

Arcing at Electrical Contacts on Closure. Part I. Dependence upon Surface Conditions and Circuit Parameters

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Citation: *Journal of Applied Physics* **22**, 955 (1951); doi: 10.1063/1.1700078

View online: <http://dx.doi.org/10.1063/1.1700078>

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and we must therefore plot

$$f(s_2, \bar{r}_2/a)/f(s_1, \bar{r}_1/a)$$

as a function of D instead of $C_0(s_2)/C_0(s_1)$. Now \bar{r}_2 and \bar{r}_1 indicate the average radii, respectively, at t_2 and t_1 . A plot of $f(s)$ for various values of \bar{r}/x is given in Fig. 2, to show the general behavior of $f(s)$.

From this graph it can be seen that for concentrations which are likely to matter, $C_0(s)$ can be used instead of $f(s)$ if $\bar{r}/x \leq 10^{-2}$. Here \bar{r} can be as small as 10^{-4} cm, in which case the stationary flow approximation can be used for particles 10^{-2} cm from the original interface. At concentrations smaller than those covered in the graph $f(s, 0.01)$ and $C_0(s)$ may differ appreciably. The larger the value of s , the larger the ratio of $f(s, 0.01)$ to

$C_0(s)$ becomes. For large values of s , however, both of these functions are extremely sensitive to the value of s , since they both contain a factor e^{-s^2} . (At low concentrations C can be approximated by $(1/\pi)(1/s)e^{-s^2}$.) A small change in D and hence in s can cause a large change in this exponential. It can be shown on this basis that an error of less than 2 percent in the evaluation of D will be made by using $C_0(s)$ instead of $f(s, 0.01)$ for $s > 3.0$.

ACKNOWLEDGMENT

The authors are indebted to Mr. B. Pinkel, Dr. S. L. Simon, and Dr. P. Schwed of NACA Lewis Flight Propulsion Laboratory for their valuable discussion and interest in this work.

Arcing at Electrical Contacts on Closure. Part I. Dependence upon Surface Conditions and Circuit Parameters

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(Received February 21, 1951)

In a low voltage circuit the occurrence of an arc between approaching electrodes is dependent upon the nature of the surfaces and upon the circuit inductance. For carbon surfaces, or noble metal surfaces which have been "activated" by operation in various organic vapors resulting in a carbonaceous layer, the limiting circuit inductance is somewhat above 10^{-3} h, which is much higher than the limiting inductance for clean noble metal surfaces. This activation by organic vapors occurs for noble metals only and for certain vapors; for example, benzene derivatives. In the case of silver and benzene vapor, it has been shown that the activation is due to adsorption of benzene onto a greasy surface layer and its decomposition there by the heat of subsequent closures. A metal surface, which has been activated by organic vapor, remains active indefinitely if there is no arcing at the surfaces; but with continued operation and accompanying arcing,

the activating material is burned away, and the surface returns to the inactive condition if no activating vapor is supplied.

Arc voltages, which are independent of current and of ambient gas, as far as tested, have been measured for a number of metals and for carbon; the arc voltage for carbon is quite erratic in the range between 20 and 30 volts, but for each of a number of metals the arc voltage is steady.

Arcing at noble metal surfaces, similar to that induced by carbonaceous material from organic vapors, can be produced also by insulating particles or insulating films. The active condition gradually disappears with continued arcing, unless there is a steady supply of insulating material to the surface.

The minimum arc current has been measured to be 0.6 amp for active silver and for carbon, and 0.03 amp for inactive silver. These are the currents at which an established arc is extinguished.

INTRODUCTION

RECENTLY reported experiments¹ have implied that erosion of electrical contacts on closure is due entirely to an arc occurring, in most cases, before the contacts touch; when there is no arc there is no erosion. That this must be at least approximately true is well established by the experiments, on the basis of energy considerations alone. The experiments prove that, when contacts close without arcing, substantially all of the energy originally stored in the circuit is still present after closure and this energy is dissipated in the *resistance* of the circuit by current flowing through it. Only when there is an arc is most of the energy dissipated *at the contacts*, and, therefore, only when there is an arc can the erosion be large. The problem of the erosion of

contacts on make is thus reduced to investigation of the conditions which determine whether or not there is an arc on make and the nature of the arc which may occur.

The experiments which prove that the energy dissipated at electrical contacts on make is not great unless an arc occurs are of two types. In the first of these, oscilloscopic records of the voltage across the condenser, which is discharged by the contacts, are found to have a closed circuit oscillation of which the initial amplitude has one or the other of two discrete values, corresponding, respectively, to the energy remaining after the loss to be expected from an arc and to the initial energy.* In the second type of experiment, to be reported elsewhere,² direct calorimetric determinations obtained with the aid of thermocouples are made of the

¹ L. H. Germer and F. E. Haworth, J. Appl. Phys. **20**, 1085 (1949).

* See the oscilloscope traces of Figs. 13a and 13c in reference 1.

² L. H. Germer, Bell System Tech. J. (October, 1951).

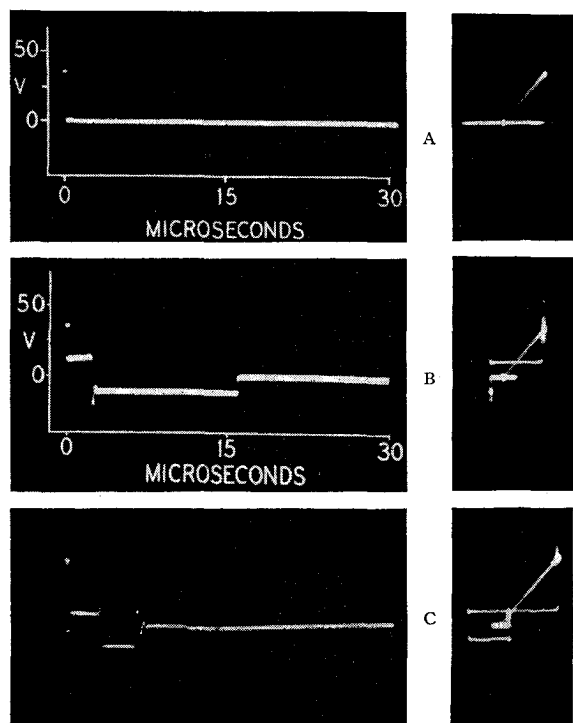


FIG. 1. Oscilloscopic records of closures of silver contacts discharging a condenser of 10^{-8} f through an inductance of 10^{-4} h. The ordinates represent voltage across the closing contacts. In the left-hand traces the abscissas are time; in the right-hand traces they are voltage across the condenser. The vertical scale is the same on all traces, but the horizontal scale of the right-hand traces is slightly different, as is evident from the fact that the sloping line representing the retrace of the oscilloscope beam is not at exactly 45° . (A) Closure at 35 volts without an arc. (B) Closure at 35 volts with an 11 volt arc. (C) Closure at 50 volts with an arc at 11 volts followed by a second arc at -11 volts.

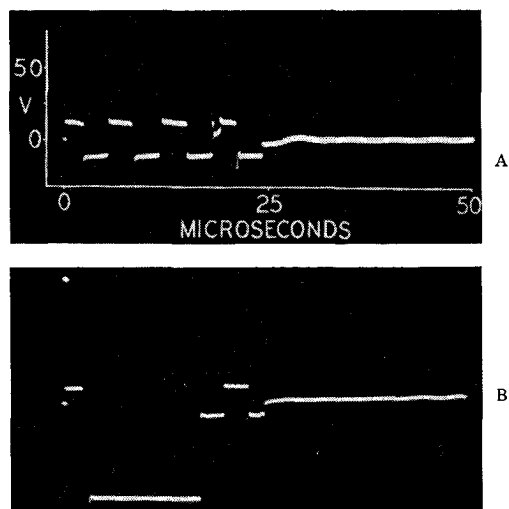


FIG. 2. (A) Record of the discharge by zinc electrodes of a condenser charged to 177 volts, showing 8 successive arcs in alternate directions. (B) Discharge by zinc electrodes of a condenser charged to 87 volts, showing 4 successive arcs interrupted by an open between the first and second.

heat dissipated upon each contact when arcing occurs and when arcing does not occur; the observations prove that, without an arc, the energy at the contacts is rather small.

In the earlier paper¹ it was stated that whether or not arcing on closure occurs in a low voltage circuit between clean contacts of platinum, palladium, gold, or silver is determined predominantly by the circuit inductance; the limiting value, below which arcing takes place and above which it does not take place, is of the order of 3×10^{-6} h and varies somewhat with circuit capacity and potential.[†] Carbon was found to behave quite differently in that arcing *always* takes place between carbon electrodes (except, of course, when the circuit potential is below the arc voltage of carbon). Later experiments described in this paper have qualified these statements to make them more nearly exact.

Since these observations were reported, other metals have been tested with results which, except for copper which behaves like the four noble metals, are not yet sufficiently well understood for publication. This paper is concerned with arcing on closure at contacts of platinum, palladium, gold, silver, copper, and carbon, with a few scattered observations on contacts of some other metals.

Although there is no arcing at clean noble metal contacts on closure unless the circuit inductance is very low, the situation is quite different if the surfaces are contaminated by carbonaceous material or by insulating particles or insulating films. In the presence of such foreign substances, arcing may occur on every closure, even when the inductance is very high. Observations of this sort led to a first attempt at a theory of the discharge, which was published at the end of reference 1, and to experiments, recently reported by Haworth,³ designed to test one of the steps in this theory.

In many experiments it has been convenient to separate and bring together crossed wires of the metal under test 60 times per second by means of a magnetic speaker unit as described earlier.⁴ Each closure discharges a condenser through an inductance, and whether or not arcing occurs is determined by observing the screen of an oscilloscope. Typical oscilloscope traces are shown in Figs. 1 and 2, which were obtained by opening a camera shutter for 1/100 sec and thus catching the record of only one closure.

The patterns of Fig. 1A represent closure at 35 volts without an arc, and those of Figs. 1B, 1C, 2A, and 2B represent, respectively, closure at 35 volts with an arc, at 50 volts with 2 arcs in opposite directions, at 177 volts with 8 successive arcs in alternate directions, and at 87 volts with 4 successive arcs interrupted by an "open" occurring between the first and second.[‡] When

[†] Reference 1, p. 1106.

³ F. E. Haworth, Phys. Rev. **80**, 223 (1950).

⁴ J. J. Lander and L. H. Germer, J. Appl. Phys. **19**, 910 (1948).

[‡] Photographs essentially similar to those traces of Figs. 1 and 2 on which the abscissa is time were reproduced as Figs. 12, 14, and 15 in reference 1. The superior clearness of the present traces is

the surfaces of contacts are in the arcing condition, the discharge of a condenser charged to a potential greatly above the arc voltage of the contacts results in successive arcs, but these are, in general, interrupted by one or more opens like that after the first arc of Fig. 2B; the occurrence of 8 successive arcs without any open, as in the pattern of Fig. 2A, is unusual.

ACTIVATION BY CARBONACEOUS MATERIAL

Traces like those of Fig. 1A are produced by the closure of moderately clean electrodes of any one of the following metals: copper, silver, palladium, platinum, or gold. The values of the voltage and of circuit inductance and capacity are immaterial, provided only that the inductance is not extremely low (less than 10^{-5} h), or the voltage very high (of the order of hundreds of volts).

The silver electrodes, which gave the traces of Fig. 1A when they were moderately clean, gave the traces of Figs. 1B and 1C after they had been operated for a few minutes at the rate of 60 times per second in an atmosphere containing benzene vapor. After the vapor had been removed, traces like those of Fig. 1B (or 1C) continued to be observed on every closure for an appreciable time until, after a minute or two, these traces were interspersed with others like those of Fig. 1A and finally *all* of the traces were like those of Fig. 1A. In further experimentation it has been found that the active condition of the contact surfaces which is responsible for the arcs is maintained indefinitely, in the complete absence of benzene, when the contacts are not operated or even when they are made to open and close continuously without discharging a condenser or breaking an electric current. It is clear that the arcing is due to something deposited on the contact surfaces by decomposition of benzene vapor, and that in the absence of vapor, this material can be gradually burned off by continued arcing. Unless the exposure to benzene vapor is near the minimum which will just cause arcing, this substance is readily seen under the microscope or even with the unaided eye. It looks like black soot.

When silver electrodes are operated in air containing various partial pressures of benzene vapor, it is discovered that the "active" arcing condition cannot be produced at pressures of 0.10 mm of mercury or lower but is produced at a pressure of 0.22 mm and at higher pressures. The limiting value at which activation can just be produced depends somewhat upon the voltage, inductance, and capacity, and also, in a rather surprising manner, upon the original cleanness of the metal surfaces, which apparently determines the extent to which benzene can be adsorbed on silver. Further experiments upon the activation of silver by benzene will be described below.

Tests have been made on a number of compounds to find which of them will activate metal electrodes, so that

due to the lower sweep speeds, which could be used because of higher circuit inductances, which in turn were possible because of the "activation" of the contacts.

TABLE I.

	Activated by:		NOT Activated by:	
	cc of substance in 9-liter bell jar (1)	mm vapor pressure (2)	cc of substance in 9-liter bell jar (3)	mm vapor pressure (4)
Substances which activate silver electrodes				
Pump oil	—	—	—	—
Turpentine	—	—	—	—
Penetrating oil	0.025	—	0.010	—
Kerosene	—	—	—	—
Butyl alcohol	—	—	—	—
Benzene	0.011	0.22	0.005	0.10
Toluene*	0.020	0.35	—	—
Xylene	—	—	—	—
Pseudocumene	0.0093	0.13	—	—
Styrene*	0.0006	0.010	—	—
Ethyl Styrene*	0.002	0.015	—	—
Phenyl Acetylene*	0.010	0.17	—	—
Cyclohexanol	—	saturated at 25°C	—	—
Cyclohexanone*	0.01	0.18	—	—
Cyclopentanone	0.035	0.75	0.015	0.32
<i>d</i> -Limonene*	0.0025	0.030	—	—
<i>l</i> -Menthone*	0.020	0.22	—	—
Pinene	—	—	—	—
Terpineol	—	saturated at 25°C	—	—
Ethyl silicate	0.005	0.04	—	—
<i>l</i> -Octene	—	saturated at 25°C	0.05	0.42
<i>l</i> -Dodecene	—	saturated at 25°C	—	—
Octylene	—	saturated at 25°C	—	—
Crotonic acid	—	saturated at 25°C	—	—
Compounds which do NOT activate silver electrodes				
Ethyl alcohol	—	—	—	saturated at 25°C
Amyl alcohol	—	—	—	saturated at 25°C
Ether	—	—	0.015	0.27
CCl ₄	—	—	1.1	21.6
Trichlorethylene	—	—	0.20	4.2
HCl	—	—	—	—
Methyl methacrylate	—	—	—	saturated at 25°C
<i>n</i> -Butyl acetate	—	—	—	saturated at 25°C
Amyl acetate	—	—	—	saturated at 25°C
Ethyl acetate	—	—	—	saturated at 25°C
Acetone	—	—	—	saturated at 25°C
Oleic acid	—	—	—	saturated at 25°C
Propionic acid	—	—	—	saturated at 25°C
<i>O</i> -Dibromo-benzene	—	—	—	saturated at 25°C

arcing occurs, and on a number of metals to find which can be activated and which cannot. In the upper half of Table I, the names of some substances which have been found to activate silver electrodes can be found; in the lower half of the table other compounds with which activation was not produced are listed. In many cases, the contacts were enclosed in a bell jar of 9 liters capacity, and the vapor pressure of the compound in question could be calculated from the amount which was placed in the jar and allowed to evaporate completely before the contacts were operated. The amounts of the substances and the calculated vapor pressures for those tests for which these were known are presented in Table I. Although a value of vapor pressure at which

TABLE II. Arc voltages.

	(L.H.G.)	(Gaulrapp)
Copper	12	12.6
Silver	11	12.3
Palladium	14	—
Platinum	15	15.3
Gold	12	12.6
Carbon	20 to 30	—
Zinc	11.5	10.9

silver electrodes cannot be activated has been obtained for only three of the compounds in the top half of Table I, the values given in column 2 for those compounds which are starred are known to be fairly close to the minimum pressures which are effective, from qualitative observation of the slowness with which arcing is initiated at these pressures.

Experiments similar to those just described for silver have been carried out with electrodes made from thirty-two (32) other elements, mostly metals, although naturally not every metal has been tried with each compound of Table I. Of these elements, the metals copper, palladium, platinum, and gold behave in a way which closely resembles the behavior of silver. None of them will arc on closure, in a high inductance low voltage circuit, if the surfaces are moderately clean. All can be made to arc by exposure to vapors of those compounds which will activate silver, as far as tested.

When arcing occurs, the arc voltage is independent of current over a wide range, as evidenced by the flatness of the lines which correspond to the arcs in Figs. 1 and 2, and is characteristic of the metal. The observed arc voltages of these five metals and of zinc and carbon are presented in Table II. The value of 15 volts for platinum is the same as that found earlier,¹ by an indirect method, for the arcing of clean platinum contacts in a very low inductance circuit.

Current-voltage curves have been determined by a number of different experimenters for arcs between various metals and at various separations. Gaulrapp,⁵ for example, has found that at sufficiently small separations, or at sufficiently low pressures, the arc voltage is independent of current, in agreement with observations reported here. Gaulrapp's values of minimum arc voltage are written down in the last column of Table II for comparison. Values from other observers do not agree so well.

Only brief references will be made in this paper to tests carried out upon elements other than copper, silver, palladium, platinum, gold, and carbon. None of the other elements tested behaves like the noble metals; but, except for observations upon carbon and zinc, only a single example of differences which have been observed will be reported here. Styrene, the vapor of which is the most effective of any tested in the activation of silver (Table I), will activate each of the noble metals promptly at a pressure of 0.1 mm, which was the lowest to which any of these metals except silver was exposed; but no one of the metals, iron, nickel, molybdenum, or tungsten, can be activated by styrene at a pressure of 2.0 mm, which was the highest tested.

The activation of noble metals by organic vapors is obviously the result of the decomposition of organic molecules to give a carbonaceous material on electrode surfaces. (Why an arc should always occur between such surfaces is not clear, but that it should occur is in line

with the fact that electrodes of solid carbon arc on closure.) As a working hypothesis it is to be presumed that the carbonaceous deposit results from decomposition of organic molecules adsorbed on the electrodes, and whether or not a particular compound will activate noble metal electrodes is determined primarily by whether or not molecules of the compound are adsorbed on electrode surfaces so firmly that, when there is local heating, they are decomposed in place rather than vaporized without decomposition. Experiments described below seem adequate to establish this hypothesis for the case of silver electrodes and benzene vapor.

The first supporting observation was the discovery that under some circumstances silver electrodes which have been freed from grease cannot be activated by benzene vapor. In one test, silver contacts were operated for 560,000 closures in air containing benzene vapor at pressures between 2.6 and 3.5 mm, each closure discharging through an inductance of 10^{-5} h a condenser of 10^{-8} f capacity charged to 50 volts. In another test, silver electrodes were operated under the same circuit conditions for 160,000 closures at 10.7 mm benzene pressure. No arcing occurred during these experiments, and the contacts appeared as perfectly clean at the end as they were at the beginning. If the experiment is attempted without scrupulous care in the avoidance of grease, for example, from the fingers, sporadic arcs are observed within the first few seconds of operation of the contacts, and very soon arcing occurs on every closure and quantities of sooty deposit are formed. One is led to postulate that benzene is adsorbed firmly on greasy silver but not on clean silver, and that adsorbed benzene is readily decomposed to form sooty material which causes arcing and is able to hold other benzene molecules so that they too can be decomposed. The following tests seem to establish this conclusion.

For silver electrodes operated in air (that is, in the absence of benzene or analogous vapor) under the above circuit conditions, initial sporadic arcing occurs if either one of the electrodes is slightly greasy, for example, from finger contact. This initial activity will, however, die out quickly with continued operation, presumably as the grease is burned off by arcs. Initial arcing occurs also if insulating particles of polishing powder, magnesium oxide, or levigated alumina, are left on the surface. This also dies out fairly rapidly, as the particles are lost from the portions of the electrodes which come together. The action of insulating films or particles in initiating electric arcs has been investigated by Haworth³ and seems to be understood, at least in a general way. Further studies of arcing initiated by insulating films will be reported in later paragraphs of this paper.

The initial arcing due to insulating particles of levigated alumina has an entirely different effect upon benzene vapor in the atmosphere than has the arcing

⁵ Much higher benzene pressures have not been tested, because this is reported to be close to the minimum pressure giving an explosive mixture.

⁵ K. Gaulrapp, *Ann. Physik* **25**, 705 (1936).

due to grease. Arcing due to grease, even very sporadic and infrequent arcing due to extremely slight greasy contamination, results in decomposition of benzene and quite prompt complete activation of the electrode surfaces with formation of sooty deposits which may vary from scanty at low benzene pressures to copious at high pressures. Arcing due to insulating particles of levigated alumina has, on the other hand, no effect at all upon benzene vapor. Silver electrodes cleaned on a polishing cloth with levigated alumina and water, with care taken to avoid greasy contamination, have been mounted for test with the metal surfaces white with the alumina powder. Initially, an arc occurs on every closure, but this arcing gradually dies out with continued operation until after perhaps 10^4 closures no more arcs are observed. This gradual dying out of the initial arcing occurs in air containing benzene vapor, up to the highest pressure tested of 10.7 mm, just as it does in air without benzene. From this experiment, the conclusion has been drawn that the activation of silver contacts by benzene vapor requires the adsorption of benzene upon a greasy surface and its decomposition while firmly held there. Arcing in the absence of grease does not decompose benzene nor produce activation. (It seems clear that the term activation which has been used here means simply the decomposition of benzene.)

The conclusion that benzene is not decomposed unless it is adsorbed upon a grease film has not been extended to electrodes of any metal other than silver. For platinum electrodes it seems not to be true; it has been found that platinum electrodes are always activated by benzene even after they have been most carefully freed from grease. Perhaps this means that benzene is firmly adsorbed upon clean platinum but not upon clean silver.

There are other restrictions upon the conclusion that activation requires a grease film on electrode surfaces. It is not true for silver electrodes and styrene vapor; activation in styrene vapor is always prompt even when the silver surfaces have been well cleaned and are apparently grease free. It is not true even for silver electrodes and benzene vapor if the voltage is sufficiently high, of the order of 100 volts or more, or if the circuit inductance is extremely low.

ARCING AT CARBON SURFACES

The observations reported, up to this point, on arcing produced at noble metal contacts by vapors of benzene or other organic compounds are incomplete and need amplification and extension. It has not been explained earlier that oscilloscope traces like those of Figs. 1B and 1C are obtained at the closure of silver electrodes which have been operated in air containing benzene under conditions which have permitted the decomposition of only a *small amount* of the compound upon the electrode surfaces, either operating for a short time or at a low vapor pressure.

If one begins to operate moderately clean silver electrodes in air containing benzene at a pressure which is

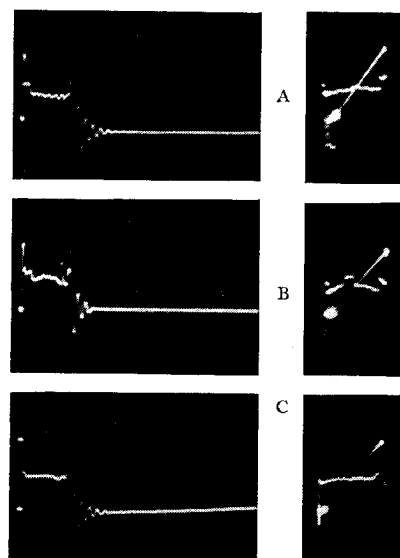


FIG. 3. Oscilloscopic traces of arcs, which are mainly carbon arcs, at contact closure. 10^{-8} f, 10^{-4} h, 50 volts, sweep time for the left-hand traces 22×10^{-6} sec. (A) and (B) Silver electrodes with a carbonaceous deposit from decomposed benzene. (C) Pure carbon electrodes.

not too low, the first closures are like those of Fig. 1A. These soon change to closures like those of Fig. 1B or 1C, but with continued operation, these are modified further to correspond to arcing at a higher and more variable voltage. Traces of this sort, from silver electrodes in air containing benzene at a rather high vapor pressure, are reproduced in Figs. 3A and 3B. If the benzene vapor is removed and operation of the contacts is continued, the type of closure soon changes back to that represented by Figs. 1B and 1C and finally to that represented by the traces of Fig. 1A.

The traces of Fig. 3A correspond to arcs at an arc voltage of about 19, and those of Fig. 3B to arcs at fluctuating potentials in the range between 19 and 30 volts. The traces of Fig. 3C, from closures of electrodes of pure carbon under identical circuit conditions, are reproduced for comparison. The conclusion that the traces of Figs. 3A and 3B represent arcs which are at least in part carbon arcs rests upon similarity with the patterns of Fig. 3C and upon the fact that a sooty deposit can be seen on electrodes which produce patterns like those of Figs. 3A and 3B.

Most arcs obtained with pure carbon electrodes exhibit greater fluctuations in voltage than appear in the traces of Fig. 3C, which were specially selected to exhibit rather steady arcs. Whereas silver arcs, Figs. 1B and 1C, for example, occur at voltages which are very steady and independent of arc current, this is not true of arcs between carbon electrodes nor of arcs between metal electrodes which have become so carbonized that they are essentially carbon arcs. Gold and copper arcs

Finally, at a still later time, closures without arcs may occur which are characteristic of insulating surface films.

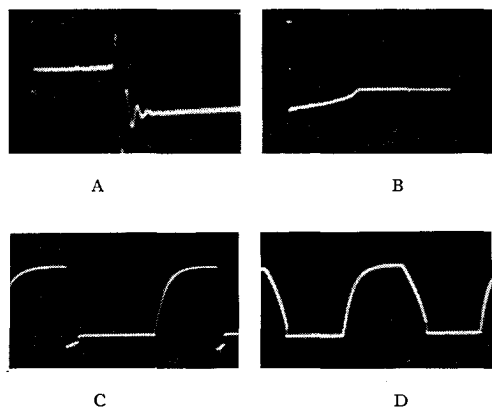


FIG. 4. Closures of silver electrodes operated in air containing ethyl silicate vapor. Circuit parameters the same as in Fig. 3. (A) Sweep time 7×10^{-6} sec, showing an arc and the subsequent open circuit. (B) Sweep time 600×10^{-6} sec, showing the history of the closure following an arc like that of Fig. 4A. The arc appears as a spot, and the following open circuit is not resolved from the beginning of the decrease of voltage caused by the flow of current through the high resistance film. Initial film resistance, 50,000 ohms. Final film resistance, 1000 ohms. (C) Arcing at electrodes covered by a thicker SiO_2 film. Sweep time $20,000 \times 10^{-6}$ sec. (D) Closure with a still thicker film. No arc. Initial film resistance 400,000 ohms.

have very steady voltages, resembling silver arcs, but platinum and palladium arcs are less stable, with voltages which fluctuate more than arcs between electrodes of silver, gold, or copper, but considerably less than arcs between carbon electrodes. These facts seem to suggest that stability of arc voltage is associated with low melting and boiling points. No understanding of the underlying phenomena is, however, implied in this observation.

The variability of the arc voltage in the traces of Fig. 3B is due in part to inherent instability of carbon arc voltages. Some of the variability is, however, due to the fact that the underlying material of the electrodes is silver and not carbon, so that there are, without doubt, some silver atoms in each arc; each arc is in part an arc in carbon vapor and in part an arc in silver vapor. Evidence for this conclusion is furnished by the fact that the average arc voltages of traces like those of Figs. 3A and 3B are intermediate between those ascribed to carbon and to silver, and by the fact that frequently, especially when the carbonization of the electrodes is not heavy, at the beginning and at the end of an arc the arc voltage is about 25, and in the middle, when the current density is highest, it is sometimes as much as 10 volts lower. (See the traces of Figs. 3A and 3B.) This is interpreted as meaning that each arc starts as a carbon arc, but when electrode vaporization becomes relatively rapid, it is more nearly a silver arc. One must conclude further than when the arc current declines sufficiently, near the end, the discharge is in many cases *again a carbon arc*.

This interpretation can be extrapolated to yield an empirical explanation of the activation of silver elec-

trodes by an organic vapor, even when the arc voltage of carbon is not observed on the oscilloscope trace (Figs. 1B and 1C). It is to be presumed that in this case the arc actually begins as a carbon arc but that the small amount of surface carbon at the site of the arc is completely vaporized so quickly that its arc voltage is not noticeable on the oscilloscope trace; the arc is a silver arc for all but a small fraction of its lifetime. When a silver surface is only slightly carbonized, the carbonization performs only the function of initiating a silver arc which could not have started if the metal surface had been free from carbon.

These observations and deductions lead one to divide the noble metal electrode surfaces upon which experiments have been carried out into three classes: (1) clean (or inactive) noble metal surfaces, (2) active metal surfaces, and (3) carbon surfaces. Class 3 is made up of noble metal surfaces which have become so carbonized that their behavior resembles that of pure carbon. Class 2 is made up of surfaces which have been so slightly carbonized that although they are probably essentially carbon surfaces at the beginning (and near the end) of each arc, they are metal surfaces for most of the lifetime of the arc. According to this view, what has been called an "active" metal surface, which is, however, not sufficiently carbonized to give an arc resembling that of carbon nor any evidence of the characteristic arc voltage of carbon, behaves at the beginning and at the end of each arc just like a true carbon surface.

ARCING INITIATED BY INSULATING FILMS

It has been pointed out above that slight contamination of noble metal contacts by finger grease may cause sporadic arcing at closure under circuit conditions for which no arcing would occur in the absence of grease. The same effect can be produced much more reliably by wiping contacts lightly with lens tissue and lanolin. When contacts which are initially slightly greasy are operated repeatedly, discharging, for example, a condenser of 10^{-6} f charged to 50 volts on each closure, initial arcing caused by grease will gradually die out until, after perhaps 10^4 closures, arcs no longer take place. Inactivity of slightly greasy noble metal contacts produced in this manner, self-cleaning by repeated arcs, represents in our apparatus, however, a precarious stability, because slight vibration of the equipment causes new portions of the contact surfaces which are still greasy to come into opposition and arcing to be resumed.

The production of arcing by surface grease bears more than a superficial resemblance to the experiments of Haworth (reference 3), and it seems altogether probable that some of the phenomena are the same, that an essential step in the development of arcs in the present experiments is a very strong electric field across an insulating grease film on the cathode produced by positive ions on the surface of the film. This conclusion is, however, not supported by experiments in which only

TABLE III. Data from the oscilloscope traces of Fig. 4. Closure of silver electrodes with SiO_2 surface films.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)		(9)		(10)		(11)		(12)		(13)	
							Arc		Closure through resistance film		Slope of trace ($\times 10^4$ v/sec)		Current through film ($\times 10^3$ amp)		Resistance of film ($\times 10^3$ ohms)		Resistance of film ($\times 10^3$ ohms)	
	Sweep time ($\times 10^{-6}$ sec)	Arc voltage (v)	Open circuit voltage V_1	Calc. circuit res. (ohms)	Arc time obs. ($\times 10^{-6}$ sec)	Closure time ($\times 10^{-6}$ sec)	Initial	Later	Initial	Later	Initial	Later	Initial	Later	Initial	Later	Initial	Later
Fig. 4A	7	15	-17	7	3	—	—	—	—	—	—	—	—	—	—	—	—	—
4B	600	same	same	same	—	250	3.0	18	300	1800	—	—	—	—	50	1	—	—
4C	20,000	—	-8, -11	—	—	1300	0.12	—	12	—	—	—	—	—	500	—	—	—
4D	20,000	—	—	—	—	2800	1.2	2.0	120	200	—	—	—	—	400	90	—	—

one electrode was initially greasy; in these tests it has been found that grease on the positive electrode is as effective in causing arcs as grease on the negative. A possible explanation of this observation is the transfer of grease from one electrode to the other when they come into contact.

The analogy with the Haworth experiment is strengthened by finding that various insulating materials work as well as grease. The same kind of initial activity, which dies out rather rapidly with continued arcing, is found for noble metal contacts which have been dusted with levigated alumina or magnesia until they appear white and tested in this condition, and for electrodes which have been dipped into a colloidal water solution of SiO_2 . It can be produced also in a closed bell jar by exposure to SiCl_4 or to ethyl silicate, both of which result in surface layers of SiO_2 .

Vapors of the two compounds SiCl_4 and ethyl silicate produce results which are qualitatively different in just the way we could easily predict. Exposure to SiCl_4 vapor in a closed bell jar results in instantaneous arcing, because SiCl_4 is hydrolyzed at once in moist air to give SiO_2 which is deposited over the surface of the equipment. In a particular experiment, 0.1 cc of SiCl_4 in a bell jar resulted at once in arcing at every closure which died out after about 2000 closures. If the initial layer of silica was uniform over all exposed surfaces, its thickness was about 700 Å. In ethyl silicate vapor, on the other hand, contacts begin to arc only after a considerable number of closures, because the compound is stable in air and is decomposed to form a layer of silica only by the heat developed at contacts during their continued operation. In a particular experiment in a bell jar filled with air containing ethyl silicate vapor at a pressure of 0.04 mm, arcing first was observed after 10^4 closures.

In our tests arcing produced by ethyl silicate vapor has always been accompanied by clear-cut evidence of an insulating film at the contacts. The insulating film and the arcing appear together, which is perhaps the best evidence we have that the film is the cause of the arcing. With continued operation in ethyl silicate, the film becomes finally so thick that no further arcing takes place.

Steps in the development of an insulating film from ethyl silicate vapor are represented by the oscilloscope traces of Fig. 4. The traces of Figs. 4A and 4B represent

the same rather early stage, the pattern of Fig. 4B, with a sweep time of 600×10^{-6} sec, showing the way in which the contacts closed following an arc like that of Fig. 4A. The patterns of Figs. 4C and 4D show closures when the insulating film had become thicker, that is, after further operation in ethyl silicate vapor.

In the trace of Fig. 4A is shown an arc at about 15 volts lasting for 3×10^{-6} sec, followed by an open at about -17 volts and lasting until after the end of the sweep, 4×10^{-6} sec later. (The calculated arc time is $\pi(LC)^{1/2} = 3 \times 10^{-6}$ sec.) That abrupt closure did not occur at the end of the open (as, for example, in Fig. 1B) is clear in the trace of Fig. 4B. On this trace the arc appears as a small spot, and the subsequent open circuit is unresolved from the rising curved line which represents discharge of the condenser through an insulating film. This discharge lasted for 250×10^{-6} sec with the initial slope of the trace corresponding to a rate of discharge of the condenser of 3.0×10^4 v/sec and the final slope to 18×10^4 v/sec. The corresponding currents through the film are $C(dV/dt) = 300$ and 1800×10^{-6} amp, and the film resistances are about 50×10^3 and 1×10^3 ohms, respectively. The pattern of Fig. 4C was obtained at a later time and corresponds undoubtedly to a thicker film. The sweep time for this pattern is so long, $20,000 \times 10^{-6}$ sec, that the arc is quite unresolved, but that there was an arc is evident from the fact that the voltage changes sign abruptly as in Figs. 4A and 4B. In the left-hand one of the two closures represented in Fig. 4C, the initial slope of the rising curve corresponds to a film resistance of 500×10^3 ohms; and metallic contact was not established until 1300×10^{-6} sec after the first touching of the resistance film. In the pattern of Fig. 4D, taken later with a still thicker silica film, there is obviously no arc at all. The initial film resistance was 400×10^3 ohms, dropping to about 90×10^3 ohms before metallic contact, the time required for this change being 2800×10^{-6} sec. Data from all of the traces of Fig. 4 are collected in Table III.

The arc voltage measured upon the pattern of Fig. 4A is $v = 15$ (column 3, Table III), which is appreciably higher than 11 volts obtained for silver which had been activated with a minimum amount of carbon from benzene vapor (Table II). It was noted in the preceding section that an organic vapor in excess of the amount required just to activate metal electrodes results in

TABLE IV. Circuit parameters for arcing at clean silver electrodes.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
C ($10^{-9}f$)	L ($10^{-6}h$)	Observed V_0 for first detectable arcing	V_0/L^\dagger	Calc. max. arc current (amp)	Observed V_0 for arcing most of the time	$V_0 - 11 \left[1 + \frac{1.3 \times 10^{-7}}{L^\dagger C^\dagger} \right]$ L^\dagger
1	1.8	50	38×10^3	0.9	91	34×10^3
	10	66	21	0.5	115	28
	48	220	32	0.9	> 275	> 37
2	1.8	38	28	0.9	85	38
	10	85	27	1.0	150	41
	48	206	30	1.3	> 275	> 37
5	1.8	31	23	1.1	63	28
	10	64	20	1.2	120	33
	48	200	29	1.9	260	35
	100	210	21	1.4	> 275	
10	1.8	24.5	18	1.0	51	22
	10	60	19	1.5	104	28
	48	171	25	2.3	214	29
	100	176	18	1.6	> 275	> 26
20	1.8	30	22	2.0	67	36
	10	77	24	2.7	123	34
	48	160	23	3.0	240	33
	100	212	21	2.8	> 275	> 26
50	1.8	13	10	0.3	35	14
	10	40	13	2.0	91	25
	48	93	13	2.6	190	26
	100	190	19	4.0	248	24
	206	240	17	3.6	> 275	> 18
100	1.8	11.5	9	0.1	44	22
	10	47	15	3.6	91	24
	48	121	17	5.0	210	29
	100	210	21	6.3	260	25
	206	222	15	4.6	276	18
250	1.8	13	10	0.7	31	13
	10	25	8	2.2	76	20
	48	84	12	5.3	180	24
	100	92	9	4.0	226	21
	206	162	11	5.2	258	17

considerable (and erratic) rise in the arc voltage. In these experiments with silica films on silver, it seems clear that a similar increase in the arc voltage has been produced by the film. The thickness of a silica film on a silver surface can, however, be adjusted so that it gives rise to arcs having the arc voltage of 11 characteristic of the underlying metal, just as in the case of arcs initiated by carbonaceous films. *This lower and characteristic arc voltage of silver is observed in the first arcs which occur when silver electrodes are operated in ethyl silicate vapor.* With continued operation the arc voltage very soon rises to higher values.

The open circuit voltage in the pattern of Fig. 4A is $V_1 = -17$ (column 4, Table III). This is related to the initial voltage $V_0 = 50$ and to the arc voltage $v = 15$ by the equation $f = (v - V_1)/(V_0 - v)$, where f is a function of the circuit parameters (reference 1, p. 1094). From the known values of C and L , one calculates the circuit resistance to be 7 ohms (column 5, Table III), which is, no doubt, chiefly in the circuit external to the arc. Yet as soon as the arc is extinguished and when the contacts

have moved toward each other until they have made physical contact, the resistance can be half a megohm. This is proof that the arc destroys the insulating film in the small spot where it strikes but leaves the film undamaged elsewhere, and the spot at which the arc occurred and where there is no film does not short-circuit the high resistance film after physical contact is established.

The difference in behavior between noble metal electrodes and electrodes of other metals is probably related to films of oxides or other compounds on the surfaces of the base metals. It has been discovered that zinc surfaces freshly cleaned by abrasion in air do not arc readily, perhaps no more readily than do clean noble metal surfaces, but that with continued operation or after standing idly in air arcing will soon occur. Arcing at zinc surfaces which have not been freshly cut is extremely reliable. This is almost certainly due to the insulating property of a normal coating of ZnO. Other base metals do not, however, give results which are so

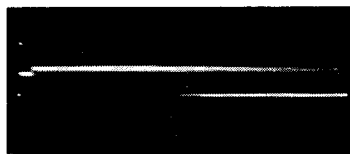


Fig. 5. Discharge by carbon electrodes through a 100-ohm non-inductive resistance of a capacity charged to 50 volts, 300 successive traces superposed. When the arc is extinguished, the potential across the contacts rises by about 4.6 volts, corresponding to a minimum arc current of 0.046 amp.

clean cut. Tin, in particular, gives very erratic results, probably because its oxide is not easily vaporized.

LIMITING CIRCUIT CONDITIONS FOR ARcing ON CLOSURE

Attention is given here to two different circuit characteristics associated with the electrode surfaces, respectively, the conditions which determine whether or not an arc will strike between closing electrodes before they touch, and the minimum arc current at which an established arc will be extinguished. These limiting conditions are not sharply defined, and statistical variation is distressingly large, but not so large that there is any possibility of confusing "active" and "inactive" noble metal surfaces.

To find the limiting circuit conditions which permit an arc to strike, clean silver electrodes have been tested for arcing at closure in series with various capacities and inductances. For each combination of capacity and inductance, the electrodes are opened and closed 60 times per second in the conventional circuit in which the capacity is discharged on each closure and then is recharged after the contacts have been separated. The potential difference is increased gradually until arcing occurs. In column 3 of Table IV are presented the voltages at which arcing is first observed and in column 6 the voltages at which arcing occurs on every, or almost every, closure. In column 4 are the quotients obtained by dividing the voltages of column 3 by the square roots of the inductances. It seems apparent that, for each capacity, the voltage necessary for an arc is approximately proportional to the square root of the circuit inductance. There is a variation of voltage with capacity which is much less marked, the voltage decreasing by a factor of 3 for a capacity increase by a factor of 250. The maximum arc currents calculated from the data of columns 1-3, using the formula $i_{\max} = (V_0 - v)(C/L)^{1/2}$ with $v = 11$ volts, are listed for later use in column 5.

If the data of column 6 are treated in the same way, one finds that there is an indicated correction at low values of capacity and inductance. A more nearly constant quotient is obtained for $(V_0 - 11)/L^{1/2}$ which possibly makes sense in that the arc voltage of silver is 11 (see Table II) and $(V_0 - 11)$ is the effective circuit voltage. The quotient $(V_0 - 11)/L^{1/2}$ appears to deviate only at very low values of L and of C from a value which is changing steadily and quite slowly with C .

TABLE V. Measurements of minimum arc currents from photographs like that of Fig. 5.

(1) Electrode material	(2) V_0 (volts)	(3) Circuit resistance (ohms)	(4) V_1 (volts)	(5) $(V_1 - v)$ (volts)	(6) Minimum current $(V_1 - v)/R$
Active silver	80	51		1.4	0.027 amp
		100		3.5	0.035
		220		8.4	0.037
	160	100		3.5	0.035
Inactive silver	50	0	-22.7		
		10	10.7		
		15	17.3		0.42
		20	20.0		0.45
		24	26.0		0.62
		100	0	-64.0	
	100	10	6.0		
		15	16.0		0.33
		20	23.3		0.61
		24	25.4		0.60
		51	44.0		0.65
		220	—		
Carbon	50	100		4.9	0.049
		220		7.8	0.036
		300		7.8-17.2	0.026 to 0.057
		430		10.5-21.7	0.024 to 0.051
		620		8.7-37.7	0.014 to 0.045
		1100		—	—
	100	100		2.0- 6.6	0.020 to 0.066
		220		5.3-13.9	0.024 to 0.063
		300		7.3-17.2	0.024 to 0.067

A last suggested correction seems to involve L and C in the same way, and this is tested out by giving in column 7 values of the quotient $[V_0 - 11[1 + 1.3 \times 10^{-7}/(LC)^{1/2}]]/L^{1/2}$. This fancy expression can be rationalized by suggesting that the term which is subtracted from V_0 is a sort of average arc voltage and that the arc voltage is really high at the beginning of each arc and approaches 11 only when the arc lasts a considerable time, when $\pi(LC)^{1/2}$ is large. The factor 1.3×10^{-7} is to be interpreted then as implying that the time required for each arc to become stable at 11 volts is of the order of $(1.3 \times 10^{-7} \pi)$ sec. Evidence will be presented in the second installment of this paper for this sort of variation of arc voltage with time after the initiation of each arc.

Measurements similar to those of Table IV for silver electrodes have been obtained for platinum electrodes also. The platinum measurements were made earlier and less carefully, but, as far as they go, they suggest much the same sort of dependence of voltage necessary to start an arc upon circuit inductance and capacity.

Although too much has been read into the data of Table IV, it is rather well indicated that the voltage necessary to strike an arc between inactive silver electrodes increases with increasing inductance rather rapidly and, more or less, as the inductance to the one-half power, and decreases with increasing capacity, only much more slowly.

For carbonized (or "active") silver electrodes the circuit inductance, which will just prevent an arc upon the discharge of a capacity of 10^{-8} f charged to a potential difference of 50 volts, varies on repeated tests in

the range between 10^{-3} and 10^{-2} h. This is higher than the corresponding inductance for clean silver electrodes by a factor between 500 and 5000. Data like those of Table IV have not been obtained for carbonized metal electrodes or for carbon.

The second desired characteristic for a closure arc, the minimum arc current for an established arc, is determined conveniently by observing on the oscilloscope the potential across closing contacts which are discharging a condenser through a fixed non-inductive resistance. When the current through the closure arc has decreased to the minimum current at which the arc can be sustained and the arc is extinguished, the voltage across the contacts rises from the arc voltage to that across the condenser. The current at which the arc went out is then the difference between the open circuit voltage V_1 and the arc voltage v , divided by the circuit resistance. To take into account statistical variation, it is convenient to open the camera shutter long enough to record a great many successive closures. A photograph of 300 superposed traces is reproduced as Fig. 5. In this figure the average value of $(V_1 - v)$ is about 4.6 volts which, on division by the circuit resistance of 100 ohms, yields 0.046 amp as the minimum arc current for the carbon electrodes of this experiment.

Data from a number of photographs like that of Fig. 5 are given in Table V. For contacts of active silver and of carbon, the potential difference $(V_1 - v)$ (column 5) is measured directly on the photographic film and this divided by the circuit resistance (column 3) gives the

minimum arc currents of column 6. For inactive silver electrodes, the arcs last such a short time that they are not recorded on the film, and the differences $(V_1 - v)$ have to be obtained by subtracting 11, the known arc voltage of silver, from the measured values of V_1 of column 4. The negative values of V_1 obtained at zero resistance and the low values obtained at 10 ohms indicate clearly that the circuit of these experiments was, of course, not strictly non-inductive, and, in consequence, results for low resistances are not reliable. No arcs occur for inactive silver at 100 volts and 220 ohms, nor for carbon at 50 volts and 1100 ohms; for these conditions, arcs of zero length would imply minimum arc currents of 0.40 and 0.035 amp, respectively.

The data of Table V show considerable variation, but they indicate that the minimum arc current for active silver is about 0.03 amp and is substantially the same as that for carbon. The minimum arc current for inactive silver is about 0.6 amp.

It is obvious that an arc cannot occur at all if the maximum current permitted by the circuit parameters, $(V_0 - v)(C/L)^{1/2}$, is below the minimum arc current. It is of interest to check this point from the data for inactive silver in Table IV. Values of $(V_0 - v)(C/L)^{1/2}$ from the data of columns 1-3 of Table IV are written down in column 5. One observes that in only three cases is this calculated maximum current below 0.6 amp, and, in general, it is many times higher.

I am much indebted to Mr. J. L. Smith for assistance with many of the experiments reported here.

Iron-Silicon Alloys Heat Treated in a Magnetic Field

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(Received January 4, 1951)

Heat treatment in a magnetic field has been found effective for iron-silicon alloys between two percent and ten percent silicon, the highest maximum permeability being obtained at about 6.5 percent silicon. In a single crystal of this composition, magnetized parallel to a [100] direction, the hysteresis loop is squared by the magnetic anneal and the maximum permeability is increased from 50,000 to 3,800,000, the highest value yet reported.

IN an investigation of the magnetic properties of iron-silicon alloys, it has been found that heat treatment in a magnetic field is effective for alloys between 2 percent and 10 percent silicon, and that the maximum effect is obtained at approximately 6.4 percent silicon. In a single crystal the hysteresis loop is squared by the magnetic annealing and very high permeability is attained (3,800,000). In this range of composition, as is known from the constitution diagram, all of the allotropic transformations in the iron have been eliminated; this means that impurities can be removed by annealing at high temperatures in pure

hydrogen, without recrystallization of the material. This fact, and the high Curie temperature, varying between 770°C and 490°C, are favorable for effective magnetic annealing.

The test specimens were made of electrolytic iron melted in a quartz crucible in a high frequency induction furnace with the silicon added under an atmosphere of helium, and were cast into ring form. They were subjected to various heat treatments; some were annealed at 1000°C for one hour in hydrogen and furnace cooled and then at 700°C for one hour in the presence of a magnetizing field of 10 oersteds. The same specimens