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THE ELECTROSTATIC FORCES OF ADHESION BETWEEN PARTICLES^{*}

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INTRODUCTION

General adhesion phenomena have been treated extensively in the literature during the last 20 years.¹ Although the adhesion of solid particles to solid surfaces has been discussed in detail by several authors,^{2, 3, 4} most references to adhesion between particles tend to emphasize one or the other phenomena, implying, and sometimes stating, that others are unimportant. An example of this is in Fuchs⁵ book where he devotes several paragraphs to the discussion of capillary forces but dismisses electrical charge as having no marked effect.

A more adequate picture of particle adhesion must recognize a variety of physico-chemical mechanisms, each becoming important depending upon the properties of the adhering particles and of the ambient environment. Table I includes a few examples of adhesion forces that may become dominant under some given condition. The table is not exhaustive, ignoring, for example, cointering of particles as well as Stephan's "apparent" adhesion.^{7,8}

Table I
Summary of Adhesive Forces

Capillary Forces	Attractive	Environment Controlled
Electrical Forces		
(1) Free Surface Charge	Repulsive	Transient (Rapid Decay)
(2) Bound Volume Charge	Attr. or Repul.	Transient (Slow Decay)
(3) Contact Electrification	Attractive	Permanent
Molecular Forces	Attractive	Permanent

The purpose of this paper is to mention only briefly our work on capillary adhesion and to give a more detailed status report on our studies related to some electrical forces of adhesion.

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CAPILLARY FORCE

Surfaces exposed to moist air are continually being bombarded by water molecules, which impinge on the surface at a rate depending upon the partial pressure of water vapor in the local environment and the ambient temperature. The return of water molecules to the gas phase depends upon local physical-chemical interactions, which determine the vapor pressure over the surface of the given deposit of water. If we consider the region of contact between two spheres of radius, r , assuming both are wetted by water, it is seen that this region constitutes a capillary and that any water accumulating in the capillary will have a curved surface, Fig. 1. From the Gibbs-Thomson relation (Kelvin equation) it is possible to predict that a water surface having a constant mean curvature, a , will be in equilibrium with an ambient partial pressure, p , according to:

$$a = \frac{2 \gamma M}{\rho R T \ln (p/p_{\infty})} , \quad (1)$$

where

γ = free surface energy of the liquid (surface tension),

M = molecular weight of the liquid,

ρ = liquid density,

R = the gas constant,

T = absolute temperature

p_{∞} = saturation vapor pressure for local conditions.

For conditions under which $p < p_{\infty}$, that is, less than 100% relative humidity (% R.H. = $100 \times p/p_{\infty}$), the mean curvature is negative. The surface of revolution having a constant negative mean curvature is a nodoid.⁹ The requirement that all forces be in balance makes it possible to calculate the parameters of the capillary layer in equilibrium at a given relative humidity. Thus, it is possible to calculate the normal component of force holding the particle to the surface for various conditions of temperature and relative humidity. In contrast to the conclusion recorded in Fuchs'⁵ book that the normal force between two spheres is constant and is equal to $2 \pi r \gamma$, (γ = liquid surface tension), independent of relative humidity, a more complete analysis of the physical system shows

that the normal force should be expressed in the form

$$F_n = 2 \pi r \gamma_s \sin^2 \theta \quad (2)$$

where

γ_s = the average free surface energy of the solid around the between of contact, ergs/cm²;

θ = same as in Fig. 1, ($\leq$ approximately 67° for sphere to sphere contact).

Furthermore, molecular kinetic considerations suggest that the growth of the capillary layer, hence the normal force, should require a finite time to reach equilibrium. Thus, an aging effect is predicted in which the adhesive force is expected to increase with time and approach a maximum value.

Experimental observations of the number of 45- μ -diam glass beads remaining on a glass surface after application of a fixed removal force have shown¹⁰ that the number of particles requiring more than 5000 times the force of gravity for removal increases approximately as an exponential function of time. The half-time, T , increases as the relative humidity decreases. The observed effects of relative humidity and of aging are in qualitative agreement with predictions based on the capillary model. However, the observed maximum force required to remove all particles as a function of relative humidity does not agree with quantitative estimates of force based on the simple model except at 100% relative humidity. The degree and direction of disagreement between theory and experiment at low relative humidity suggest that significantly more water condenses in the capillary than would be expected by application of the Gibbs-Thomson relation assuming bulk properties of water to apply. To date, no clearly successful test of the Gibbs-Thomson relation has been performed for microscopic capillaries. On the contrary, work of Shereshevsky¹¹ over the past 30 years seems to indicate that the condensation of a polar liquid in a microscopic conical capillary yields amounts that are much more than would be predicted based on the Gibbs-Thomson equation. That work apparently has been verified by similar results of Chmutov.¹²

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A tentative explanation of these findings is that, due to the proximity of much of the capillary volume to solid walls, a long-range orientation may be imposed on the molecules of the liquid thereby lowering the effective vapor pressure over the liquid surface. This suggestion seems to be supported by Fedyakin's¹³ observation of a reduction in the coefficient of thermal expansion and in viscosity and by Kurosaki's¹⁴ work on dielectric properties of adsorbed water. All of these authors suggested some degree of structuring in the liquid water to explain their results. While this point is still debatable, additional work underway in our laboratory and elsewhere can be expected to help clarify the physical model necessary to predict adhesion forces between particles as affected by surface and environmental parameters. Whatever detailed model may result, experiment clearly shows that:

(1) A finite time is required to reach the equilibrium force after contact or after a change in relative humidity;¹⁵

(2) A hysteresis effect is observed in that the equilibrium force attained in drying down to a given R.H. from previous equilibrium at 100% R.H. is greater than the force reached in approaching the same given condition from initial contact;¹⁶

(3) The maximum capillary force of adhesion between two equal spheres is predictable and assuming zero contact angle the maximum force at 100% relative humidity is

$$F_c \leq 2 \pi r \gamma_s \sin^2 67^\circ = 2.66 d \gamma_s \text{ dynes (maximum),} \quad (3)$$

however, it may be expected that most particles will be held with forces smaller than this.

MOLECULAR FORCES

On the molecular and atomic levels, adhesion may be controlled by physical or by chemical phenomena. A list of typical molecular forces is given in Table 2.

Table 2
Molecular Forces

Force	Range	Contacting Materials
London-van der Waals	long	all materials
Dipole-dipole; dipole-polarizable molecule	short	polar molecules-polarizable molecules
Hydrogen bonds	short	OH containing materials and oxygen or nitrogen rich surfaces
Metallic bonds	short	metal-metal
Image bonds	short	metal-surfaces containing permanent dipoles.

When two spheres, significantly larger than molecular size, are in contact the areas in close enough proximity for the short range interactions to be effective are very small. Thus, we usually consider only the London-van der Waals component in solid-solid adhesion. Clearly, this simplification is inadequate if the surfaces are deformable or if in some other way relatively large surface areas are brought into close approximation.

In a recent paper Krupp¹⁷ suggests that the closest distance of approach of a sphere to a plane is probably within $\pm 30\%$ of 4×10^{-8} cm.

Based on work of Bradley¹⁸, Hamaker¹⁹ and Krupp¹⁷ the molecular force of adhesion between two rigid spheres of diameters, d_1 and d_2 , can be estimated to be

$$F_M = A \frac{d_1 d_2}{z^2 (d_1 + d_2)}, \quad (4)$$

where A = constant depending on the composition of the contacting surfaces (avg. approx. 4.5×10^{-13}). Thus, for two equal rigid spheres of diameter d' , in centimeters

assuming the closest distance of approach, z , is 4×10^{-8} cm the molecular force of attraction is approximately

$$F_M = 141 d', \text{ dynes.} \quad (5)$$

Unlike the other forces mentioned in this paper where d is the diameter of the average surface, i.e., irregularities that are small with respect to d can be ignored, it should be noted that for the case of molecular attraction, d' , represents the diameter of the small asperities which are in actual contact and not that of the average surface. Thus, except for interlocking asperities the force is less than would be calculated by equation (5) based on the diameter of the mean spherical surface.

ELECTRICAL FORCES

It is a common experience to see dust accumulations on charged plastic surfaces and not uncommon to observe particles violently transported under the action of an electrical field. Static electrification is such a part of the everyday environment it is not surprising that many writers refer to the accumulation and the effects of free surface charge as if this were the only significant electrical phenomenon affecting adhesion. That, of course, is not true, there being a variety of electrical charge effects that may predominate under various conditions.

Particle Conductivity

To discuss the behavior of conductive particles it is necessary first to decide what we mean by "conductive". The fundamental property of conductors is that free electrical charge can reside only on the surface. Consequently, with respect to free surface charge, it is only necessary that the particle surface be conductive. Although the formation and the exact physical nature of conductive layers are not completely understood, it is well known that this property is affected by the composition and the mode of formation of the surface as well as the nature of the local environment.

Fuchs⁵ observed that mineral oil droplets behave in a polarizing field as if they are conductive and suggests that all particles can be assumed to be conductive. In our experience, many particles composed of normally insulating substances can behave as if they were conductive in that they can acquire a highly mobile surface charge. For

example, a small sphere, composed of quadruply distilled sulfur, suspended by a nylon thread between two charged plates was observed to oscillate between the two plates with no detectable delay at contact. Similarly, glass and lucite particles also were seen to behave as if they were "conductive." On the other hand, Carnauba wax spheres remained in contact with the plate for long periods of time and gave no indication of charge accumulation. Thus, while we agree that in the particulate form some nominally insulating materials may behave with respect to free surface charge as if they were conductive, still we urge caution against applying this term to such particles without adequate testing under similar environmental conditions of particle formation, dispersion and handling.

Conductive Particles on a Charged Conductive Plane

Of the several forces affecting particle adhesion the only case that consistently leads to a net electrostatic repulsion is that of a conductive particle on a charged conductive plane. The geometrical relationships for a disk-shaped particle, a hemispherical particle and a spherical particle on a plane are shown in Fig. 2. From fundamental electrostatics it can be shown that the force of repulsion on a unit area of a charged conductor is given by

$$P = 5.65 \times 10^{19} \frac{\sigma_o^2}{k} \text{ dynes/cm}^2, \quad (6)$$

where σ_o is the surface charge density (coulombs/cm²) and k is the dielectric constant of the surrounding medium. This may be applied to the case of a flat conductive flake, a flat conductive agglomerate or a layer of particles on a charged conductive surface. For a disk of diameter, d (centimeters), the normal repulsive force is

$$F = 1.78 \times 10^{20} \frac{d^2 \sigma_o^2}{k} \text{ dynes (disk)}. \quad (7)$$

Similarly, there is a classical solution for a hemispherical conductor in contact with a charged conductive plane.²⁰ The field, normal to the surface, at every point on the hemisphere is given as a function of the angle θ (see Fig. 2 by

$$E(\theta) = 3E_o \cos \theta. \quad (8)$$

From (8) the electrical pressure acting on the hemisphere can be determined at every point and the total force normal to the plane can be calculated by integrating the vertical

component of pressure over the entire surface. Thus, for the hemisphere of diameter d (cm),

$$F = \frac{9 \pi d^2 \sigma_o^2}{16 \epsilon} = 2.00 \times 10^{20} \frac{d^2 \sigma_o^2}{k} \text{ dynes (hemisphere).} \quad (9)$$

Although it is true that not all particles are perfect spheres, still most particles are more nearly spherical than they are hemispherical. Unfortunately, the case of a conductive sphere in contact with a charged conductive plane is not readily soluble in closed form by classical methods. An analog solution has been obtained based on a new method developed by Karioris and Fish.²¹ The analog result is approximated by

$$E(\theta) = (0.8696 \cos^2 \frac{\theta}{2} + 3.6304 \cos^4 \frac{\theta}{2}) E_o \quad (10)$$

from which it is seen that the field at the surface of a charged plane, E_o , is perturbed by the presence of a conductive sphere; the field at the top of the sphere is approximately 4.5 times the field at the plane far away from the sphere. Thus, further deposition in the vicinity of a sphere on the plane will be more likely to occur on top of the first sphere, etc., leading to the growth of a dendritic deposit which is frequently seen. From (10) the normal component of force can be determined by integration to be

$$F = 5.03 \times 10^{20} \frac{d^2 \sigma_o^2}{k} \text{ dynes (sphere).} \quad (11)$$

The analog solution confirms Maxwell's²² theoretical conclusion that for two contacting spheres, differing greatly in size, the average surface charge density of the smaller sphere will be $\frac{\pi^2}{6}$ times that of the larger one. Taking the plane to be an infinite radius sphere of average surface charge density σ_o (coulombs/cm²), the total charge acquired by contacting sphere of diameter, d (cm), is

$$q = \pi d^2 (\frac{\pi^2}{6} \sigma_o) = 5.17 d^2 \sigma_o \text{ (coulombs).} \quad (12)$$

Two Contacting Spheres

At present we do not have complete solutions for the charge distribution and the electrostatic force for two contacting spherical particles. However, the two extreme cases of relative size have been solved and the results provide a means of estimating the magnitude of the force and the charge acquired by an uncharged spherical particle after contacting another charged sphere.

For the extreme case in which one sphere is very much smaller than the other the results given in equations (11) and (12) may be used. In this case σ_0 is taken to be the average surface charge density on the large sphere that would be observed if all of the initial charge on both spheres before contact resided on the larger one. For two equal spheres σ_0 is taken to be the average charge density on one sphere having the algebraic sum of the initial charges of both. The contribution to the total charge density, σ_0 , added by the smaller sphere depends upon the square of the ratios of the diameters hence may be neglected for a small sphere contacting a much larger one. In the absence of a complete solution, an approximation to the charge acquired by the smaller sphere, valid at the extremes, is given by

$$q = \pi d^2 \sigma_0 \left[\frac{\pi^2}{6} - \left(\frac{\pi^2}{6} - \frac{1}{2} \right) \frac{d}{d_0} \right], \text{ for } d \leq d_0, \quad (13)$$

where d is the diameter of the smaller sphere and d_0 is the diameter of the larger one.

The repulsion force between two equal spheres may be estimated using the result of Thomson²³ that the centers of charge in two equal, contacting spheres are 2.550 r apart. Treating the distributions of charge as if they were two equal point charges, q (coulombs), separated by 1.275 d (cm), the force can be calculated to be

$$F = \frac{q^2}{4 \pi \epsilon (1.275 d)^2} = 5.54 \times 10^{18} \frac{q^2}{kd^2} \text{ (dynes), for } d = d_0. \quad (14)$$

Equation (11) for a small sphere contacting a very large sphere can be expressed in the same form as equation (14) where q is taken to be the charge on the small sphere after contact (equation 13). Thus, q can be related to σ_0 and substitution in equation (11) yields an expression for the force on the small sphere, given by

$$F = 18.82 \times 10^{18} \frac{q^2}{k d^2} \text{ (dynes), for } d \ll d_0. \quad (15)$$

When expressed in terms of the final charge, q , on the smaller sphere, the repulsion force varies only by a factor of about 3.4 as the ratio of diameters ranges from 1 to 0. Again, as in equation (13), an approximation of the force on the small sphere may be obtained by assuming a linear variation with the diameter ratio. This assumption leads to the expression

$$F = \frac{q^2}{k d^2} \times 10^{18} (18.82 - 13.28 \frac{d}{d_0}) \text{ (dynes).} \quad (16)$$

Bound Charge

In contrast with the high mobility of charge carriers in conductive media, electrons, and their counterparts, holes, can become trapped in the structure of solid dielectrics and maintain approximately a given geometrical distribution for long periods of time. If, by some means, electrons and holes are separated and trapped the result is the establishment of a polarization in the dielectric medium. A similar result is obtained by the orientation of molecules having a permanent dipole moment by the application of high electrical fields while a molten material is allowed to solidify (thermoelectrets).²⁴ The retention of internal polarization is frequently referred to as persistent internal polarization. Such a volume polarization constitutes a vector field, $\vec{P}$, representing the dipole moment per unit volume.²⁵ This vector field can be treated in terms of an equivalent space charge distribution

$$\rho = \vec{\nabla} \cdot \vec{P}, \quad (17)$$

along with an equivalent surface charge density

$$\sigma = \vec{P} \cdot \hat{n} \quad (18)$$

where $\hat{n}$ is a unit vector, normal to the surface.

* Based on corrected value given in footnote, p. 8.

In addition to the space and surface charge densities related to the polarization vector field, excess electrons, or holes, may be trapped in the medium. This may occur, for example, by the absorption or emission of high energy electrons by the solid material. The resulting space charge distribution is persistent and can be treated mathematically in the same way as that due to polarization.

The influence of persistent, or bound, charges on the deposition and adhesion of two micron diameter Xerox powder is illustrated in Fig. 3. Specimens of plexiglas and of Carnauba wax were irradiated with high energy electrons through a well defined aperture. Approximately one hour after irradiation the specimens were set on edge and exposed to a cloud of airborne particles which deposited almost exclusively on the irradiated areas. The bound charge in this case was the result of polarization through the forward scattering of secondary electrons and the trapping of these and many of the primary electrons.

Although the bound charge is persistent it is not permanent as will be seen in Fig. 4. It is seen that the effective surface charge density decreases, approximately exponentially, with time. Even after almost a month significant effective charges were observed.

Contact Electrification

Differing with the transient nature of free surface charge and of trapped space charge, contact electrification is an equilibrium phenomena which is essentially permanent. It is a quantum mechanical effect that can be described with reference to Fig. 5, which depicts schematically the electron energy levels for two different solid bodies before and after electronic equilibrium. For simplicity the energy levels are sketched for a temperature of absolute zero. Electron energy equilibrium is attained by one material losing some of its electrons to the other until a constant potential difference, the contact potential, is reached.

If the capacitance of a sphere with respect to an equal and opposite sphere of a different composition can be obtained, it is possible to calculate the charge acquired and the force at contact. An expression for the capacity of the first conductive sphere with respect to the midplane is given in Fig. 5.²⁶ The force resisting separation of the sphere from its initial position with respect to the midplane is equal to the rate of change of

energy content with respect to distance in the direction of separation. From basic electrostatics it can be shown that the energy content depends only on the capacitance and the potential of the sphere referred to the plane. If the movement of the sphere is assumed to be slow with respect to the time required to reestablish equilibrium, then the potential, which is half the contact potential difference between the spheres, will remain constant and the force is related to the derivative of the capacitance with respect to separation distance.

It may be noted that the time to reach electron equilibrium for given local conditions is greater the larger is the distance separating the two solid surfaces. Also, since at equilibrium the potential, V , is constant and the capacitance, C , decreases with distance, equilibrium is approached by losing excess charge from the sphere. Thus, if the separation is fast enough some residual charge will remain on the sphere. The amount of residual charge depends upon the speed of separation of the surfaces and upon the properties of the environment, but will not exceed Q_1 , given by the expression in Fig. 6.

Values for the contact potential of many materials may be found in various handbooks, however it is well recognized that this parameter is a sensitive function of surface structure and composition which may vary by at least $\pm 10\%$ from the average across the surface of a given material and the observed average may differ by a much greater amount from tabulated values. Consequently, only the roughest of approximations can be obtained from handbook values. For this reason, Fig. 6 includes a factor K times the difference in the contact potentials, ϕ_1 and ϕ_2 , to emphasize the deviation from gross properties of the materials involved. Without direct measurement under the conditions of interest, not much can be known about the contact potential difference except the approximation that V will vary from essentially zero to on the order of a few tenths of a volt for similar materials, and may be as high as a few volts for dissimilar solids.

Although the infinite series for $Y(x)$, and $Y'(x)$ are divergent when $x = 1$, i.e., at mathematical contact, they are well enough behaved for $x = 1.0000001$. The computer solutions have been normalized by factors found to produce approximately constant values for a very wide range of the ratio of sphere diameter, d , to the closest

distance of approach, z (see Table 3). Assuming, as we did for molecular force, that z is 4×10^{-8} cm, then the average values from Table 3 are applicable to spheres ranging from 0.008 to 176 microns diameter for sphere to plane problems, or from 0.004 to 88 microns diameter for two equal spheres. Either of these ranges includes the majority of the particles dealt with in aerosol physics or powder technology. Using the average normalized values, the result for the range $20 \leq \frac{d}{z} \leq 4.4 \times 10^5$, is

$$Y(x) \approx 0.327 + 0.246 \ln \left(\frac{d}{z} \right), \quad (19)$$

and
$$Y'(x) \approx 0.123 \left(\frac{d}{z} \right). \quad (20)$$

Table 3

Tabulation of Normalized Results from Computer Solution for $Y(x)$ and $Y'(x)$

$\frac{2z}{d} = (x-1)$	$-(x-1) Y'(x)$	$Y(x) + A \ln (x-1)$
2×10^{-6}	0.172	0.447
4.5	0.211	0.490
1×10^{-5}	0.237	0.507
2	0.247	0.508
4.5	0.250	0.506
1×10^{-4}	0.250	0.502
2	0.250	0.499
4.5	0.250	0.496
1×10^{-3}	0.249	0.492
2	0.249	0.491
4.5	0.247	0.489
1×10^{-2}	0.245	0.488
2	0.241	0.490
4.5	0.233	0.497
0.1	0.218	0.512
0.2	0.198	0.537

From this the maximum acquired charge, and the force may be calculated: for the sphere of diameter, d (cm), in contact with a plane

$$Q = Vd[0.363 + 0.273 \ln (\frac{d}{z})] \times 10^{-12} \text{ (coulombs)}, \quad (21)$$

and
$$F = 1.36 V^2 \frac{d}{z} \times 10^{-6} \text{ (dynes);} \quad (22)$$

and for two equal spheres

$$Q = Vd[0.182 + 0.137 \ln (\frac{d}{z})] \times 10^{-12} \text{ coulombs}, \quad (23)$$

and
$$F = 0.34 V^2 \frac{d}{z} \times 10^{-6} \text{ dynes.} \quad (24)$$

SUMMARY

In summary, it may be useful to compare the magnitudes of the various adhesive forces for a given size particle. Table 4 includes estimates of the forces in the order of their discussion in this paper rather than some supposed order of significance. Clearly, the actual relative importance depends upon many separate factors in addition to the diameter which enters as the first power in some cases, as the second in others and, in the case of gravitational force, as the third power. For the purpose of this comparison the particles are taken to be 10 micron diameter glass spheres.

Table 4

Estimates of Adhesive Force for 10 micron Diameter Glass Spheres

Type of Force	Sphere to Plane (dynes)	Two Equal Spheres (dynes)
Capillary	< 0.9	< 0.8
van der Waals	< 0.3	< 0.1
Free Surface Charge	< 4×10^{-3}	< 7×10^{-9}
Contact Potential	< 0.1	< 3×10^{-4}
Gravity	1×10^{-6}	

Capillary forces may be expected to vary, being less if the surface free energy of the solid is less than the 300 ergs/cm^2 assumed here. Such variation is not uncommon, in fact our observations¹⁵ have shown as much as a factor of 4 lowering of the average surface free energy with a gradation of values up to the maximum. Thus, at 100% relative humidity, one would expect to find particle to plane forces ranging from about 0.2 to 0.9 dynes.

As pointed out before, the van der Waals force depends upon the diameter of the contacting roughness elements. It may safely be assumed that the occurrence of an atomically smooth surface having a curvature the same as the average surface of the gross sphere, in contact with an equally smooth plane is very improbable. Thus, the expected force may be much less, perhaps by a factor of 10, than that shown in the table.

Repulsive forces resulting from the accumulation of free surface charge on contacting conductors are dependent upon the available local concentration of charge. Because of surface, volume and atmospheric leakage the local density of charge is limited. Although the question of what is the maximum charge on a particle or a surface is not fully understood, it may be assumed that, in ordinary atmospheric environments, charge densities are not likely to exceed about $27 \times 10^{-10} \text{ coulombs/cm}^2$. This would be equivalent to about $5 \times 10^{10} d^2$ electron charges on an isolated sphere. We have observed adventitious surface charges as high as about $1 \times 10^{-10} \text{ coulombs}$ in an air conditioned building. Thus,

depending on the environment, perhaps 27×10^{-10} may be assumed as a practical maximum charge density and is used in the table, although such densities may be expected to be rare indeed. It will be noted that even though the sphere-plane force may significantly exceed the force of gravity, its maximum value is smaller than the other estimated maximum adhesive forces. Only for larger particles or if the other mechanisms are inoperative will free surface charge be the dominant factor. Furthermore, it is clear that a single particle is not likely to bear enough free charge to overcome the attractive forces after contacting another particle.

If we assume that the sphere and plane are of dissimilar materials then the difference in contact potential may be as great as 2 volts. The tabulated value was obtained by assuming the closest distance of approach is 4×10^{-8} cm and that V is 2 volts. For similar materials, such as the case of two spheres, the contact potential difference may be on the order of 0.2 volts as used in the table.

It is seen that any one of the mechanisms discussed can become large enough to completely overwhelm the force of gravity. Still, because of the sensitivity of these forces to surface and environmental conditions it is difficult to form an estimate of the lower limit or the average adhesive force without specific experimental evidence.

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Fig. 1 Equilibrium Capillary Sphere to Sphere Contact.

NORMAL PRESSURE ON A CHARGED SURFACE $= \frac{1}{2} \epsilon E^2 = P$

TOTAL UPWARD COMPONENT OF FORCE $= \iint (P \cos \theta) dA$

Fig. 2 Conductive Particles on a Charged Surface.

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PLEXIGLASS 1 MeV

CARNAUBA WAX 1.9 MeV (FRONT)

PLEXIGLASS 1.9 MeV

CARNAUBA WAX 1.9 MeV (BACK)

Fig. 3 Powder Patterns of Electron Irradiated Dielectrics.

Fig. 4 Decay of Charge in Electron Irradiated Dielectrics.

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Fig. 5 Contact Potential Electrification.

CAPACITANCE $C_1 = 8 \pi \epsilon R Y(x)$ (SPHERE 1)

$$x = 1 + \frac{z}{R}$$

$$Y(x) = \sum_{n=0}^{\infty} \frac{\sqrt{x^2 - 1}}{[x + \sqrt{x^2 - 1}]^{2n+1}}$$

FORCE

$$F_z = \frac{d u}{d z}$$

$$\text{ENERGY CONTENT } U = \frac{1}{2} C V^2$$

POTENTIAL DIFFERENCE $V = K(\phi_2 - \phi_1) = \text{CONSTANT}$

$$F_z = -\pi \epsilon V^2 Y'(x)$$

CHARGE

$$Q_1 = \frac{C V}{2} = 4 \pi \epsilon R V Y(x)$$

Fig. 6 Contact Electrification Equations.

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