FILM PHENOMENA, GENERAL. All of the foregoing information in sections 1.1 through 1.6 has been presented with the assumption that the metallic surfaces of the electrical contact were perfectly clean. Except for surfaces in outer space or in a hard vacuum, perfectly clean surfaces exist only as laboratory curiosities. In a real-life environment, metallic surfaces will be covered with a film of some type.

Base metals (reactive metals such as copper, aluminum, iron, nickel, etc.) that are exposed to air quickly form a surface film of metal oxide as well as sulfides, chlorides, and other compounds when the air has its usual contaminants. In a few minutes (at times within seconds) these films are from l0 to 30 Angstroms thick. Then the films gradually grow to thicknesses of several hundred Angstroms.

Contrary to the layman's popular belief, noble metals also have films on their surfaces; however, the films are much thinner than with base metals. The films on noble metals consist of such things as adsorbed gases, water vapor and organic molecules, but they are usually innocuous because of their small thickness of less than 20 Angstroms. This will be explained in detail in the next section.

Films of oxides, sulfides, carbonates and other "oxidation" products of metals are good insulators or at least semi-conductors whenever they are of sufficient thickness. Thus they can interfere with the free flow of electrons between atomic lattices of two mating contacts. The conditions under which they interfere noticeably can now be considered.

Thin Films and Tunneling. Base metal contacts that have had their films removed a few minutes before testing, conduct quite efficiently even though we know that there is a thin film present. It happens that if the films are less than about 20 Å thick, they conduct at low impressed voltages by the *tunnel effect* despite the fact that they are insulators in bulk form. Tunnel effect exists because of the wave nature of conduction electrons as embodied in quantum mechanics.

Tunnel resistance (R_{ft}) as a function of Brinell hardness (H) of the underlying metal and the applied load (P) in grams is calculated from

$$R_{ft} = 10^5 \frac{\sigma_t H}{P} \qquad \textbf{Eq. 1.8}$$

where the tunnel resistivity (σ_t) is expressed in ohms cm^2. This tunnel resistance should, technically speaking, be added to the bulk resistance (R_B) and the constriction resistance (R_c) in order to determine the total resistance (R_T) of contact members, or

$$R_T = R_B + R_c + R_{ft} \qquad \textbf{Eq. 1.9}$$

When forces are at the level of a few grams and the metal restistivities moderate (as in alloys) the tunnel resistance term can be neglected according to our practical experience. This is probably due also to the presence of multiple a-spots and elongated a-spots that exist in most cases, both of which decrease the calculated constriction resistance, thereby counter-balancing any tunnel resistance that is present. Mechanical fracture of such thin films also makes it unlikely for them to have a great effect. Voltages higher than about 30 mv also help to obliterate the effect of tunnel resistance.

In the case of laboratory experiments that search out contact mechanisms, the R_{ft} term should be included. Table 1-1 shows some typical values of tunnel resistivities for a few film thicknesses. It is apparent that this resistivity is increasing rapidly as a function of film thickness.

Film Thickness (Angstroms)	Tunnel Resistivity (σ_t) (Ωcm^2)
5	10^{-8}
15	10^{-7} to 7×10^{-7}
20	2×10^{-7} to 10^{-6}
100	10^{-3} to 10^{-2}

Table I-1. Typical tunnel resistivities for various film thicknesses

Thick Films and Fritting. We will call films *thick* when they are about 100 Å or more in average thickness. Conduction by tunnel effect can be neglected at these thicknesses. Aside from mechanical fracturing of the film to allow intimate metal to metal contact, the only other way that current can flow efficiently is to electrically puncture the film. Such electrical puncturing is called fritting.

When the voltage level across an insulating *thick* film reaches about 10^5 to 10^6 volts/cm, electrons start to flow in selected areas of the film. The selected area are those where the film is thinnest or where its composition makes it more conductive than elsewhere, as tarnish films are notoriously variable both in thickness and composition. This localized current heats the film and underlying metal and the film is punctured, which allows intimate metal to metal contact. The metal to metal contact is signified by a sudden decrease in voltage drop across the contact members. At this stage we say that *fritting* has taken place. A metallic bridge exists in the parted film.

After fritting has taken place, a cross section of the contacts on a magnified scale would appear schematically as in Fig. 1-7. Notice that the load bearing area consists of the metallic bridge, metal that is touching but not micro-welded, and a portion that remains covered with film.

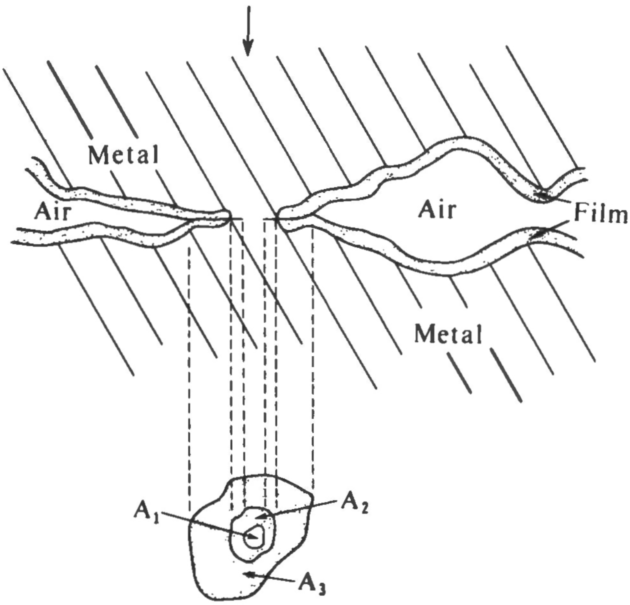

Fig. 1-7. **Condition after fritting. A_1 is area of metallic bridge or microweld, A_2 is where metals touch without weld; insulating films touch at A_3. All three areas help support the mechanical load P.**

Once a film has been fritted and a given current level established, a further increase in current will cause a widening of the hole through the film due to the thermal and electrical stresses on the film . Contact resistance will decrease accordingly.

In regard to the voltage necessary to cause fritting, i.e., the 10^5 to 10^6 volts/cm mentioned, one exception should be noted. This is the fact that *any voltage less than 30 millivolts will not permanently damage a film.* The importance of this fact will become apparent when application and testing are discussed in later sections.