UCRL-2321
Unclassified-Instrumentation Distribution

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

Contract No. W-7405-eng-48

A CRITERION FOR VACUUM SPARKING DESIGNED TO INCLUDE BOTH R. F. AND D. C

W. D. Kilpatrick

September 4, 1953

Berkeley, California

A CRITERION FOR VACUUM SPARKING DESIGNED TO INCLUDE BOTH R.F. AND D.C.

W. D. Kilpatrick

Radiation Laboratory, Department of Physics,
University of California, Berkeley, California

September 4, 1953

ABSTRACT

An empirical relation is presented which represents a boundary between no vacuum sparking and possible vacuum sparking. Metal electrodes and r.f. or d.c. voltages are used. The criterion fits several orders of surface gradient, voltage, gap, and frequency. Current due to field emission is considered necessary for sparking but in addition, energetic particles are required to initiate a cascade process which increases the field emission currents to the point of sparking. An elementary cascade process is outlined, but the data upon which it is based is not fully stated.

A CRITERION FOR VACUUM SPARKING* DESIGNED TO INCLUDE BOTH R. F. AND D. C.

W. D. Kilpatrick

Radiation Laboratory, Department of Physics,
University of California, Berkeley, California

September 4, 1953

Since there exists no universal definition of sparking, it is defined, for the purposes of this paper, as an occurrence in time at which there is a spontaneous, abrupt, and complete (first order) dissipation of electrically stored energy for a given voltage across a gap between metal electrodes. The proposed criterion deals only with single-gap sparking, ignores effects involving the quantity of stored energy, includes "practical" vacuums of 10^{-3} to 10^{-7} mm pressure, includes metal electrodes which are not especially prepared, and does not include the presence of external magnetic fields. Under these conditions, sparking in a vacuum generally occurs at much lower voltages than would be expected if field emission were the mechanism for its initiation. It is desirable to establish how low these voltages may be and to indicate a possible mechanism.

Since by definition, a spark requires an abrupt change in the prevailing dissipation of energy, fundamental cascade processes must be involved. Available theories[1, 2, 3, 4] for sparking differ widely in their premises and criteria, and in addition, the details of initiation, maintenance, and possible cascade processes are not stated or are not agreed upon. Available theories suggest one of the following as a criterion for sparking.

1. $E \geq$ const.
2. $J \geq$ const.
3. $VE \geq$ const.
4. $\gamma\delta \geq$ const.

---

* The term "vacuum arc" is also applicable.

where E is the surface gradient at the cathode, V is the total voltage across the gap, J is the area current density over some small cathode area, γ is the ratio of secondary electrons to ions, δ is the ratio of secondary ions to electrons. The general indication is that for any theory there is some critical constant. The different points of view apply only to d. c. conditions, and the supporting evidence in some cases is based on the maximum voltage at which d. c. sparking is only moderately probable after extended conditioning procedures, e. g. spark clean-up. None of these criteria fit the r. f. case generally.

Some work at 200 mc[5] and later with d. c. by the author has led to an empirical criterion which, on the other hand, includes both r. f. and d. c., and implicitly includes two conditions:

a. There is a lower boundary for sparking voltages below which no sparking should be observed, even prior to or during conditioning.

b. Particular energies (to be discussed), that are absorbed by a cathode electrode just prior to a spark, are to be taken into account for initiating a cascade process.

The proposed criterion fits experimental data for $10^{-5} <$ gap < 10 cm., $30 <$ voltage $< 1.2 \times 10^{6}$ volts, $9 \times 10^{4} <$ surface gradient $< 8 \times 10^{7}$ volts/cm, and d. c. $<$ frequency < 3000 mc.

A cascade process is apparently the key to a suitable spark criterion. The cascade process, on which the proposed criterion is based, assumes that there is evolution of a localized expanding region of increasing gas pressure from the cathode surface, creation of ions in this gas, space charge neutralization, increased electron emission from ion back bombardment, further evolution of gas, further creation of ions, etc. The gas evolution may be initiated by supplying energy to the cathode surface in several ways, such as energetic particle bombardment and thermal heating.

If the gradient is less than approximately 10^{7} volts/cm, then the electron current due to field emission will be small. The presence of a few ions which can be accelerated in the gap to a maximum energy of W electron volts will supply cathode energy; hence electrons and neutral gas will be emitted from the cathode. As a result of the emitted electrons and neutrals, a cascade process follows which may terminate in a spark, in that an abrupt change in the dissipation of stored energy occurs. This case of low gradient and high energy is characteristic of poor vacuum systems (10^{-3} to 10^{-7} mm), where sufficient ions are available for the cascade process.

On the other hand, if high surface gradients (i. e. 10^{7} to 10^{8} volts/cm) are possible, there will be considerable electron emission. In general, this is uncommon and occurs with well outgassed systems and a residual gas pressure of 10^{-11} to 10^{-12} mm. In order for an abrupt change in current to occur, assuming that no residual gas ions are present for bombarding the cathode, the only particles available for ionization and hence neutralization of the electron space current will be those released from the cathode by thermal energy and the cascade process previously described. The energy per particle to be considered could be associated with the melting point of the cathode metal, or $W = (3/2)\,kT$. When these high temperatures are reached without ion bombardment, the cascade process can start, and a spark necessarily follows.

In general, a current I_o dependent on the field E will be described by the equation:

$$I_o \sim E^2 e^{-b/E}$$

where b depends on cathode surface conditions. On a theoretical basis, Sommerfeld and Bethe[6] have derived an expression for current, including the effects of cathode temperature, in which I_o for relatively low gradients is multiplied by a function of kT. An attempt to fit this equation to minimum sparking voltages led to $f(W, E) = \text{const.}$, where W is the maximum possible energy of a particle at the electrode surface prior to a spark. In the absence of field accelerated particles, this energy would be determined by $(3/2)\,kT$. Further speculation, including cascade effects, led to the successful empirical criterion:

$$WI_o = WE^2 \left\{ \exp\left(-\frac{1.7 \times 10^5}{E}\right) \right\} = 1.8 \times 10^{14}$$

where W is in electron volts, E is cathode gradient in volts/cm, and the constants are relatively insensitive to the kind of metal electrodes or the kinds of vacuum systems that are used. This proposed criterion includes r. f., d. c., and pulsed d. c; and determines a threshold below which no sparks should be observed during or prior to conditioning procedures. Furthermore, the boundary values plotted in Figs. 1-A and 1-B are a lower limit in the sense that they may be raised by conditioning procedures such as outgassing, cleaning the electrodes, or spark clean-up.

Figures 1-A and 1-B assume the presence of H_1^+ when poor vacuum systems are to be considered, since the evolved gas is probably hydrogen. This assumption is based on an experiment done by the author after observing that the residual gas pressure in a small vacuum system increased concurrently with a spark and persisted sometimes for several seconds. A mass spectrometer attached to the system detected the presence of a great deal of hydrogen but no trace of other gases. Possible sources of hydrogen could be: machine oil, vacuum pump oil (if an oil pump were used), absorbed water, or interstitially absorbed hydrogen. Identifying the gas is necessary for computing the maximum ion energy W in an r. f. system.

A list of conditions associated with each point plotted in Figs. 1-A and 1-B is to be found at the end of this paper. For static d. c., the maximum energy W which an ion may have is taken as the energy of a singly ionized particle crossing the gap from anode to cathode. For r. f., ions need *not* cross the gap from one electrode to the other but may start in the gap space.

In order to find the maximum r. f. energy W, it is necessary to compute a factor that takes into account the variation in intensity and in time of the electric field as the particle moves in the gap. A solution of the equations of motion must include an optimum phase angle $\phi_o = \omega t_o$ at which the particle should start in order to gain energy and to then bombard the cathode electrode with maximum energy W. The results of a non-relativistic solution assuming plane-parallel fields are plotted in Fig. 2. In order that the solution may be fitted to any frequency, any gap, any kind of particle, and any voltage, the quantity V^* (which represents the highest-energy, non-relativistic, multipactor voltage and π degrees transit time) is defined as:

$$V^* = (g/\lambdabar)^2 \, m_o c^2/\pi q \qquad \text{(N.R.)}$$

where g is the gap length, $\lambdabar = \lambda/2\pi$, λ is the propagation wavelength in free space, and q is the change of a particle with $m_o c^2$ rest energy in electron volts. In Fig. 2, maximum W/V is plotted against V/V^*, where V is the peak r. f. voltage which appears across the gap.

It may be simpler in some cases, where $V/V^* < 1$, to find the maximum W from the relation which represents an oscillation-migration trajectory:

$$W = 2\,(qE\lambda)^2/m_0c^2 \qquad (\text{N.R.}), \quad V < V^*$$

where E is the cathode gradient in volts/cm. and where the ion suffers no gas collisions in transit. It is emphasized that this equation may be used instead of Fig. 2 in the r.f. computations.

Although the vacuum spark criterion presented has been obtained empirically, its agreement with available data over a wide range substantiates at least the form of the expression. The fact that it is presented in terms of measurable quantities should make it useful. It seems certain that a cascade mechanism involving ions is required especially at the lower gradients since severe limitations are placed on cathode bombardment energy by various r.f. and pulsed d.c. conditions. There is also no reason to suppose that the mechanism is basically different for high gradients, as indicated previously.

In order to check the criterion further, the cathode gradient and ion bombarding energy could be made to vary independently not only by a change in the configuration of the cathode, but by other means as well. One method would be to fix a surface gradient and then bombard the cathode with particles whose energy exceeded

$$\int_{\text{anode}}^{\text{cathode}} E(g)\,dg.$$

where E(g) is the gradient in the gap g. A condition of this kind is found in a multiple-gap Van de Graaff generator column. The difficulty in using data from a multiple-gap arrangement is that a breakdown in one gap will discharge the whole column, and it is necessary to determine the bombarding energy W which is associated with the particular gap that triggers the column breakdown. Another method for varying W and E independently of the applied voltage, is to use the increased emission from Malter[7] layers. The W and E used in the criterion, would then be:

$$W = \int_{\text{anode}}^{g-x} E(g)dg$$

$$E = E_{\text{layer}} = -\left(\frac{\partial V}{\partial x}\right)_{\text{cathode}}$$

where x is the layer thickness. In order to determine W, it is possible to establish an emitting Malter layer with an anode voltage V_1, then change V_1 momentarily to V_2 so that no electrons arrive at the anode. The quantity $q(V_1 + V_2)$ is then the maximum available energy W. Notice that the cascade process can now occur in a weak field, and that the apparent average cathode gradient of voltage/gap is much lower than the actual cathode surface gradient.

The cascade process would have a sound basis if the probability of neutral gas evolution from a surface bombarded by energetic ions were known to be sufficient. Since the cascade process depends, in part, on both neutral and secondary electron emission from ionic bombardment, it would be difficult to distinguish only the evolution of neutral gas per incident ion by controlled bombardment, because the secondary electrons would ionize part of the evolved neutral gas.

In addition, it would be desirable to know the probability distribution of the number of secondary electrons per ion from ionic bombardment including field as well as energy effects. Several energy dependent, average coefficients of secondary electrons per ion were found by Bourne[8] in which he observed practically no field dependence; but his data covered only a small change in field, 14 to 55 kv/cm at 140 kv. Furthermore, according to the proposed criterion, the field or total voltage must be higher than any used by Bourne or Trump and Van de Graaff[9] in order for any marked effect to take place, and the use of higher field is complicated by the onset of sparking. A comparison of data by Hill, et al.,[10] Trump and Van de Graaff,[9] and Bourne,[8] indicates the possibility of a gradient effect which becomes important with higher gradients when contaminants are present. If such information were available, a possible upper limit at which the probability for sparking would approach unity might be computed.

ACKNOWLEDGMENTS

Particular acknowledgments are made to Dr. S. W. Kitchen for interpretations regarding the data presented, to K. W. Ehlers for the empirical data on d. c. as well as aiding in the formulation of the spark criterion, and to Dr. L. W. Alvarez for making this investigation possible.

REFERENCES

1. L. Tonks, Phys. Rev. 48, 562 (1935).
2. W. P. Dyke, Bull. Am. Phys. Soc., Rochester (1953), paper N-4.
3. L. Cranberg, Journ. App. Phys. 23, 518 (1952).
4. J. G. Trump and R. J. Van de Graaff, Journ. App. Phys. 18, 327 (1947).
5. UCRL-1907, (1952).
6. A. Sommerfeld and H. Bethe, Han. der Phys. XXIV/2, 440.
7. L. Malter, Phys. Rev. 50, 48 (1936).
8. H. C. Bourne, Jr., et al, Bull. Am. Phys. Soc. Rochester, (1953) paper E-3.
9. J. G. Trump and R. J. Van de Graaff, Journ. App. Phys., 23, 264 (1952).
10. Hill, et al, Phys. Rev. 55, 463 (1939).

DATA LIST AND COMPUTATIONS

The following items refer by number to Figs. 1-A and 1-B. Undoubtedly more information about minimum sparking potentials between metal electrodes in a vacuum is available, but the sources are not known to the author.

1. W. P. Dyke - American Phys. Soc., Rochester Meeting, 1953, paper N-4. Using pulsed d. c., and a field emission microscope with small tungsten emitter points for a cathode, a critical current density of $10^7 < J < 10^8$ amp/cm was reported to be characteristic of spark breakdown. The tungsten was clean (10^{-12} mm pressure), and the cleanliness was monitored by the emission pattern. Assuming the local temperature of the tungsten was about 3000°C at the time of the spark and the measured field was 8×10^7 volts/cm. in the region supporting emission, leads to the following which is plotted in Figs. 1-A and 1-B for pulsed d. c.:

   $W = (3/2)\,kT = 0.39$ ev.
   $E = 8 \times 10^7$ volts/cm.
   $W/E = 4.6 \times 10^{-9}$ cm.
   gap ≈ [illegible] cm.

2. P. Kisliuk - Am. Phys. Soc., Rochester Meeting, 1953, paper E-5. D. C. breakdown over small gaps (~1000 Å) was reported at 3×10^6 volts/cm, where ions were apparently involved.

   $W = 30$ ev.
   $E = 3 \times 10^6$ volts/cm.
   $W/E = \text{gap} = 10^{-5}$ cm.

3. Stanford Linear Accelerator, 2856 MC - Oil vacuum pumping is used, and the surfaces that are subject to highest electric field are the loading discs which are machined from OFHC copper. The discs are about 1 in. apart, and $V/V^* << 1$ for protons. Accelerator tube and construction details may be obtained from the Stanford Microwave Laboratory report No. 185, February, 1953. Apparently outgassing of the metal discs occurs concurrently with sparking at the discs, and

a surface gradient which empirically seems to correspond to the outgassing is about 5×10^5 volts/cm at a disc surface. Assuming this gradient for the onset of sparking due to protons leads to:

$$W = \frac{2(5 \times 10^5)^2 \ (\frac{10.5}{2\pi})^2}{931 \times 10^6} = 1.5 \times 10^3 \text{ ev.}$$

$$E = 5 \times 10^5 \text{ volts/cm.}$$

$$W/E = 3 \times 10^{-3} \text{ cm.}$$

$$\text{gap} \cong 2.5 \text{ cm.}$$

4. Author (unpublished) -D. C. In an oil pumped system, without liquid nitrogen trapping, 3/8 in. diameter copper hemisphere electrodes were used. The electrodes were "coated" with a thin film of oil by rubbing in the palm of the hand. Minimum d. c. breakdown voltages lead to the following:

$$W = 3 \times 10^3 \text{ ev.}$$

$$E = 3.4 \times 10^5 \text{ volts/cm.}$$

$$W/E = \text{gap} = 8.9 \times 10^{-3} \text{ cm.}$$

5. J. W. Beams, Phys. Rev. 44, 803 (1933). - D.C. A mercury pool was used for a cathode. It was indicated that the presence of water or organic material would cause lower sparking potentials than when pure redistilled mercury was used. The lowest gradient was 3.5×10^5 volts/cm and the highest obtained was 1.8×10^6. If the lower value is used, for a gap reportedly 2.5×10^{-2} cm, then for minimum sparking potentials,

$$W = 8.7 \times 10^3 \text{ ev.}$$

$$E = 3.5 \times 10^5 \text{ volts/cm.}$$

$$W/E = \text{gap} = 2.5 \times 10^{-2} \text{ cm.}$$

6. Author (unpublished) -D. C. In an oil pumped vacuum system with no liquid nitrogen trapping, 3/8 in. diameter hemispheres of Al, Monel, and stainless steel were used. Contrasted with Item 4, above, the electrodes were degreased, wiped, and cleaned with concentrated HNO_3 followed by dilute HNO_3. Within 10 percent, the minimum d. c. sparking potentials were all the same.

$W = 1.5 \times 10^4$ ev.
$E = 2.4 \times 10^5$ volts/cm.
W/E = gap = 6.3×10^{-2} cm.

7\. Author, UCRL-1907, 200 m. c. - A mercury vacuum pump was used. Liquid nitrogen traps were used throughout the series of experiments, and the traps were designed for many molecular reflections between the pump and the evacuated system. Of the several different metal electrodes used,[**] and various electrode surface configurations used, sparking thresholds occurred for 170 kv/cm < surface gradient < 400 kv/cm. In all cases $V/V^* \ll 1$, and for protons the minimum condition is:

$W = 3.5 \times 10^4$ ev.
$E = 1.7 \times 10^5$ volts/cm.
$W/E = 2.1 \times 10^{-1}$ cm.
gap $\cong$ 7 cm.

[**] Cu(OFHC), Rh, Au, Cr, Mo, Al, Sn.

8\. Author (unpublished)-D. C. Oil vacuum pump, no liquid nitrogen, 3/8 in. diameter copper hemispheres electrodes, thin oil film deposited on the electrodes.

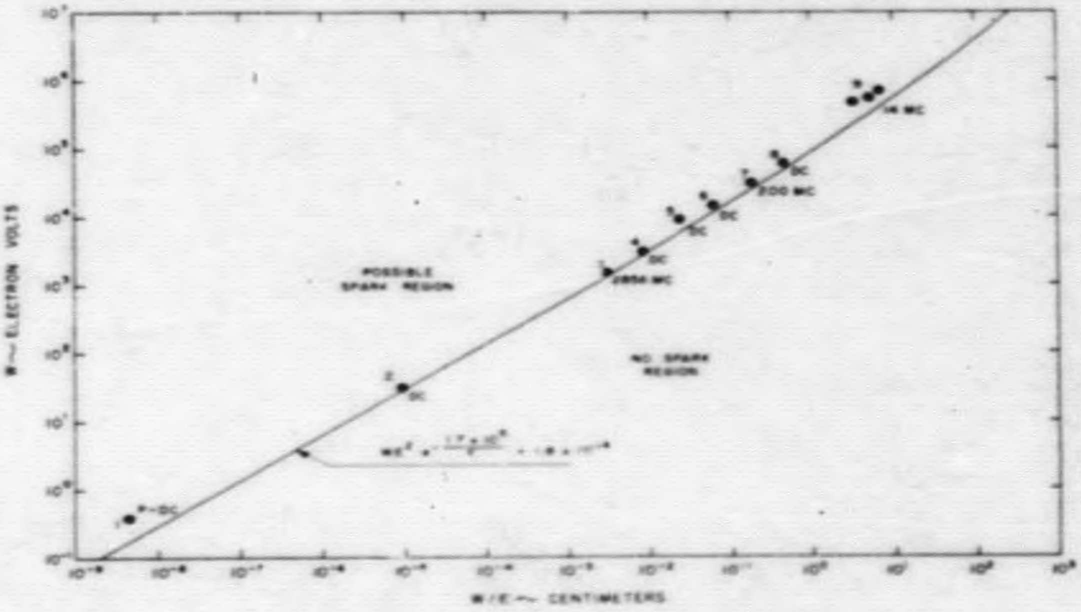
$W = 6 \times 10^4$ ev.
$E = 1.31 \times 10^5$ volts/cm.
W/E = gap = 4.57×10^{-1}.

9\. Heard and Chupp, UCRL-1962, 14 M. C. - An oil pump with liquid nitrogen traps were used. Although minimum spark potentials were not the object of the research program, the lowest values recorded for inconel are:

780 kv, gap = 3-3/8 in.
530 kv, gap = 2-3/8 in.
530 kv, gap = 1-3/8 in.

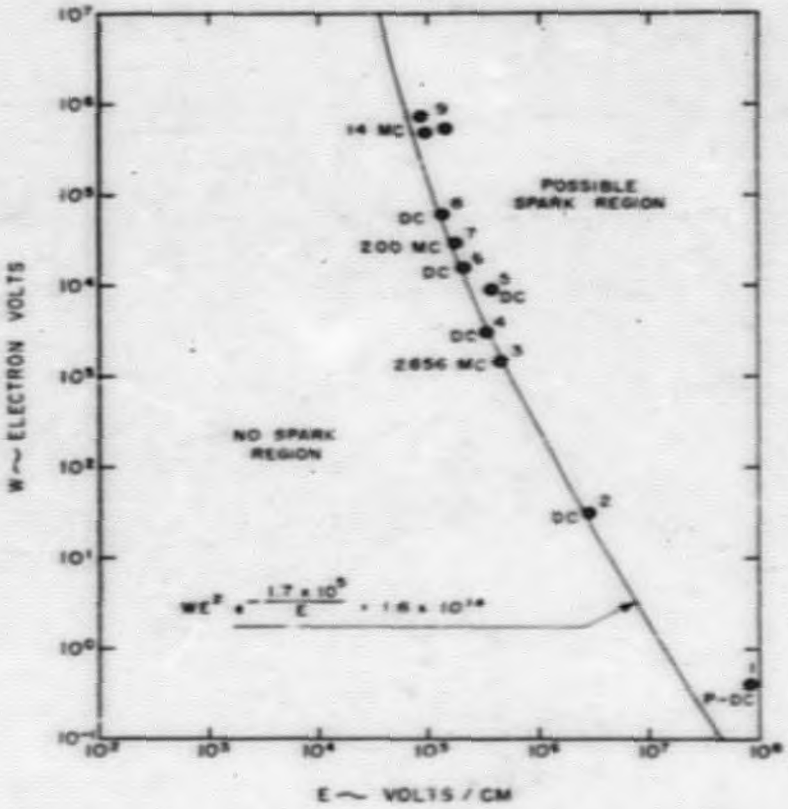
These values and essentially plane parallel fields, leads to the following, using transit times from Fig. 2.

$W = 7.1 \times 10^5,\ 5.0 \times 10^5,\ 5.2 \times 10^5$ ev.
$E = 9.1 \times 10^4,\ 8.8 \times 10^4,\ 1.5 \times 10^5$ volts/cm.
W/E = 7.8, 5.7, 3.43 cm.



MU-6174

Fig. 1 A



MU-6143

Fig. 1 B

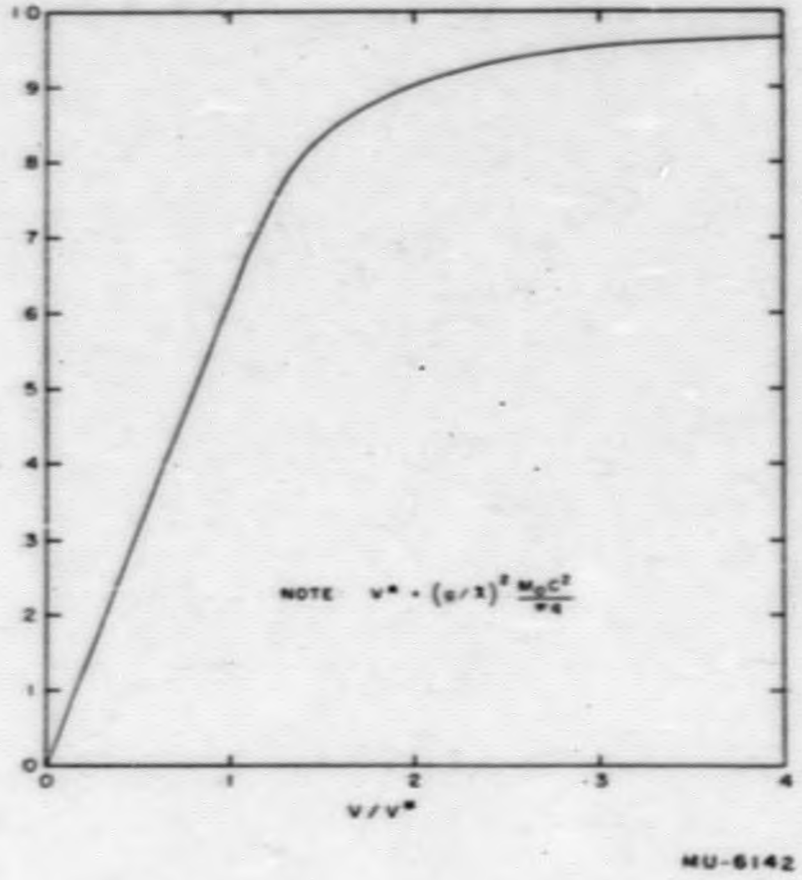


Fig. 2