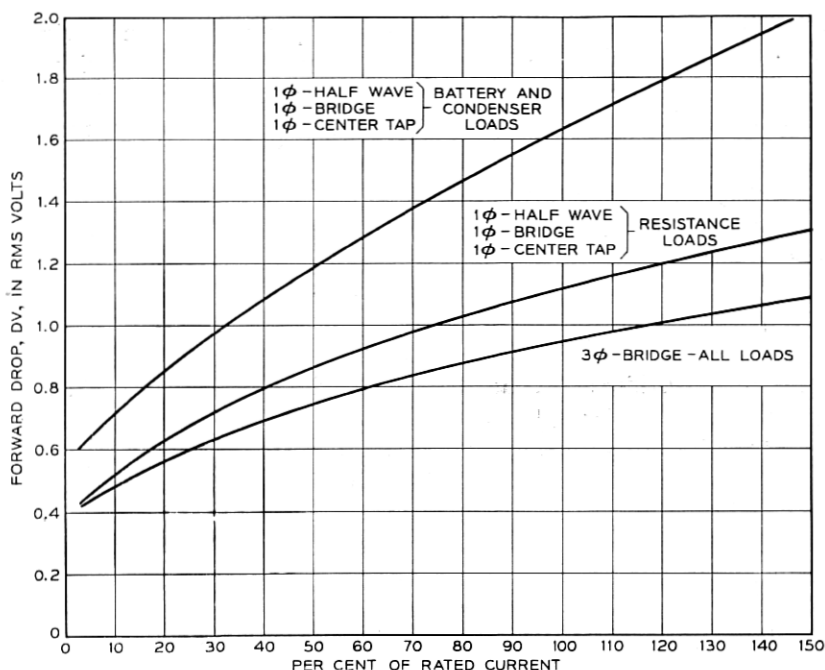
Fig. 9 — Dynamic forward voltage drop per cell.

forward rms voltage drop per cell (DV) obtained from Fig. 9 is 1.10 volts at 100 per cent normal rated current. From the formulas in Table III, the input voltage is:

$$Eac = 1.15Edc + 2nDV,$$
$$Eac = 1.15 \times 48 + 2 \times 2 \times 1.1 = 59.6 \text{ volts rms.}$$

This input voltage is required for a new or unaged stack. Since the stack ages under service operating conditions, additional input voltage will be required to maintain the original dc output. It is considered good practice to design for a 100 per cent increase in the initial forward voltage drop (DV) of the stack. The aged stack, then would require

$$Eac = 1.15Edc + 2(2nDV),$$
$$Eac = 1.15 \times 48 + 2(2 \times 2 \times 1.1) = 63 \text{ volts rms.}$$

The amount by which an increase of 100 per cent in the forward voltage drop or forward resistance will change the output is dependent upon the design of the circuit. It depends upon the ratio in per cent of the forward rectifier stack resistance to the total circuit resistance including

the transformer, ballast, load, etc. For most practical design considerations, one or more aging taps on the input transformer to provide 5 to 10 per cent additional voltage, will compensate for the forward aging.

It should be emphasized that the curves in Figs. 6, 7, 8 and 9 are based upon empirical data obtained on new rectifier stacks and the characteristics will vary slightly depending upon normal manufacturing variations in the voltage current characteristics mentioned earlier in this article.

AGING

Selenium rectifier stacks are subject to aging. Aging is defined as any persistent change (except failure) which takes place for any reason in either the forward or reverse resistance characteristics. The important factor in selenium rectifier aging is the increase in the forward voltage drop which results in a decreased dc output. For normal rectifier applications aging of the reverse current is not critical.

For design purposes, a selenium stack is considered to have reached the end of its useful life when the stack input voltage required to maintain rated output voltage exceeds the rms reverse voltage rating assigned by the manufacturer. Operation beyond this limit will result in overheating of the selenium cells and rapid failure of the stack.

The extent and rate of aging of selenium stacks cannot be predicted mathematically. Aging characteristics must be determined by actual test involving lengthy time consuming projects. To determine whether a given rectifier stack will give satisfactory performance for five years, as an example, tests would have to be conducted for this period. Aging can be accelerated by operation at high temperatures or at load currents above normal, but no accepted correlation exists between this type of aging and that obtainable under normal operating conditions.

Aging data were obtained on sample rectifier stacks obtained from different manufacturers in this country. The samples were set up on life test racks as single phase full wave rectifiers and were operated continuously at normal room ambient temperatures. For the duration of the tests, the 60-cycle ac input voltage to the stacks was kept constant at approximately 10 per cent below the maximum rms voltage rating. The stacks operated into a resistance load. The resistance was selected so that the rectifiers operated at rated dc load currents. The resistance was not changed thereafter.

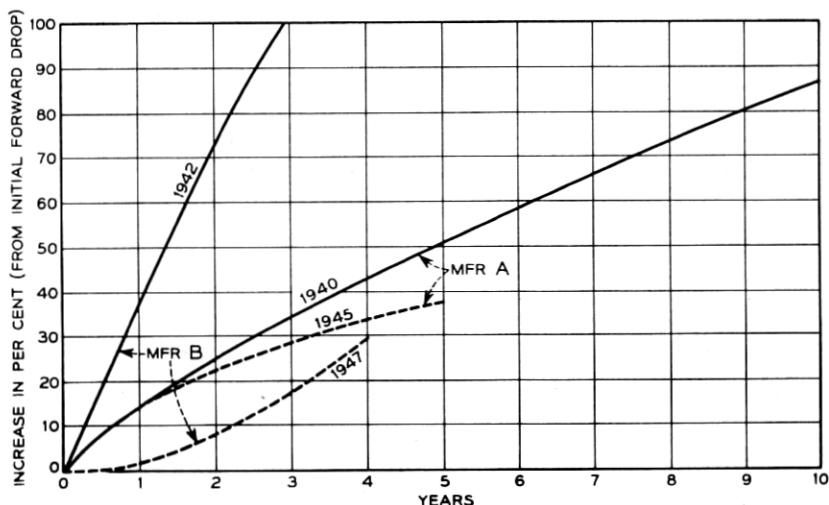Long term forward aging characteristics of selenium rectifier stacks

Fig. 10 — Forward aging characteristics of 18-volt cells.

assembled with cells rated at 18 volts rms are shown in Fig. 10.* After 10 years (approximately 90,000 hours) continuous operation, the forward drop on one supplier's product increased approximately 90 per cent. A second supplier's product increased 100 per cent in 3 years under similar operating conditions. Further development programs by each manufacturer resulted in improved aging qualities as indicated by tests made on stacks obtained at a later date.

By introducing changes in their manufacturing techniques, the industry eventually increased the voltage ratings to 26 volts rms per cell. This change in processing, however, raises the question — how has the operating life been affected? Fig. 11* clearly illustrates that although many manufacturers are commercially producing 26-volt cells, the life expectancy is vastly different.

In order to save space, weight and critical materials, manufacturers are attempting to produce cells with still higher voltage ratings. Most companies have had a 33-volt cell development program under way for some time, but again the problem of aging must be considered. Fig. 12* compares the forward aging of 26- and 33-volt cells after 5,000 hours operation. It is evident that in all cases except one, the 33-volt cells age substantially faster than the 26-volt cells. The exception is manufacturer "E" who has not produced 26-volt cells but has commercially processed

* The designations A, B, C, etc. shown on all aging curves are not to be interpreted to represent the same manufacturer's product on each of the figures.
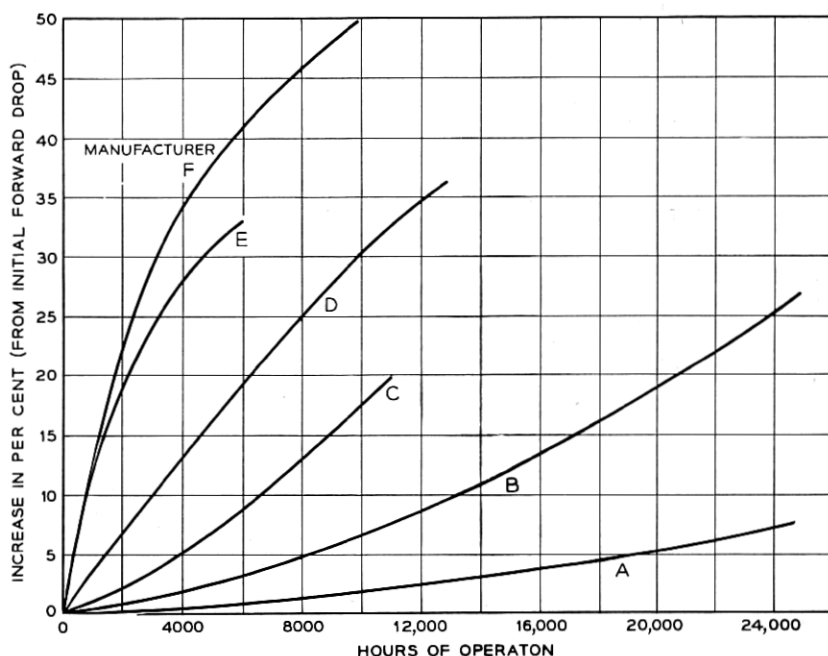
Fig. 11 — Forward aging characteristics of various suppliers 26-volt cells.

33-volt cells for several years. Again, there is a wide difference in the rate of aging in the various manufacturers' products.

Continued aging tests on stacks made by manufacturer "E" show that after 21,000 hours of continuous operation, the forward voltage drop has increased only 8 per cent. Extrapolation of these data indicate a life expectancy of thirty years.

It should be emphasized that the data on the 33-volt cells, with the one exception, were taken on experimental stacks obtained from various companies while they still were in the research and development stages of processing the 33-volt cell. Undoubtedly, further development programs on this type of cell will result in improved aging qualities.

Fig. 13 shows clearly what happens to the aging rate as manufacturers attempt to increase still further the voltage rating. These data are based upon 26-, 33- and 40-volt cells made by one supplier who is commercially producing cells with these ratings. The aging rate is accelerated greatly as the voltage rating is increased.

All the foregoing aging data were taken on stacks operated at rated load currents. A longer operating life may be expected if selenium stacks are selected to operate at lower load currents. As shown in Fig. 14, the aging

at 50 per cent normal current rating is about one half that at rated current. Above normal rating, the aging is accelerated to a greater degree. These data were obtained on a particular supplier's stacks with 26-volt cells, but similar behavior has been observed on other suppliers' products, including stacks assembled with 33- and 40-volt cells.

The behavior of the reverse current during these aging studies indicates that the reverse current generally decreases slightly during the first few months of operation and then remains substantially constant thereafter. A few manufacturers' rectifiers, however, show the opposite effect. The current rises slightly before leveling off. For normal dc power applications, these changes are insignificant.

As previously discussed, selenium stacks are rated for operation at +35°C ambient temperatures and should be derated at higher ambients for normal life expectancy. However, the problem frequently arises — what life can be expected at high ambient temperatures and why cannot aging qualities be predicted over a short time interval under accelerated conditions, such as high ambient temperatures? Fig. 15 shows data obtained on four different suppliers' product when operated at a +80°C ambient temperature. The temperature of the selenium cells under these conditions (ambient plus temperature rise) is about 100°C. For comparison purposes, data are included for similar stacks aged at normal
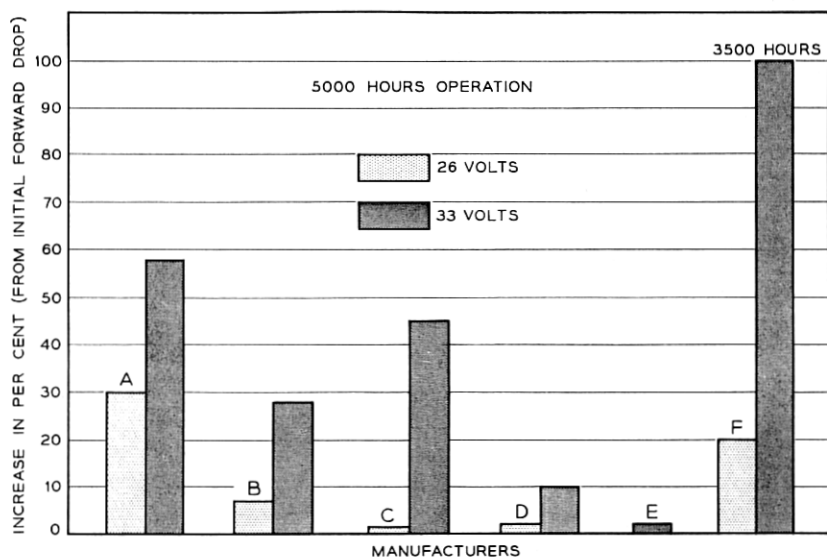

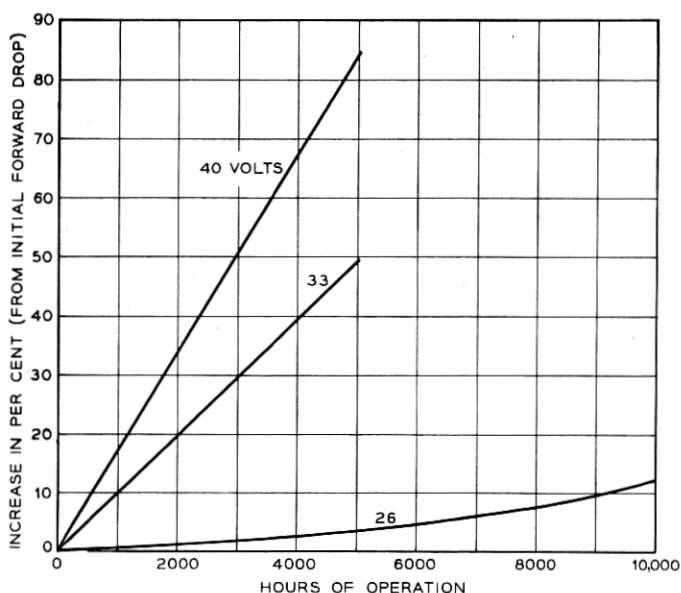Fig. 12 — Forward aging characteristics. Comparison of 26- and 33-volt cell ratings.

Fig. 13 — Forward aging versus cell voltage rating.

room temperatures. It is readily evident that at +80°C ambient (1) the forward aging rate is increased (2) the different manufacturers' stacks age at different rates and (3) there is no definite correlation of the aging rate with normal operation at room temperature. As previously mentioned under room temperature operation, longer life can be expected if stacks are operated at reduced current loads. At 80°C ambient however, three of the four manufacturers' stacks aged as much at half load as at full load.

CONCLUSIONS

The development and use of selenium rectifier stacks in this country has been quite rapid in the last ten years. The voltage ratings per cell have increased from 14 volts rms to 26 and 33 volts on a commercial basis. The trend in the selenium industry seems to indicate that cell voltage ratings will be further increased.

The proper selection and procurement of selenium rectifier stacks and their application to dc power supplies for large scale industrial or military projects usually require considerably more information than can be obtained from published data in manufacturers' catalogs. Considerable differences have been observed in the performance of similar stacks
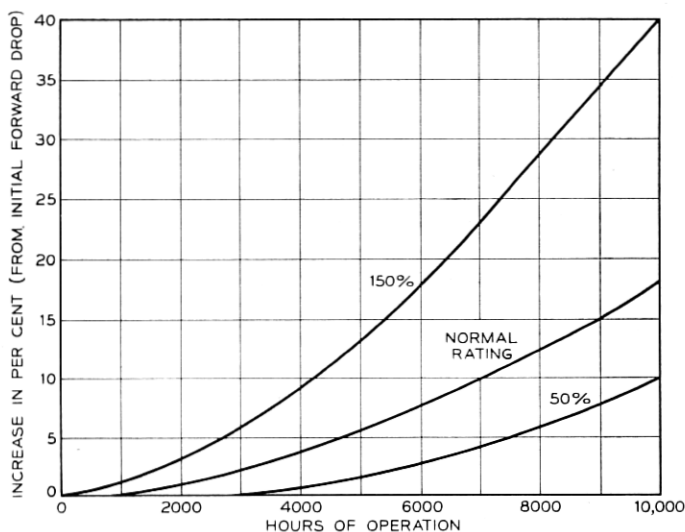
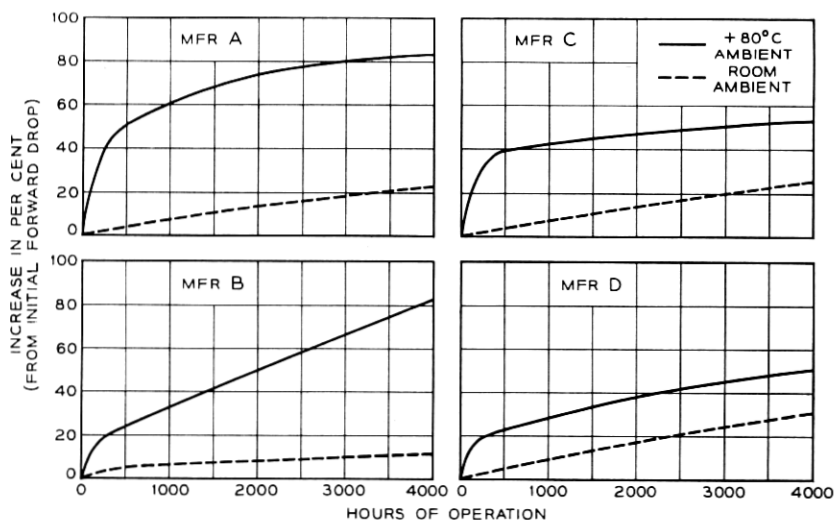Fig. 14 — Effect of load current on forward aging.

Fig. 15 — Forward aging characteristics. Comparison of room and +80°C ambient temperature operation. 26-volt cells, resistance load, rated dc amps, input voltage — 80 per cent normal for +80°C ambient and 90 per cent normal for room ambient.

furnished by different manufacturers. To appraise properly the qualities of different manufacturers' stacks, the *stability of the life characteristics* should be considered more important than the initial characteristics.

There is very little information published by the selenium manufacturers regarding the life expectancy of their product. Aging appears to be directly related to the individual manufacturing techniques used by each supplier. The life of selenium rectifier stacks seem to decrease as the cell voltage rating is increased. Longer life can be expected if stacks are operated at load currents below the present ratings given in the manufacturers' literature.

Selenium rectifier stacks properly designed and conservatively rated can be expected to give satisfactory performance for 10 to 20 years. Careful consideration of the rate and extent of aging must be evaluated so that proper allowance may be made in the circuit design to obtain maximum life expectancy.

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