

voltages and the approximate validity of the empirical 12.5th-power rule. It may be seen that the median life of a group of heaters decreases rapidly with heater temperature. Consequently, the most generally effective method for increasing heater life is to reduce the operating temperature.

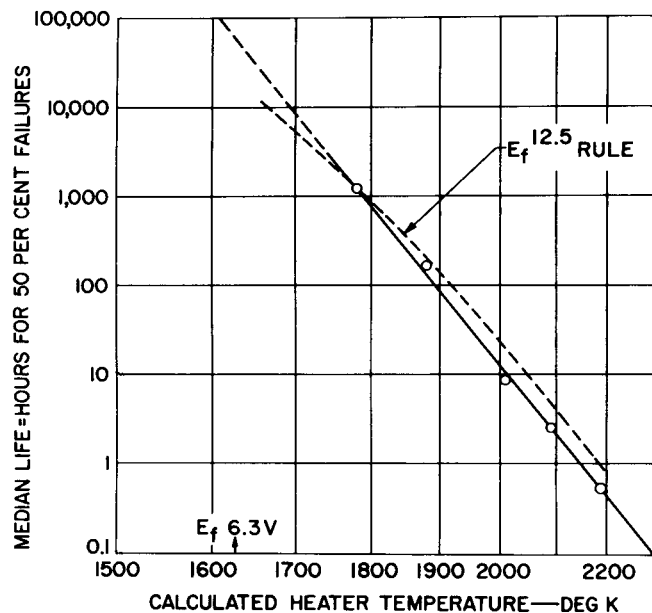


Figure 12. Typical Dependence of Heater Median Life On Heater Temperature (i. e., heater voltage) During a Life Test

The complete pattern of failures for the same lot of tubes considered above is shown in Fig. 13 on graph paper with a cumulative probability of failure scale as the ordinate and the logarithm of the testing time as the abscissa. As can be anticipated from theory, a series of parallel lines provides the best over-all picture of the experimentally observed percentages of tube batches that have failed after any given time of testing. From Fig. 13, it may be concluded that, at least for this particular lot of tubes, the failure distribution was approximately normal with respect to the logarithm of time, and that the failure pattern to be expected at any temperature level could be estimated with some reliability from tests at other temperatures. Similar test results have been obtained on other tube types under substantially different test conditions.

Detailed consideration of such heater-failure patterns indicates that even when failures are all of the same type (as was true in the previous case), there should be an initial period with a high time rate of failure. After this period, the failure rate will decrease. Experimental attempts to improve the heater quality of a lot of tubes by "testing out" the early-hour failures have resulted in some quality improvement among the survivors.

Heater-Cathode Bias

During regular life tests, voltage gradients as high as 20,000 to 40,000 volts per centimeter exist across

the heater insulation. At the high temperatures of heater operation, the mobility of many contaminants in aluminum oxide is appreciable and electrolysis through the heater coating may result. With heater-positive biases ($+E_{HK}$), positive-ion contaminants can migrate through the insulation from the heater towards the cathode. For heater-negative biases ($-E_{HK}$), the direction of migration of positive-ion contaminants is from cathode to heater. Because different types of contaminants are introduced into the heater-cathode system with different polarity biases, the possible occurrence of heater-cathode shorts, rising filament current, and heater-cathode leakage on life is strongly sensitive to the heater polarity. Furthermore, preliminary studies indicate that increasing the heater-cathode potential difference increases the rate of the electrolysis effects. If, however, the voltage is raised beyond a critical value (dependent on temperature), instantaneous breakdown of the insulation will occur. Life tests at zero bias or with ac bias have shown features characteristic of both heater-positive and heater-negative tests.

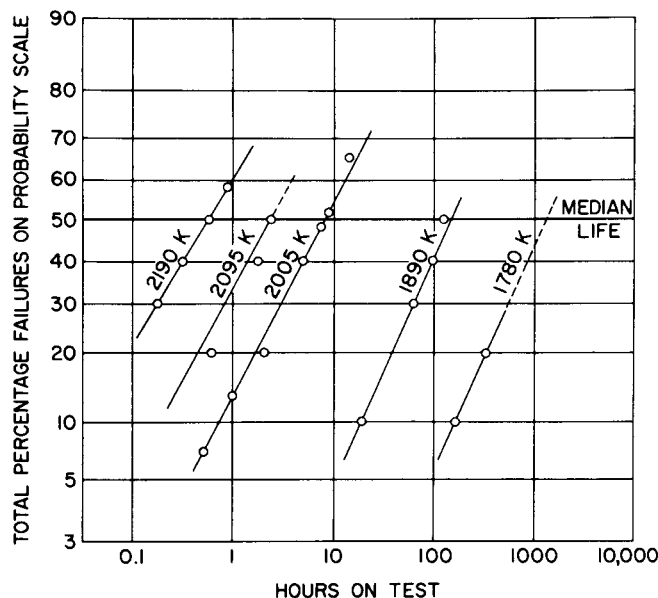


Figure 13. Typical Cumulative Probability Failure Patterns for Heaters Operated at Several Heater Temperatures

Heater-Positive Biases. Heater-positive biases are specified for most life tests because of a reputedly greater severity in terms of the occurrence of heater-cathode shorts — especially under continuous-heater-voltage testing. With this polarity, positive ions will migrate towards the negative cathode. High heater cathode leakage, when caused by positive-ion contaminants in the insulation coating, is usually reduced rapidly because the positive ions are electrolysed to a free surface and vaporized away from the heater-cathode system.

The electrolysis of positive tungsten ions from the heater wire into the heater coating is a potentially undesirable effect of testing with a heater-positive bias.^{7,13} The tungsten ions apparently originate from

heater wires which become mildly oxidized in heater manufacture, in tube processing, or during the life test itself. This effect is deduced because tubes showing it can usually be associated with a given production lot of tubes. Once tungsten ions have been electrolysed into the heater coatings, they will either combine chemically with the heater coating or be reduced to metallic tungsten particles, producing not only a visible darkening of the previously white insulation, but also a serious deterioration of the dielectric strength of the insulation. Tube failure may then result through "tungsten crater" heater-cathode shorts or through the effects of rising heater current as the coating is darkened.⁷

The typical tungsten-crater heater-cathode shorts that are associated with heater-positive life have been described in detail by Metson¹⁴ and his co-workers. Their work also suggests that electrolytic decomposition of the aluminum oxide may be an additional factor in the oxidation of the tungsten wire. Three distinct phases were noted during the course of failure: (1) a slight greyish staining of the outer surface of the heater coating at localized areas, (2) an intensification of color at the center of the stains, and finally (3) a crater-type failure evidenced by a small black slagged area on the heater coating. It is characteristic of this type of failure that, in spite of the darkened area, leakage between heater and cathode generally remains low until a few minutes before actual breakdown of the insulation.

The visible darkening of areas of the heater coatings, which is associated with the early stages of tungsten-crater shorts, can, if widespread, cause tube failure through rising heater current. In this case, tube failure may be due to an increase of heater current beyond specifications or, more usually, to the early deterioration of tube characteristics as the cathode becomes overheated because of the additional power supplied by the heater.

In a series of extensive tests to study this problem⁷, it was noted that the darkening of the heaters occurs only under heater-positive life test conditions, and proceeds more rapidly at higher temperatures and higher heater-cathode voltages. The increasing heater current is due mainly to the increased thermal emissivity of the visibly darkened coating which improves the efficiency of heat transfer between heater and cathode. In severe cases, the blackening of the heater coating may be sufficient to cause the heater current to rise by 10 to 20 per cent in the course of 1000 hours under normal testing conditions. Statistically designed experiments have shown that this problem can be largely overcome by use of suitable aging schedules. An alternate possibility, of course, would be to reduce the operating temperature of the heater to slow down the rate at which these effects occur.

Heater-Negative Biases. With heater-negative biases, the previously considered darkening of the insulation coating does not occur, and the heaters retain their original white appearance throughout life. On the other hand, electrolysis of metallic ions into the heater coating from the cathode may result, causing increasing heater-cathode leakage and embrittlement of the heater wire or both. A third effect, which occurs on cycling

tests, is an increased rate of heater growth.

Increasing heater-cathode leakage on life, especially +I_{HK} (leakage measured with the heater positive) is a typical symptom of heater-negative or "zero" bias conditions. Gas bombardment of the cathode with sufficient intensity to splatter cathode material on the heater can, however, produce similar symptoms, but this occurrence may be readily detected by examination of the cathode. Life tests at RCA and elsewhere have shown that the possible development of +I_{HK} leakage occurs most rapidly when the heater is operated under a high negative bias voltage. This high negative bias causes an increased rate of contamination of the heater coating by electrolysis of the more active additives of the cathode base metal into the insulation. The +I_{HK} leakage which develops under zero-bias life conditions will increase less rapidly than under negative-bias conditions because electrolysis does not occur. Finally, under heater positive tests, the electrolysis is in the reverse direction and leakage is usually maintained at low levels. Fortunately, since the highest heater-cathode leakage tends to occur with a "direction" opposite to that of the test, the polarity of the heater and cathode need to be interchanged before it can be detected. This unidirectional leakage effect is illustrated in Table VI. The data indicate that leakage occurred because of the accumulation of contaminants in the insulation. The contaminants produce leakage unless actively electrolysed away from the cathode. Considerable success in reducing the development of such leakage on heater-negative or zero-bias life tests has been obtained by use of cathodes with low levels of magnesium.

A similar effect, which has been reported to occur under heater-negative conditions, is the electrolysis of nickel from the cathode onto the heater wire.¹⁵ Nickel, when present in even minute amounts, will severely embrittle tungsten. As a result, the ability of a heater wire to withstand intermittent operation without breaking could be substantially reduced.

The greatest severity of heater-negative biases, however, usually occurs on intermittent tests due to an increased rate of heater growth. While heater growth will also occur with zero or heater-positive biases, it is apparently accelerated by a factor of two or three under the heater-negative conditions.^{6,7} Such heater growth occurs when a heater is alternately heated and cooled, and is unable to expand and contract freely within the cathode. As a result, the heater becomes progressively distorted. In coiled heaters, the coil can stretch to a clearly visible extent. In the most severe cases, where Dowmo wire has been used, heater coils have stretched to nearly twice their original length and have caused tube failure after touching the glass bulb or other components. The corresponding effect in folded heaters, is that the once straight heater legs assume a curly or twisted shape. Failures, in this case, may eventually occur when bare heater apices come in contact with one another or with the cathode. The thermal stressing of the intertwined folded heater legs, which cannot expand and contract freely as the heater is cycled, may also produce substantial numbers of broken heater wire failures, especially after the wire has become embrittled through recrystallization or

nickel contamination. Reduction of the heater design temperature to below 1550 K has generally eliminated such complaints.

Table VI

A comparison* of Heater-Cathode Leakage Levels Resulting from Heater-Positive, Zero-Bias, and Heater Negative Operation to Illustrate Electrolysis Effects.†

Hours on Regular Life Test	Heater at +50 volts throughout Life		Heater at zero volts throughout Life		Heater at -50 volts throughout Life	
	+I _{HK}	-I _{HK}	+I _{HK}	-I _{HK}	+I _{HK}	-I _{HK}
0	<0.1 μ a	<0.1 μ a	<0.1 μ a	<0.1 μ a	<0.1 μ a	<0.1 μ a
1000	110	1.7	97	2.2	8.2	2.0
2500	170	1.8	150	2.7	11.5	4.0

*The rate of leakage development illustrated here is unusually high

†The leakage measurements, +I_{HK} and -I_{HK}, were made at various down periods during life with the heater 100 volts positive and 100 volts negative respectively. The tube tested was type 5751

HEATER-CATHODE LEAKAGE

Definition and Characteristics

Heater-cathode leakage is an undesired flow of current between heater and cathode in spite of the insulation coating on the heater wire. Although the currents involved are relatively small (usually of the range 0.01 to 100 microamperes) at normal operating temperatures, they can produce undesirable effects on circuit performance¹⁶ so that measurement of this leakage current is standard for rating almost all tube types.

The size of the leakage current depends on the magnitude and polarity of the voltage between heater and cathode. It is customary to report the leakage values measured when the heater is 100 volts positive with respect to the cathode (+I_{HK}) or 100 volts negative with respect to the cathode (-I_{HK}). Fig. 14 shows two typical heater-cathode leakage characteristics. In one case, the heater-positive (+I_{HK}) leakage is the higher, and in the other case the heater-negative (-I_{HK}) leakage is the higher. It is quite typical, however, that in neither case are the "positive" and "negative" leakage currents equal nor does the leakage current increase linearly with increasing voltage as would be expected from an impedance obeying Ohm's law. Although the values of +I_{HK} and -I_{HK} tend to average out to about the same levels on tubes with commercially-low leakage levels, it is usually characteristic that in "high-leakage" lots of tubes the +I_{HK} values predominate while in "very low-leakage" lots, the -I_{HK} values more often predominate. A third way in which the heater-to-cathode-leakage characteristic differs from that of an "Ohm's law resistor" is that the leakage current will not generally fall to zero when zero bias is applied between heater and cathode and, as a result, the heater cathode impedance becomes small at very low biases. Such effects are important in heater hum; in critical low-level circuits, the heater is frequently operated at a level 20 to 50 volts above cathode potential to avoid

the zero-bias region. Studies of this effect by pulse measurements on unipotential heaters indicate that it is only partially due to the applied heater voltage which supplies thermal energy to the heater wire. It may be noted that if electron emission contributed to leakage, the current would not be expected to become zero at zero applied bias. This observation suggests that electron emission is a factor in heater-cathode leakage.

Decay and Polarization

When a voltage is applied between heater and cathode, initial "surges" of leakage current are observed which invariably decay to lower levels with time. After the voltages are removed, the heater cathode system recovers to its previous state, and the decay and recovery cycle may be repeated. Such temporary leakage decay is called polarization.

Polarization is a typical symptom of systems in which conduction of current is associated with the presence of charged carriers having appreciable mobility. The effect of an applied voltage is to cause a drift of the charged carriers. Consequently, complex voltage gradients, which are dependent upon the distribution and number of the carriers at any time are developed. At equilibrium, most of the voltage drop will normally occur in the vicinity of an electrode and, thus, only the remaining fraction of the originally applied voltage is effective in promoting current flow through the rest of the system. Consequently, the equilibrium current level can be substantially below initial levels.

Current decay and complex voltage gradients throughout the Al₂O₃ insulation coating are observed in heater-cathode leakage studies¹⁷ indicating that ionic contaminants play a major role in leakage. One noteworthy consequence of the effects of polarization is that most of the static heater-cathode impedance is developed at the boundaries of the insulation coating and, therefore, increased insulation thicknesses would not be expected to produce proportionately increased resistance. On the contrary, the most noticeable effect of an increased amount of insulation can be that it introduces a greater total amount of leakage-producing contaminants into the heater-cathode system and, therefore, may require substantially longer processing to achieve equivalently low leakage levels.

Measurements of heater-cathode leakage at various times show both rapid-decay time constants (milliseconds) and slow-decay time constants (minutes). At normal heater temperatures, much of the loss is recoverable although the over-all leakage level may be continually reduced during prolonged measurements since contaminants are vaporized out of the system. The extent of the decay period and the amount of initial leakage current will depend markedly on the state of the heater-cathode system before measurement. For example, if the heater-cathode bias were suddenly changed from a high negative value to a high positive value, an unusually large initial leakage current surge would be noted. Due to such effects, it is standard practice in testing tubes to preheat tubes for several minutes with the same heater-cathode bias that is to be used during measurement of the leakage current. In

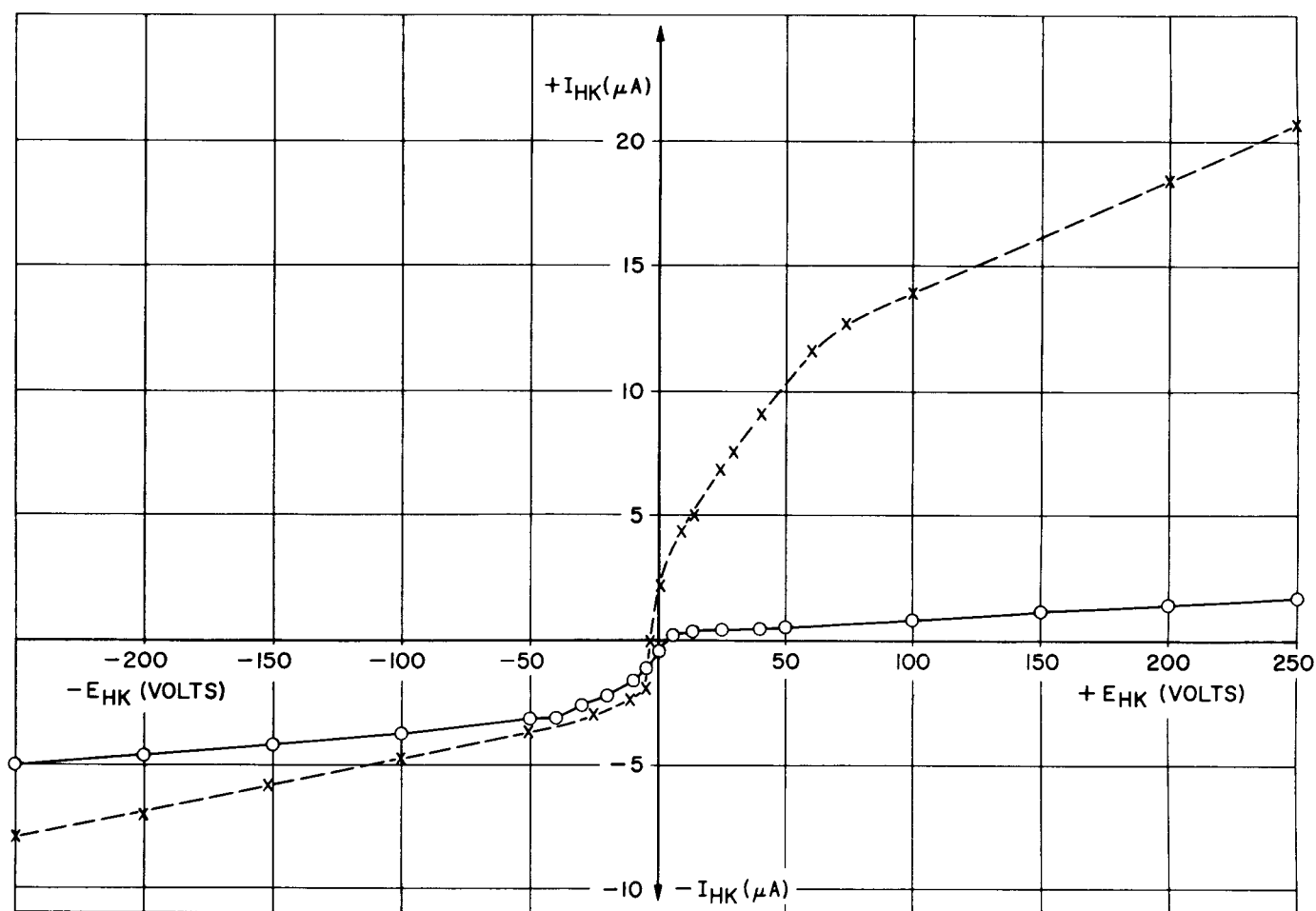


Figure 14. Typical Heater-Cathode Leakage Characteristics on Two Different Tubes by Conventional DC Methods of Measurement

this way, much of the transient leakage current can be eliminated and, consequently, reasonably stable meter readings can be obtained.

The decay effects associated with heater-cathode leakage can have an important influence on leakage measured under different conditions. Fig. 15 shows the heater-cathode impedance of a tube measured at different frequencies. The impedance is substantially lower at the higher frequencies since the rapidly reversing polarities accentuate polarization effects. Fig. 16 shows the leakage measured on a tube by two techniques. The upper dashed-line curve gives the heater-to-cathode-leakage pattern when a 60-cycle sweep with increasing voltage is applied between heater and cathode. The lower dashed-line curve is for decreasing sweep voltage; here, distinct evidences of hysteresis caused by leakage decay are observable. The upper, solid-line, curve shows the peak leakage measured by pulse techniques (1 millisecond, 60 pulses per second).

Distribution of Heater-Cathode Leakage Values

Heater-cathode leakage values invariably occur in highly skewed statistical distribution patterns. It is characteristic that extreme variations are found in "identically" processed tubes; leakage values varying

by a ratio of 100 to 1 are not uncommon in measurements on a large lot of tubes.

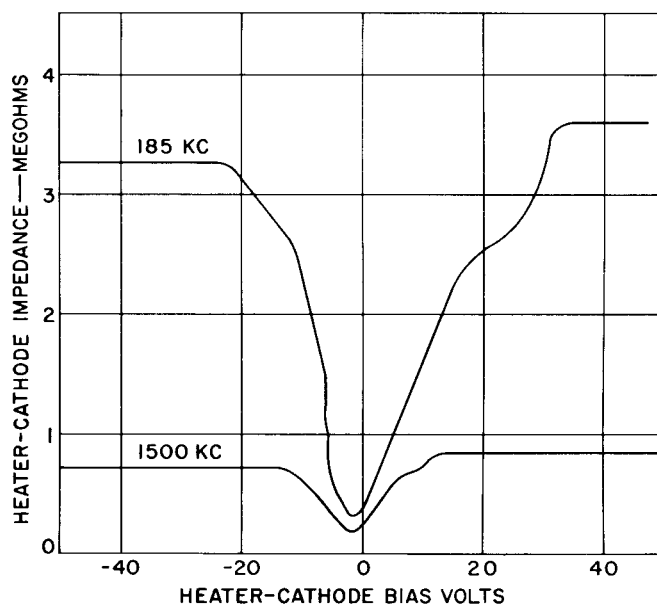


Figure 15. Typical Frequency Effects on Heater-Cathode Impedance

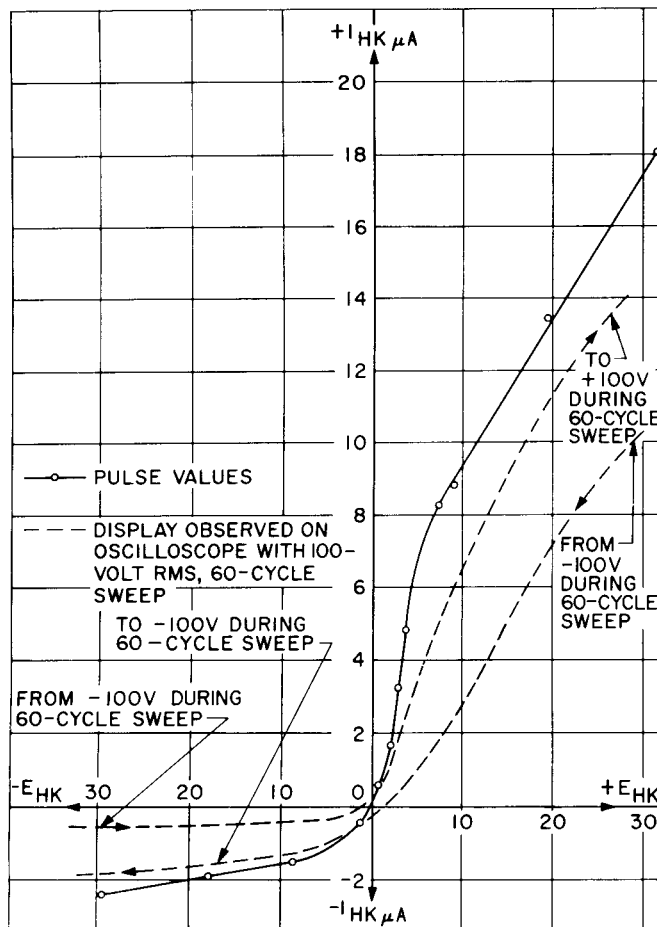


Figure 16. Heater-Cathode Leakage Characteristics Measured by Different Methods on the Same Tube to Illustrate the Effects of Polarization

Because of the highly skewed distribution, a conventional statistical treatment of leakage data, which presupposes a normal, Gaussian distribution, may not be satisfactory. For example, one "high" leakage value might outweigh twenty low leakage values, if straight arithmetic averages were used. From a purely statistical point of view, a more satisfactory, simple method of handling such highly skewed distributions would be to take the logarithms of all leakage data and then to analyse these logarithms in the conventional manner (i. e., to assume a logarithmo-normal distribution). In this way, any single "wild" measurement will not receive excessive emphasis. In this type of statistics, the important parameter is not the average, but the median (the leakage level above and below which, ideally, 50 per cent of the measurements fall). The need for adopting such a logarithmic distribution is easily justified theoretically if it is assumed that the assignable causes of variation are in some manner connected with temperature variability. Since chemical reaction rates depend logarithmically upon temperature, it would follow that a logarithmic distribution of leakages could then result from slight temperature variations.

In Fig. 17, the applicability of a logarithmic distribution of leakage values to experimental data is indicated.

This plot is made on cumulative probability graph paper and shows an actual distribution of heater-to-cathode-leakage measurements on both linear and logarithmic scales. The straight-line relationship for data plotted on the logarithmic scale indicates that a logarithmo-normal distribution provides a reasonable fit to the leakage data.

Changes of Leakage after Tapping of Tube

Changes in heater-cathode resistance on a small percentage of a lot of tubes after drop-testing, vibration, tapping, cycling the heater voltage on and off, or even after normal handling and storage is one of the major heater-cathode-leakage problems.¹¹ Tests indicate that the leakage in any tube can be altered after sufficiently severe tapping; it is usually possible to increase and decrease the leakage alternately by locating appropriate points of impact. Fortunately, leakage produced in such a manner will normally disappear after a few hours of operation at normal filament voltages or after a shorter period at increased voltages.

Heater movement within the cathode is without doubt the cause of such variable leakage values. Factory experience indicates that such effects are greatest with tube constructions having short or flat cathodes, loosely fitting heaters, or whenever opportunities for heater movement exist. Conversely, these effects are minimized, for example, by the use of rigid mounts and inverted pinched cathodes which restrict movement.

In tube types where $+I_{HK}$ leakage has sporadically appeared after normal storage, some success in maintaining uniformly low-leakage levels has been achieved by use of a severe hotshot stage near the end of the aging schedule. Such a high-temperature treatment will tend to vaporize contaminants from all parts of the heater insulation, as contrasted with normal aging schedules where contaminants may be thoroughly electrolysed away only from those areas which have been in contact with the cathode. A possible confirmation of the latter effect may be inferred from tests in which it was found that cycling heaters on and off during aging to cause artificial heater movement could considerably reduce the percentage of tubes which subsequently would develop leakage. In addition, such high-temperature treatment results in the vaporization of a visible layer of insulation onto the inner surface of the cathode. Although the importance of such thin insulating films on the metallic surfaces of the heater-cathode system is difficult to evaluate accurately, it is possible that they are the most important factor in achieving high heater-cathode resistances. In this sense, it may be noted that although hydrogen-fired heaters or heaters removed from low-leakage tubes usually have lower leakage values immediately after sealexing than unprocessed control heaters, the leakage values are rarely low enough to be commercially acceptable without additional aging of the tubes. The missing factor could well be that such thin insulating layers are not formed.

Effect of Heater Temperature on Leakage

A temporary increase (or decrease) in heater temperature caused by a change in heater power will al-

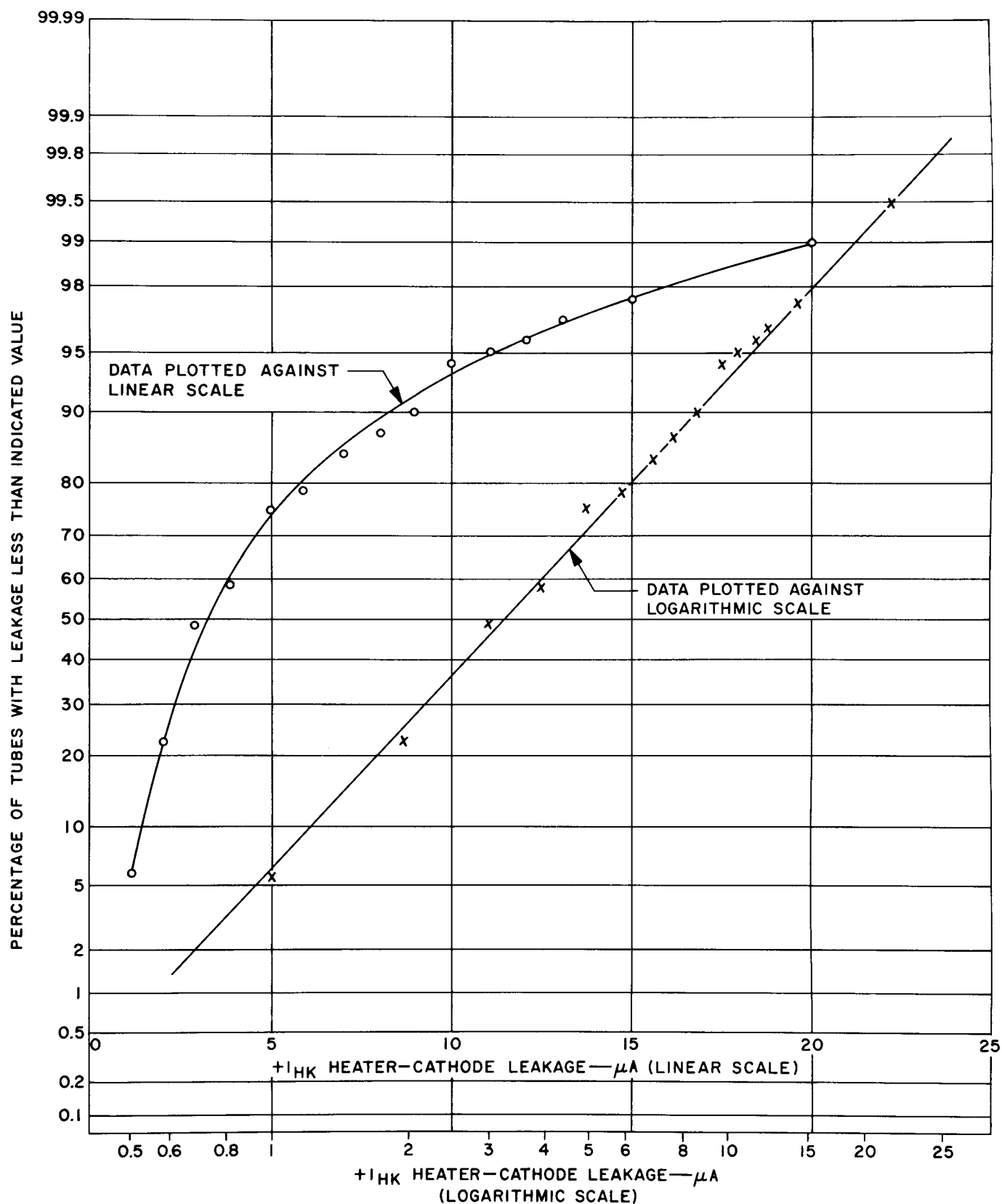


Figure 17. Distribution of Heater-Cathode Leakage Values ($+I_{HK}$) on Cumulative Probability Graph to Show That the Logarithms of Leakage Have an Approximately Normal Distribution (120 tubes)

ways result in a temporary increase (or decrease) in heater-cathode leakage. As shown in Fig. 18, such leakage changes exponentially with the reciprocal of absolute temperature in a manner characteristic both of conduction and emission phenomena.

mensions but does not change the total rated power dissipation of the heater.

The data in Fig. 18 show that the temperature dependence of the $-I_{HK}$ leakage (measured with the heater

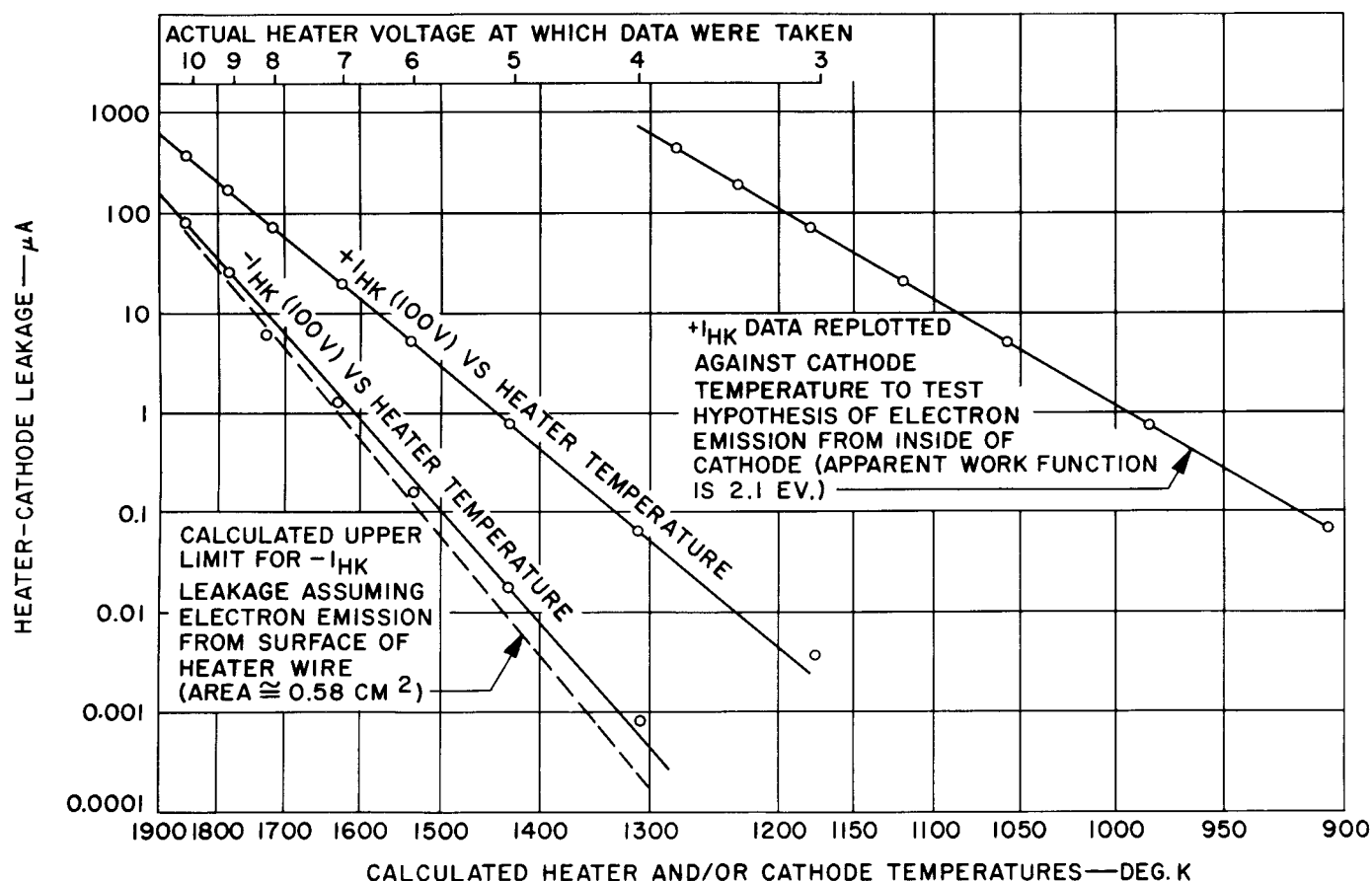


Figure 18. Typical Dependence of Heater-Cathode Leakage on Heater Temperature Resulting from Changes in Heater Voltage

It cannot generally be inferred from such a temperature dependence, however, that a normally "hot" heater will always have greater heater-cathode leakage than a corresponding normally "cool" heater. This could only be concluded if commercial leakage levels were so low that the ultimate capability of the heater-cathode system were being approached. In the more usual case, commercial leakage levels are well above the ultimate levels because of contaminants in the system. Over the limited temperature range normally used in heater operation, contamination levels are apparently of greater importance than actual heater temperatures in determining leakage levels. As indicated under the subsequent discussion of heater size, it is easier to age out leakage of the type caused by contamination from a small "hot" heater than from a corresponding colder but, of necessity, larger heater. A further factor to be considered is that, regardless of the heater-wire temperature, so long as the power dissipated by the heater remains fixed, the cathode temperature will not change. Thus, any factor in heater cathode leakage which depends only upon the cathode temperature will not be basically altered by a change in heater design which merely changes the heater di-

negative) and the $+I_{HK}$ leakage (measured with the heater positive) is not the same. This observation provides strong evidence that the two types of leakage do not result from the same effect. The simplest explanation is that in the former case, the leakage was dependent upon electron emission from the tungsten heater wire, while in the latter case the leakage was due to electron emission from the inside surface of the cathode.

The order of magnitude of the $-I_{HK}$ heater cathode leakage, which could be due to electron emission from the tungsten heater wire, is readily obtained from heater dimensions and the known electron emissive properties of tungsten. A comparison of this type is shown in Fig. 18; the correspondence between measured and calculated leakage levels for this set of data over a wide temperature range is striking.

In a similar manner, the order of magnitude of the $+I_{HK}$ leakage may be explained under the assumption that it is produced by electron emission from the inside of the cathode. In this case, however, the $+I_{HK}$ data must be plotted against cathode temperature,