**Arcing Systems.** For our purposes an arc will be defined as a gaseous electrical discharge involving electrons, metal vapors and ions. It is characterized by high current density in the arc column and high electrode temperatures. Other gaseous discharges such as the spark\(^1\) and glow discharge\(^1\) will be important only to the extent that they help initiate an arc.

Contacts in the “make and break” category can arc when they are in the process of establishing a current flow (i.e., “making”) or interrupting (“breaking”) the flow of current provided certain conditions are met. When a space exists between two polarized contacts they become electrodes whose instantaneous spacing, relative voltage and ability to provide sufficient current will determine whether or not an arc will exist. Composition and conditions of the atmosphere in the electrode gap also have an influence on arc initiation and duration.

Electrical erosion of contacts during an arc is substantial. This erosion limits the life and reliability of contact systems that operate in an arcing mode. Thus the arc is an important aspect of contact theory.

**Closure Arcs.** Arcs which begin their life as two contacts approach each other, will be called closure arcs. Other names for this class of arc are make arcs and pre-contact arcs. These arcs are initiated in one of three ways, the first of which occurs when the voltage across the contacts is a few hundred volts or more, depending on the ambient gas, its pressure\(^2\) and, of course, the distance between the electrodes. The relation of these variables is given by the Paschen curve, as shown in Fig. 1-11. Note that the voltage necessary for breakdown has a minimum value of 330 V, and depends on the product of the pressure (p) and the spacing (s). In this figure p is in millimeters of mercury and s is in millimeters.

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1. The spark consists principally of an electron avalanche while the glow discharge is characterized by a relatively low cathode temperature and low current density, such as found in a neon tube. The contact erosion they cause is ordinarily considered as part of the arc erosion.
2. To be strictly correct the voltage and spacing that is necessary depend on the density of the ambient gas rather than its pressure. The two are related, however, and to account for temperature changes an "equivalent" pressure $p_z$ can be calculated from

$$p_z = p_{rt} \frac{T_{rt}}{T_z}$$

where temperatures are expressed in degrees Kelvin. Subscript $rt$ refers to room temperature.
As an example of the use of the Paschen curve, take the case of two contacts in normal air (760 mm pressure) which have 500 volts applied to them and their initial spacing is 0.5 mm. The product $p \times s$ then equals $760 \times 0.5 = 380$, which puts us on the right hand side of the curve. This $p \times s$ would require about 2500 volts for an arc to ignite. Since the available voltage is 500 V no arc will occur. As these contacts are moved closer and closer together the product $p \times s$ also decreases and eventually a product value of slightly under 20 will be reached at which time an arc will start. If the source continues to supply enough power, the arc will burn until the contacts are fully closed. Product values to the left of the 330 volt minimum are of use only when a certain $p \times s$ relationship exists and then the voltage is applied. The left rising portion of the curve is seldom of practical significance.

The sequence of events in a Paschen breakdown is an electron avalanche, which immediately results in a glow discharge, which then, in negligible time, forms the real arc.

From the Paschen curve it would appear that closure arcs cannot occur below 330 V, but this is not so, as even the casual observer will recall seeing arcs on closure at voltages much lower than 330 V. This brings us to the second mechanism for closure arc initiation, namely field emission.

When contacts are approaching each other, even with voltages well below the Paschen minimum breakdown voltage, the voltage gradient or volts/cm becomes increasingly large. Without delving deeply into the exact physical processes, which are still disputed among the physicists, we can reason that when the field strength reaches a high enough value, electrons can be pulled from the cathode toward the anode. Some of these electrons will bombard the anode causing heat; some will collide with molecules of the ambient gas in the gap, causing positive ions which ions will bombard the cathode, producing heat and more electrons to cause a rapid regenerative cycle resulting in a true arc. Usually a voltage gradient of $10^6$ to $10^7$ volts/cm is required for this field emission from cold surfaces, but the apparent field is increased by a factor of 100 or more at the sharp peaks or whiskers that can exist on typical contact surfaces.

A third way in which a closure arc can be formed is by the momentary touching of small asperities. Being unable to conduct the current without gross heating, temperature reaches the boiling point of the metal, resulting in the formation of a metal vapor which then becomes an arc.

**Opening Arcs.** Arcs which are initiated as two mated or closed contacts (conducting through their metallic a-spots) are separated, will be called opening arcs. Other names found for this class of arc are drawn arcs, post-contact arcs, separating arcs and break arcs.
Explanation of the opening arc again requires an assumption that the power source can deliver adequate voltage and current to the contacts. These voltage and current values will be discussed more in detail later.

As contacts separate, a molten metal bridge appears between the contact surfaces due to joule heating of the steadily decreasing area of intimate contact, as already explained. The molten bridge continues to decrease in area as separation continues and the temperature approaches the boiling temperature of the metal. When this extremely hot column ruptures, temperatures at the parted surfaces are high enough to cause thermionic emission of electrons from the cathode surface. In traveling to the anode, these electrons cause ionization of ambient gas and anode metal providing the necessary ingredients of the arc.

**Arc Characteristics.** A fully developed stable arc of sufficient length has a potential distribution, as shown qualitatively in Fig. 1-12. The cathode drop region is very thin and accounts for a substantial portion of the voltage drop across the total arc. Within the positive column region (the visible part of most arcs) the potential gradient is much smaller than in the cathode drop region. Another steep voltage gradient is seen terminating at the anode surface. For a given electrode material, the drops at the cathode and anode are fairly constant and their sum represents the characteristic arc voltage seen in contacts of the type considered here; i.e., where arcs are much less than a centimeter in length. In an opening

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![Diagram](image)  
**Fig. 1-12.** Voltage within an arc vs. distance from cathode to anode.
arc the *characteristic arc voltage* is the value to which voltage across the contacts rises as an arc forms. This voltage will persist (increasing only slightly with distance) until the arc ceases.

An oscillograph of opening contacts would appear as in Fig. 1-13. At the beginning the contacts are closed with a negligible voltage drop across them, represented by region A. As they are opened, a molten bridge forms and the voltage drop increases during B. When the bridge ruptures, the voltage immediately jumps to the characteristic arc voltage of 12 volts in this case. The arc burns at the voltage during C until further separation extinguishes the arc and voltage abruptly rises to the source voltage, in this case 18 V.

![Oscillograph of an opening arc](image)

**Fig. 1-13.** Representation of an oscillograph of an opening arc. Contacts are closed at A, molten at B and arcing at C. Source voltage is 18 V.

Each clean contact material has its own *minimum arc voltage* \( (V_m) \) and *minimum arc current* \( (I_m) \) which are necessary in order to sustain an arc. The two are inter-related and are not singular values; thus the higher the source voltage, the lower the minimum current can be for an arc to continue burning; the higher the current is, the lower the source voltage that will allow an arc to continue. \( V_m \) and \( I_m \) are essentially properties of the cathode material and the ambient atmosphere and are derived by noting the values of voltage and current at which an established arc ceases to burn. Since the values for \( I_m \) and \( V_m \) are derived for strictly ohmic circuits free from inductance and capacitance, care must be used in their applica-
tion. Fig. 1-14 shows the asymptotes that are called $V_m$ and $I_m$. Table 1-3 lists values of $V_m$ and $I_m$ that have been found by various experimenters.

![Graph showing voltage and current combinations at which an arc goes out. Silver electrodes in air. Arc length in mm. After Holm.](image)

**Fig. 1-14.** Voltage and current combinations at which an arc goes out. Silver electrodes in air. Arc length in mm. After Holm.

<table>
<thead>
<tr>
<th>Material</th>
<th>$I_m$ (Amperes)</th>
<th>$V_m$ (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>.01-.03</td>
<td>15-22</td>
</tr>
<tr>
<td>Silver</td>
<td>.4-.9</td>
<td>11-12.5</td>
</tr>
<tr>
<td>Gold</td>
<td>.38-.42</td>
<td>11.5-15</td>
</tr>
<tr>
<td>Palladium</td>
<td>0.67</td>
<td>15</td>
</tr>
<tr>
<td>Platinum</td>
<td>.67-1.1</td>
<td>15-17.5</td>
</tr>
<tr>
<td>Paliney® 7</td>
<td>0.1</td>
<td>10-12</td>
</tr>
</tbody>
</table>

**Table 1-3.** Minimum Arc Currents and Voltages

**Short Arcs.** When an arc exists with electrode spacing so small that the anode is near the cathode drop region (i.e., the positive column is very short), practically all of the electrons emitted from the cathode bombard the anode at high velocity. They have not lost energy in ion-forming collisions on their trip to the anode. The anode is then heated so that it has a higher temperature than the cathode and material transfer is from anode to cathode.
Another way of explaining the short arc and its accompanying anode erosion is by making use of the fact that in an ordinary arc, the column diameter increases from cathode to anode. If the electrodes are far enough apart, the anode heating is distributed over a relatively large area whereas the cathode spot remains small, so the cathode erodes more than the anode. However, when the electrode spacing is very short, there is little fanning out of the arc so that the anode spot heats more than the cathode spot (see Fig. 1-15) and thus the anode erodes more than the cathode. From the erosion it causes, the short arc is also called an anode arc. Arcs which are longer are termed cathode arcs since the cathode suffers the erosion.

![Fig. 1-15. Representation of a short arc and a plasma arc.](image)

Each contact material has its own critical spacing ($s_c$) below which an anode arc prevails and above which a cathode arc is dominant. For pure silver the critical distance is $3 \times 10^{-3}$ mm and for palladium it is $5 \times 10^{-4}$ mm.

**Activation.** In the presence of certain hydrocarbon vapor, arcing causes carbonaceous deposits on the contact surfaces which enhance subsequent arcing. It activates the surfaces. Platinum, palladium, gold, silver and copper are capable of activation, but none occurs on tungsten, molybdenum, iron or nickel. The principal effects of activation are the lowering of the electrical field at which an arc will begin and a lowering of the minimum arc current. Both of these serve to increase erosion. Also there is a change in the visual appearance of the electrodes with active vs inactive arcs. The customary mound and crater of the inactive arc is changed to an erosion that is uniform over a larger area with active arcs. Evidently a carbonaceous spot is destroyed during an arc and each subsequent arc originates on a new spot. In general, an active arc causes about four times the erosion of that caused by an inactive arc.
**General Comments on Arcing.** The field of arcing is a vast one that could occupy a textbook in its own right. ASTM Committee B04 on electrical contacts lists the following major variables which affect the rate of arc erosion:

1. Shape, diameter and thickness
2. Contact velocity and maximum arc length
3. Contact orientation with respect to earth gravity
4. Environment (gas, liquid, its type, pressure, temperature)
5. Arc current, source voltage, load circuit
6. Arc time
7. Contact bounce
8. Contact body temperature
9. Number of arcing operations
10. Arc motion (such as by magnetic fields)
11. Polarity

An attempt has been made in the foregoing sections to point out many important features of arcing even though the Ney alloys are not intended for long life under arcing conditions. For a more complete treatise of arc phenomena, the reader is referred to the texts of Holm\(^{18}\) and Jones\(^{21}\) and the work at Bell Telephone Laboratories by Germer and associates\(^{15, 22}\).