THE INFLUENCE OF FOOD PHYSICAL PROPERTIES ON TRANSFER
EFFICIENCY AND ADHESION IN A TUMBLE DRUM PROCESS

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By
Deirdra Renee Johnson, B.S.

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Master’s Examination Committee:
Dr. Sheryl Barringer, Adviser
Dr. John Litchfield
Dr. Michael Mangino

Approved by

[Signature]
Adviser
Graduate Program in Food Science and Nutrition
ABSTRACT

The purpose of this study was to investigate the influence of the food properties moisture content, resistivity, surface oil content, and surface roughness on the adhesion and transfer efficiency of different food products.

Food items were coated using a tumbling system equipped with electrostatic coating equipment (Spray Dynamics, St. Clair, MO).

Surface oil content was determined by dipping each food item in previously weighed petri dishes containing petroleum ether and measuring the amount of weight gain after the petroleum ether evaporated. Moisture content was determined by drying each food sample in a vacuum oven for 24 hr and calculating the amount of weight lost. Surface roughness was determined by scanning the surface of each food item using an optical profilometer. Resistivity was measured by applying voltage to a powder resistivity test cell (Electrostatics Solutions, Bassett, Southampton, Hampshire, U.K.) containing 5 cm$^3$ of ground food item. The actual amount of current exiting the test cell was measured using an electrometer (Model 614, Keithley Instruments, Inc., Cleveland, OH) and the resistivity was determined by the following equation: $\rho = (KV)/I$, where $\rho =$ resistivity, $K$ is the cell constant which is equal to 0.014, $V =$ the voltage applied to the test cell, and $I =$
the current exiting the test cell. Three maltodextrin powders, four salt powders, and one sucrose powder was used to coat the food items.

Transfer efficiency increased with increasing surface oil content for both nonelectrostatic and electrostatic coating. The higher the surface oil content of the food being coated, the more efficient the coating will be. Transfer efficiency also increased with decreasing moisture content for both nonelectrostatic and electrostatic coating. High moisture present in the food made the target more conductive, resulting in the loss of the electrostatic image charge faster. As a result, lower transfer efficiency was achieved. At high surface roughness values, transfer efficiency of the food powders to the food targets was high and fairly constant but at low surface roughness the transfer efficiency values varied. No trend was established for food resistivity value with transfer efficiency for both nonelectrostatic and electrostatic coating. Carbohydrates (maltodextrin and powdered sugar) were shown to produce higher transfer efficiency values than salt.

Moisture content, resistivity value, surface oil content, and surface roughness had no influence on the adhesion of the food products coated nonelectrostatically and electrostatically.
DEDICATION

Dedicated to the memory of my father who always pushed me to strive for academic excellence

You will be missed but always remembered.

Dr. Horace Johnson

May 5, 1942- August 9, 2004
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First and foremost I would like to thank God. Without him none of this would be possible. Thanks to my numerous family members and friends who were present to support me during my matriculation here at The Ohio State University.

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VITA

April 23, 1980.......................................................... Born-Staten Island, New York

2003................................................................. B.S. Agricultural Engineering

Florida A&M University

2003-present .................................................... Graduate Research Assistant

The Ohio State University

FIELDS OF STUDY

Major Field: Food Science and Nutrition
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................... ii
DEDICATION ......................................................................................................... iv
ACKNOWLEDGMENTS ......................................................................................... v
VITA ....................................................................................................................... vii
LIST OF FIGURES ................................................................................................. xi
LIST OF TABLES .................................................................................................. xiv
CHAPTER 1 ........................................................................................................... 1
INTRODUCTION ..................................................................................................... 1
CHAPTER 2 ........................................................................................................... 4
LITERATURE REVIEW .......................................................................................... 4
  2.1 Coating Systems ........................................................................................... 4
  2.1.1 Seasoning Applications ............................................................................. 5
  2.1.2 Flavoring Methods ...................................................................................... 5
  2.2 Electrostatic Powder Coating ......................................................................... 6
  2.2.1 Electrostatic Coating Equipment ................................................................. 7
  2.2.2 Electrostatic Theory .................................................................................... 8
  2.2.3 Coulomb’s Law .......................................................................................... 8
LIST OF FIGURES

Figure 4.1: Effect of food surface oil content on nonelectrostatic transfer efficiency for carbohydrates .........................................................39

Figure 4.2: Effect of food surface oil content on nonelectrostatic transfer efficiency for salts .................................................................39

Figure 4.3: Effect of food surface oil content on electrostatic transfer efficiency for carbohydrates .........................................................40

Figure 4.4 Effect of food surface oil content on electrostatic transfer efficiency for salts .................................................................40

Figure 4.5: Effect of food surface oil content on nonelectrostatic adhesion .......41

Figure 4.6: Effect of food surface oil content on electrostatic adhesion ..........42

Figure 4.7: Effect of food moisture content on nonelectrostatic transfer efficiency for carbohydrates .........................................................44

Figure 4.8 Effect of food moisture content on nonelectrostatic transfer efficiency for salts .................................................................45

Figure 4.9 Effect of food moisture content on electrostatic transfer efficiency for carbohydrates .........................................................45
Figure 4.10: Effect of food moisture content electrostatic transfer efficiency for salts..................................................................................................................46

Figure 4.11: Effect of food moisture content on nonelectrostatic adhesion..............47

Figure 4.12: Effect of food moisture content on electrostatic adhesion......................47

Figure 4.13: Effect of food surface roughness on nonelectrostatic transfer efficiency..........................................................................................................................50

Figure 4.14: Effect of food surface roughness on electrostatic transfer efficiency........51

Figure 4.15: Effect of food surface roughness on nonelectrostatic adhesion.............51

Figure 4.16: Effect of food surface roughness on electrostatic adhesion...................52

Figure 4.17: Effect of food resistivity value on nonelectrostatic transfer efficiency.....53

Figure 4.18: Effect of food resistivity value on electrostatic transfer efficiency........53

Figure 4.19: Effect of food resistivity value on nonelectrostatic adhesion...............55

Figure 4.20: Effect of food resistivity value on electrostatic adhesion.......................56

Figure 4.21: Transfer efficiency vs powder type for nonelectrostatic coating..........57

Figure 4.22: Transfer efficiency vs powder type for electrostatic coating...............58
LIST OF TABLES

Table 4.1: R Squared Values of surface oil content and nonelectrostatic and electrostatic transfer efficiency ................................................................. 38

Table A.1: Resistivity Values of Food ........................................................................................................ 67

Table A.2: Moisture Content of Food Items ............................................................................................. 67

Table A.3: Surface Oil Content of Food Items .......................................................................................... 68

Table A.4: Surface Roughness of Food Items ............................................................................................ 68

Table A.5: Particle Sizes of Powders Utilized .......................................................................................... 69
CHAPTER 1

INTRODUCTION

Electrostatic coating has been used extensively by the metal paint finishing industry since 1947 to apply liquids and powders onto a wide range of products such as refrigerators and office furniture (Clark 1995). The basis of electrostatic coating is the attraction between the negatively charged powder and the nearest grounded object (Alexander 1980). Electrostatic powder coating technology is gaining popularity in the food industry due to increased coating uniformity and decreased powder waste. Snack foods account for over $25 billion in annual sales in the food industry (Enggalhardjo and Narsimhan 2005). The substantial growth of the market for extruded snack foods has focused attention on the technological problems of flavoring them (Blanchfield and Ovenden 1974). Seasonings are used to add color as well as taste to improve consumer appeal of the finished product (Hanify 2001). Although the practical purpose of applying seasonings is to apply them in a consistent and uniform manner, many manufacturers are faced with problems which include overuse of expensive seasonings, poor seasoning distribution on the product, poor adhesion of the seasonings to the product, and the formation of dust caused by the temporary suspension of powder particles in the air (Anonymous 1992; Clark 1995; Hanify 2001). The presence of high
amounts of dust indicate that a large portion of the powder is not captured by the desired target (Ricks and others 2002).

Transfer efficiency is used as an indicator of how efficient the coating process is. Research has shown that transfer efficiency improves with the use of electrostatics (Anonymous 1996). Using several food powders, Ricks and others (2002) found a 68% percent increase in coating efficiency with the use of electrostatics.

Adhesion of the seasonings to the product is important to many aspects of the snack food production process. Without adequate adherence, salt ends up in the applicator recycle or in the package (Burg 1998). In electrostatic adhesion, the mirror image charge induced on the substrate causes an attraction between the particle and the substrate and creates an electric field between them that holds the powder to the substrate (Hughes 1997). The adhesion force caused by the image charge reduces the loss of coating from shaking or dropping off the product (Biehl and Barringer 2003).

Adhesion force is influenced by several different interactions. The principal interactions that are encountered in particle adhesion include molecular interactions, electrostatic interactions, liquid bridges, double layer repulsion forces, and chemical bonds such as polar and metallic bonds (Ranade 1987). Other properties such as surface roughness and resistivity also have an influence on the adhesion force. The highest possible resistivity should be sought so that once the particles alight on their final target, charge relaxation will be slow and good adhesion will be assured (Hughes 1997). Although work has been done on the adhesion of dry seasonings particles onto tortilla chips (Enggalhardjo and Narsimhan 2005), there is little published data on the adhesion of dry seasonings on different food products. Therefore, the objective of this study is to

2
investigate the influence of food properties moisture content, resistivity, surface oil content, and surface roughness on the adhesion and transfer efficiency of different food products coated electrostatically and non-electrostatically.
CHAPTER 2

LITERATURE REVIEW

2.1 Coating Systems

The increasing acceptance of flavored snacks began to take effect during the period 1965 to 1968 (Smith 1974). The introduction of mechanical salting/flavoring equipment had a major impact on the increasing popularity of flavored snacks.

In some snack food seasoning processes, it is necessary to apply coatings as the product is transported on a conveyor (Hanify 2001). Vibratory, open wire belt, and closed fabric belts are some of the conveyors that can be used. When it is desirable to coat all sides of the product, each side should have a uniform appearance, so when a conveyor-based coating system is designed it must be designed in such a way that it includes a mechanism for turning the product over to not only season the top surface but also all surfaces of the product. Another consideration when designing a conveyor-based coating system is providing a means to collect and recover excess seasonings because the product does not cover 100% of the conveyor.

Coating drums are usually used for flavoring snacks (Hanify 2001). The purpose of a coating drum is to expose all surfaces of the base product to the various seasonings applied (Hanify 2001). In this system snack foods are gravity fed into a revolving drum
that is open at both ends and mounted at an angle (Madl 2000). The drum is typically made out of stainless steel. Flights, or raised edges inside the drum lift the product and help to facilitate the tumbling of the product to the discharge end of the drum while helping to expose all sides of the product to the seasonings being applied.

2.1.1 Seasoning Applications

Single-stage coating and two-stage seasoning are two basic types of seasoning applications. In general, dry seasonings are usually applied. Oil based seasonings can also be applied as well as liquid smoke, soy sauce, or any other water-based flavoring material (Hanify 2001). An auger inside a horizontal distribution tube is a common method to distribute seasonings. The distribution tube creates a “curtain” of applied seasoning (Hanify 2001). In two-stage seasoning a liquid must be applied to the surface of the product before the dry seasoning is applied. This is necessary because not enough liquid is present on the surface of the products to allow adhesion of the seasonings. The liquid application zone is separated from the dry coating zone, allowing the two additives to be controlled independently (Hanify 2001).

2.1.2 Flavoring Methods

Early salting equipment consisted of either a vibrating tray feeder or a grooved roller and brush mounted over the transfer system after cooking and prior to packaging the snacks (Smith 1974). As the roller turned, it dropped salt onto the snack foods passing below it on the conveyor. This equipment is still used for salt but not for other seasonings.
Another method used to flavor snack foods is pneumatic application (Madl 2000). In pneumatic application salt is mixed with air in a venturi. The air/salt mixture is then conveyed to a distribution cabinet, where nozzles blow the salt/air mixture onto the product as it moves along the conveyor.

A mesh belt type dispenser is another method of flavor application (Madl 2000). The dispenser straddles the conveyor similarly to the roll salter. Seasonings are dispensed from a hopper onto a mesh belt, which is useful for preventing clumping. The seasonings are dispensed unto the product moving along a vibratory conveyor below the mesh belt.

Challenges exist with these traditional methods of coating. Metering screws used in the food industry simply convey material to a set point (Clark 1995). The result is unevenly coated products with poor flavor distribution, consumer complaints, and contaminated equipment (Biehl and Barringer 2003).

To combat the problem more seasoning is added which leads to an increase in waste and overuse of seasonings (Clark 1995). By adapting and harnessing the techniques being used increasingly to paint cars, refrigerators, and washing machines by powder coating, a new method to coat snack products utilizing electrostatics was developed (Pannell 1980). The electrostatic methods reduce wastage onto processing equipment and the enhanced efficiency and distribution of flavor coatings provide significant economic and product quality benefits (Law 2001).

2.2 Electrostatic Powder Coating

Electrostatic spray coating is a spraying process that employs electrical charges to attract atomized particles to a work surface. The concept of electrostatic powder coating
originated in the USA around the 1950s (Bailey 1998). Harold Ransburg first successfully commercialized an electrostatic painting method by using a conventional spray gun directing the droplet stream through a high-voltage grid of fine corona wires positioned between the grounded gun and target (Law 2001).

Electrostatic powder coating is based on the theory that electrically charged particles of seasoning will seek out a grounded product and give an even coating (Madl 2000). The prime requirement for all powder coating systems and processes that rely on electrostatic particle handling is that of imparting electrical charge, usually unipolar, to individual particles (Hughes 1997). In electrostatic powder coating, powder particles are sprayed through an area of strong electric field and high free ion concentration (Guskov 1996). As the powder particles exit the spray gun, propelled by air they physically collide with ionized air molecules produced by the corona discharge, with the number of collisions determining the degree of charging (Guskov 1996).

2.2.1 Electrostatic Coating Equipment

On snack foods, corona-charged preparations of conductive flavorings and salts are electrostatically applied (Law 2001). To adapt electrostatic technology to the snack seasoning industry, the base product must be grounded (Hanify 2001). In a tumble drum process, the base product is grounded by contact with the coating drum that is grounded.

In a tumble drum, seasoning is fed into a mixing area where a wire is suspended near the falling curtain of seasoning. This wire is electrified and it generates an electric field, which the powder coating is dispensed (Madl 2000). As the seasoning passes through the electric field, each particle is charged. Electrostatic force promotes separation
of powder particles from other particles because it imposes a negative charge on the particles and the like charges repel each other (Ricks and others 2002). Because the particles repel each other they form a uniform cloud. When they land on the product being tumbled through a drum about 12 inches from the seasoning dispenser, they spread themselves out resulting in an even coating of seasoning on the product (Madl 2000).

In corona-charging systems involving a gun, a sharply non-uniform electric field is created between a gun and part by applying high voltage potential to a pointed electrode (Guskov 1996). As voltage is applied to the gun electrode, charge accumulates at the tip until it exceeds the dielectric strength of air (Horinka 1995). As the powder particles exit the spray gun, propelled by air, they physically collide with ionized air molecules produced by corona discharge, with the number of collisions determining the degree of charging (Guskov 1996).

2.2.2 Electrostatic Theory

Electrostatics is the study of the phenomena associated with charged bodies that are at rest or moving and the interactions between each other. Hughes (1997) defines electrostatic forces as those forces created by the interactions between charged particles and an electric field.

2.2.3 Coulomb’s Law

Electrical forces are created by the interaction between charged particles and an electric field (Hughes 1997). Electrostatic forces on powder particles arise primarily from the presence of net electric charge on the particles or externally applied electric fields (Feng and Hays 2003). The coating material is therefore attracted to the target by the
electrical force described by Coulumb’s Law. Coulumb’s Law states that charges of the same polarity are repelled from each other, while charges of opposite polarity attract each other (Hughes 1997). Coulumb’s Law can be described by the following mathematical equation:

$$F = \frac{q_1 \times q_2}{4\pi\varepsilon_0\varepsilon_r r^2}$$

Where:

$q_1, q_2 =$ charge

$r =$ distance

$\varepsilon_0 =$ permittivity of free space ($8.8 \times 10^{-12}$ F/m)

$\varepsilon_r =$ permittivity of the medium in which the particle exists

2.2.4 Charging Methods

The charging of particles by ions from a corona discharge was investigated in the 19th century and led to the development of the electrostatic precipitator (Bailey 1998). Corona charging is the most widely used method of particle charging in powder coating (Hughes 1997). In corona charging systems, a sharply non-uniform electric field is created between a gun and part by applying high voltage potential to a pointed electrode (Guskov 1996). The electrode can also be a fine gauge wire. As voltage is supplied to the electrode, charge accumulates in the vicinity of the electrode until it exceeds the dielectric strength of the air, which is measured to be about 30 kilovolts per centimeter at normal conditions of pressure and humidity (Horinka 1995).
Charging of powder particles by negative ions occurs according to ion attachment (Bailey 1998). Free electrons or ions are always present in the air (Guskov 1996). When an electron passes through a strong electric field, it moves along the field lines and is accelerated by the field force. While accelerating along the field lines, the electron eventually collides with an air molecule splitting the air molecule to form two secondary electrons and one positive ion. The secondary electrons formed also move along the field lines, splitting new molecules and creating more ions and electrons. This process is known as corona discharge. The air breakdown or corona discharge usually manifests itself as a relatively low energy continuous process that is ultimately responsible for the particle charging in the electrostatic systems (Hughes 1997). In an electric field, an uncharged powder particle will distort the external electric field in such a way that some field lines will be going towards the particle’s surface, entering at a 90° angle, passing through it, and exiting at a 90° angle (Guskov 1996). Free ions present in the electric field follow the field lines towards the surface of the uncharged powder particle. The powder particle’s charge is increased because the free electrons are captured by the particles field of polarization (Guskov 1996). The powder particle charging process will continue until the charge accumulated on the particle is great enough to create the particle’s own electric field (Guskov 1996).

The process of corona discharge is governed by Pauthenier’s equation (Guskov 1996). The charging is mostly affected by the field strength, powder particle size and shape and the time the particle spends in the charge area. Pauthenier’s equation is expressed as the following mathematical equation:
\[ q_s = E_o r^2 \pi \left[ \frac{3\varepsilon}{(\varepsilon+2)} \right] \]

Where:

\( q_s \) = the saturation charge on a particle
\( E_o \) = the electric field intensity
\( R = \) the particle radius
\( \varepsilon = \) the dielectric constant of the particle

Another charging method is tribocharging or frictional charging. There is no high voltage source in tribocharging. The energy comes from the force and velocity with which the powder contacts the internal walls of the spray gun (Horinka 1995).

2.3 Transfer Efficiency

Transfer efficiency is the amount of powder deposited onto the target in a coating system divided by the amount of powder applied into the coating system (Ratanatriwong and others 2003). Cross and others (1980) defined transfer efficiency as the weight of powder deposited in a given time divided by the total weight of the powder emitted in the same time. The transfer efficiency of the powder coating process and the quality of the final coating depend critically on the mean particle size and the width of the size distribution function (Bailey 1998). The consistency and uniformity of the powder-
coating layer tends to be better as smaller particle sizes are used and the width of the distribution function narrows (Bailey 1998).

2.3.1 The Effect of Particle Size on Nonelectrostatic Transfer Efficiency

Ricks and others (2002) and Ratanatriwong and others (2003) found for nonelectrostatic coating, as particle size increased, transfer efficiency increased. Biehl and Barringer (2003) found that for nonelectrostatic coating, as particle size decreased, transfer efficiency increased. The same trend was observed by Miller and Barringer (2002) who found that as hollow pyramid salt and crush flake salt particle size decreased, nonelectrostatic transfer efficiency increased.

2.3.2 Flowability

Ricks and others (2002), Biehl and Barringer (2003), and Ratanatriwong and others (2003) found for nonelectrostatic coating, as flowability increased, powder deposition increased. Powders that flow well are able to maintain a uniform curtain over the entire length of the electrode, therefore charging efficiently, resulting in higher transfer efficiency.

2.3.3 Shape

The salt shape was also a significant factor in nonelectrostatic transfer efficiency with crushed flake salt providing the best coating efficiency, followed by hollow pyramid salt, cube salt, and porous salt (Miller and Barringer 2002).
2.3.4 Electrostatic Improvement

Research has shown that transfer efficiency improves with the use of electrostatics (Anon 1996). Ratanatriwong and others (2003) found a significant improvement in transfer efficiency with all seasonings when electrostatic coating was utilized. Biehl and Barringer (2003) found a 15% overall improvement in transfer efficiency when electrostatics was used. Using electrostatics at 25 kV, coating efficiency improved over nonelectrostatic coating for 10 of the 16 powders used (Ricks and others 2002).

2.3.5 Charge to Mass

In the electrostatic coating process the charge on the powder particles is one of the most important quantities (Ong and others 1975). The electrostatic forces greatly enhance the coating uniformity and improve the transfer efficiency (Castle 2001). The larger the charge a powder can attain, the greater the attraction it has for substrate, resulting in greater transfer efficiencies (Mazumder and others 1997). Increased charge to mass improves coating efficiency because particles are more attracted to the grounded surface (Ricks and others 2002). The charge to mass ratio gives an indication of how efficiently the electrostatic coating system is charging the powder particles (Hughes 1997). Biehl and Barringer (2003) found that as charge to mass ratio increased, electrostatic transfer efficiency increased which was similar to the trend reported by Ratanatriwong and others (2003). The greater the surface area, the higher the charge to mass ratio and theoretically, the greater the coating efficiency (Miller and Barringer 2002).
2.3.6 The Effect of Particle Size on Electrostatic Coating

Biehl and Barringer (2003) found that for electrostatic coating, as particle size decreased, transfer efficiency increased. This trend was also reported by Ricks and others (2002) and Miller and Barringer (2002). Small particles are more susceptible to course alterations resulting from electrostatic forces because they have low inertia and are affected less by gravitational forces than large powders (Ricks and others 2002). Therefore the smaller particles are more easily carried by the air currents induced in the tumble drum and are more evenly dispersed across the food product.

2.3.7 The Effect of Oil on Transfer Efficiency

Miller and Barringer (2002) also studied the effect of oil on the transfer efficiency. They found that for all salts used, the more oil on the popcorn, the more efficient the coating.

2.4 Adhesion

The term adhesion signifies sticking together of two similar or dissimilar materials (Mittal 1977). Particle adhesion is the result of forces, which exist between particles and a solid surface in contact, where the solid surface can be a particle surface itself (Podcezeck 1998). Kaelble (1971) defines adhesion as the molecular force exerted across a surface of contact between unlike solids that resists interfacial separation. The adhesion of dust particles and powders constitutes the interaction of microscopic particles with a solid surface due to forces which depend both on the properties of the bodies in contact and on those of the surrounding medium (Zimon 1969).
Thermodynamic or reversible work of adhesion, $W_A$, is the change in free energy when the materials are brought into contact, and it is the same as the amount of work expended under reversible or equilibrium conditions to disrupt the interface. A minimum charge of $3 \times 10^{-4}$ C/kg is required for adhesion (Cross and others 1980).

2.4.1 Adhesion Forces

Forces causing adhesion include Lifshitz-van der Waal Forces, capillary forces, electrical forces also known as “electric double-layer forces”, and electrostatic image forces or “Coulomb Forces.” Adhesion can be a long-range force such as gravitational or Coulombic, acting from the center of the particle, but more usually, it is a short-range force originating from molecular forces such as van der Waals attractions of the particle surfaces (Kendall and Stainton 2001). The primary adhesion forces for a dry uncharged particle on a dry uncharged surface are the van der Waals and electrostatic forces (Busnaina and Elsawy 2001).

Basic or fundamental adhesion means the summation of all interatomic or intermolecular interactions at the interface (Mittal 1977). Forces between solids are predominately of attractive nature and cause adhesion of particles to each other and to surfaces (Ranade 1987). Particle surface interactions include molecular interactions, electrostatic interactions, capillary forces, and double-layer repulsion forces.

Molecular forces are based on van der Waals dispersive interactions. The van der Waals force is the dominant adhesion for particles less than 50 μm (Busnaina and Elsawy 2001). Van der Waals forces arise from the high frequency movement of the electrons in the atoms or molecules giving rise to momentary areas of charge concentrations called
dipoles (Busnaina and Elsawy 2001). The dispersive interactions between these dipoles
and the induced dipoles in neighboring atoms are summed over all atoms (Mullins and
others 1992).

The van der Waals force for a spherical particle attached to a planar surface is
given as (Busnaina and Elsawy 2001):

\[ F_{vdw} = AR/6z^2 \]

Where:
- \( A \) is the Hamaker constant
- \( R \) is the radius of the spherical particle
- \( z \) is the separation distance between the particle and the substrate

For smooth surfaces, the average separation distance between the two surfaces is
taken as 0.4 nm (Busnaina and Elsawy 2001).

Van der Waals dispersive interactions are represented by the Hamaker constant,
A. Two theories led to the formulation of the Hamaker constant. The first theory is the
London-van der Waals theory or simply the “microscopic theory.” The second theory is
the Lifshitz theory or the “macroscopic theory.”

Electrostatic force constitutes the main force of attraction for particles larger than
50 μm in diameter (Busnaina and Elsawy 2001). The electric force helps the powder
particle overcome aerodynamic and gravity forces and stay at the substrate’s surface to
allow the creation of the electrostatic image force (Guskov 1996). The electrostatic image
force (\( F_{el} \)) is given as (Busnaina and Elsawy 2001):

\[ F_{el} = Q^2/6(D + z_0)^2 \]
Where: 

- $Q$ is the particle charge
- $D$ is the particle diameter
- $Z_0$ is the separation distance

Particles adhere by electrostatic image forces for as long as charge remains on the deposited particles (Bailey 1998). The charge on the surface of the powder particle that is in intimate contact with the target will be neutralized, but this is only a small portion of the overall charge (Ricks and others 2002). The majority of the charge remains on the particle due to high surface resistance. Since the distance between the powder particle and the target is now small, based on Coulomb’s law the attraction force between the charged particle and its “image” charge will be large, increasing adhesion (Hughes 1997). When two dissimilar materials are brought into contact, a charge transfer takes place which results in the formation of an electrical double layer (Mittal 1977). The charges will not only attract each other retaining the powder particle on the surface, it also creates another electric field between themselves (Guskov 1996).

Ranade (1987) described two basic types of electrostatic interactions. The first electrostatic interaction arises from the difference in the work functions of two different materials resulting in a contact potential $\Phi_c$. The contact potential has a maximum value of 0.5 V. Charges are subsequently produced in the surface layers of the particle and the surface. This force is given by Krupp (1967) $F_{el} = \pi \varepsilon_0 d_p/2 \times \Phi_c^2/Z_0$, where $Z_0=0.4$ nm, 1 $\mu$m particle, and the force equals 1 mdyne. The second electrostatic interaction arises due to the electric charge on the particle or substrate surface. The Coulomb interaction of the
charged particle resting on a surface is equivalent to an interaction between the particle and its "image" resulting in \( F_{ad} = \frac{Q^2}{6(d_p + Z_0)^2} \)

Under ambient conditions, and in the absence of any significant triboelectrification, particle adhesion is dominated by a non-surface specific capillary force, which arises from a thin layer of water molecules absorbed on the surface (Price and others 2002). In humid environments, liquid can condense between the particle and substrate, giving rise to a very large capillary force, which increases the total force of adhesion (Busnaina and Elsawy 2001). The capillary force is given by:

\[ F_c = 4\pi \gamma_{LV} \]

Where: \( \gamma_{LV} \) = the surface tension for the liquid-air interface

\( r \) is the radius of the spherical particle

Capillary forces depend on liquid surface tension, and water creates significant surface tension (Ranade 1987). As surfaces come into contact, condensed water wicks into the capillary spaces between the contiguous surfaces, forming a concave-shaped meniscus (Price and others 2002). The meniscus formed draws the bodies together due to surface tension and reduces the pressure of the liquid (Ranade 1987). Laplace pressure acting across the meniscus and the surface tensitional force at the liquid/air interface induces an attractive force between contiguous surfaces (Price and others 2002). The attractive force is shown by the following equation: \( F_c = F_{LV} + F_p \), where \( F_c \) is the total force due to the pressure of the water, \( F_{LV} \) is the force caused by the surface tension, and
F_p is the Laplace or capillary pressure. Zimon (1969) found that capillary forces dominate when relative humidity is above 70%.

2.4.2 Factors that Influence Adhesion

The adhesion of electrostatically deposited powder layer depends primarily upon the following parameters: 1) conductivity of the substrate, 2) particle charge distribution, 3) electrical resistivity of the powder, 4) thickness of the powder layer, and 5) the particle size distribution (PSD) of the powder (Sims and others 2000). Stözel and others (1997) found that adhesion increased with increasing specific charge.

2.4.3 Surface Roughness

Surface roughness is defined as semi or completely random variation in the surface height. Surface roughness is measured using a profilometer. Profilometers measure the physical depth of surface irregularities using some form of diamond or bush-type stylus and arm that travels in a straight line for a specific “cutoff” or sampling length (Hebert 2004). Profilometers measure surface characteristics in the micron scale.

Hebert (2004) describes four common methods used to calculate surface roughness.

- Ra (average roughness) is the average of the peak and valley distances measured along the centerline of one cutoff length.
- Rq (root mean square) is the average of only the heights of all points measured in one cutoff length
- Rz (ten-point average) is the average of the five highest peaks and the five lowest valleys measured in one cutoff length
- $R_t$ ($R_{max}$) is the value of the vertical distance between the five highest peaks and the five lowest valleys measured along one cutoff length.

Adhesion between nominally flat surfaces is strongly influenced by roughness (Johnson 1998). Pretzels and most crackers have relatively smooth surfaces that don’t accept seasoning well (Burg 1998). The effect of surface roughness on Van der Waals forces is highly dependent on the nature of the roughness (Ranade 1987). The van der Waals forces can increase due to particle and/or surface deformation that increases the particle contact area (Busnaina and Elsawy 2001). The surface roughness does not only influence the Lifshitz-van der Waals force but the magnitude of the capillary forces also (Podczeck and others 1997). Macroscopic substrate roughness provides mechanical locking of the adherate and a large surface area for bonding (Mittal 1997).

Mechanical interlocking is the oldest adhesion theory and it simply states that materials would adhere because of locking through their pores and asperities (Michalski and others 1997). Porous surfaces of extruded snacks or braided products have more surface area to attract and hold seasonings (Burg 1998). If the surface asperities are much smaller than the powder particles, less mass is present in the immediate vicinity of the contact plane and results in reduced adhesion force. No intimate contact between the particle surface and the substrate surface also leads to decreased adhesion by producing uncoated areas of voids or vacancies. By increasing the effective contact area, increased adhesion may result. Surface topography also has an impact on the friction of materials, which may favor adhesion (Michalski and others 1997).

Workers have found that increased roughness increases adhesion of electrolytically deposited metals (Mittal 1977). Ibrahim and others (2000) found that
gelatin capsule surfaces with low surface heterogeneity and high-contrast friction exhibited high lactose particle adhesion and gelatin capsule surfaces with low surface heterogeneity and low contrast friction exhibited low lactose particle adhesion. Price and others (2002) found that increasing substrate surface roughness lead to a high variability in adhesion energy measurements, which suggested that the contact area between lactose powder particles and drug surface plays a critical role in the adhesion properties.

2.4.4 Particle Size

Adhesion forces are also affected by particle size. Adhesion force tends to decrease with increasing particle size, fine particles adhering best and large particles adhering least (Kendall and Stainton 2001). Busnaina and Elsawy (2001) found that the adhesion removal efficiency was lower for smaller particles in the 20-60 µm range than larger particles in the 100-500 µm range.

Enggalhardjo and Narsimhan (2005) found that the adhesion force was smallest for fine particles (32 to 64 µm) and increased progressively for medium (64 to 125 µm), large (125 to 180 µm), and coarse particle sizes (180 to 300 µm). Banerjee and Mazumder (1996) found that adhesion force increased with increasing particle diameter size, which was opposite to the trends found by Kendall and Stainton (2001) and Busnaina and Elsaway (2001).

Mullin and others (1992) found that particle detachment force increased as glass sphere diameter increased. Also in contrary, Guskov (1996) stated that the attraction force between charged powder particles and their mirror reflection is stronger because larger powder particles usually accumulate a higher total charge.
Adhesion forces dominate small particles and large particles are dominated by gravity. Attractive forces become increasingly significant for fine particles because the particle mass varies to the third power of the particle size (Ranade 1987).

2.4.5 Moisture

Condensation of water vapor can take place in the gap between bodies on contact due to air humidity. The presence of water vapor in the ambient atmosphere can affect the adhesion of particles to solid surfaces (Ibrahim and others 2000). At high humidities (above 50%) capillary condensation may form a liquid phase in the contact zone and under right conditions increase adhesion by capillary forces (Ranade 1987). Absorbed water film can aid in the dissipation of electrical charges on solid surfaces. In the absence of electrical charge effects, there is usually an increase in the adhesion tendency of a particle to a surface with an increase in relative humidity. The presence of moisture may soften the surface of the particle and/or solid substrate due to water sorption, and the surface force-induced deformation increases the contact area and consequently the adhesion force (Ibrahim and others 2000). Busnaina and Elsawy (2001) found that adhesion increased as relative humidity decreased below 45%. This was due to charge build-up and the increase of electrostatic forces that occurs in low relative humidity.

2.4.6 The Effect of Oil Content on Adhesion

Oil content also has an influence on adhesion. Enggalhardjo and Narsimhan (2005) found that the adhesion force increased as oil content increased from 24% to 28%. This implies that the adhesion force increases with increasing oil content.
2.4.7 Powder Resistivity

Powder resistivity also has an influence on the powder coating and charging process. Bailey (1998) identified the following three ranges:

1. Range (i): $\rho > 10^{13}$ Ω-m. Powder particles in this range are insulating and their charge relaxation times are from minutes to hours. Due to their long charge relaxation times, charged particles are retained on the work piece for sufficient time. Powders in this resistivity range have good adhesion.

2. Range (ii): $10^{13}$ Ω-m > $\rho > 10^{10}$ Ω-m. The powder coating performance of powders in this range are hard to predict. The charge decay of the powder particles is only for a few minutes and adhesion is usually poor.

3. Range (iii): $\rho < 10^{10}$ Ω-m. Powder particles in this range act as conductors. These particles charge effectively in a corona discharge but on contact with a metal substrate, charge is lost quickly. Powders in this resistivity range generally have poor adhesion.

2.4.8 Adhesion Measurements

There are several experimental methods used to measure powder adhesion. These methods include 1) varying the slope of a surface, 2) the microbalance technique, 3) the pendulum method, 4) the centrifuge method, 5) the vibration method, and 6) the aerodynamic and hydrodynamic method. The centrifuge method, vibration method, and aerodynamic and hydrodynamic method are useful for micrometer-sized particles (Ranade 1987). In the vibration method, particles are placed on an acoustic transducer and their separation is measured as a function of frequency and amplitude of the vibrator.
(Krupp 1967). Air or nitrogen blow-off guns are also useful in measuring powder adhesion but they are only effective in removing large particles (>10 μm) from the surface (Ranade 1987). In the flow method, particle separation is measured as a function of rate and direction of an air jet (Krupp 1967). In the gravity method, the particle is suspended so that the gravity component, which tends to separate the particle, can be continuously increased by increasing the inclination of the substrate to which it adheres (Krupp 1967).

Stözel and others (1997) used three techniques to measure electrostatic powder adhesion. The first method involved the centrifugal spinning of a powder-coated cylinder. A powder layer was sprayed on the outer surface of a cylinder that was rotating at differing speeds. The cylinder was 99 mm and the maximum rotational speed was 10,000 rpm that corresponded to an acceleration of 5300 g/min. The collecting vessel was grounded with an R-C combination. The speed was increased continuously to the maximum speed within 60 s.

The second method was the impulse drop test method (Stözel and others 1997). Metal work pieces measuring 10 x 10 cm² were coated with 25 g of powder using different spraying systems. The sample was dropped from a height of 25 cm down an inclined slope of 80°. After each drop test the amount of powder remaining on the metal work pieces was measured.

The third method was the micro air pulse method (Stözel and others 1997). In this method computer generated micro air pulses were used. The total integrated blow time to remove the powder layer was used as a qualitative measure of adhesion.
2.5 Resistivity

In all applications requiring charging of particles, knowledge of the particles’ resistivity is essential and critical with regard to system behavior (Hughes 1997). To ensure that powder deposition times are sufficiently long, powder particle resistivity must be high.

2.5.1 Resistivity Measurement

The bulk resistivity cell technique is one of the simplest and widely used methods developed for the measurement of resistivity. The sample is poured into the cell and subjected to steady dc potential (V), while the current (I) flowing in the external circuit is measured (Hughes 1997). A typical powder resistivity test cell is shown in Figure 4.1. The powder resistance can be determined by calculating it from the Ohm’s law relationship:

\[ R = \frac{V}{I} \]

Where:

\[ R = \text{resistance (} \Omega \text{)} \]
\[ V = \text{dc voltage (} V \text{)} \]
\[ I = \text{current (} A \text{)} \]

By knowing the cell electrode dimensions and spacing, the specific resistance, or resistivity of the sample can be calculated by:

\[ \rho = \frac{R \cdot a}{l \cdot \Omega m} \]

Where:
\[ \rho = \text{resistivity (}\Omega\cdot\text{m}) \]

\[ a = \text{electrode area (}\text{m}^2) \]

\[ I = \text{electrode spacing (m)} \]

### 2.6 Food Powders

The real breakthrough for the snack industry was the introduction of flavoured and ready salted crisps (Pannell 1980). Powder coating adds value to foods, especially snack foods, by adding flavor and variety (Ricks and others 2002).

#### 2.6.1 Food Powder Classification

Food powders can be classified by usage, major chemical component, process, size, moisture sorption pattern, or flowability. Powders are usually characterized at two levels, that of the individual particles and that of the powder in bulk (Peleg 1983). Most food particles have a similar solid density, the density of the solid material disregarding internal pores, of about 1.4-1.5 g/cm³ depending on the moisture content (Peleg 1983). Particle density is the ratio of the particle actual mass and the particle actual volume. Biehl and Barringer (2003) found that particle density was a significant factor in predicting nonelectrostatic transfer efficiency. Transfer efficiency increased with increasing particle density.

#### 2.6.2 Food Powder Dustiness

Mechanical attrition of food powders into dust usually occurs during handling or processing, when the particles are subject to impact and frictional forces (Peleg 1983).
Many materials used in the food industry such as flour, sugar, curry powder, cheese custard, and chocolate, when in the form of dust, can cause violent explosions if ignited accidentally (London 1975). Electrostatic effects and the humidity of the air can have an effect on the magnitude of the dustiness of powdered materials (Hjemsted and Schneider 1996). Elayedath and Barringer (2002) found an 80% dust reduction when electrostatics was used to coat anticaking agent on shredded cheese using a conveyor belt applicator and a 49% dust reduction when a tumble drum system was used. Particle size, shape, and the tendency to agglomerate are other factors that also affect the dustiness of a powdered material.

2.6.3 Maltodextrin

Maltodextrin is defined as any polysaccharide of glucose residues in β- (1,4) linkage. The FDA defines maltodextrins as products having a DE less than 20. Dextrose equivalence (DE) is a measure of reducing power compared to a dextrose standard of 100 with the higher DE having the greatest extent of starch depolymerization (Kuntz 1997). In appearance, maltodextrin is a white, odorless powder.

2.6.4 Maltodextrin Production

Maltodextrin is produced in the same method as regular corn syrup, however the starch conversion process is only carried out for a short period of time. The starch is cooked, and then acid and/or enzymes are used to break the starch into smaller polymers (Kuntz 1997). These smaller polymers are composed of several dextrose molecules held together by very weak hydrogen bonds. Partial hydrolysis allows the maltodextrin to maintain its basic polymeric structure.
2.6.5 Maltodextrin Uses

Maltodextrins have applications in the confectionary industry and beverage industry. In the confectionary industry, maltodextrins are used to increase flexibility, prevent granulation, lower sweetness, change taste, improve institutional framework, and prolong the storage life of sweets (Kuntz 1997). In the beverage industry, maltodextrins are used as a raw material to increase natural smell, reduce nutritional loss, and improve dissolubility (Kuntz 1997). Maltodextrins are superior flavor carriers and carbohydrate sources in instant beverage mixes, sports drinks, and soft drinks (Anon 2001). Maltodextrins have high viscosity and foam stability and are often used as foam stabilizers in beer.

2.6.6 Salt

Common salt or sodium chloride is considered by the FDA as GRAS or safe for its intended use. Salt serves many purposes. The Food and Chemicals Codex defines food-grade salt on the basis of its purity (Kuntz 1994).

2.6.7 Salt Manufacture

Most salt manufactured in the United States comes from underground deposits. The salt can be mined conventionally or removed by dissolving the salt with circulating water and collecting the brine (Kuntz 1994). This brine goes through a vacuum pan process, where it is clarified and purified before it is crystallized. This process results in a concentric or cubic form that is separated into various size grades using a screening process.
Another method to manufacture salt involves using the Alberger or grainer method. This method produces a unique, irregular crystal with stair-step sides, also described as a hollow quadrilateral pyramid (Kuntz 1994).

The dendritic process uses sodium ferrocyanide to alter the crystallization process. The result is a porous, star-shaped crystal (Kuntz 1994). Salt can also be pressed by smooth compacting rolls to make flake salt or grinded to a fine particle using grinding rolls to make what is termed flour salt.

2.6.8 Salt Uses

Using salt as a flavor enhancer is probably one of its most popular functions (Kuntz 1994). Sodium chloride (NaCl) is integral to the sensory profile design of salty snacks (Burg 1998). Besides contributing its own basic "salty" taste, salt brings out natural flavors and makes food more acceptable. Expert panels have reported that low levels of salt in solution also give a sensation of sweetness (Kuntz 1994).

Another of salt’s most valuable characteristics involves the control of microorganisms (Kuntz 1994). This results in two very useful functions: preservation of foods and control of the fermentation process. Salt protects food safety by retarding the growth of certain microorganisms. It preserves foods by creating a hostile environment for certain microorganisms. Within foods, salt brine dehydrates bacterial cells, alters osmotic pressure, and inhibits bacterial growth and subsequent spoilage (Anon 2005). In fermented foods such as pickles, meats, and dairy products, salt suppresses the growth of spoilage organisms and pathogens while allowing the lactic acid bacteria to produce acid (Kuntz 1994).
Salt gives proper texture to processed food. In bread dough it strengthens gluten, providing uniform grain, texture, and dough strength (Anon 2005). It also slows the gas production by the yeast, promoting a cell structure that creates an acceptable texture (Kuntz 1994). Salt provides the color, aroma, and appearance that consumers expect, and creates the gel necessary to process meats and sausages (Anon 2005). In most food applications—for flavoring, preservation and chemical reactions—salt must be in solution to function (Kuntz 1994).
CHAPTER 3

METHODS AND MATERIALS

Popcorn (Pop Weaver Gourmet Popcorn Sweet or Caramel Corn, Weaver Popcorn Co., Inc., VanBuren, IN) was popped in an automatic natural gas popper (Cretors Corp., Chicago, IL) at 95.6 °C and auger speed of 20 rpm. Eight food items with different resistivity values were used. These food items consisted of Whole Grain Wheat Crackers (Triscuits®, Nabisco, East Hanover, NJ), Saltine Crackers (Unsalted Tops, Walmart Stores Inc., Bentonville, AR), Oval Butter Crackers (Townhouse Crackers®, Keebler, Elmhurst, IL), Circular Butter Crackers (Ritz Crackers®, Nabisco, East Hanover, NJ), Fried Pork Rinds (Cona Potato Chip Company, Zanesville, OH), Rice Cakes (Hain Pure Foods Uniondale, NY), Wheat Crackers (Wheat Thins®, Nabisco, East Hanover, NJ), and Tortilla Chips (Kroger, Cincinnati, OH). Four different sizes of salt, three different sizes of maltodextrin, and one size of sucrose were used to coat the food items. The salts sizes used were Salt A (15.48 μm, Morton Extra Fine Salt, Morton Inc., Chicago, IL), Salt B (39.3 μm, Alberger Microsize® 66 Fine Salt, Cargill, Inc., Minneapolis, MN), Salt C (55.6 μm, Alberger Fine Flake, Cargill, Inc., Minneapolis, MN), and Salt D (103.4 μm, Premier Prepared Fine Flour, Cargill, Inc., Minneapolis, MN). The maltodextrin sizes used were Maltodextrin A (37.2 μm, Maltrin®
M520, Grain Processing Corporation, Muscatine, IA), Maltodextrin B (48.3 μm, Maltrin® M100, Grain Processing Corporation, Muscatine, IA), and Maltodextrin C (65.5 μm, Maltrin® M100, Grain Processing Corporation, Muscatine, IA). The sucrose size used was Sucrose A (25.39 μm, 10X powdered sugar, North Arkansas Wholesale, Bentonville, Ar). Maltrin® M100 is a spray dried, water-soluble glucose polymer with a DE less than 20, while Maltrin® M520 is a 10 DE, bland white carbohydrate product designed for use in low-moisture food systems and finely milled dry blends.

The popcorn and food items were coated using a tumble drum system (Master Series™ Tumble Drum, Spray Dynamics, Ltd., St. Clair, MO) equipped with electrostatic coating equipment (Enhancer Electrostatic Spice/Powder Application System Model 1500, Spray Dynamics, Ltd., St. Clair, MO). The food powder was continuously dispensed into the tumble drum using a dry ingredient hopper and auger (Uni-Spense® Spray Dynamics, Ltd., St. Clair, MO) and soybean oil (Gordon Food Service, Grand Rapids, MI) was dispensed using Spray Dynamics Liquid Applicator (Model Master Series 1, St. Clair, MO).

The initial popcorn flow rate was determined by running the popcorn hopper, conveyer belt, and tumble drum at speed 6 (12.25 rpm). Popcorn was continuously fed into the hopper and allowed to flow out until a steady state was achieved. The popcorn flow rate was determined by collecting the popcorn for 30 s in a previously tared container. The container was then weighed. The popcorn flow rate was calculated by multiplying the weight by two, which gave the flow rate in g/min. This process was repeated three times in order to obtain the average popcorn flow rate. The desired powder flow rate was based on a 7% powder application flow rate. To obtain the desired powder
flow rate, the initial average popcorn flow rate was multiplied by 7%. The actual powder flow rate was determined by allowing the ingredient hopper to run while leaving the holes of the distribution tube completely open. The powder was collected on a previously tared aluminum covered cardboard for 30 s, and then weighed. The powder flow rate obtained was multiplied by two in order to give the rate in g/min. This process was repeated three times in order to obtain an average powder flow rate. The flow rate obtained was accepted if it was ± 1.0 % of the desired powder flow rate range. The oil flow rate was determined by collecting oil in two previously tared containers for 30 s at an opening of 10 µm and a setting of 60 pulses/min. The oil flow rate obtained was multiplied by two in order to give the rate in g/min.

The popcorn and food items were coated at 0 kV and 25 kV. The popcorn and food items were coated at a relative humidity range of 30-36 % and a temperature range of 13.8-30 °C. The powder transfer efficiency was determined by weighing the food items before and after to determine how much coating was applied. The amount of oil deposited on the food items was determined by allowing the food items to run through the tumble drum while the ingredient hopper was turned off. The amount of oil deposited was calculated by subtracting the initial weight of the food items from the final weight. The amount of oil was subtracted from the total amount of coating to determine how much coating was actually deposited on the food items. The percent transfer efficiency was determined calculated by the following equation.

\[
% \text{ Transfer Efficiency} = \frac{\text{total weight of coating} - \text{amount of oil}}{\text{g powder/min}} \times 100
\]

(g popcorn/min)
The relative % transfer efficiency was obtained by dividing each individual transfer efficiency by the highest transfer efficiency obtained during the electrostatic or nonelectrostatic run. Six samples each from the electrostatic and non-electrostatic coating trials were collected for each of the nine food items in triplicate. The reproducibility between the samples was determined by calculating the relative standard deviation. The percent adhesion was determined by using a blower mounted on a ring stand. The food items were blown continuously at 13.72 m/s at 45 degrees for 30 s. Percent adhesion was determined using the following formula.

\[
\text{\% Adhesion} = 100 - \left( \frac{\text{amount powder loss after blowing}}{\text{amount powder gained during coating process}} \right) \times 100
\]

Powder particle size was determined by the polydisperse model using the Malvern Mastersizer (X standard bench, Worcesthershire, U.K.). The particle size measurement used was \( D(v, 0.5) \), which is called the mass medium diameter (MMD). It is the particle size in which 50% of the sample is smaller and 50% of the sample is larger. The resistivity of the food items was determined using a powder resistivity test cell (Electrostatics Solutions, Bassett, Southampton, Hampshire, U.K.) filled with 5 cm\(^3\) of ground food item. Voltage (172.2 V) was applied to the cell via a high voltage supply unit (ABC Regulated DC Supply, Kepco, General Electric Co., Flushing, NY). The actual amount of current exiting the test cell was measured using an electrometer (Model 614, Keithley Instruments, Inc., Cleveland, OH). The measurements were done in triplicate. The resistivity of the food items was calculated using the following equation: \( \rho = (KV)/I \), where \( \rho \) is resistivity, \( K \) is the cell constant which is equal to 0.014, \( V \) is the voltage applied to the test cell, and \( I \) is the current exiting the test cell.
Food surface oil content was determined by dipping 3 pieces of each individual food for 30 s in pre-weighed Petri dishes containing petroleum ether. The Petri dishes were weighed after all of the petroleum ether evaporated. Surface oil was determined as the difference between the final weight of the Petri dish and the initial weight of the Petri dish. Moisture content was determined by drying three pieces of each individual food sample in a vacuum oven (Model 281A, Fisher Scientific, Hampton, NH) at $9.1 \times 10^4$ Pa and 60°C for 24 h. The initial weight of the samples was subtracted from the final weight to determine how much moisture was present. Surface roughness was determined by scanning the surface of each food sample in ten different spots using a Profiometer (Veeco, Woodbury, NY). An average $R_z$ roughness value was obtained from the 10 data points. Correlations were determined by plotting the physical properties against transfer efficiency and adhesion.
CHAPTER 4

RESULTS AND DISCUSSION

To determine the influence of food physical properties on transfer efficiency and powder adhesion, four sizes of NaCl, three sizes of maltodextrin, and one size of sucrose was used to coat different food items electrostatically and nonelectrostatically. The food items had various moisture contents, surface oil contents, surface roughness values, and resistivity values. Composition effects have mainly been studied for metals, oxides, and plastics but not food so there is little literature that tells how food composition affects the adhesion and the transfer efficiency of food items coated electrostatically and nonelectrostatically.

4.1 Effect of Surface Oil Content on Transfer Efficiency and Adhesion

Ratanatriwong and others (2003) define transfer efficiency as the amount of powder deposited onto the target in a coating system divided by the amount of powder applied into the coating system. Transfer efficiency is important because it influences how much seasoning is coating the product. Seasonings are compounded to add color as well as taste to improve the consumer appeal of the finished product (Hanify 2001). Mittal (1977) defines adhesion as the sticking together of two similar or dissimilar materials. Particle adhesion results from forces that exist between particles and a solid
surface in contact (Podczeck 1998). Adhesion is important because it determines how much seasoning will actually stay on the product once it has been coated.

For both nonelectrostatic (Fig 4.1 and Fig 4.2) and electrostatic (Fig 4.3 and Fig 4.4) coating, all powders showed an overall increase in transfer efficiency with an increase in food surface oil content. The R^2 values ranged from 0.6489 to 0.9335 (Table 4.1). Oil serves as a tack agent for dry seasonings and is used to hold the flavoring onto the snack piece (Hanify 2001). Miller and Barringer (2002) found for all salts tested that there was an overall significant increase in coating efficiency of popcorn as percent oil increased. By increasing the oil content, a higher coating efficiency may be obtained. No correlation was established between nonelectrostatic (Fig 4.5) and electrostatic (Fig 4.6) adhesion and surface oil content, which was not expected because previous studies have found that adhesion increases with increasing oil content. Enggalhardjo and Narsimhan (2005) found that the adhesion force increased as the oil content of tortilla chips increased from 24% to 28%. A possible explanation for this is that the tumbling action of the coating drum rubbed most of the loose powder off during the coating process. In a tumble drum the food product is picked up by flights near the bottom of the drum and lifted as the drum rotates. Once the product reaches a critical height from the bottom, it begins to turn or roll down to the bottom of the drum where the lifting process begins again (Hanify 2001). It is this tumbling action that rubs the loose powder off the product.
<table>
<thead>
<tr>
<th>Powder</th>
<th>Electrostatic Transfer Efficiency</th>
<th>Nonelectrostatic Transfer Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl A</td>
<td>0.9133</td>
<td>0.9092</td>
</tr>
<tr>
<td>NaCl B</td>
<td>0.8101</td>
<td>0.7426</td>
</tr>
<tr>
<td>NaCl C</td>
<td>0.7262</td>
<td>0.7572</td>
</tr>
<tr>
<td>NaCl D</td>
<td>0.856</td>
<td>0.9335</td>
</tr>
<tr>
<td>Maltodextrin A</td>
<td>0.6509</td>
<td>0.6583</td>
</tr>
<tr>
<td>Maltodextrin B</td>
<td>0.7951</td>
<td>0.7631</td>
</tr>
<tr>
<td>Maltodextrin C</td>
<td>0.6489</td>
<td>0.7895</td>
</tr>
<tr>
<td>Sucrose A</td>
<td>0.7872</td>
<td>0.7850</td>
</tr>
</tbody>
</table>

Table 4.1: R square values of surface oil content and electrostatic and nonelectrostatic transfer efficiency
Figure 4.1: Effect of food surface oil content on nonelectrostatic transfer efficiency for carbohydrates

Figure 4.2: Effect of food surface oil content on the nonelectrostatic transfer efficiency for salts
Figure 4.3: Effect of food surface oil content on electrostatic transfer efficiency for carbohydrates

Figure 4.4: Effect of food surface oil content on electrostatic transfer efficiency for salts
Figure 4.5: Effect of food surface oil content on nonelectrostatic adhesion
Figure 4.6: Effect of food surface oil content on electrostatic adhesion

Zimon (1969) found that the presence of oil on the surface increases the adhesion of particles as a result of the corresponding tackiness. He determined that the mechanism of adhesion to an oily surface was influenced by the thickness of the oil layer. The thicker the oil layer, the more deeply the particles penetrate into the layer. Enggalhardjo and Narsimhan (2005) also found that adhesion force increased as oil content increased. The presence of free surface oil on the food items contributes to the surface tackiness, which also affects adhesion. Due to the presence of oil, the hardness of the surface is reduced so that charged powder adheres to the target more strongly (Price and others 2002). In contrast, Halim (2004) reported that the high resistivity of oil, which coats the surface of the product, minimizes the transfer of charges from the ground to the target, resulting in weaker Coulomb’s force.
4.2 Effect of Moisture Content on Transfer Efficiency and Adhesion

In order to decrease the scatter, the transfer efficiency graphs in this section were graphed by composition (carbohydrates and salts). For both nonelectrostatic (Fig 4.7 and Fig 4.8) and electrostatic (Fig 4.9 and Fig 4.10) coating, all powders displayed an overall decrease in transfer efficiency with increasing moisture content for all the food items coated with the exception of whole grain crackers. This is true because the higher the moisture content, the more conductive the target is. Therefore the target loses the electrostatic image charge faster therefore decreasing transfer efficiency. The electrostatic image charge is a charge of equal and opposite polarity that is induced in a target when in contact with charged powder particles (Guskov 1996). The electrostatic image charge is important because it attracts the charged powder particles and retains them on the surface of the target.

Lenaerts (1966) found that the generation of static charge in paper could be controlled by the introduction of moisture into the paper by pretreatment or by moistening of the paper rolls therefore increasing the conductivity of the paper. The same phenomenon can also occur in powders. Grosvenor and Staniforth (1996) stated that pre-storage of powders at elevated humidities, wetting the powder with a mist, or powder coating in a high humidity environment increases charge decay rates. At higher levels of relative humidity, it is more difficult to generate and sustain a charge (Vinson and Liou 1998). Radwan and others (1992) found that the higher the water content in oil, the lower the charging tendency of the oil. Bowling (1986) offered another perspective. He stated that when moisture is present on the surface of a target, the electrostatic image force is greatly reduced because the liquid shields the charge.
Figure 4.7: Effect of food moisture content on nonelectrostatic transfer efficiency for carbohydrates
Figure 4.8: Effect of food moisture content on nonelectrostatic transfer efficiency for salts

Figure 4.9 Effect of food moisture content on electrostatic transfer efficiency for carbohydrates
Fig 4.10 Effect of food moisture content on electrostatic transfer efficiency for salts

For both nonelectrostatic (Fig 4.11) and electrostatic (Fig 4.12) coating there was no discernable trend between moisture content and adhesion. However, other studies have found relationships between moisture and adhesion. Ranade (1987) found that adhesion could increase in a high humidity environment due to the formation of capillary condensation and the increase of capillary forces. Busnania and Elsayy (2001) found that adhesion increased in a low relative humidity (below 45%) due to the build-up and increase of electrostatic forces. Ibrahim and others (2002) also found that moisture could increase the adhesion force by softening the surface of the target and increasing the contact area between the powder particle and the target surface.
Figure 4.11: Effect of food moisture content on nonelectrostatic adhesion

Figure 4.12: Effect of food moisture content on electrostatic adhesion
4.3 Effect of Surface Roughness on Transfer Efficiency and Adhesion

Surface roughness is semi or completely random variation in the surface height. Surface roughness determines if powder will become physically trapped in pores. Surface roughness is calculated by using four common methods. Those methods include $R_a$ (average roughness), $R_q$ (root mean square), $R_z$ (ten-point average), and $R_t$ (R max). Although $R_a$ is the most common surface roughness parameter used in North America, it is not a good discriminator for different types of surfaces and cannot differentiate between peaks and valleys. Because foods with different surface roughness were used in this experiment, a parameter was needed that could distinguish between different surfaces. Therefore in this experiment $R_z$, the most common surface roughness parameter used in Europe, was used instead of $R_a$.

For non-electrostatic (Fig 4.13) and electrostatic (Fig 4.14) coating at low surface roughness the transfer efficiency values varied, but at high surface roughness the transfer efficiency values were high and fairly constant. The effect of surface roughness on van der Waals forces is highly dependent on the nature of the roughness (Ranade 1987). The surface roughness of the target affects the true contact area, which affects the strength of the van der Waals force (Cross, 1987).

For non-electrostatic (Fig 4.15) and electrostatic (Fig 4.16) coating there was no correlation between adhesion and surface roughness. Different studies have found conflicting results. Burg (1998) stated that porous surfaces have more surface area to attract and hold seasonings. Busnaina and Elsaway (2001) found that van der Waals forces increase due to particle and/or surface deformation that increases the particle contact area. By increasing the effective contact area, increased adhesion could result.
(Michalski and others 1997). Ibrahim and others (2002) found higher lactose particle adhesion with gelatin capsule surfaces exhibiting low surface heterogeneity and high-contrast friction.

However, a rough surface can also decrease adhesion. Zimon (1969) found that adhesion to microscopically rough surface was smaller than to a smooth or macroscopically rough surface. Halim (2004) found that smooth material increased the van der Waals forces and increased the percent adhesion of powdered sugar to the targets she was coating.

The size of the powder particles and surface pores can also have an effect on the adhesion force. If powder particles are bigger than the surface asperities, less mass is present in the immediate vicinity of the contact plane and adhesion force is reduced (Ranade 1987).
Figure 4.13: Effect of food surface roughness on nonelectrostatic transfer efficiency
Figure 4.14: Effect of food surface roughness on electrostatic transfer efficiency

Figure 4.15: Effect of food surface roughness on non-electrostatic adhesion
4.4 Effect of Target Resistivity on Transfer Efficiency and Adhesion

There have been few transfer efficiency studies conducted that have used food resistivity as the independent variable; however, studies have been performed using the resistivity of targets such as metal and plastic as well as the resistivity of different powders as independent variables. In this study no discernable trend was observed between food resistivity and nonelectrostatic (Fig 4.17) and electrostatic (Fig 4.18) transfer efficiency. When charged, good insulators such as plastic would repel charged particles depositing on the surface resulting in poor transfer efficiency coating (Bailey 1998). By using a low resistivity metal target, more powder would deposit on the target than the insulating plastic target (Bailey 1998).
Figure 4.17: Effect of food resistivity value on nonelectrostatic transfer efficiency

Figure 4.18: Effect of food resistivity value on electrostatic transfer efficiency
Previous studies have also been conducted using powder resistivity as the independent variable. In a corona system, the lowest resistivity possible is desired to achieve good transfer efficiency of charge to the particles (Hughes 1997). This is because the powder particles can easily pick up charge from the air if they have a low resistivity value. Bailey (1998) found that particles having low resistivity charge effectively in a corona discharge. Biehl and Barringer (2004) reported that the lower the resistivity of a powder, the higher the electrostatic transfer efficiency in a conveyor coating system. In glucose-lactose mixtures, lactose develops more charges during tribocharging than glucose due to lower resistivity of lactose (Murto, M. and Laine 2000). In electrocopying machines, the ink particles must be low resistivity to be charged and attracted to the paper substrate.

Artana and others (1999) found no relation between the ability of a powder to store charge and its resistivity, however, they did discover that the charge by flow electrification in a pneumatic conveyor increased with increasing resistivity. However, Bailey (1998) found that powders having high resistivity are insulating and have a charge relaxation time of minutes to hours so that charged particles are retained on the workpiece for sufficient time, therefore resulting in high adhesion.

No discernable trend was observed between resistivity and nonelectrostatic (Fig 4.19) and electrostatic (Fig 4.20) adhesion for all food items coated. However, previous studies have found relationships between resistivity and adhesion. Sims and others (2000) found greater electrostatic adhesion on low resistivity targets. The lower the target’s resistivity, the more readily charges flow from the ground. The surface substrate must be electrically conductive (low resistivity) to remove the induced charge
so further powder deposition is uninhibited (Grosvenor and Stainforth 1996). Halim (2004) found significant improvement in adhesion on low resistivity products such as aluminum foil, saltine crackers, and bread targets using electrostatics. High electrostatic and nonelectrostatic adhesion was observed for pork rinds and potato chips (Halim 2004), which both happen to be high resistivity products. Pork rinds and potato chips are high resistivity products due to the presence of oil. Oil increases the resistivity of the product. The high resistivity oil minimizes the transfer of charges from the target to the ground, therefore, maintaining the attraction between the powder and the target. Oil is also a tack agent, therefore it traps more powder to the surface of the target.

![Figure 4.19: Effect of food resistivity value on nonelectrostatic adhesion](image)

55
4.5 Transfer Efficiency vs Powder Type

Higher transfer efficiency was achieved for maltodextrin and sugar than salt for nonelectrostatic (Fig 4.21) and electrostatic (Fig 4.22) coating. This may be because salt is a more conductive powder than maltodextrin and sugar; therefore, it would lose charge more quickly when coming in contact with the grounded food resulting in lower transfer efficiency. Bailey (1998) stated that conducting particles do tend to charge more highly while passing through a corona zone, however, if the conductivity is too high the particles lose charge quickly upon contact with a grounded workpiece and so may detach from the surface. It can also be observed that greater electrostatic and nonelectrostatic transfer efficiency was obtained with the carbohydrates (maltodextrin and sugar) than the salts. A similar trend was also observed by Ricks and others (2002), who also found greater
Barringer (2005) who found greater nonelectrostatic and electrostatic efficiencies using maltodextrin and sugar than salt.

Figure 4.21: Transfer efficiency vs powder type for nonelectrostatic coating
Figure 4.22: Transfer efficiency vs powder type for electrostatic coating

4.6 Conclusion

Transfer efficiency increases with increasing food surface oil content for nonelectrostatic and electrostatic coating. The higher the surface oil content of the food being coated, the more efficient the coating will be. Food moisture content plays a role in the coating process. Transfer efficiency increases with lower food moisture content. High moisture makes the food target more conductive, resulting in the loss of the electrostatic image charge faster, therefore resulting in lower transfer efficiency. At high surface roughness, transfer efficiency of the food powders to the food targets was high and fairly constant but at low surface roughness the transfer efficiency values varied.
Resistivity had no influence on the transfer efficiency and adhesion of food products coated nonelectrostatically and electrostatically. Carbohydrates (maltodextrin and powdered sugar) were shown to produce higher transfer efficiency values than salt.
LIST OF REFERENCES

ADM. 2001. Maltodextrin [online]. Oregon: Oregon state University, Carbohydate
http://food.oregonstate.edu/ref/carbohydrate/malto_adm.html

Alexander A. 1980. Electrostatic principles applied to smoking technology. Food

81(12):14,17.


August 2005]. Available from World Wide Web:
http://www.saltworks.us/salt_info/si_SaltInFood.asp

Artana G, Torchard G, Putier F. 1999. Electrical characteristics and mechanical behavior
of powders of the animal feeding industry. J Electrostat 47:3-12.

Bailey AG. 1998. The science and technology of electrostatic powder spraying, transport

Banjeree S, Mazumder M. 1996. Adhesion of charged powders to metal surface in
powder coating process

Biehl HL, Barringer SA. 2003. Physical properties important to electrostatic and
nonelectrostatic powder transfer efficiency in a tumble drum. J Food Sci


Halim F. 2004. The importance of food powder characteristics and relative humidity to the electrostatic adhesion. MS Thesis. The Ohio State University. Columbus, Ohio.


APPENDIX A
<table>
<thead>
<tr>
<th>Food</th>
<th>Resistivity (Ω·m)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Grain Wheat Crackers</td>
<td>$6.26 \times 10^8$</td>
<td>$2.0 \times 10^7$</td>
</tr>
<tr>
<td>Wheat Crackers</td>
<td>$6.95 \times 10^8$</td>
<td>$3.0 \times 10^6$</td>
</tr>
<tr>
<td>Oval Butter Crackers</td>
<td>$7.13 \times 10^8$</td>
<td>$3.0 \times 10^6$</td>
</tr>
<tr>
<td>Saltine Crackers</td>
<td>$7.46 \times 10^8$</td>
<td>$9.0 \times 10^6$</td>
</tr>
<tr>
<td>Circular Butter Crackers</td>
<td>$8.09 \times 10^8$</td>
<td>$4.0 \times 10^6$</td>
</tr>
<tr>
<td>Tortilla Chips</td>
<td>$8.30 \times 10^8$</td>
<td>$4.0 \times 10^6$</td>
</tr>
<tr>
<td>Pork Rinds</td>
<td>$8.34 \times 10^8$</td>
<td>$2.0 \times 10^7$</td>
</tr>
<tr>
<td>Rice Cakes</td>
<td>$9.46 \times 10^8$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

Table A.1: Resistivity Values of Food Items

<table>
<thead>
<tr>
<th>Food Items</th>
<th>Moisture Content (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice Cakes</td>
<td>0.058</td>
</tr>
<tr>
<td>Pork Rinds</td>
<td>0.059</td>
</tr>
<tr>
<td>Tortilla Chips</td>
<td>0.0653</td>
</tr>
<tr>
<td>Wheat Crackers</td>
<td>0.0819</td>
</tr>
<tr>
<td>Circular Butter Crackers</td>
<td>0.1133</td>
</tr>
<tr>
<td>Oval Butter Crackers</td>
<td>0.1165</td>
</tr>
<tr>
<td>Saltine Crackers</td>
<td>0.1418</td>
</tr>
<tr>
<td>Whole Grain Wheat Crackers</td>
<td>0.2419</td>
</tr>
</tbody>
</table>

Table A.2: Moisture Content of Food Items
<table>
<thead>
<tr>
<th>Food</th>
<th>Surface Oil (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saltine Crackers</td>
<td>0.0037</td>
</tr>
<tr>
<td>Circular Butter Crackers</td>
<td>0.0080</td>
</tr>
<tr>
<td>Wheat Crackers</td>
<td>0.0100</td>
</tr>
<tr>
<td>Oval Butter Crackers</td>
<td>0.0127</td>
</tr>
<tr>
<td>Tortilla Chips</td>
<td>0.0154</td>
</tr>
<tr>
<td>Whole Grain Wheat Crackers</td>
<td>0.0384</td>
</tr>
<tr>
<td>Rice Cakes</td>
<td>0.0497</td>
</tr>
<tr>
<td>Pork Rinds</td>
<td>0.0714</td>
</tr>
</tbody>
</table>

**Table A.3: Surface Oil Content of Food Items**

<table>
<thead>
<tr>
<th>Food</th>
<th>Surface Roughness (Rz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oval Butter Crackers</td>
<td>15.71</td>
</tr>
<tr>
<td>Saltine Crackers</td>
<td>15.71</td>
</tr>
<tr>
<td>Circular Butter Crackers</td>
<td>16.32</td>
</tr>
<tr>
<td>Wheat Crackers</td>
<td>17.06</td>
</tr>
<tr>
<td>Whole Grain Wheat Crackers</td>
<td>17.63</td>
</tr>
<tr>
<td>Pork Rinds</td>
<td>19.47</td>
</tr>
<tr>
<td>Tortilla Chips</td>
<td>21.13</td>
</tr>
<tr>
<td>Rice Cakes</td>
<td>25.61</td>
</tr>
</tbody>
</table>

**Table A.4: Surface Roughness of Food Items**
<table>
<thead>
<tr>
<th>Powder Name</th>
<th>Particle Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maltodextrin A</td>
<td>37.2</td>
</tr>
<tr>
<td>Maltodextrin B</td>
<td>48.3</td>
</tr>
<tr>
<td>Maltodextrin C</td>
<td>65.5</td>
</tr>
<tr>
<td>NaCl A</td>
<td>15.5</td>
</tr>
<tr>
<td>NaCl B</td>
<td>39.3</td>
</tr>
<tr>
<td>NaCl C</td>
<td>55.6</td>
</tr>
<tr>
<td>NaCl D</td>
<td>103.4</td>
</tr>
<tr>
<td>Sucrose A</td>
<td>25.4</td>
</tr>
</tbody>
</table>

Table A.5: Particle Sizes of Powders Utilized