and heat shields are all worthy of attention. Additional launch vehicle payload capability appears available through use of later versions of the Delta series.

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Electroadhesive Devices for Zero-*g* Intra/Extravehicular Activities

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Introduction

FOR an astronaut to accomplish the wide range of tasks expected in future space missions, a rapid and versatile method of temporarily attaching him and his equipment to the spacecraft or worksite is needed. One method of effecting essentially unlimited maneuvering capability or worksite tiedown is being evaluated at the Langley Research Center (LRC). This method utilizes electroadhesive forces and offers a means of adhering to any conductive surface. LRC is evaluating electroadhesors to determine the attachment force levels obtainable, the range of useful application, and the practical configurations of electroadhesive devices.

Electroadhesion Theory

Electroadhesion is an electrostatically induced attractive force between surfaces. Traditionally, electrostatic forces have been considered too weak to be of practical use. Recently, however, studies by the Chrysler Corporation under contracts to LRC, MSFC, and the Air Force have shown that electrostatic forces of useful magnitude can be produced and maintained.

The studies by Chrysler have demonstrated that when two oppositely charged conductors are separated by only a thin, but imperfect, insulating material, significant adhering forces between the conductors result. Figure 1 illustrates Paschen's Law, which partially explains this phenomenon. Note that the potential difference at which breakdown of the media separating the charged materials takes place is a function of the product Pd, where P is the pressure of the prevailing medium and d is the separation distance of the materials. The minimum breakdown potential is about 300 v which, at sea level pressure, corresponds to a separation distance of 0.01 mm. Increasing or decreasing the product Pd from this point increases the breakdown voltage and therefore the sustainable electric field. The adhering force per unit is a function of the applied potential; therefore, it is desirable that the applied potential be high but less than the breakdown voltage. These conditions can best be met if Pd is adjusted such that operation occurs on the part of the curve to the left of the minimum breakdown potential. The low pressures inside spacecraft cabins and the vacuum conditions of space are particularly conducive to the use of this part of the curve.

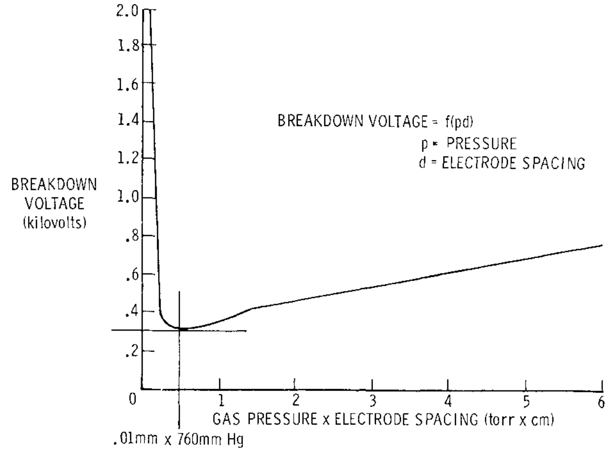

Fig. 1 Breakdown voltage vs gas pressure-electrode spacing product in air, illustrating Paschen's Law.

An essential element of the electroadhesion phenomenon is the thin, imperfect insulating material between the charged conductors. Experiments have shown that the electroadhesive forces obtainable are highly sensitive to the resistivity and chemical composition of the insulating material. Apparently some migration of electric charge occurs through the imperfect insulator which reduces the separation of opposite charges without allowing significant discharge.

Figure 2 shows some typical characteristics of electroadhesion. Note that the adhesive force per unit area is a fairly linear function of applied voltage in a region above a certain minimum voltage. Beyond this region a plateau is reached, however. Decreasing the atmospheric pressure raises the level of this plateau. The curve also shows that the current required by the device is in the microampere range and that reducing the atmospheric pressure reduces this requirement. Extending these curves to vacuum conditions results in a force plateau of around 30–40 psi and a current requirement of 1 μA or less allowing high forces to be maintained with little energy consumption.

Initial Development Studies

Because environmental pressures in space are favorable to electroadhesion, and because of the previously mentioned space applications of electroadhesion Langley awarded a proof-of-principle contract study of the phenomenon to the Chrysler Corporation. This study resulted in a preliminary

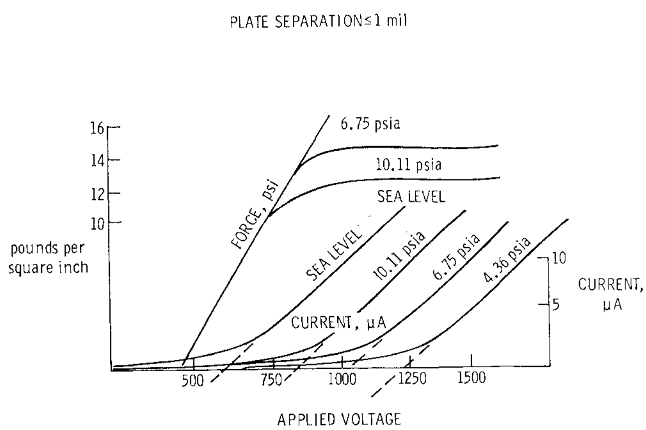

Fig. 2 Typical electroadhesor characteristics.

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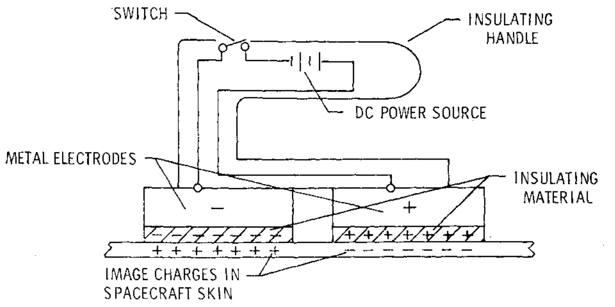

Fig. 3 Two-pole electroadhesor.

definition of electroadhesion and the construction of several prototype electroadhesors. Figure 3 is a sketch of an electroadhesive handhold. In the prototype devices, the high voltages required were obtained from a solid state oscillator (powered by ordinary pen light batteries) whose voltage was increased by a transformer then rectified by a solid state voltage doubler. The device in Fig. 3 is bipolar, consisting of two coated plates which become oppositely charged upon application of power. Then these plates contact a conducting surface, they impress upon the surface an electric field which produces migration of charges within the surface such that charges of a given polarity in the electroadhesor line up with charges of opposite polarity in the surface. The forces of attraction between these opposing charges produce the adhesion. The theory of electroadhesion and the study contract results are reported in Ref. 1.

Contracts for related work in electroadhesion were let by Marshall Space Flight Center and Wright-Patterson Air Force Base (WPAFB). No new information was reported.

LRC Electroadhesor Evaluation Program

The development of electroadhesors is dependent on the requirements of the particular applications. Thus, the development of electroadhesors requires much basic research. Such research determines the characteristics and capabilities of practical electroadhesive devices. Simulation of typical tasks determine the required characteristics. Concurrent with the simulation studies, actual electroadhesors must be developed having the characteristics found necessary in the simulation studies. Following these studies, spaceflight verification is required before electroadhesors become operational tools.

LRC is presently conducting the following two basic programs to determine the task requirements and electroadhesor capabilities.

1. I/EVA task requirements

A simulation study to investigate the characteristics (force levels, torques, etc.) of a series of I/EVA tasks representative of those expected in future space missions has been initiated. The simulation studies will be conducted in the LRC water-immersion simulation facility, and all tests will utilize electromagnets for attachment. Electromagnets simulate, to a large degree, electroadhesors and can be designed to provide a wide range of force levels and configurations. The tasks to be evaluated will primarily consist of: 1) astronaut maneuvering using handholds, shoes, and handrails; and 2) cargo transfer for packages having various sizes and masses and varying handhold locations. The tests will be conducted both with and without pressure suits.

Preliminary studies to develop electromagnet hardware have been initiated and have produced representative electromagnets for use as handholds and shoes. Initial indications in the cargo-handling studies are that the capability to move handholds to various locations on the package during transfer has a large advantage over a fixed position handhold, in that it permits variations in box c.g. location and varying control of package during transfer.

2. Electroadhesor hardware evaluation

The LRC contract provided basic experimentation to determine electroadhesor capabilities, and factors that influence the electroadhesive phenomenon and to develop prototype devices. LRC inhouse work has consisted of enhancing the electroadhesive devices obtained from Chrysler by increasing the voltage, varying the insulating material and method of introducing charges to the spacecraft surface and changing mechanical configuration to meet operational considerations. Several devices representative of two methods being used to produce the electrostatic field were constructed. These included bipolar devices evolving from the concept shown in Fig. 3 as well as those which directly introduced a d.c. ground to the conductive surface through the use of pins. Both devices utilize a thin sheet of insulating material on their bases. These devices are being evaluated.

Concluding Remarks

Initial studies of the electroadhesive phenomenon have indicated that electroadhesors are potentially usable as zero-g assistive devices for a range of intra- and extravehicular activities. These uses generally are related to astronaut and cargo maneuvering, worksite restraint and tool and equipment tiedown. Further studies are required to completely define the capabilities and applicability of electroadhesors.

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Effect of Lift Variation on the Impact of a Rolling Re-Entry Vehicle

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Nomenclature

A = reference area, ft^2
$C(\ )$ = Fresnel's cosine integral [Eq. (12)]
C_D = vehicle drag coefficient
$C_{L\alpha}$ = vehicle lift-coefficient-curve slope when $\alpha = 0$, deg^{-1}
CR = crossrange, ft
DR = downrange, ft
g = gravitational acceleration, 32.2 ft/sec^2
h = altitude, ft
I = moment of inertia about the vehicle roll axis, slug-ft^2
P = roll rate, rad/sec
R = radius of the base of a conical surface of possible dispersed trajectories, ft
$S(\ )$ = Fresnel's sine integral [Eq. (12)]
t = time, sec
V = vehicle velocity, fps
W = vehicle weight, lb
x, y, z = moving coordinates
X, Y, Z = Newtonian coordinates
α = trim angle of attack, deg

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