Developments in Trustworthy-Valve Techniques*

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IT HAS NOT been uncommon for designers of radio and radar equipment to state categorically that valves are inherently unreliable. Such criticism has been regarded with some scepticism by valve engineers, who have ample evidence of trouble-free operation of certain valves, such as those used in long-distance telephone repeater and carrier systems, and therefore were able to visualise suitably designed valves that could be manufactured by mass-production methods and yet give reliable operation under certain special mechanical conditions.

Valve-manufacturing methods are determined simply by the economics of supply and demand, and the valve maker must be sure that the many complicated piece parts that are used to build a modern receiving valve and the special finishing processes that are employed are all devised to secure ease of assembly and rapid exhaust so that the valves manufactured shall be salable. The standard of reliability possible is therefore commensurate with the price, and a delicate balance between these two has been maintained in a highly competitive market over the past twenty years. From the point of view of the engineer then, practical reliability is a flexible term that involves compatibility between the requirement and the price that the user is prepared to pay.

The acceptance of the fact that there were many usages where the low-price limitation imposed by the commercial radio and television market does not apply has permitted the valve engineer to embark on this quest for the better valve. It would appear that the urgency of the need has stampeded certain sections of the industry into crash action, which has often been based on questionable hypotheses—it has been argued that a valve is necessarily more reliable if it is a robust version of its commercial equivalent. This approach is crude and wasteful, and a scientific attack should be regarded as being the right one. Such an approach was made by establishing laboratory equipment that would simulate field conditions wherever possible. Then, having created a standard of testing by well-defined and repeatable methods, a comprehensive study was made of the electrical and mechanical performance of the valves for which special requirements existed.

1. *Special Testing for Reliability*

1.1 FIELD FAILURES

To establish suitable tests by which reliability can be measured it is necessary to get a proper understanding of the causes of valve failure. This may be done by analysing valves returned from various fields of usage.

The predominant failures are:—

A. Short circuits.

B. Disconnections.

C. Glass faults resulting in poor vacuum.

D. Heater faults.

E. Emission faults.

F. Noisy valves.

1.2 MANUFACTURING FAILURES

Examination of the methods of valve manufacture shows that failures may be attributed to two main causes, which we describe as "manufacturing variations" and "manufacturing errors."

The various possibilities that can occur in production may be illustrated in histogram form. In Figure 1, *A* shows the normal distribution of a particular parameter for a batch of valves when production is held in strict control, and *B* is the shift in distribution resulting from the uniform variation of any factor that influences a particular parameter. Such uniform variations occur when parts of the valve are manufactured either to the extremes of a tolerance or when processes are carried out for too short or too long a time.

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Figure 1C indicates an enlarged distribution caused by the relaxation of production control such as the use of components outside limits. The results characterized in *B* and *C* are attributed to manufacturing variations.

Figure 1D illustrates a condition where the bulk of the manufacture is satisfactorily controlled but a small number is out of limits. Such a case is caused by faults in production defined as manufacturing errors. These will vary with the efficiency of the plant and personnel and an example of such is the random accidental distortion of grids during assembly, resulting in high anode current at cut-off.

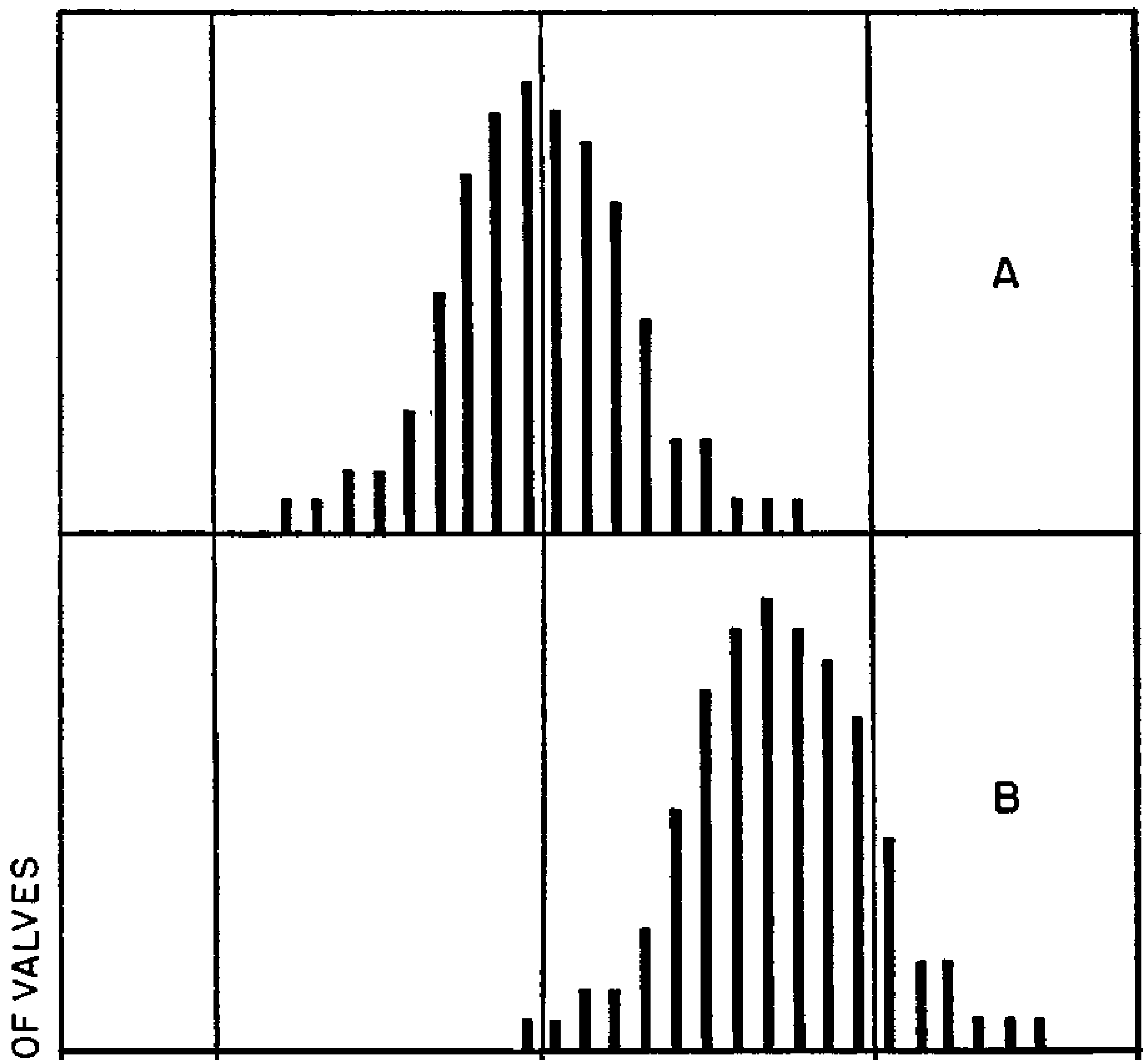

Figure 1—Histograms showing the distribution of a particular parameter in batches of valves as follows:

A—Normal condition with product in control.

B—The effect of a manufacturing variation with the product in control.

C—The effect of a manufacturing variation when the product is out of control.

D—Normal condition but with the inclusion of manufacturing errors.

It is obvious that to achieve reliability it is essential that all these causes be minimised and it is therefore important that methods of testing be devised to reveal and highlight them.

In this respect the manufacturing error is the more difficult to deal with because, unless the whole process of manufacture is suspect, faults attributable to a particular error rarely exceed 3 per cent. Nevertheless, this small order of faulty valves will contribute to the probability of catastrophic failure and therefore such valves must be removed and this can be done only by testing every valve.

In the case of manufacturing variations, it is possible sometimes to employ statistical methods of testing but in general the sample size required to ensure an adequately small customers' risk is so big a proportion of the batch that it is not worthwhile to attempt sample testing. To ensure that every valve lies in the required distribution it is desirable that each shall be tested individually. The batch quality is assessed from the number of rejections and a figure of 5 per cent has been set as the maximum permissible number to achieve the standard required. By careful planning it is usually possible to do this by the same tests that are used to check manufacturing errors.

1.3 Testing Procedure

A general testing procedure can be built up on the basis of the analysis of failures and the method of dealing with each fault will be discussed individually because the special tests necessary to improve the quality of the product by the elimination of errors and the control of variations depend on the nature of the particular fault. The tests required are given in Table 1.

1.3.1 *Short Circuits*

As a rule, short circuits are due to manufacturing errors, but cases do arise when they can be attributed to manufacturing variations.

They are either complete short circuits or transient short circuits that occur when the valve is struck or vibrated. All valves are therefore checked for both types of short circuit. The complete short circuit is usually rejected by tests prior to electrical characteristic testing, whilst the transient short circuit is revealed later on in the sequence of testing by excessive noise output developed across a suitable anode load resistor under 50-cycle-per-second vibration conditions.

TABLE 1

Basic Tests Required

Test	Purpose	Extent
Manufacturing Errors	To eliminate random faults in production	100 per cent
Manufacturing Variations	To control and eliminate faults caused by trends in production	100 per cent or statistical
Design	To ensure that the basic valve materials and the basic design remain unchanged	Sample

1.3.2 Disconnections

Disconnections are either permanent or intermittent and are dealt with at the same time as short circuits.

1.3.3 Glass Faults Involving Insertion Losses With Miniature Bases

Except where severe mishandling occurs, insertion loss during installation of the valve in its socket is caused by inadequate compressive strain in the base or by hard or misaligned pins.

Since glass bases are machine-made, any fault will be uniform within the batch and therefore design tests for pin position, pin hardness, and strain are sufficient. It is usual to inspect a sample from each batch for pin position and then to check for hard pins and poor strain by means of a standardized test that consists of a thermal shock to the valve base whilst it is stressed by a tapered metallic plug placed so that it distorts all of the pins outwards.

1.3.4 Other Glass Faults

Glass cracks are due to excessive strain in the glasswork or to internal or external fissures formed during manufacture and which develop at later stages. These glass faults include cracked bases, bulbs, and pips or "tip-offs." Since the product will contain both manufacturing variations and manufacturing errors, a test is designed to cover both types of fault; each valve in the batch is tested. This test consists of a double thermal shock; the valve is immersed in boiling water and allowed to warm for 10 seconds and is then thrust into water at 20 degrees centigrade. By this means, the internal and external fissures may be developed into cracks and usually the severely strained envelopes break as well. Typical of the results found with this test are the rejections shown in Table 2 on commercial-type valves produced by various manufacturers.

TABLE 2

Glass Faults Discovered By Thermal Test

Type	Per Cent Loss	Cause
6AL5	52	Cracked bases
6AM6	24	Cracked bases
1S5	21 27	Cracked bases Cracked tip-off
1R5	10 42	Cracked bases Cracked tip-off
6AM6	3	Miscellaneous
9D6	0·3	Miscellaneous

1.3.5 Heater Failures

The nature of a heater makes it liable to random manufacturing errors and therefore each valve must be checked. The test chosen consists of a sudden electrical overload applied in the cold state. The open-circuit voltage used is adjusted so that about twice the normal surge current flows and the time of testing is limited to about 7 seconds. This test will destroy all mechanically weak heaters that have been damaged during assembly and yet will not harm good valves. Typical results on valves of several types are given in Table 3.

In addition to this test, all valves are checked for heater–cathode insulation, which reveals both errors and variations, whilst a sample is taken from each batch for special switching life test. This switching test is arranged so that the heater is run for one minute and switched off for three minutes and is a design test that will reveal the quality of the materials used in the manufacture of the heater.

TABLE 3

Heater Faults Found By Test

Type	Per Cent Loss	Cause
9D6	0·5	Miscellaneous
9D6	1·0	Miscellaneous
12AT7	10·0	Uncoated leg too long

1.3.6 Emission Failures—Catastrophic Nature

Emission failure in early life may be due to a manufacturing variation or to manufacturing errors. As it is not usually possible to detect the probable failure by emission checks at the normal test point, a more sensitive means of indicating cathode activity is needed.

One method of testing includes a 48-hour stabilizing period during which the valve is operated under approximately class-*A* conditions. After this treatment, each valve is re-tested for electrical characteristics including emission at the test point. Not only are the space requirements for 48-hour life tests embarrassing when the production of thousands of valves is needed, but it is doubtful whether all catastrophic failures can be eliminated in this way unless the characteristics of each valve are measured before and after the life test and the results compared.

Tests on early life performance of valves have shown that the main variations of contact potential and emission occur in the first few hours. With most valve types, we have established that a life test of 3 hours is sufficient to give reasonable stability and if used in conjunction with a sensitive emission test on each valve it will reveal the potential failure. The method of assessing cathode activity is to adjust the heater voltage to give 1·5 watts per square centimetre of total cathode area and, with the grid of the valve at a low negative potential, to draw a space current of about 20 milliamperes per square centimetre of cathode area. Figure 2 shows the grid-voltage–heater-voltage relation for a radio-frequency pentode as being typical of the testing theory. Tests on valves show that where grid voltage is adjusted to maintain a steady space current then both manufacturing errors and variations are obvious after a 3-hour run. This is illustrated in Figures 3 and 4. In both of these cases, the reject valves were satisfactory at the normal test point and yet began to fail after about 100 hours of life.

1.3.7 Noisy Valves

Both manufacturing variations and manufacturing errors can be checked by measuring the noise output produced across an anode load with

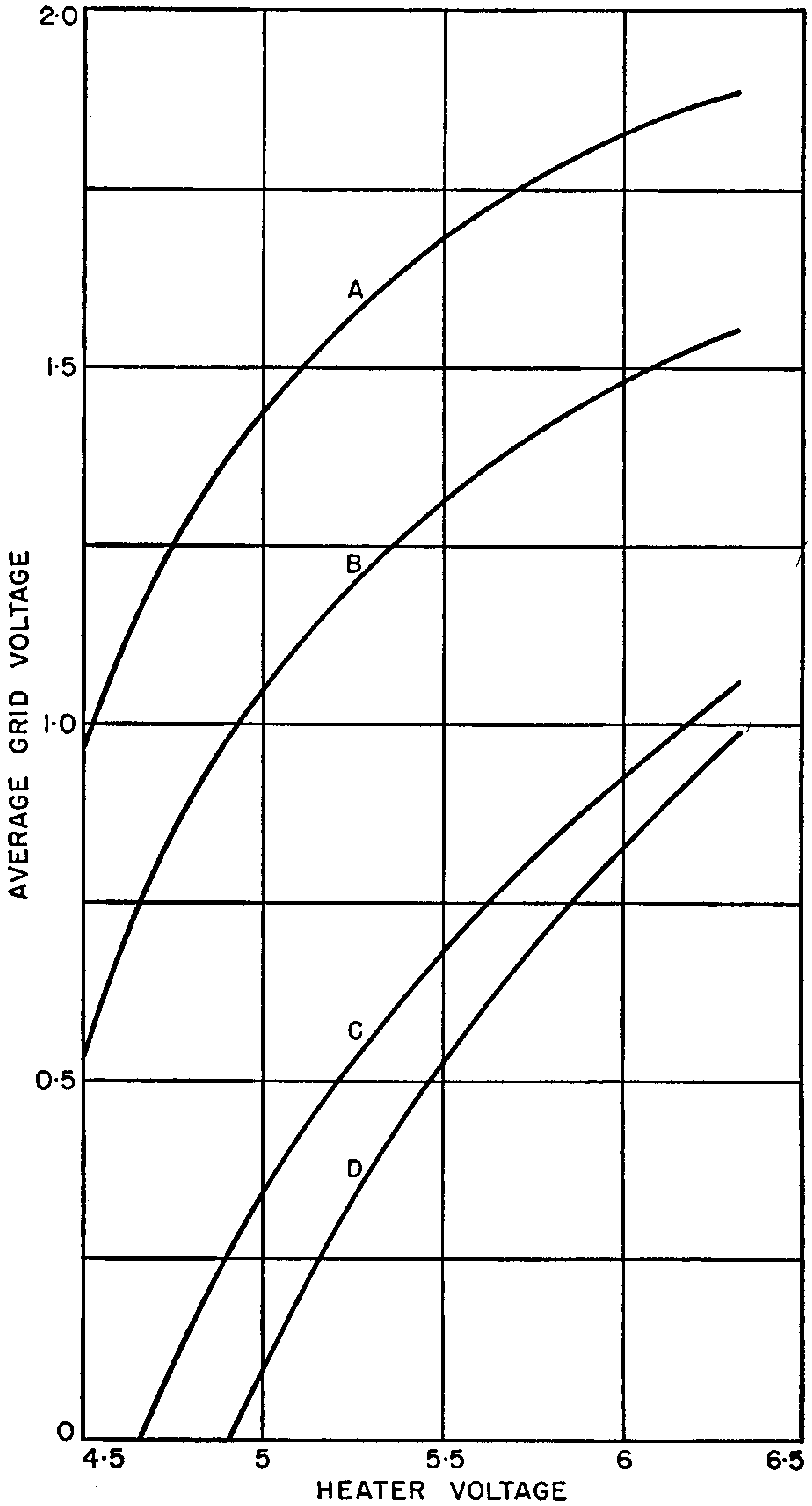

Figure 2—Curves of V_g against V_h for a constant I_a of 10 milliamperes in a *6AM6* valve. Curve *A* is initially, curve *B* after 20 minutes, curve *C* after 3 hours and 13 minutes, and curve *D* after 10 hours.

the valve operated under approximately class-A conditions whilst being vibrated at 50 cycles per second. Figure 5 shows the distribution within a batch of valves and illustrates how the manufacturing error is eliminated. When manufacturing variations affect the result the distribution becomes skew as in Figure 6.

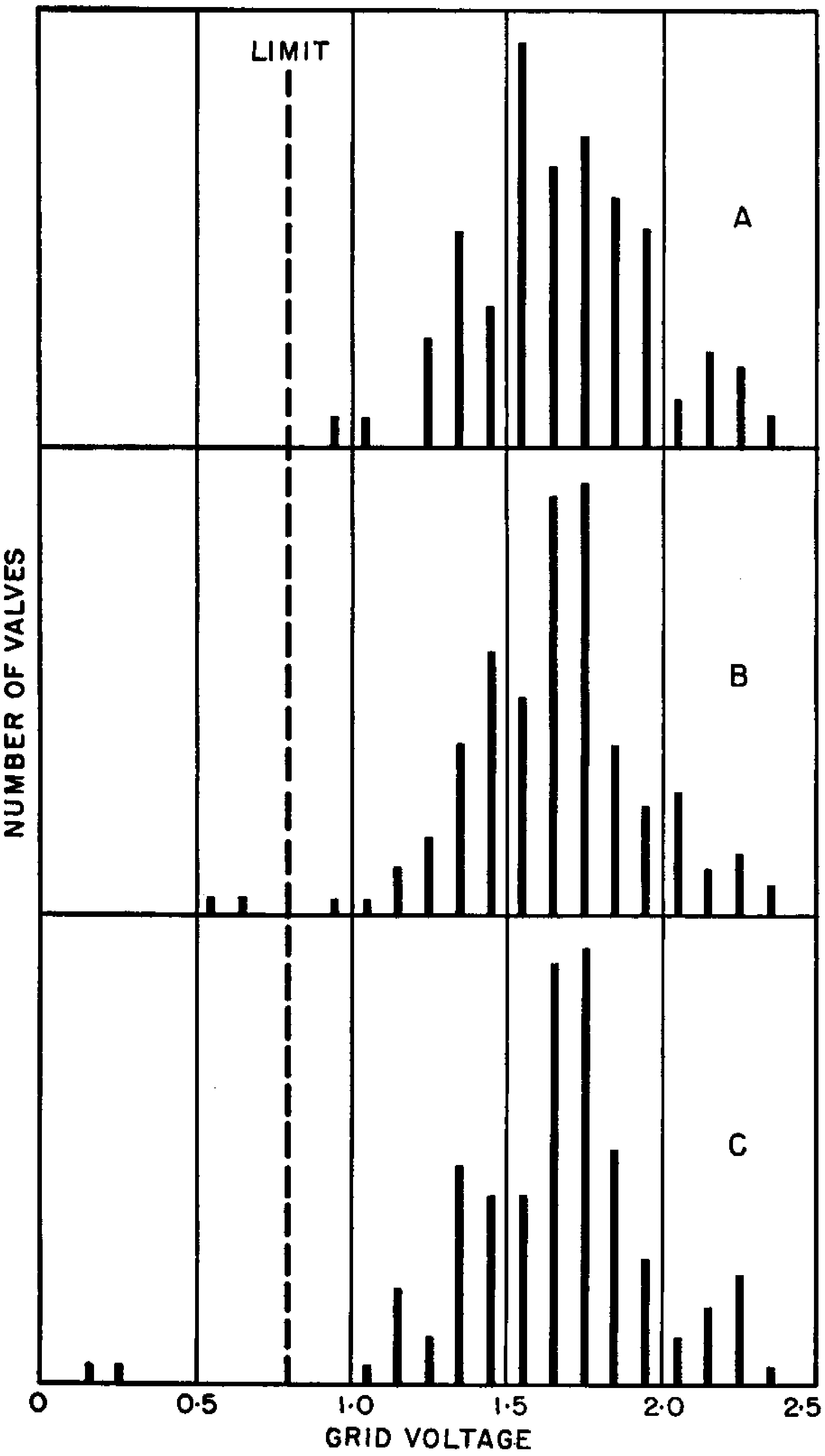

Figure 3—Histograms showing the grid voltage at constant anode current for a batch of *6AM6* valves operated at $V_h = 5 \cdot 1$ volts. Curve A is initially, B is after 3 hours, and C is after 10 hours. The valves suffering from manufacturing errors are revealed after 3 hours.

Test results show this method to be best for finding intermittent short circuits and disconnections, lint, et cetera.

1.4 Selective Tests Applied to Commercial Valves

The tests that have been described and the methods of analysis apply to the common faults that are met in normal usage. By employing these tests in addition to the electrical characteristic tests required to maintain a strict control over the product it is possible to select from normal commercial production a proportion of valves that have an improved reliability over normal manufacture. This is not at variance with the essential idea of valve reliability but rather supports it. For usage in equipments not liable to excessive mechanical vibration or shock,

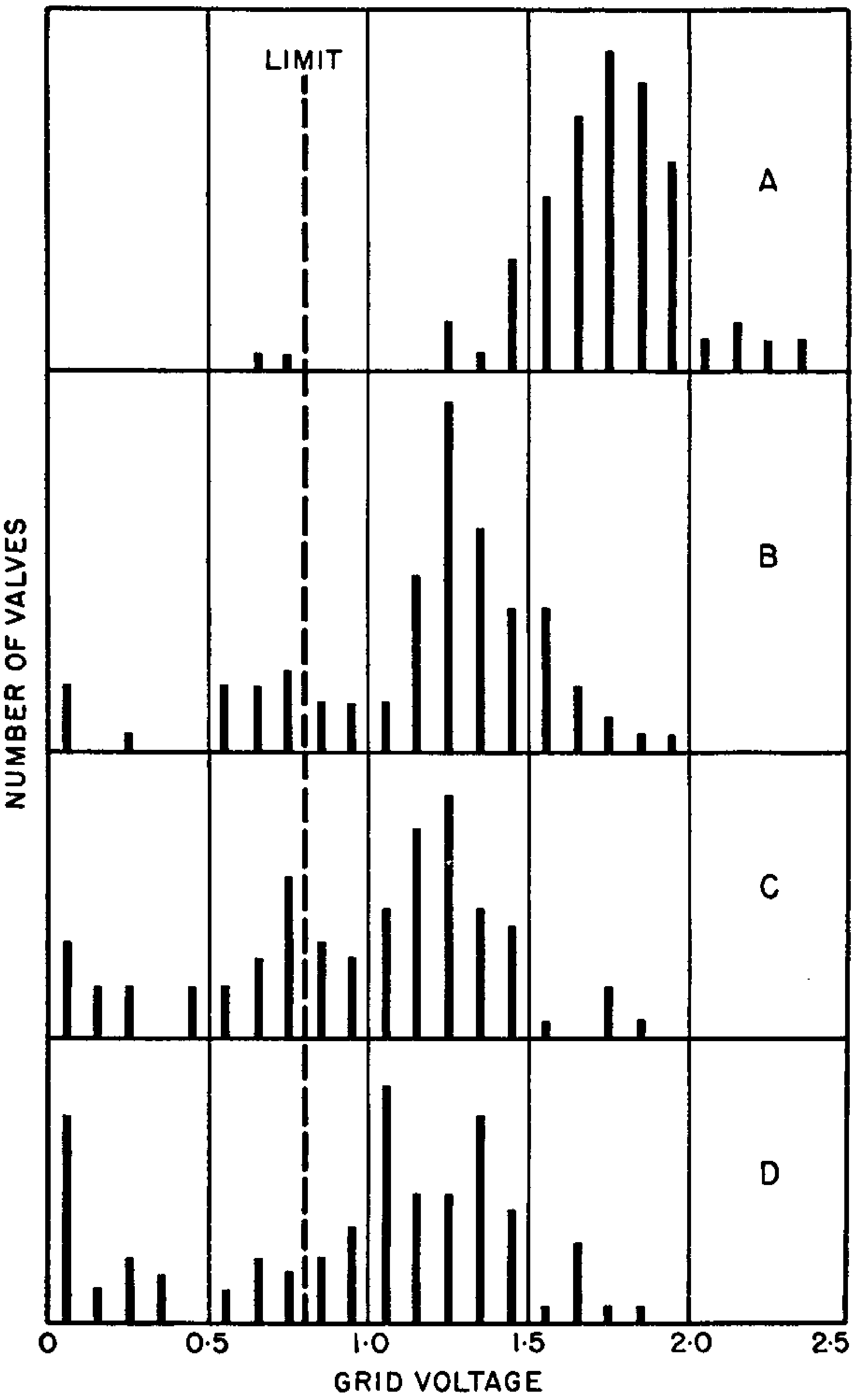

Figure 4—Histograms of grid voltage under conditions as in Figure 3 for a batch of *6AM6* valves suffering from a severe manufacturing variation. Curve A is initially, B is at 1 hour and 2 minutes, C at 3 hours and 13 minutes, and D is at 10 hours of life.

valves selected in this way give a high standard of performance that may be termed reliable. Even where mechanical movement is an essential requirement such valves show an improvement over the rejection rate of valves of unselected manufacture.

Experience with the selection of commercial radio valves by special tests has shown that in England it has formed a satisfactory interim measure before the fully reliable valves are freely available and from the engineer's point of view it has proved that the basis of reliable-valve production is controlled uniformity of the product. In this respect the use of statistical methods to determine the order of spread of characteristics and of histograms to show the effects of manufacturing errors have been found invaluable. Such an approach has led to the inevitable minor changes in commercial-valve design that have benefited the normal user and has permitted the specification of certain assembly criteria for the design of the fully reliable valve.

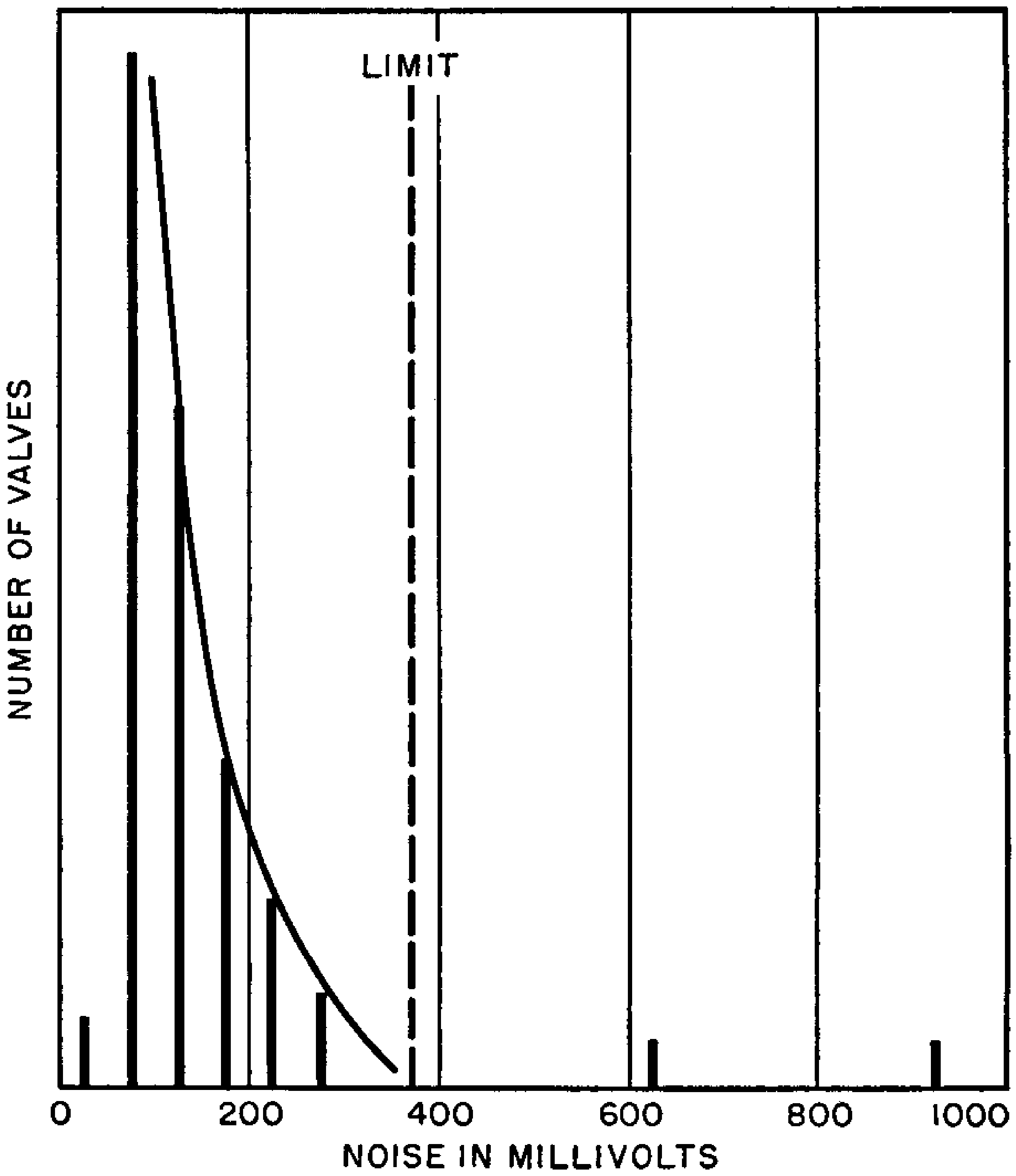

Figure 5—Histogram showing how manufacturing errors causing excessive noise may be detected by measuring the noise output developed across a 2000-ohm anode load with the valve vibrated at 50 cycles per second at an acceleration of 4*g*.

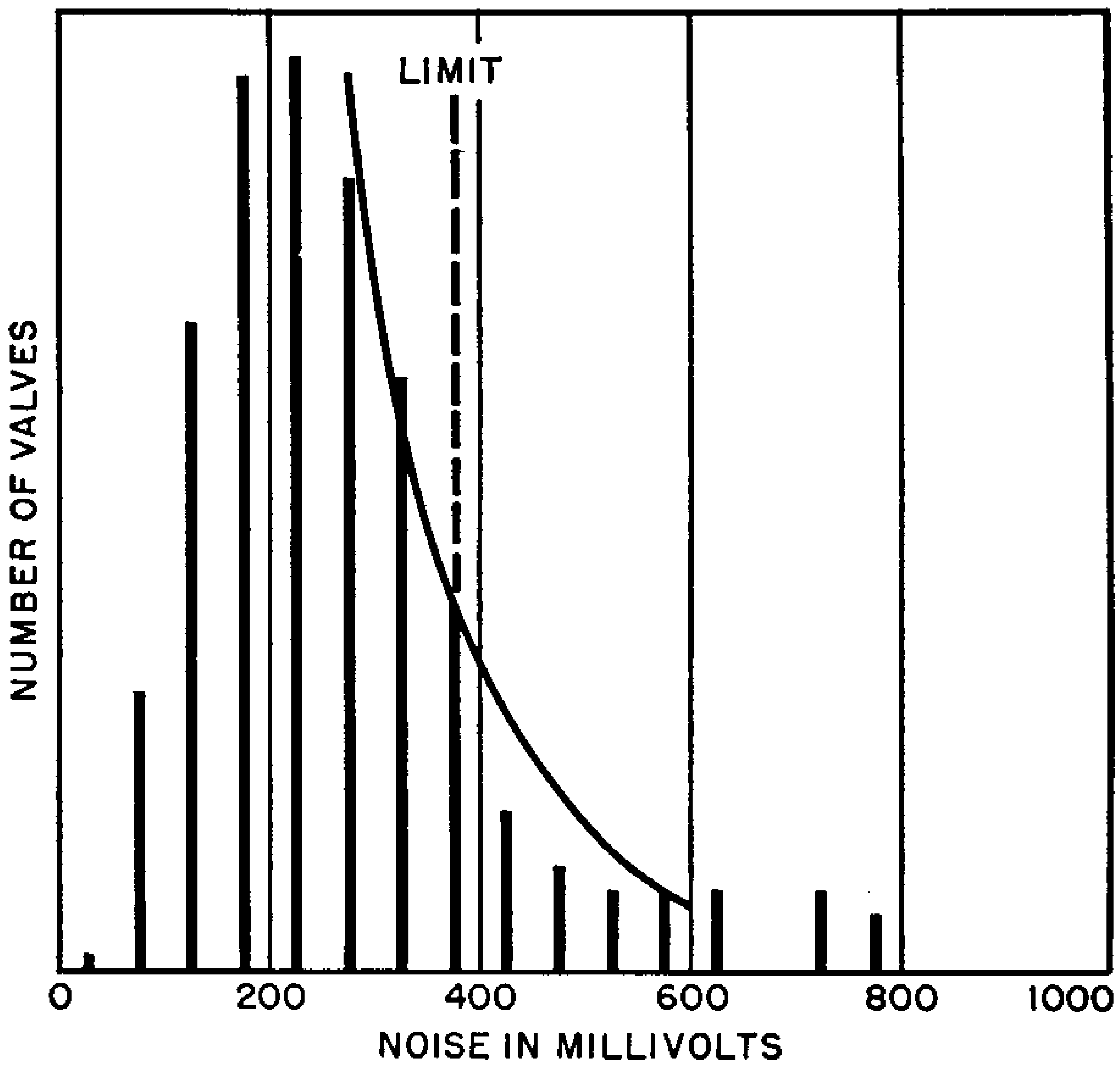

Figure 6—Histogram derived under the same conditions as Figure 5 but showing how manufacturing variations cause a larger spread of noise within a batch of valves.

2. *Special Tests for Trustworthy Valves*

2.1 General

If the only mechanical requirement for valves was that they should withstand a vibration of fixed amplitude, frequency, and wave shape, or a known repetitive shock, the design of valves to operate satisfactorily under such a particular condition would be relatively easy and the mechanical tests to check the initial engineering design and the quality of the product in mass production could all be conducted in a copy of the actual apparatus. The user would generally favour such a procedure, but valve engineers distrust such tests from bitter experience because, as the field of application of a valve increases, its behaviour must be known under many separate conditions, and such a method would result in a multiplicity of test equipments, each catering for a particular requirement. Unfortunately there has been a tendency for the earlier work on reliability to progress in this way and certain manufacturers have been cluttered up with mechanical test apparatus that gives an undefinable disturbance to the valve. Notable among such equipments are the many variations of mechanical bumper.

The principal mechanical requirements of the reliable valve are that it shall give noise-free operation under conditions of vibration, shall continue to operate satisfactorily after shock or high accelerations, and shall have a reasonable life under such conditions. In both the United States and Britain these requirements have been covered by a testing procedure consisting of a sinusoidal-vibration test and a resonance test for noise, a mechanical test for shock, and a continuous sinusoidal-vibration test for fatigue. It is necessary however to interpret the results of such tests similarly to the earlier analysis of field failures in order that the fullest use can be made of the information obtained during testing.

2.2 Noise Testing

A high noise output produced under vibration may be due to transient short circuits or disconnections, lint, loose electrodes, or to the fundamental vibration of the electrodes themselves.

Mechanical faults and lint constitute manufacturing errors that are minimized by close control over the valve-assembly procedure but as they represent a cause of valve failure they must be eliminated by testing.

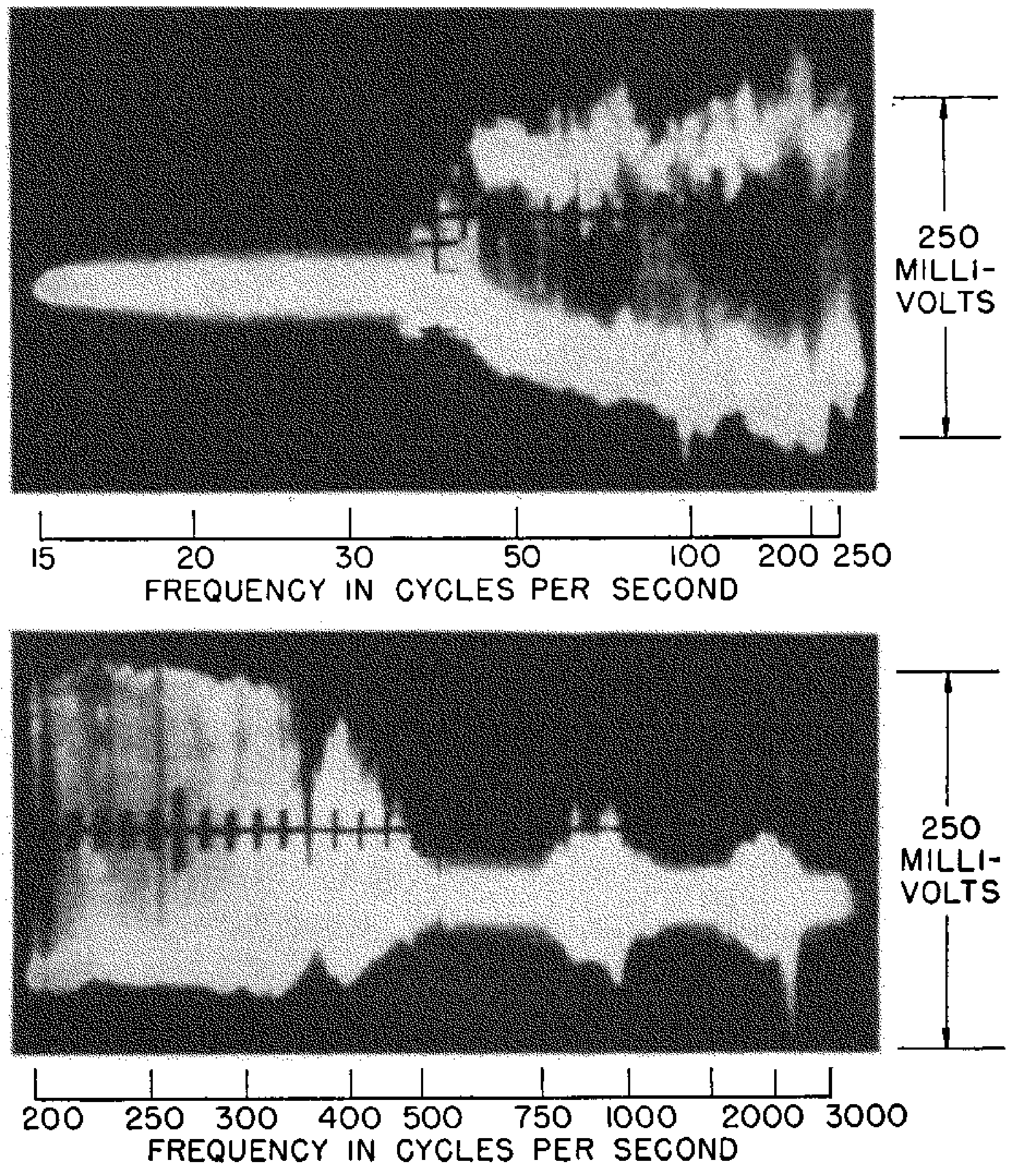

Figure 7—Noise spectrum of a miniature radio-frequency pentode.

Figure 7 shows the noise output from a typical pentode valve over the frequency range of 15 to 3000 cycles per second. The high noise output in the lower frequencies between 30 and 400 cycles per second is due to loose electrodes, which constitute a manufacturing variation.

The faults detailed above are adequately revealed by a 50-cycle-per-second vibration test with an acceleration of 4*g*.

The fundamental vibration of the electrodes is determined by their physical constants—dimensions and properties of the constituent materials—and once the design has been established it is important to check that the production does not vary from the prototypes. This is done by sample testing conducted on an electromagnetic transducer under controlled conditions. Such a machine is described by E. G. Rowe.[12]

Whilst this machine will permit detailed examination of noise output at resonance it is easier to test every valve by an audio-frequency feedback method in which the valve is placed in the first stage of a high-gain amplifier having a linear response characteristic from 15 to 3000 cycles per second and which is terminated by a loudspeaker facing free space. The valve is placed in front of the speaker, care being taken to ensure that there is no rigid connection between it and the speaker. As a production test the gain is preset and valves that cause the circuit to break into regenerative feedback are rejected. Figure 8 is a photograph of such an equipment whilst Figure 9 gives the gain distribution in a batch of pentode valves. The degree of repeatability of measurement with untrained operators is to within 1 decibel in a range from 60 to 80 decibels.

2.3 Shock Testing

The basic shock requirement is that the valve shall operate satisfactorily during and after a high acceleration and therefore it is important that the definition of shock shall be concise so that correlation with users' equipment is possible.

The behaviour of the valve under shock is a design feature because failures are due to the movement and distortion of the electrodes, which

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[12] References will be found in the bibliography, section 7.

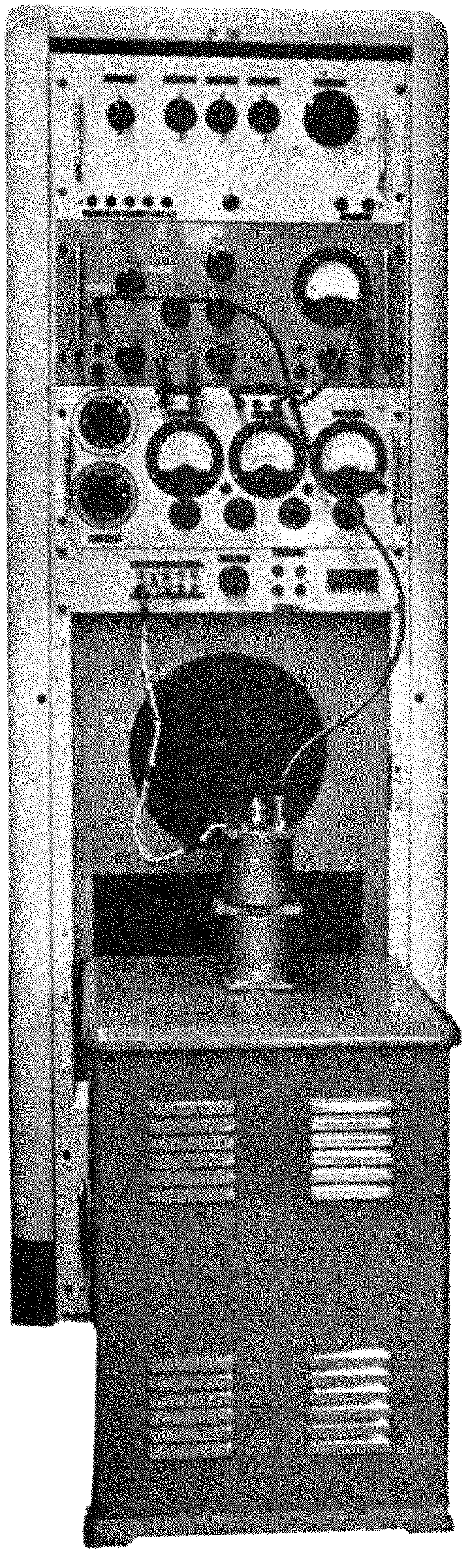

Figure 8—Audio-frequency-feedback test gear. This apparatus is simple to operate and provides a rapid production test for noise caused by electrode vibration.

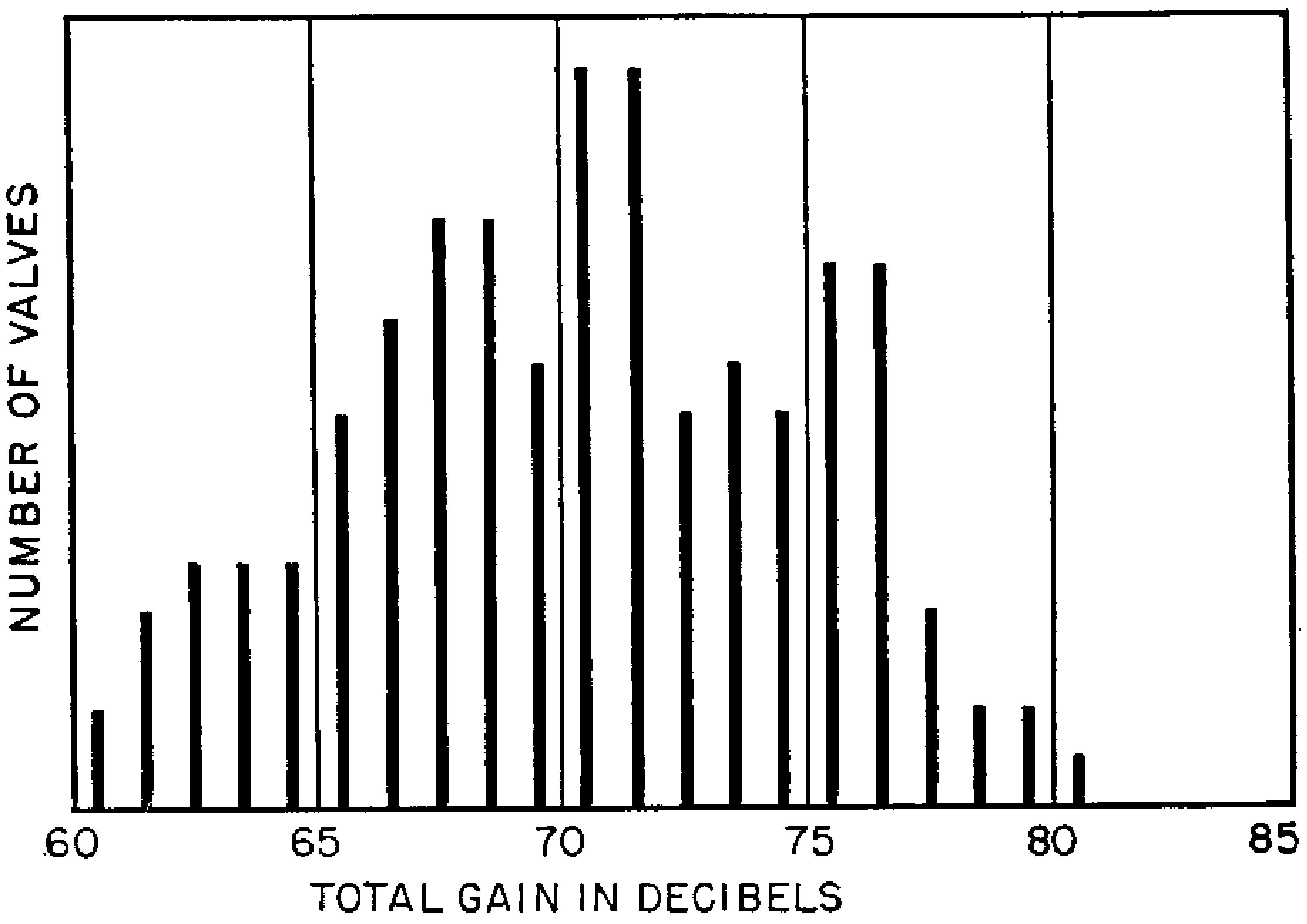

Figure 9—Gain in decibels required to start regenerative feedback with the valve 8 inches (20 centimetres) from the speaker and in a position giving a resonance for a batch of high-frequency pentodes. The mean value is 70·3 decibels.

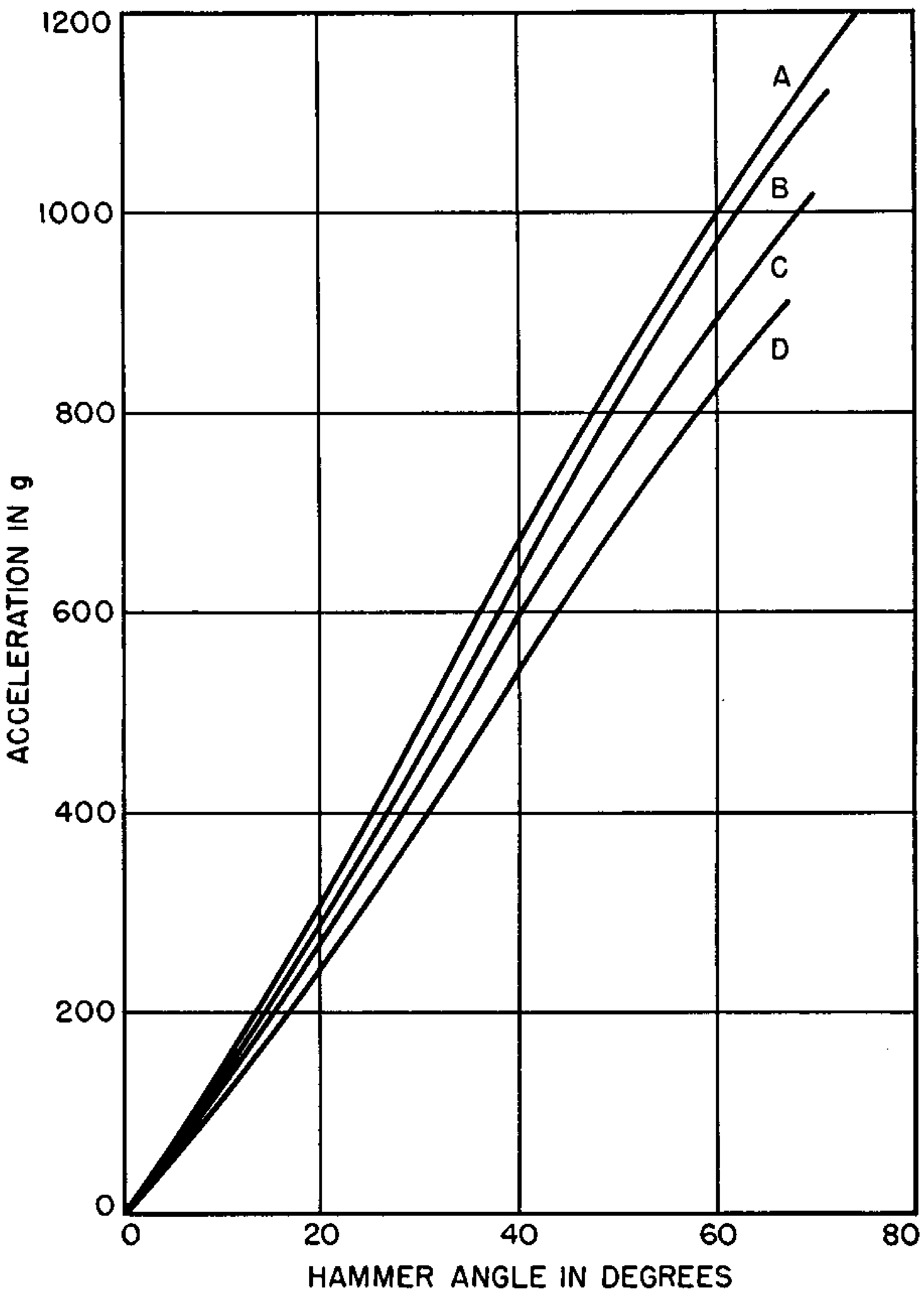

Figure 10—Calibration of a Taft–Pierce high-impact shock machine. The method of mounting is significant and *A* is for the table alone, *B* is with phosphor-bronze clamps, *C* includes a layer of felt, and *D* is with a thin rubber lining.

are dependent on the physical properties of the materials of which they are made. The apparatus used for performing the acceleration test is a modified form of the Taft–Pierce shock machine and has been described by R. J. E. Whittier[13] and others. Calibration of the machine is best done by using a parallel-plate capacitor with one plate connected to the moving table and the other to the frame, this being more accurate than the crystal methods.

Figure 10 shows an acceleration chart for such a machine and, as the method of holding the valve influences the acceleration it actually receives, correction factors are given for various mountings.

2.4 FATIGUE TESTING

Each individual user has his own conception of the critical frequency for fatigue testing. In addition to this complication is the fact that the actual frequency measured on any particular application is rarely sinusoidal and yet from an engineering standpoint it is desirable to correlate all vibrations to a sinusoidal movement.

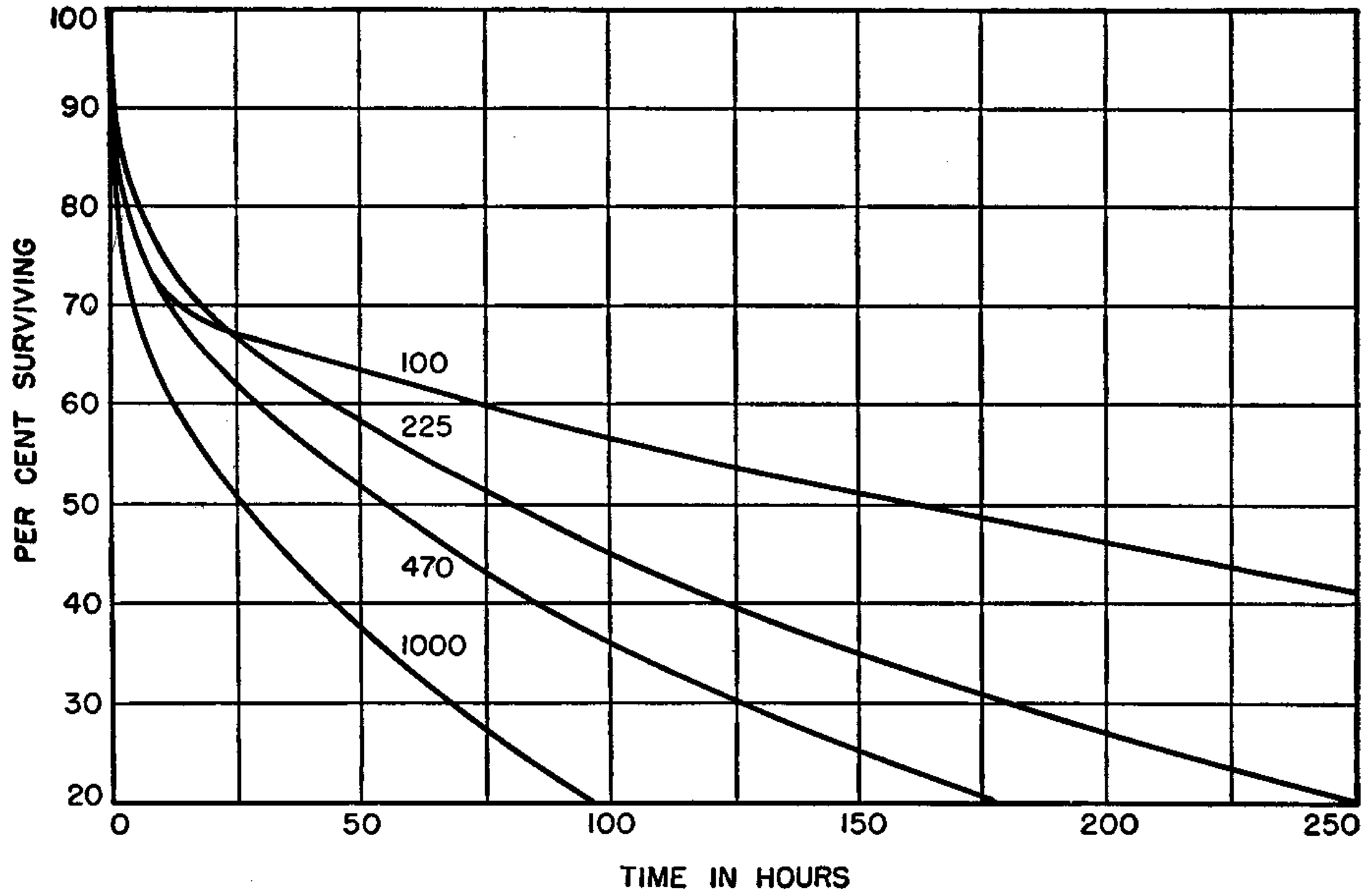

Figure 11—The survival rate for samples of 100 valves each from a batch of high-frequency pentodes measured at different frequencies as indicated on each curve. The acceleration in every case was $4g$.

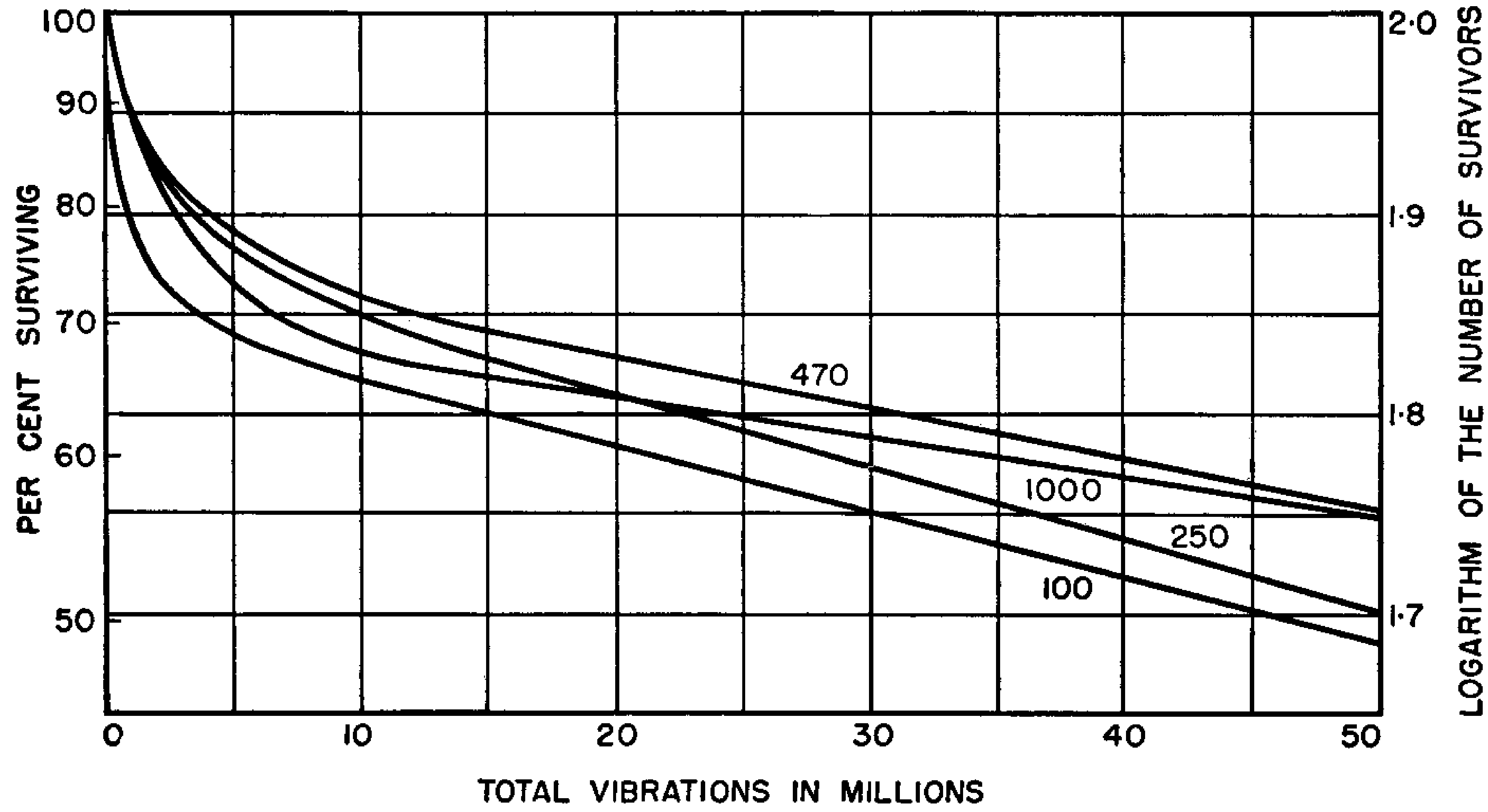

Figure 12—Showing Figure 11 replotted as the logarithm of the percentage survivors against the number of vibrations. The frequency of vibration is indicated and it is clear that the curves are quite similar.

Tests have been conducted on valves of commercial manufacture at frequencies of 1000, 470, 225, and 100 cycles per second whilst the valves were being operated and continuously monitored for noise and anode current. These tests show that the survival curves all have the same general shape as may be seen in Figure 11. By redrawing these diagrams as functions of the number of vibrations (Figure 12), it is clear that valve failure becomes independent of frequency, provided the acceleration is constant and that the excitation frequency does not

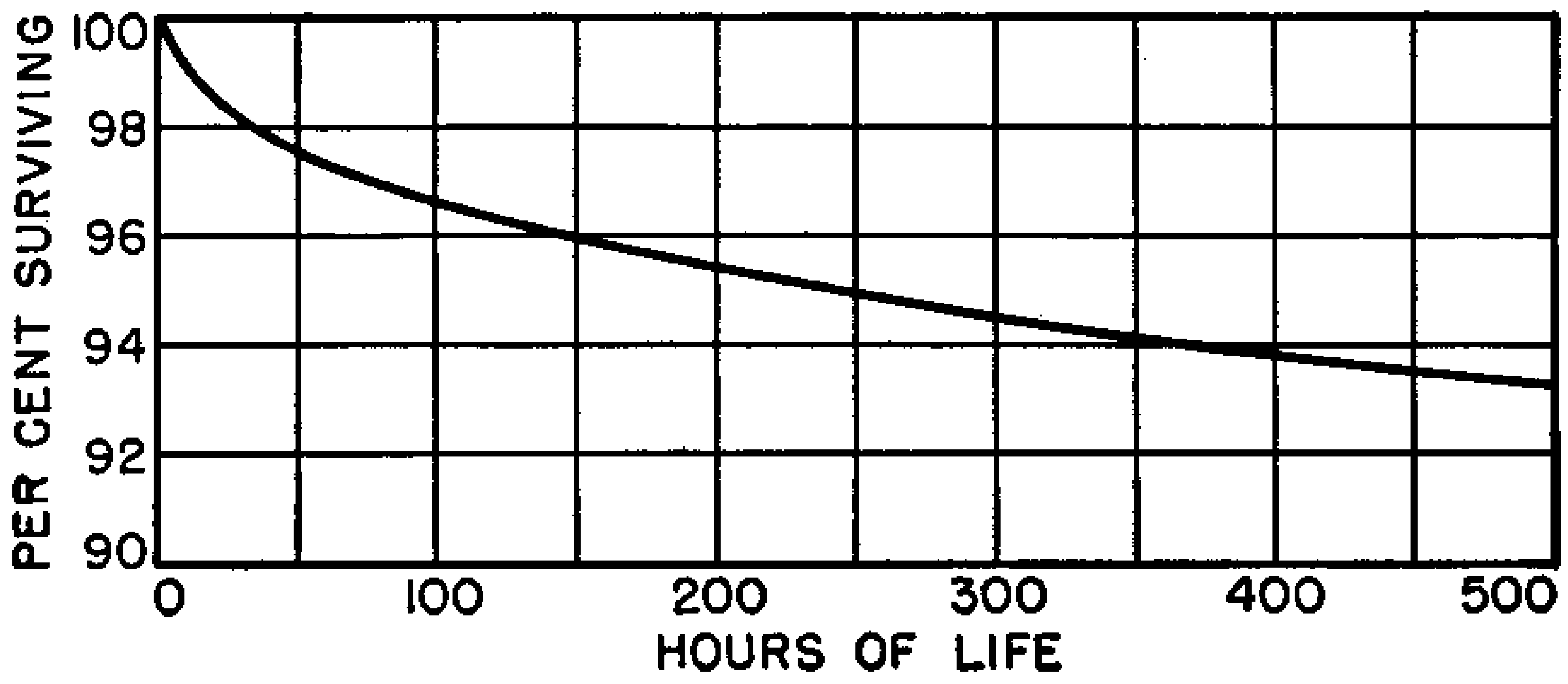

Figure 13—A typical survival curve for a batch of commercial-type valves shows an exponential rate of failure with time.

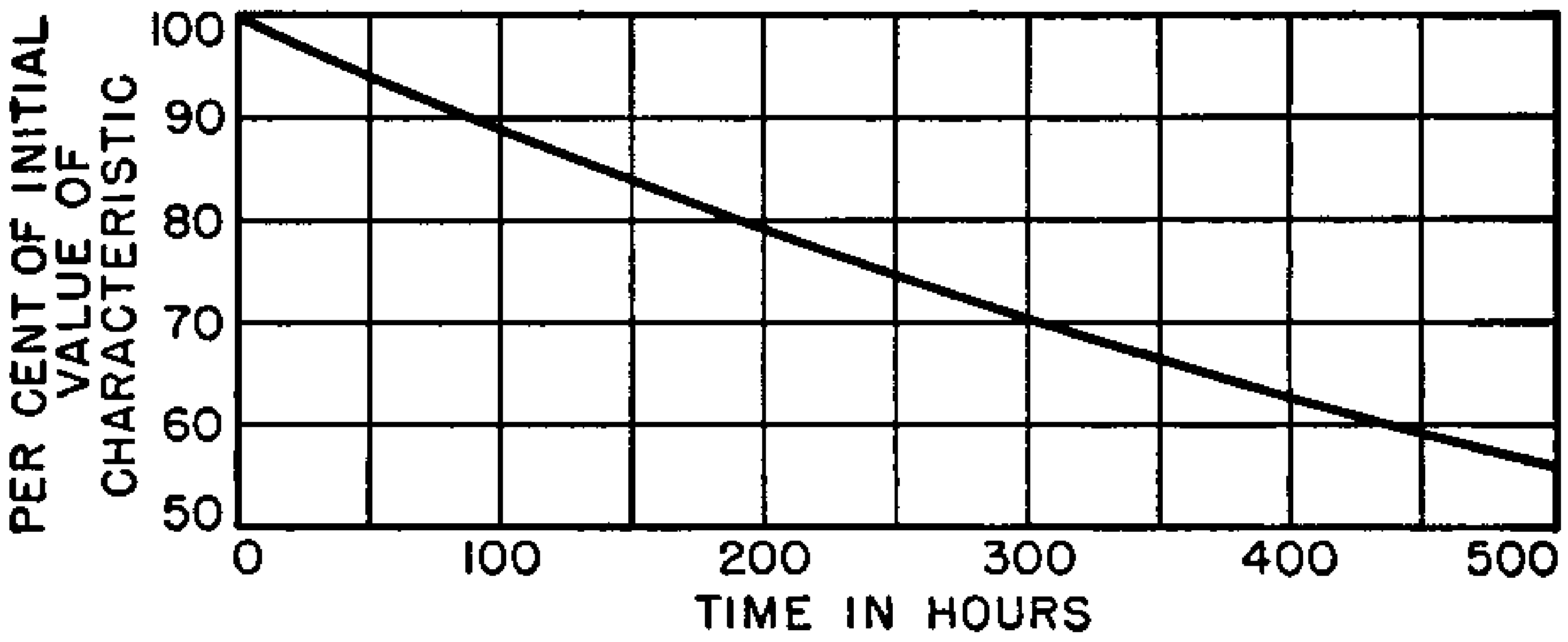

Figure 14—Typical variation of anode current of a commercial miniature pentode with time shown as a percentage of the initial value.

coincide with the resonant frequency of one of the components.

The reliable valve has a survival curve that does not include the high initial failures shown in Figures 11 and 12.

2.5 Life Testing

Life testing of commercial valves over many years has shown that the survival curves have a shape typical of that shown in Figure 13. The first part of the curve has a steep slope and is due to the high incidence of catastrophic failure; after this the failure rate is much slower and follows approximately an exponential law.

The controlled manufacture of the reliable valve and the quality level that is achieved by the testing sequence ensure that the number of catastrophic failures is very small but adequate control of this feature calls for a much larger sample for life testing. This sample consists of 20 valves from each batch and to increase the sensitivity of the scheme it is usual to consider the results of 5 batches as a continuous moving average.

It is difficult to ascertain the failure rate of the reliable valve because it normally involves very long periods of life testing. However, since the predominant failures are due to falling emission or heater failure a reasonable index of valve quality may be obtained by considering the percentage change of valve characteristics and by switching tests conducted on the heaters.

The percentage fall of characteristics also tends to follow an exponential curve (Figure 14). By examining the average fall on a small group of valves it is possible to estimate the average life in terms of the life-test conditions and arbitrary end-point. As a rule, anode current is selected as the variable and the arbitrary end-point as a 50-per-cent fall. Figure 15 indicates the application of this method to small samples of four types of commercial valves. This approach gives a very sensitive index of valve quality.

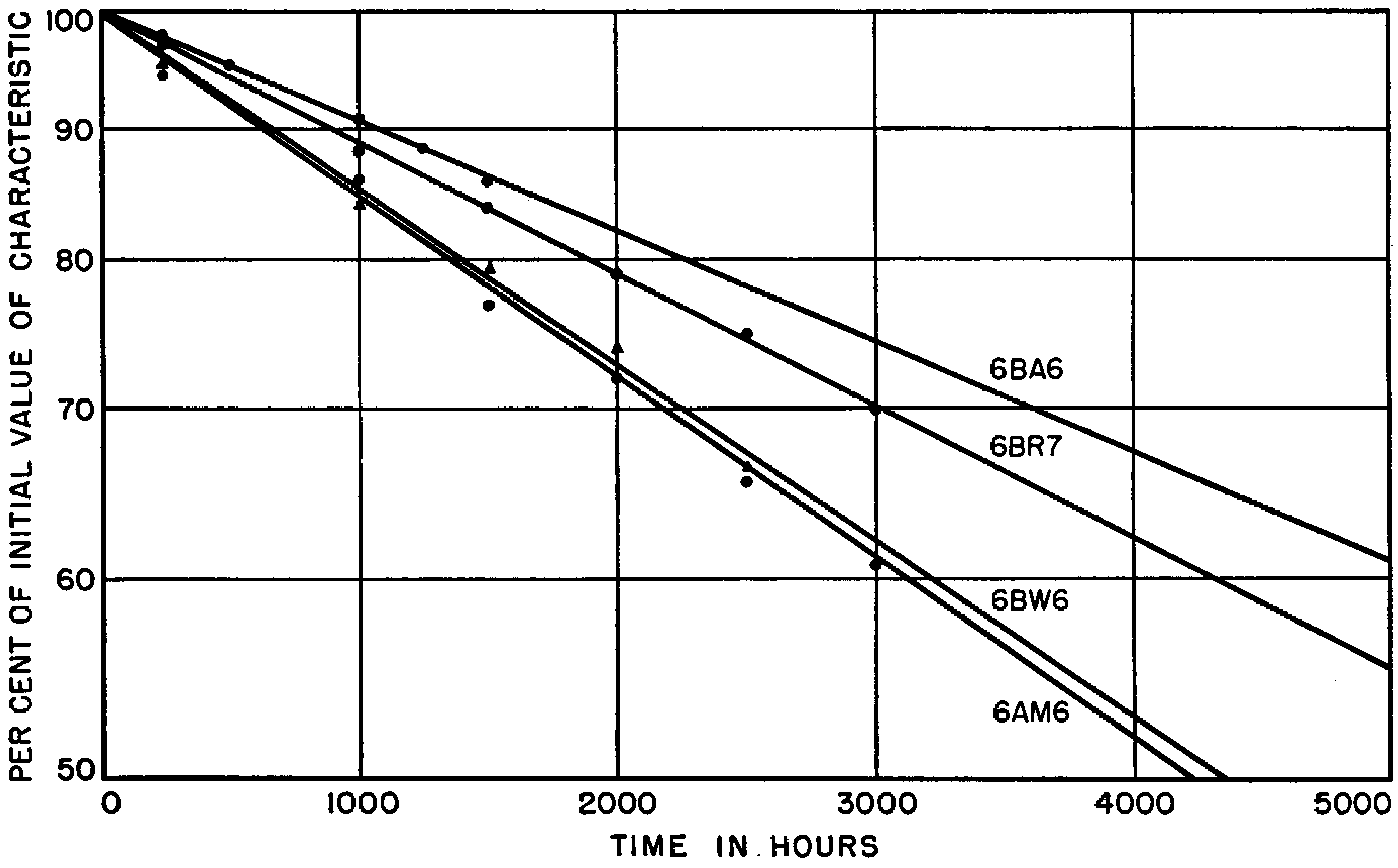

Figure 15—Extrapolated characteristics showing the use of the average fall of the characteristics of a batch, which may serve as an index of valve quality. In each case the sample size was 4 and the valves were of commercial manufacture.

The heater testing is conducted at the same time as fatigue testing.

2.6 SUMMARY OF COMPLETE TESTING PROCEDURE

Tests designed to safeguard against the normal field rejects have been described and the reasons for choosing 100-per-cent or sample testing have been explained. In addition to the electrical tests a description has been given of special mechanical tests and of life tests. It remains to set out the order in which the tests are performed so that the maximum amount of information can be obtained about each batch with the minimum of testing time. The scheme shown in Table 4 is followed with valves received from the exhausting station.

TABLE 4

COMPREHENSIVE TESTING PROCEDURE

Test	Remarks
Thermal Shock for Glass	Extract a sample for inspection of pin position and return to batch. Extract a sample for thermal-shock test (section 1.3.3) and destroy after testing.
Short-Circuit at High Voltage	
Heater Flash	
Activation	
Short-Circuit and Continuity	
Electrical Characteristic	
Vibration	Extract a sample for check of characteristics before 3-hour life run and return to batch (quality control).
Short Life–3 Hours	Recheck the sample to assess drift of characteristics (quality control) and return to batch.
Underheating to Find Catastrophic Failures	
Store	Extract a sample for life test and destroy after testing. Extract a sample for resonance test and return to batch. Extract a sample for fatigue test and destroy after testing. Extract a sample for shock test and destroy after testing.
Feedback	
Electrical Retest After Shelf Life	

Failures in excess of 5 per cent for the full tests and failure to meet the sample tests cause batch rejection.

The testing scheme applies equally to continuous production although the illustrations are relative to a batch. When continuous production is used it is necessary to take samples at regular intervals and to maintain a moving average of the results of 100-per-cent tests. For the batch system, production must be sufficiently large for batches of 500 or more valves to be tested at a time. Below this figure, production processing tends to become inconsistent and the product is liable to go out of control.

3. Design Considerations for Reliable Valves

3.1 REDUCTION OF NOISE

Noise due to manufacturing errors such as short circuits, disconnections, and lint is minimized by manufacturing large quantities of valves under the most-efficient production-control methods.

The design engineer is not vitally concerned with such noise but must concentrate rather on noise produced by electrode rattle and by the fundamental vibration of the electrodes themselves.

Rattle noise is caused by the unsatisfactory locking of electrodes and the order of importance of such locking considerations is from the cathode outwards. The effect is aggravated by the fact that the top of the valve usually moves more than the base under conditions of vibration and because of the high compliance between insulator and bulb the movement is transferred to the electrodes. In addition, the electrode structure must remain relatively unrestricted at the top end because locking tapes, connections, et cetera, are best applied at the base end. Considerable reductions in rattle noise may be achieved by using two insulators instead of one at the top end of the valve and by ensuring that the holes in which the electrodes are held are a tight fit. However, this double insulator can adversely affect valve performance by excessive local cooling of the cathode sleeve. Because heater switching causes expansion and contraction of the cathode thereby enlarging the hole in which it fits it is essential to make the cathode-to-mica fit as tight as possible bearing in mind the above limitations and this is usually done by locking the cathode with a bead or bell shape or by pinching as shown in Figure 16. The second insulator is not in contact with the cathode.

A further improvement can be made by locking the grids in the insulator by means of tapes fixed to the insulator and welded to the grid leg. By taking these precautions, rattle noise has been eliminated almost completely in the reliable valve.

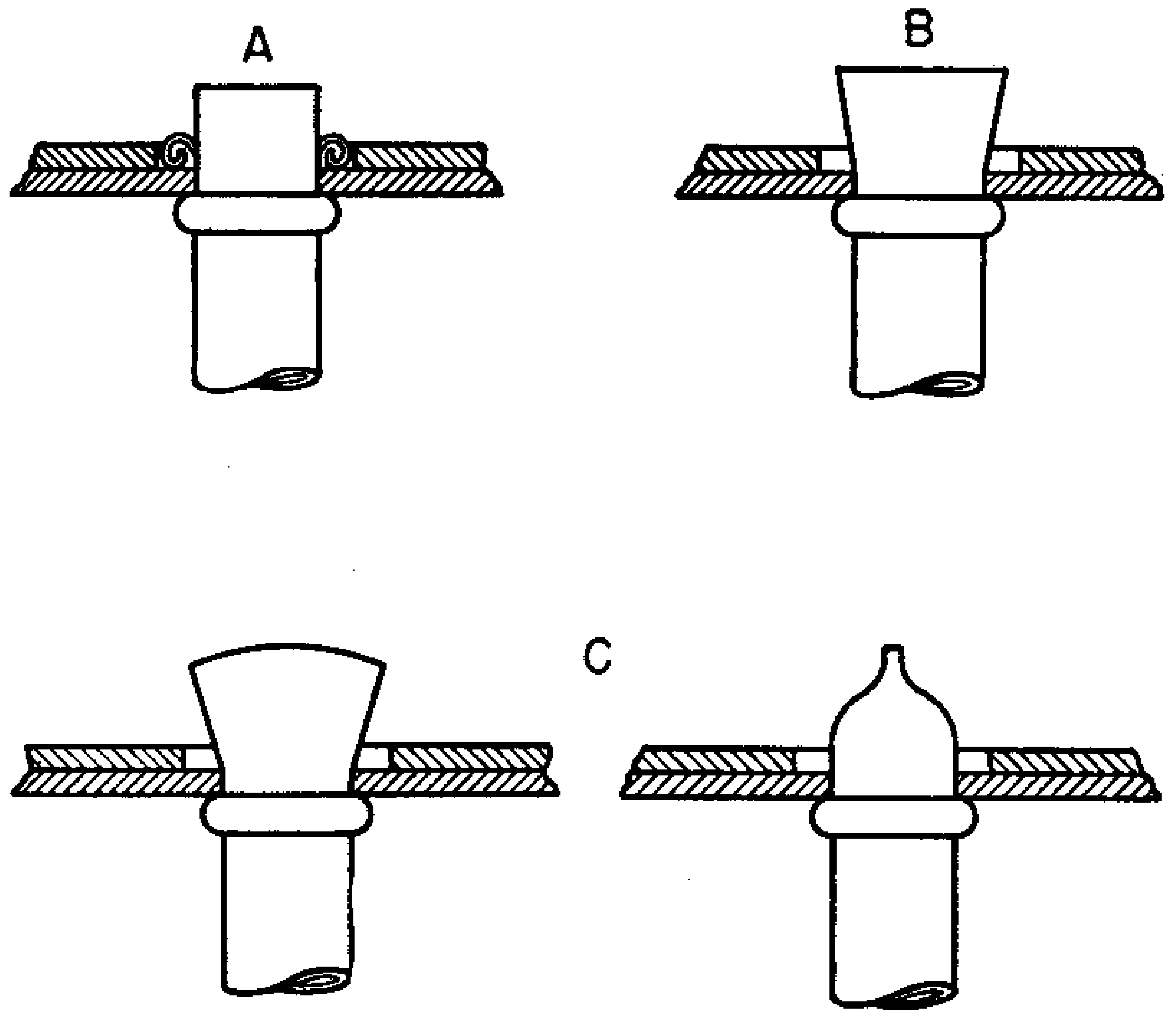

Figure 16—Methods of locking cathodes. At top left is the eyelet form, top right is the bell shape, and at the bottom are front and side views of the pinching technique.

Resonance noise is produced by the fundamental vibration of the electrodes themselves. Investigation of this problem has shown that the resonant frequency of grid support wires, grid laterals, cathodes, and most other parts may be predicted accurately by empirical formulae.

For nickel cathodes, the resonant frequency for circular cross sections is given by

$$f = \frac{1{\cdot}42 \times 10^5 (r_1^2 + r_2^2)^{1/2}}{l^2}$$

and for rectangular cross sections by

$$f = \frac{1{\cdot}64 \times 10^5 (a^2 + aa' + a'^2)^{1/2}}{l^2},$$

where r_1 and r_2 are internal and external radii, a and a' are the internal and external dimensions across either of the principal axes through the centre of gravity of the cross section, and l is the length between insulators; all dimensions are in inches. For grid support wires of any material, the resonant frequency is given by

$$f = \frac{1}{2\pi l^2}\left[\frac{19\,Yr^2}{\rho\{1 + (\bar{w}/w)\}}\right]^{1/2},$$

where r is the radius of the wire, l is the length between the insulators in inches, w is the weight per unit length, $\bar{w}$ is the weight per unit length of half the lateral wires attached to the support, Y is Young's modulus in dynes per square centimetre, and ρ is the density of the material in grammes per cubic centimetre.

For the commonly used materials, the formulae become:—

for nickel,

$$f_{\mathrm{Ni}} = \frac{1{\cdot}3 \times 10^5 \times r}{l^2\{1 + (\bar{w}/w)\}^{1/2}},$$

for copper,

$$f_{\mathrm{Cu}} = \frac{1{\cdot}088 \times 10^5 \times r}{l^2\{1 + (\bar{w}/w)\}^{1/2}},$$

for 5-per-cent chrome copper,

$$f_{\mathrm{CrCu}} = \frac{1{\cdot}09 \times 10^5 \times r}{l^2\{1 + (\bar{w}/w)\}^{1/2}},$$

and for mild steel,

$$f_{\mathrm{Fe}} = \frac{1{\cdot}42 \times 10^5 \times r}{l^2\{1 + (\bar{w}/w)\}^{1/2}}.$$

A simplified calculation for grid lateral wires is obtained by approximating the profile either to the arc of a circle or to a rectangle as shown in Figure 17 and the formulae become:—

for the arc of a circle,

$$f = \frac{0{\cdot}17r}{(2{\cdot}78d^2 + 0{\cdot}558R^2)}\left(\frac{Y}{\rho}\right)^{1/2}$$

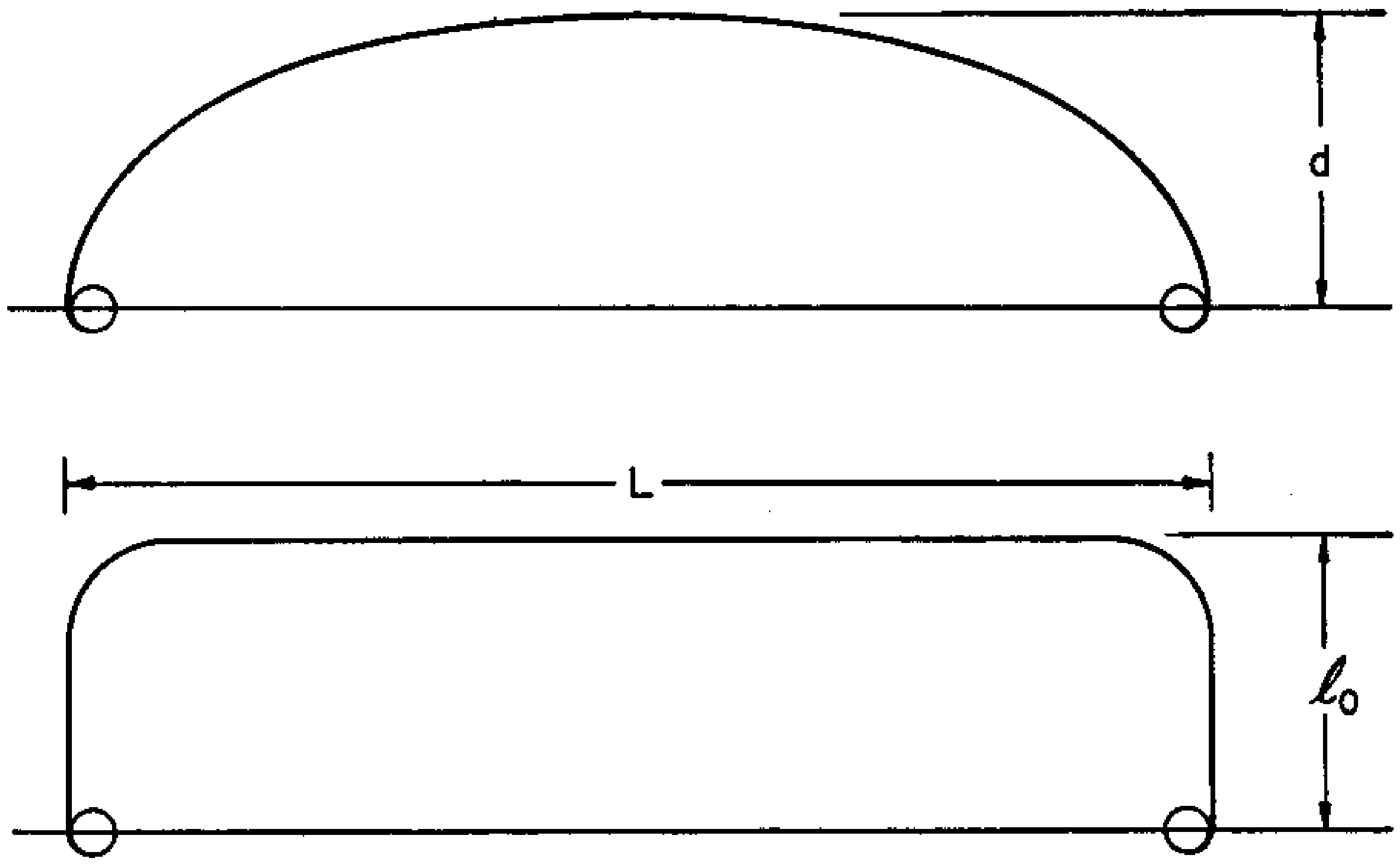

Figure 17—Grid profiles used for computing vibration frequencies.

and for a rectangular section,

$$f = \frac{0{\cdot}17r}{(2{\cdot}9l_0{}^2 + 0{\cdot}325L^2)}\left(\frac{Y}{\rho}\right)^{\frac{1}{2}},$$

where r is the radius of the wire, d is the depth of the arc, and R is the radius of the arc; l_0 and L are the dimensions of the rectangle (all measurements being in inches), Y is Young's modulus, and ρ is the density.

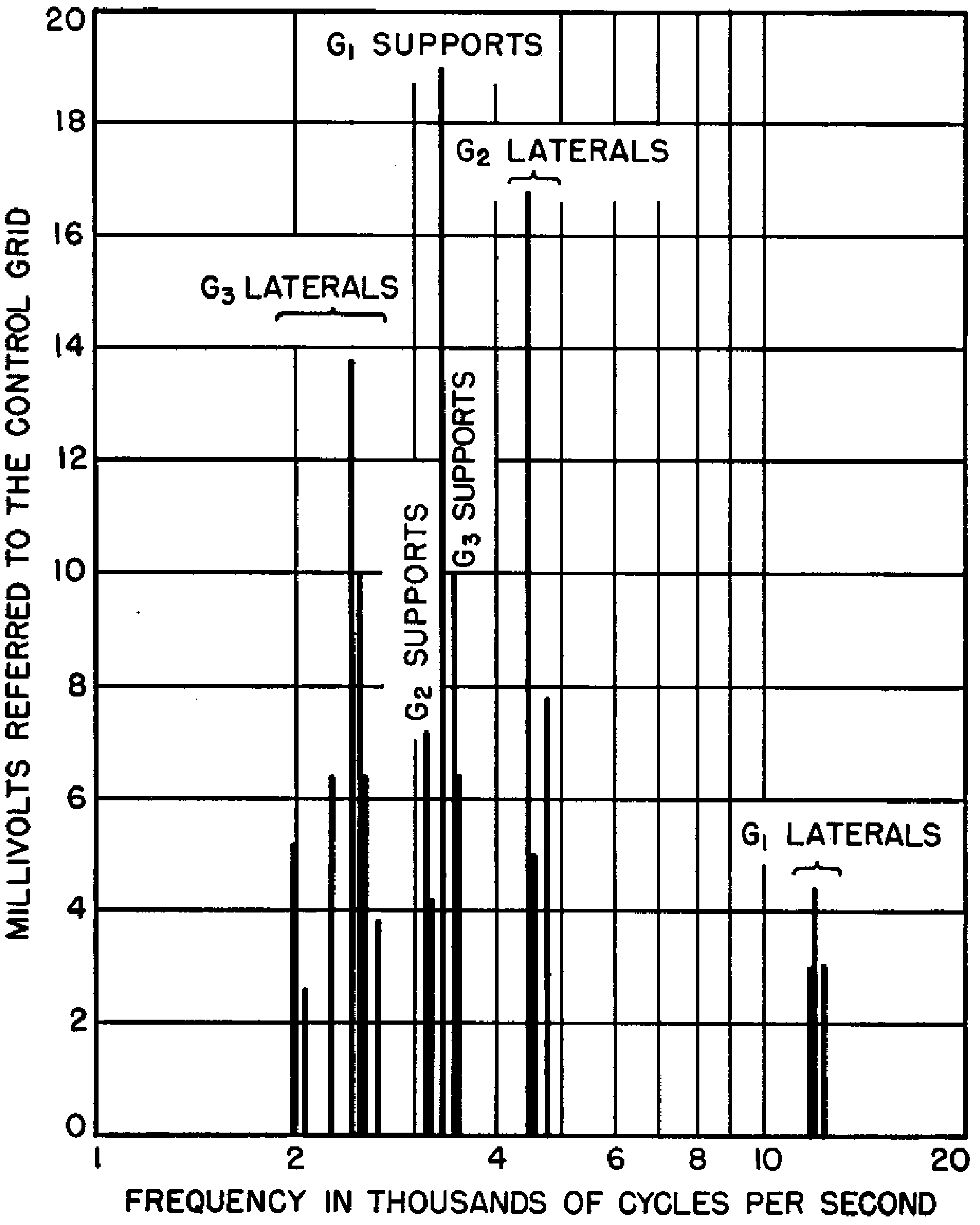

Figure 18—Resonance diagram for a vari-μ radio-frequency pentode.

Figure 18 shows a typical resonance diagram marked with the frequencies due to various grids, et cetera. In general, the noise output produced at resonance appears to vary with the square root of the applied acceleration and there are few resonances below 1000 cycles per second. Most cathodes are well up in the 3-kilocycle-per-second region and most resonance noise is created by the individual grid lateral wires and tends to spread in a band about the mean calculated figure. Suppressor grids usually have the lowest resonant frequency and typical cases show a band width of 300 to 400 cycles per second.

Little can be done to reduce the resonance noise produced by the grid laterals except by the choice of material and size to ensure that the frequency is as high as possible. The noise produced by grid supports resonating may be improved by about 1·67 times by clamping the support at both ends and this practice is used in special cases where exceptionally low values of noise are required. This is shown diagrammatically in Figure 19.

It is unfortunate that the general improvements that are incorporated in the reliable valve to guard against low-frequency rattle and fatigue usually result in a more-rigid structure that then offers less compliance between the individual electrodes and the exciting forces. For example, the double insulators are a better fit in the glass bulb and therefore transmit energy more easily to the electrodes. In cases where trouble has resulted, it has been found necessary to change the materials of the grid in order to increase the resonant frequency.

Comparison of experimental batches of valves and production samples to assess the results of changes can only be made by measuring a quantity of valves, preferably by the audio-frequency feedback method.

3.2 Effects of Fatigue Vibrations

The examination of valves that have failed under fatigue testing shows that they divide into three classes consisting of those which in a relatively short time show high grid currents and/or falling emission due to gas evolution because of breaking up of the insulator pips,

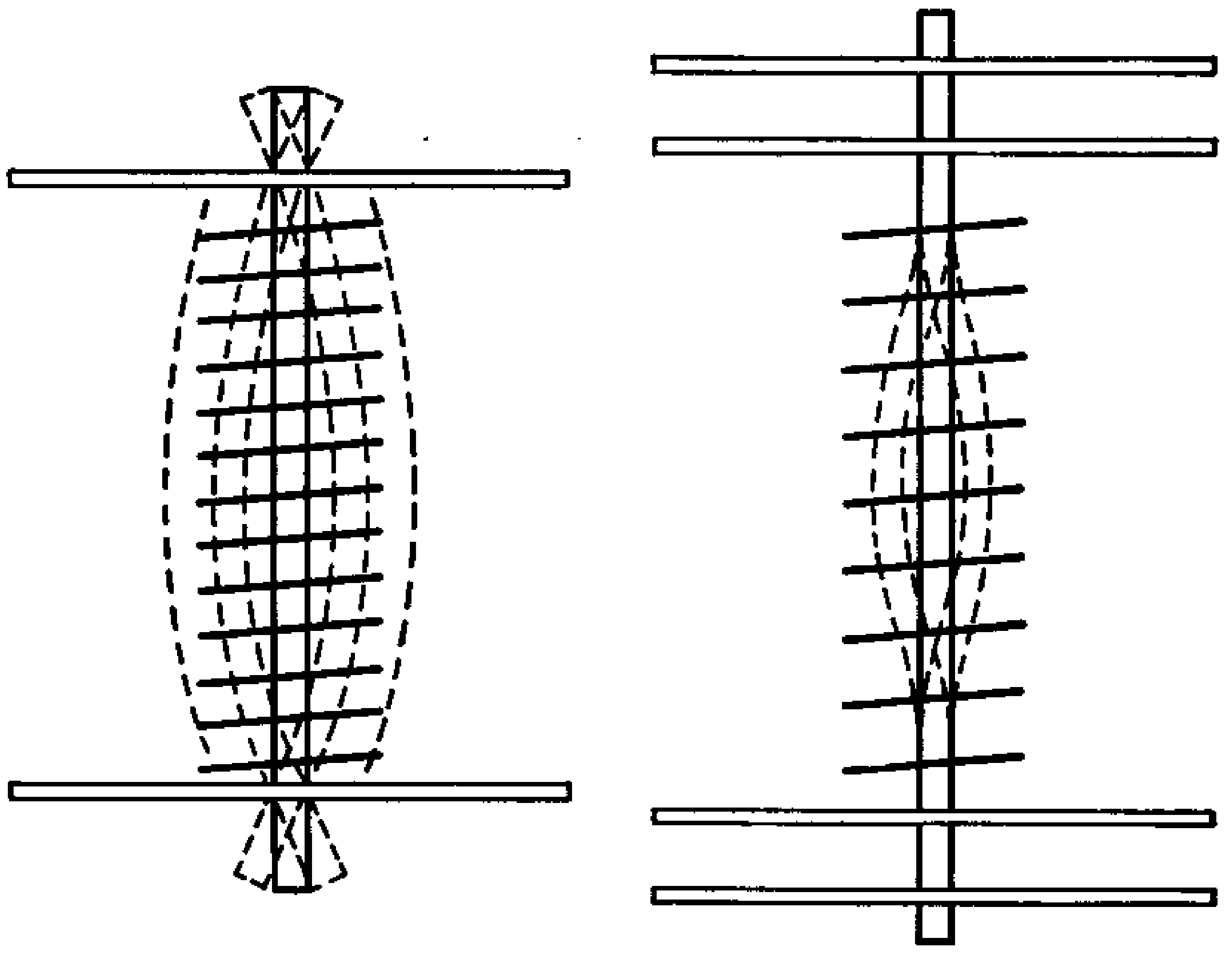

Figure 19—The freely vibrating grid structure has a resonant frequency of approximately 1100 cycles per second. With the ends locked, the frequency is increased to about 1700 cycles per second.

those that give rattle noise over a longer time interval because of the wearing of slots and holes holding the electrodes; and finally those with fractured connecting links and stem wires due to the ultimate fatiguing of the piece-parts.

The mounting position of the valve under vibration has a considerable effect on the resultant type of failure. Vibration parallel to the main axis is the most important as it is the usual position and this produces wear of the insulator pips or snubbers. Vibration across major and minor axes produces wear of the holes holding the electrodes, the major-axis position being the more severe.

The ordinary commercial valve is often prone to the first type of failure because it has a relatively loose structure designed to permit rapid assembly and this allows a considerable differential movement of mount and glass bulb under vibration with consequent production of mica dust and gas poisoning of the emission. To reduce this effect, it is necessary to stop the differential movement from occurring, and this may be done by ensuring that the bottom insulator is rigidly attached to the glass stem either by the method used to assemble the valve or directly by using eyelets or metallic tapes clinched in the insulator and welded directly to the stem wire. The top insulator is then rigidly clamped to the assembly. To achieve the maximum rigidity, it is better to weld tapes across the electrode lugs projecting through the top insulator than to bend the lugs over, unless the bending is done mechanically. In general, structures in which the insulators are supported around the periphery are to be preferred and therefore where there is not adequate support, extra supporting members are necessary. Both insulators are designed with protruding pips around the periphery to take up the variations in bulb size and are controlled to give a good tight fit. When these precautions have been taken the wear of insulators gives the same order of rejection as the general fatigue of the rest of the valve.

The wear of electrode holes and slots may be considered as a second-order effect and can be reduced by attention to design. Round holes should be used where possible and if shaped electrodes are to be held it is necessary that the securing lugs be positioned so that vibration is prevented in all directions. Improvement that can be obtained in the method of supporting an anode by ensuring that the two lugs are at right angles is shown in Figure 20. In all cases double insulators at the top of the valve are to be preferred and, where possible, additional aids such as grid straps should be provided in order that movement of the electrodes be damped adequately.

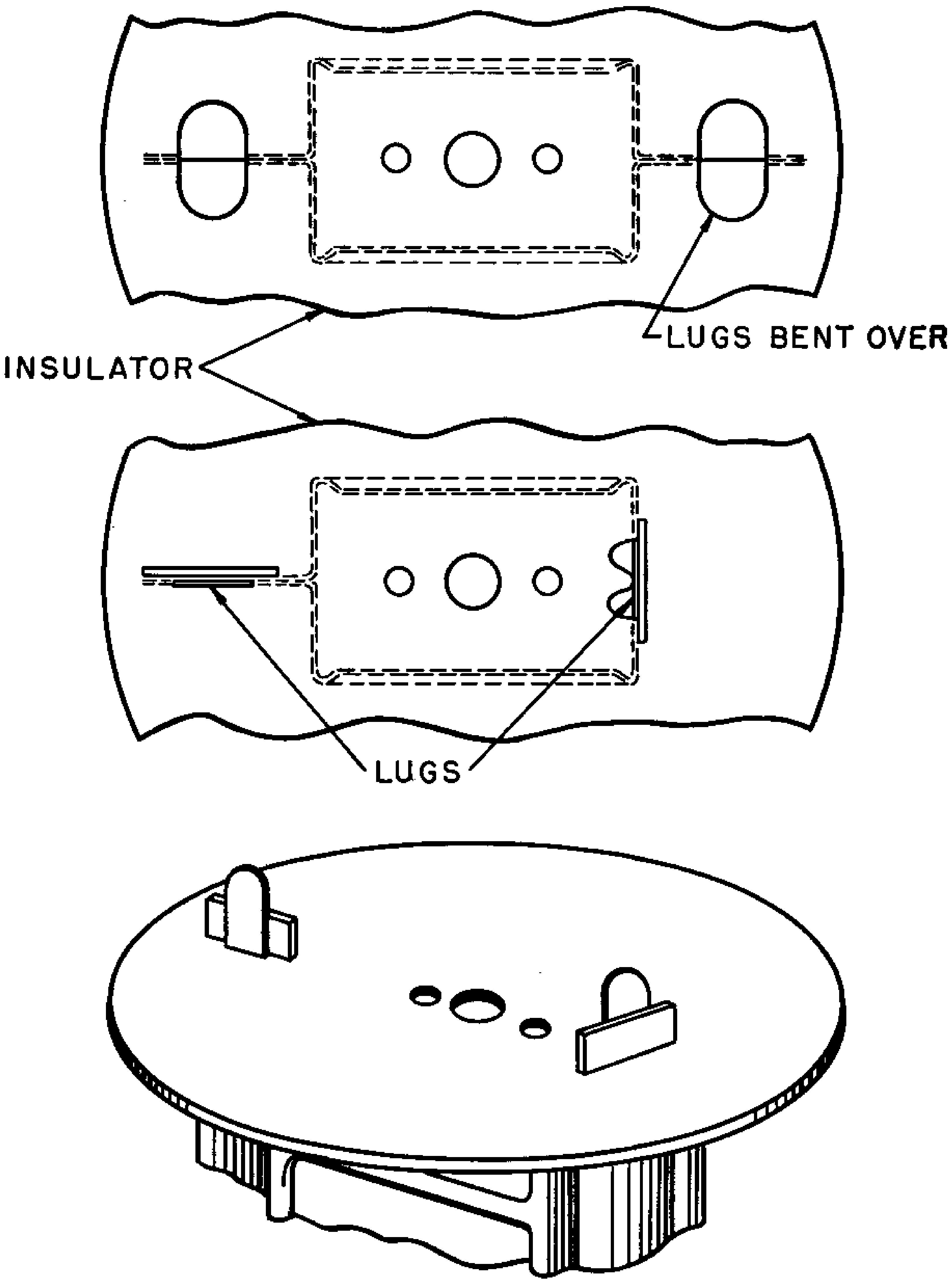

Figure 20—The upper drawing shows the old form of inserting two lugs through the insulator and bending them over to secure the anode. The lower two figures show the new method of putting the lugs at right angles and welding the locking strap to the lug.

The third-order effects of fatigue, due to the actual fatigue of the metallic parts especially of connecting links and stem wires, are avoided only by complete changes of technique from the modern method of the soft-glass base.

3.3 Effects of Shock

Two effects of shock have been noted, the first being an emission phenomenon and the second a distortion of the electrodes.

Figure 21 shows the difference in grid voltage required to give a reference anode current of 10 milliamperes in a typical high-slope pentode valve before and after shock testing. It has been noted in general that the initial shock appears to cause a general reduction of the anode current in the valve and that further shocks do not cause such serious changes. The reason for this is not clear because apart from this slight shift of characteristic there does not appear to be any other change.

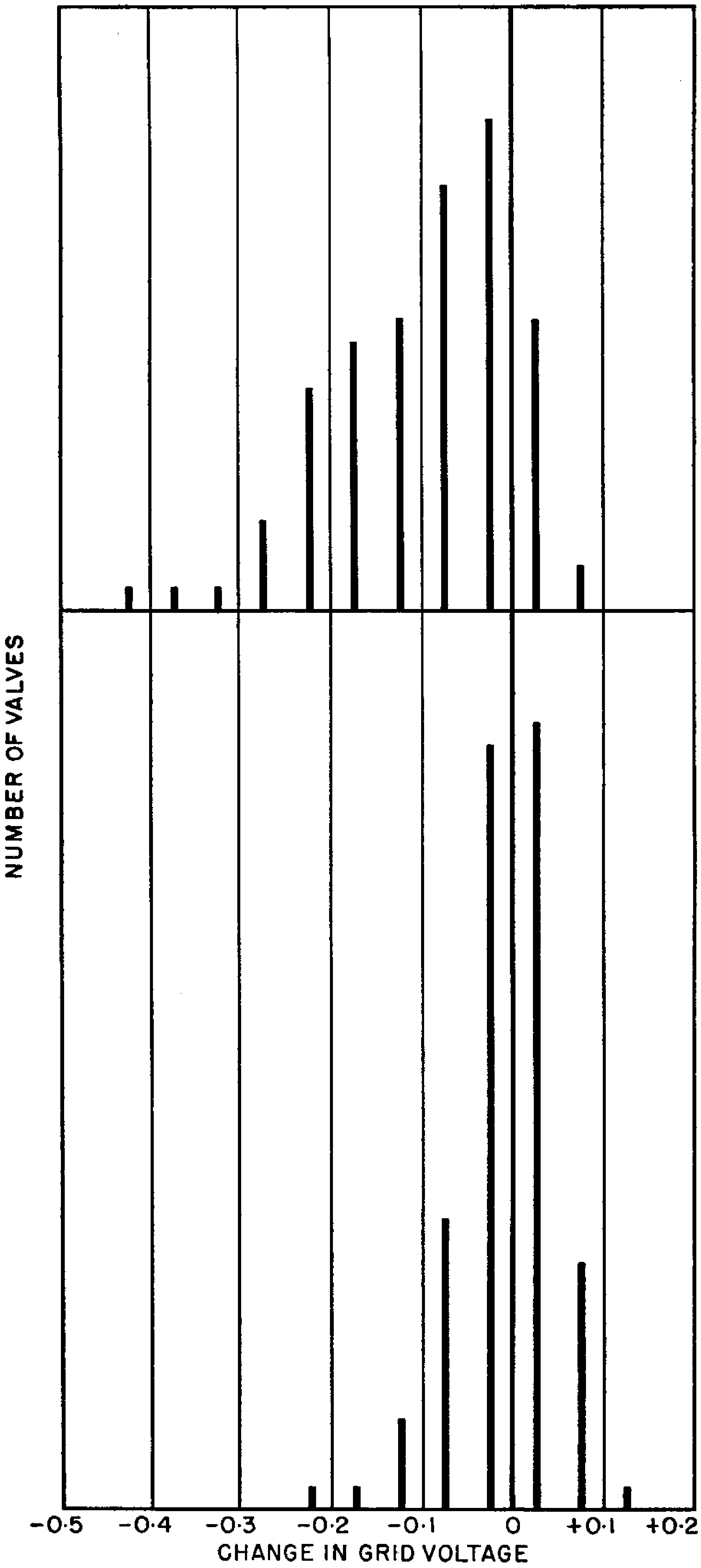

Figure 21—These two sets of histograms are for a single batch of high-slope pentode valves. The change in grid voltage required to produce an anode current of 10 milliamperes after one impact is shown at top. The lower histogram shows the relatively small effect of five successive blows after the initial shock.

The second effect of shock is electrode distortion and, generally, valves will withstand a higher acceleration when the direction of force is parallel to the principal axis. The characteristic effects of shock in this direction are discrete changes of anode current, cut-off, and capacitance that increase as the shock becomes greater up to the limiting point where the assembly is completely distorted. In the two other axes the amount of distortion of grids, et cetera, is proportional to the degree of shock and only comparably small values of acceleration can be tolerated. The time of impact is important for very-short-duration shocks, but where the acceleration remains constant over a period the amount of damage does not appear to be a function of time. This point has been proved by centrifuge tests.

Improvements to the shock performance when the acceleration is parallel to the principal axis may be made by rigidly attaching the bottom insulator to the stems of the valve in at least three equidistant places around its periphery, and then ensuring that all electrodes, especially the grids and cathode, are locked securely in one or other of the insulators. The distortion caused by shocks across the other axes may be reduced by making the assembly as short as possible and by using the thickest and strongest materials.

4. General

Production techniques including process control, raw-material quality checks, and methods of inspection and assembly, et cetera, have not been discussed although they have an important bearing on the final result. The engineering approach to the subject, including the detailed analysis of causes of rejection will give a very precise indication of production efficiency when instituted in the form of the tests described. In this respect it must be emphasized that the essence of good reliable-valve manufacture is the controlled uniformity of the product and such a

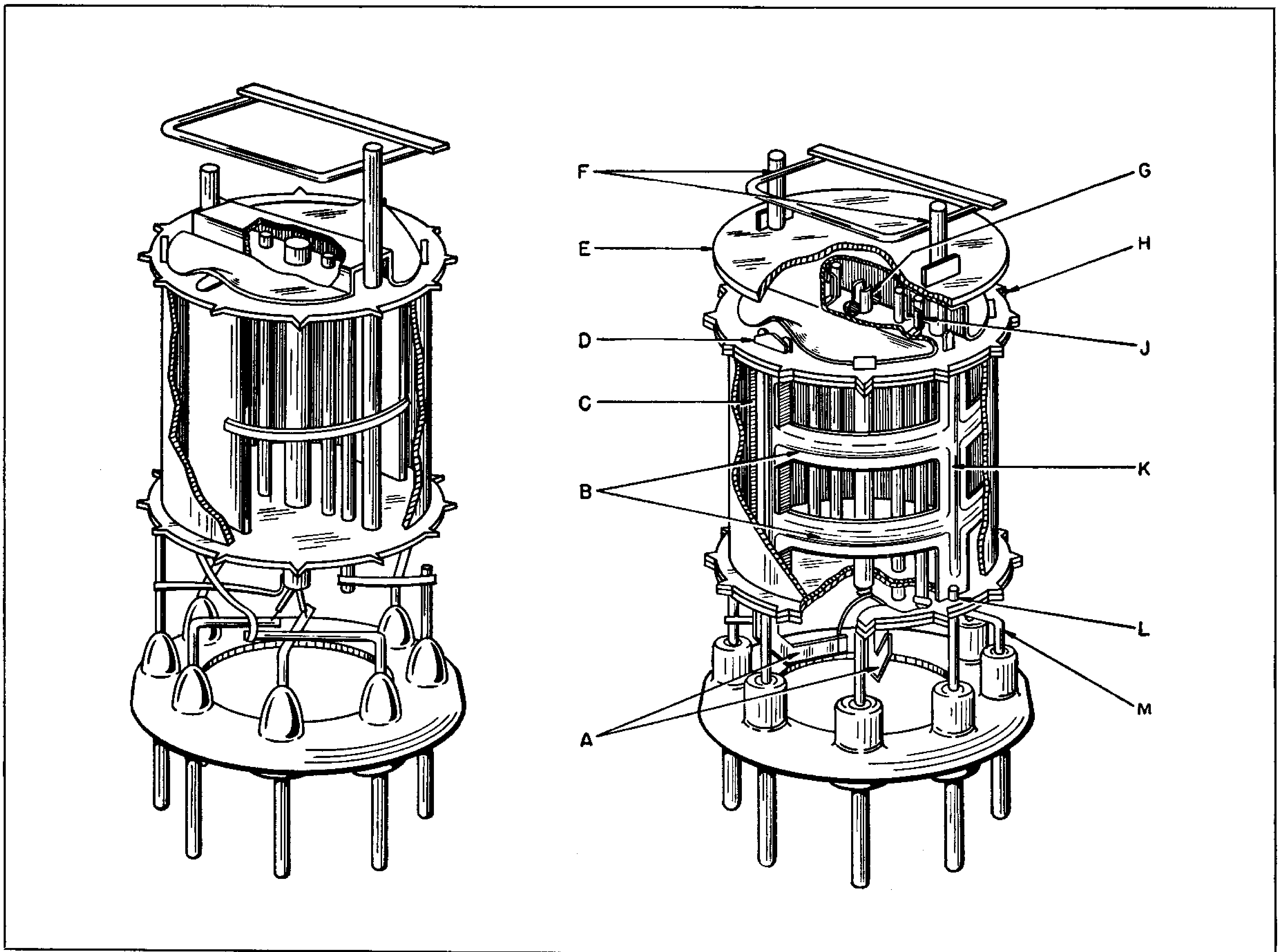

Figure 22—The drawing at the right shows an ideal reliable valve. The features that are stressed as contributing to trustworthy performance include: *A*—heater bars fixed to mica insulators and welded to the valve leads, *B*—one-piece ribbed anode structure with two bars, *C*—edges of anode bent out for strength, *D*—two lugs on anode locked by strap to mica insulator, *E*—insulator protects valve structure from getter splash, *F*—getter assembly welded in two places, *G*—cathode locked in top mica insulator, *H*—double mica insulators, *J*—grid locking clips in mica insulator, *K*—extra anode support, *L*—extra support, and *M*—valve leads welded directly to half supports.

state of affairs can only exist when sufficient quantities of valves are being made that the individual operator becomes familiar with the job.

5. *Conclusions*

The engineering approach inevitably culminates in certain general design methods, which are best illustrated by a hypothetical case of a reliable-valve design, shown in Figure 22. Valves of this type in controlled manufacture will pass all of the tests designed to prove the mechanical performance and it remains only for the full field results to be correlated to find out if the present performance level is satisfactory. Results to date indicate that the general standard of associated circuit equipment will now become the limiting factor to most electronic apparatus.

6. *Acknowledgments*

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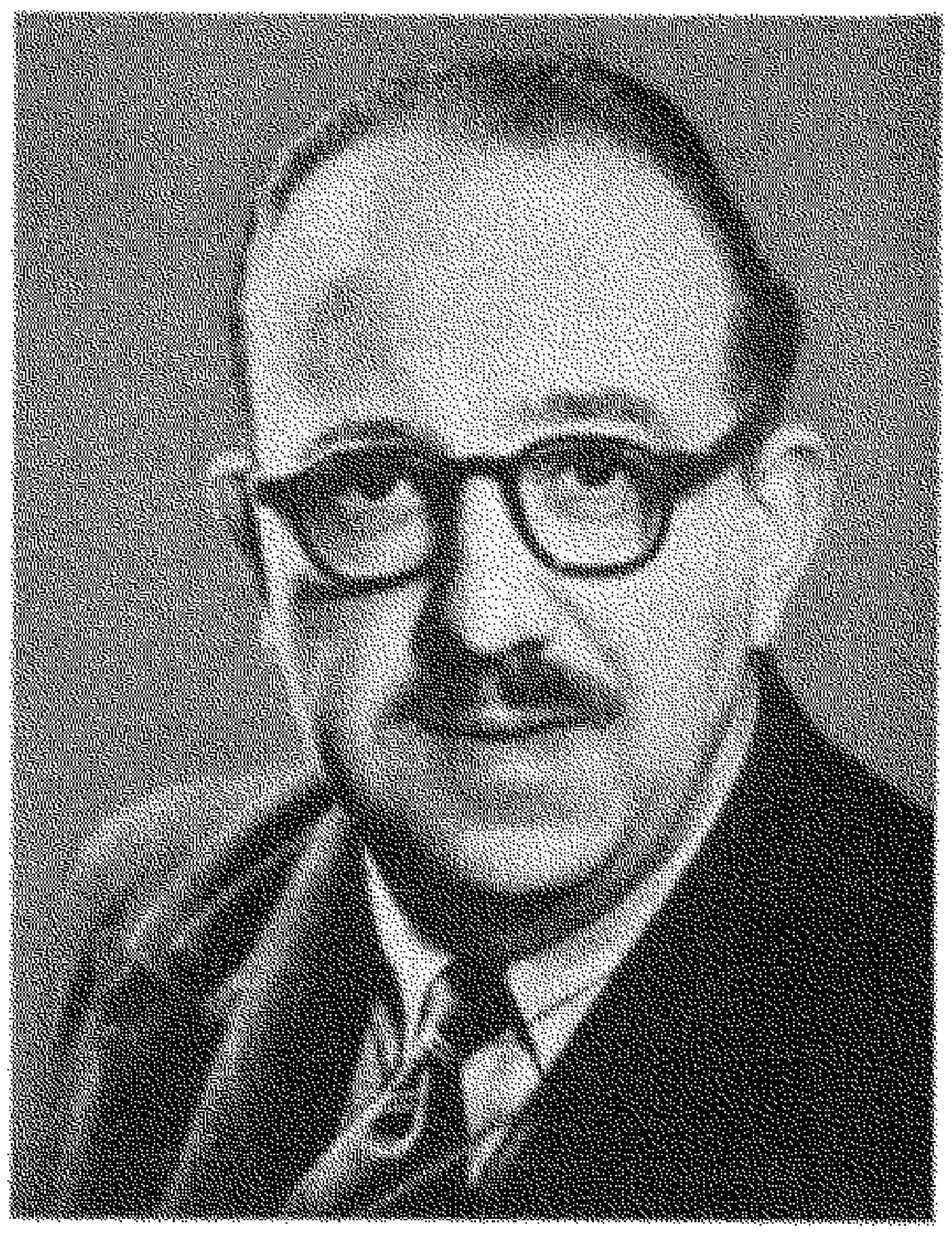

Ernest G. Rowe

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Peter Welch. A photograph and biography of Mr. Welch, coauthor of the paper on trustworthy valves, will be found on page 72 of the March, 1954 issue.