Powder Coatings for Antimicrobial Applications

GORDON
ARCHITECTURAL+ENGINEERED SOLUTIONS

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Introduction

We live in an extremely complex world full of many dangers. Contemporaneous with the writing of this paper, the world is currently dealing with one of those dangers; a microscopic, pathogenic virus known as CoVid-19. Since late 2019, a pandemic has reached nearly every inhabited area on the planet involving a novel corona virus for which we have virtually no immunity. This event, which is notably the most significant health crisis in about 100 years, has forced a series of changes in our lives, many of which may become permanent, in attempt to better protect ourselves and our habitats from pathogenic microbes. This paper will attempt to reinvigorate some existing technology that has been around for many years and can serve to assist in the mission of protection from microbial organisms with whom we share this planet. Let's begin by giving an overview of what constitutes a microbe.

A microbe is typically [but not always] a single-celled organism and can originate from a number of classifications. These include bacteria, fungi, viruses, protozoa, and chromista, and any of these can cause health issues in humans. However, the vast majority of microbes actually are harmless to people and, in fact, are actually necessary and beneficial to keep balance in our ecosystem. This balance is specifically why the use of antimicrobial products is sometimes necessary. For example, *Pseudomonas aeruginosa*, a common bacterium that exists in soil, water, and skin flora, can become critically infectious for certain places in the body such as the cornea if the eye is severely scratched or in the lungs of cystic fibrosis patients.

Understanding the delicate balance in nature, as is relates to microbes, is extremely important. Many microbes can serve us well in keeping our ecosystem running smoothly, but there are certain microbes that pose a threat to our health and well-being. The setting of exposure, obviously, has a place in the conversation. For example, a person undergoing a bone marrow transplant cannot afford to be exposed to any foreign invader as their immune system is completely compromised. The environment in which they receive treatment must be immaculately clean.

Depending on the nature of the setting, the compound used for cleaning is chosen. While disinfectants do a great job of cleaning, there is little residual effect realized. Antimicrobial powder-coated surfaces offer residual protection between disinfection cleanings. These coatings have been around for more than twenty years in their current form and definitely have a valuable role in hygienic maintenance.

Gordon Inc. is a major manufacturer of architectural metal for a number of market segments, one of which being Ceiling Systems, Wall Systems, Lighting, and Air Filtration Systems for Healthcare Facilities, High Traffic Public Areas, and Cleanroom Environments. For more than two decades these components have been powder coated and, in their deployment, require regular cleaning with disinfectants, sporicides, or sanitizers depending on the environment that is to be maintained. An available antimicrobial finish is offered as an option for these components and is specially formulated to withstand the rigors of frequent maintenance.

This paper will explain the use of antimicrobial coatings, as well as, their functionality, efficacy, testing methods, and regulatory limitations on performance claims. The information, when applicable, will be cited to its source. Testing data presented in this paper will be credited to the entity overseeing that work and is intended to be used for the demonstration of efficacy of the active ingredient [in the coating] against the microorganism(s) being tested. This paper, however, does not intend to make any health claims, statements regarding the elimination of specific microorganisms or the like, or to use any language that falls outside of compliance with 40 CFR 152.25(a). This regulation prohibits making health claims that extend beyond the coated article itself with regard to antimicrobial properties. It also prohibits making statements that could be construed as public health statements through implicit or explicit language.

This paper, however, will show empirical data as to the performance of the coating with regard to antimicrobial efficacy, as well as, discussing the relevant use of antimicrobial, powder coated articles, their cleaning maintenance, and expected performance. It is the reader's prerogative to assess the benefit of the coated article's performance as an integral part of a larger environment. Obviously, every application has a set of situational variables that must be considered. This paper will attempt to provide as much useful information as is currently known and remove the mystique often associated with this subject matter.

What Does Antimicrobial Actually Mean?

Antimicrobial is made up of the word anti, against or opposite, and microbial, that which is related to a microorganism. Antimicrobial, in its current form, is quite general and can pertain to many methods of opposing microorganisms. Antimicrobial use has been common practice for at least 2000 years. Ancient Egyptians and Greeks used specific molds and plant extracts to treat infection, as well as, realizing the antimicrobial properties of certain metals in which they stored food and drink. We will briefly cover some of these in detail later in the paper.

In the 19th century, microbiologists such as Louis Pasteur and Jules Francois Joubert observed antagonism between some bacteria and discussed the merits of controlling these interactions in medicine. Louis Pasteur's work in fermentation and spontaneous generation led to the distinction between anaerobic and aerobic bacteria. The information garnered by Pasteur led Joseph Lister to incorporate antiseptic methods, such as sterilizing surgical tools and debriding wounds into surgical procedures. The implementation of these antiseptic techniques drastically reduced the number of infections and subsequent deaths associated with surgical procedures. [1]

Antimicrobial, as a classification, is a very broad-based collection of compounds which can include antibacterial, antifungal, antiviral, etc. In addition, there are antiseptics, biocides, virucides, sporicides, sanitizers, etc.; all of which ultimately either kill, or inhibit the proliferation of a target group of microorganisms. The nomenclature of the compound typically indicates the target group of microbes and the action that is executed by the compound. For example, a virucide is any physical or chemical agent that deactivates or destroys viruses.[2][3] This differs from an antiviral drug, which inhibits the proliferation of the virus.

Antibacterials are among the most commonly used drugs and among the drugs commonly misused by physicians, for example, in viral respiratory tract infections. As a consequence of widespread and injudicious use of antibacterials, there has been an accelerated emergence of antibiotic-resistant pathogens, resulting in a serious threat to global public health. The resistance problem demands that a renewed effort be made to seek antibacterial agents effective against pathogenic bacteria resistant to current antibacterials. Possible strategies towards this objective include increased sampling from diverse environments and application of metagenomics to identify bioactive compounds produced by currently unknown and uncultured microorganisms as well as the development of small-molecule libraries customized for bacterial targets.[4]

Antifungals are used to kill or prevent further growth of fungi. In medicine, they are used as a treatment for infections such as athlete's foot, ringworm, and thrush and work by exploiting differences between mammalian and fungal cells. Unlike bacteria, both fungi and humans are eukaryotes. Thus, fungal and human cells are similar at the molecular level, making it more difficult to find a target for an antifungal drug to attack that does not also exist in the host organism.

Antimicrobial pesticides include compounds used for controlling microbes on surfaces and compounds that are integrated into materials for the same purpose. For example, antimicrobial compounds that are incorporated into coatings or plastics would fall into this category; as well as, products that are used for specific cleaning of surfaces for the preservation of public health. According to the U.S. Environmental Protection Agency (EPA), and defined by the Federal Insecticide, Fungicide, and Rodenticide Act, antimicrobial pesticides are used in order to control growth of microbes through disinfection, sanitation, or reduction of development and to protect inanimate objects, industrial processes or systems, surfaces, water, or other chemical substances from contamination, fouling, or deterioration caused by bacteria, viruses, fungi, protozoa, algae, or slime.

The EPA monitors products, such as disinfectants/sanitizers for use in hospitals or homes, in order to ascertain efficacy.[5] Products that are meant for public health are therefore under this monitoring system, including products used for drinking water, swimming pools, food sanitation, and other environmental surfaces. These pesticide products are registered under the premise that, when used properly, they do not demonstrate unreasonable side effects to humans or the environment. Even once certain products are on the market, the EPA continues to monitor and evaluate them to make sure they maintain efficacy in protecting public health.

Public health products regulated by the EPA are intended to control microorganisms infectious to humans in any inanimate environment. The more commonly used public health antimicrobial products include the following: [5]

- Sterilizers (Sporicides): Eliminate all bacteria, fungi, spores, and viruses.
- Disinfectants: Destroy or inactivate microorganisms (bacteria, fungi, viruses,) but may not act as sporicides (as those are the most difficult form to destroy). According to efficacy data, the EPA will classify a disinfectant as limited, general/broad spectrum, or as a hospital disinfectant.
- Sanitizers: Reduce the number of microorganisms, but may not kill or eliminate all of them.

Non-public-health products regulated by the EPA are used to control growth of microorganisms of economic and aesthetic significance and are not considered to be human health related: [5]

- algae,
- odor-causing bacteria,
- bacteria which cause spoilage, deterioration or fouling of materials and microorganisms infectious only to animals. This general category includes products used in:
    - cooling towers
    - jet fuel
    - paints
    - treatments for textile and paper products.

Regardless of the compound, antimicrobials are a permanent staple of daily life for humans to aid in the maintenance of our health and respective habitats. As the world continues to change and new microbial threats emerge, the construct and deployment of these substances will also change. In many cases, a microbe may evolve such that the effectiveness of a viable antimicrobial compound could be diminished or completely upended. In the next sections we will explore some of the mechanisms of these compounds and how their potency is likely to be preserved despite mutagenic changes that microorganisms naturally undergo.

What is an Antimicrobial Powder Coating and What Makes It Work?

An antimicrobial powder coating contains a compound that is integrally combined, through the extrusion process, or alternatively, thermo-bonding process. The compound can be either organic or inorganic in nature with the function of preventing the growth or proliferation of a type of microorganism. These powder coatings are typically thermosetting, meaning they are chemically crosslinked in the presence of heat to form a continuous, infusible coating film. They are relatively conventional powder coatings in all respects with the exception of an integrated, specially engineered compound that performs the function of resisting microbes.

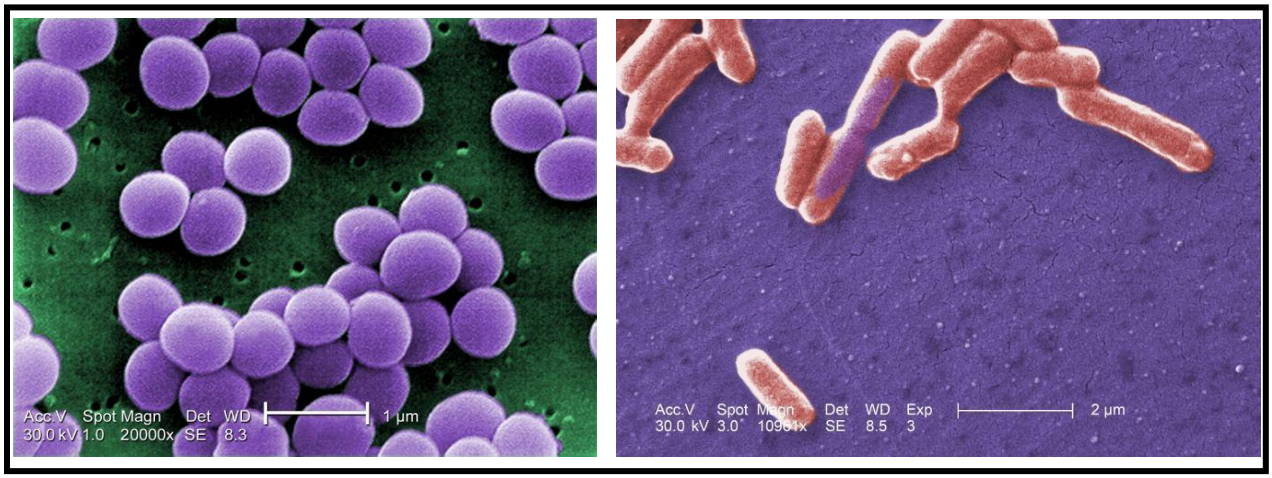


Figure 1. Microscopic photo of *Staphylococcus aureus* (left) and *Escherichia coli* (right)

The active ingredient, as mentioned above, can be either organic or inorganic. Simply put, organic antimicrobials act on very specific organisms similar to the way antibiotics do. While organic antimicrobials can be quite effective on target microbes, they can lose their efficacy due to the microbe developing resistance to the compound. This is evolution at work; adaptation and natural selection perpetuating mutations so that the microbe can survive the changing environment. This was observed not so long ago with the MRSA (Methicillin-resistance *Staphylococcus aureus*) bacteria that had become resistant to beta-lactam antibiotics. This strain of staph is responsible for many difficult-to-treat infections, of which humans are susceptible. [6]

Inorganic antimicrobials that are based on metal ions have a much larger array of microbes on which they are effective. Unlike their organic-based alternatives, microorganisms do not develop resistance to metal-ion based antimicrobials. For the purposes of this paper, we will focus on this type, as this is technology employed by Gordon, Inc. on its powder coated articles.

Inorganic antimicrobials which utilize metal ions are the most commonly utilized compounds for residual effect in many applications such as textiles, plastics, and coatings. This is due to their controlled release of ions which is prompted by moisture which lends itself to mobility and exchange with other ions.

The anatomy of the inorganic compound is generally composed of two main parts: the carrier particle and the metal cation. There are several choices of each of these components. With regard to the metal ions there are typically three elements that are employed: copper, zinc, or silver.

The antimicrobial mechanisms of copper have been studied for decades and are still under investigation. Researchers today believe that the most important mechanisms include the following:

- Elevated copper levels inside a cell causes oxidative stress and the generation of hydrogen peroxide. Under these conditions, copper participates in the so-called Fenton-type reaction — a chemical reaction causing oxidative damage to cells.
- Excess copper causes a decline in the membrane integrity of microbes, leading to leakage of specific essential cell nutrients, such as potassium and glutamate. This leads to desiccation and subsequent cell death.
- While copper is needed for many protein functions, in an excess situation (as on a copper alloy surface), copper binds to proteins that do not require copper for their function. This "inappropriate" binding leads to loss-of-function of the protein, and/or breakdown of the protein into nonfunctional portions.

Zinc (Zn), as an antimicrobial, has been in use for approximately ninety years, even though its functionality was not fully understood until about ten years ago. Zinc oxide, being one of the most common forms of supplying Zn (II) ions has been used as a topical medication for bacterial infections for folliculitis as well as ingested in many cold remedies to keep respiratory illness at bay. It is also used in combination with other compounds to treat coatings for residual antimicrobial effect.

The last common metal ion for antimicrobial properties is silver, which is the metal ion that is present in Gordon Inc.’s powder coatings. In the next section, we’ll discuss silver and its antimicrobial properties in detail, but it is important to focus on the other main component of these compounds which it the carrier particle.

For metal ions to work efficiently, they need a carrier particle to elicit the controlled release of them in the powder coating film. Since these ions do not have motility, per se, they have to be released when the conditions are ideal for the proliferation of microbes, typically in moist (or humid) environments. Over the last twenty-five years, there have been dozens of inorganic antimicrobial products introduced into the market. The most common variables of these [pertaining to powder coatings], however, are the type of carrier particle, the loading amount, and the method of incorporation.

The carrier particle is the second most important factor in the make-up of an inorganic antimicrobial compound. This particle has to be easily incorporated into the powder coating, it cannot detract from any of the powder coating’s other performance properties, and it must efficiently release the silver ions as needed to achieve maximum efficacy. The current state of the art for this application is glass. There have been several companies that have worked with specially formulated glass compounds that are doped with silver. Glass allows the silver to be introduced to the powder coating formulation through extrusion, which

yields the most homogenous mixture and each and every particle of powder coating contains silver ions to offer cross-sectional distribution in the coating film.

Other carriers that have been incorporated in this application are kaolin clays, which impart an objectionable color effect on the powder as well as not being extrudable. Cubic zirconium has been effectively used, and while having no negative effect on color, efficacy of this particle decreases substantially when, during manufacture, the powder coating goes through the milling process. Zeolites are also used in some commercially available compounds, but glass carriers have generated the best results in antimicrobial efficacy and applied cost. Gordon, Inc. has been using these coatings for twenty years and has been active in the research and development activities associated with this technology.

How do Silver Antimicrobial Compounds Work?

The antimicrobial properties of silver have been known to cultures all around the world for many centuries. The Phoenicians stored water and other liquids in silver coated bottles to discourage contamination by microbes. The Egyptians used bowls and containers made of silver to store fruits and other foods to prevent them from prematurely spoiling. Silver dollars used to be put into milk bottles to keep milk fresh, and water tanks of ships and airplanes that are "silvered" are able to render water potable for months. In 1884 it became a common practice to administer drops of aqueous silver nitrate to newborn's eyes to prevent the transmission of *Neisseria gonorrhoeae* from infected mothers to children during childbirth. [7]

In 1893, the antibacterial effectiveness of various metals was noted, and this property was named the oligodynamic effect. Silver became commonly used in medical treatments, such as those of wounded soldiers in World War I, to deter microbial growth.[8] It was later found that out of all the metals with antimicrobial properties, silver has the most effective antibacterial action and the least toxicity to animal cells.[9]

Once antibiotics were discovered, the use of silver as a bactericidal agent decreased. However, with the discovery of antibiotics came the emergence of antibiotic-resistant strains such as CA-MRSA and HA-MRSA, the flesh-eating bacteria. Due to increasing antibiotic resistance, there has recently been a renewed interest in using silver as an antibacterial agent. The availability of new laboratory technologies such as radioactive isotopes and electron microscopy has greatly enabled us to investigate the antibacterial mechanism of silver in recent years.

Silver is widely distributed in the earth's crust and is found in soil, fresh and sea water, and the air. It is readily absorbed into the human body with food and drink and through inhalation, but the low levels of silver commonly present in the bloodstream (< 2.3 µg/L) and in key tissues like liver and kidney have not been associated with any disease or disability. Silver is not an acknowledged trace element in the human body and fulfills no physiological or biochemical role in any tissue even though it interacts with several essential elements including zinc and calcium. Physiologically, it exists as an ion in the body.

Silver has a long history in the treatment of human diseases, including epilepsy, neonatal eye disease, venereal diseases, and wound infections. It has been employed in water purification and is currently used to safeguard hospital hot water systems against Legionella infections. Principle routes of human exposure to silver nowadays are through its widespread use as an antimicrobial agent in wound care products and medical devices, including in-dwelling catheters, bone cements, cardiac valves and prostheses, orthopedic pins, and dental devices. In each case, the antimicrobial properties of silver (see Figure 2) are dependent upon release of biologically active silver ion (Ag^+) from metallic silver (including nanocrystalline forms), silver nitrate, silver sulfadiazine, and other silver compounds incorporated in the various devices, and its lethal effect on pathogenic organisms.

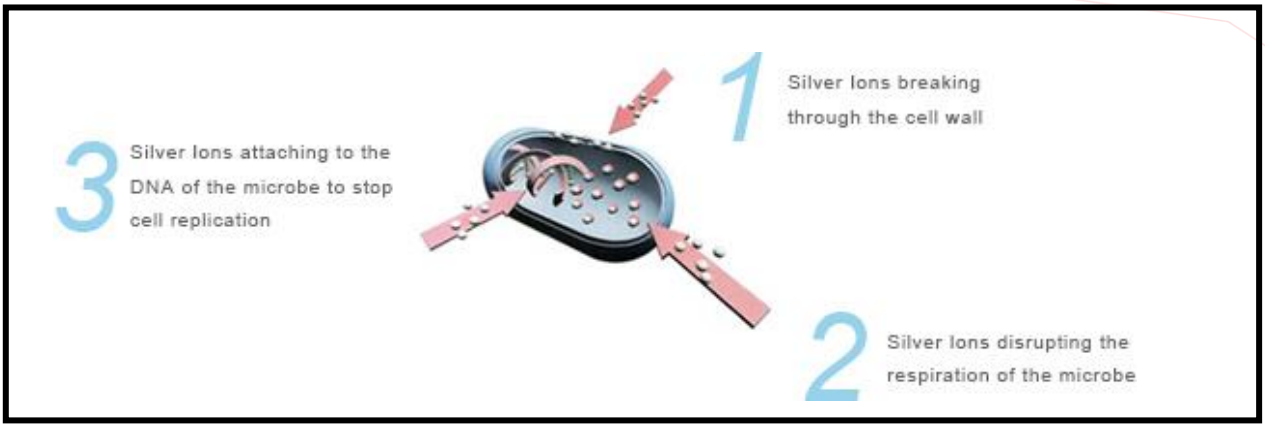


Figure 2. Diagram illustrating different functionalities of silver ion efficacy upon microbe.

Experience has shown that a large proportion of the silver ions released from medical devices not required for antimicrobial action is disseminated into tissue fluids and exudates, where it combines with albumins and macroglobulin. These silver-protein complexes are absorbed into the systemic circulation to be deposited in key soft tissues, including the skin, liver, kidney, spleen, lungs, and brain. Unlike the well-documented neurotoxic metals including lead and mercury, silver does not appear to be a cumulative poison and is eliminated from the body through the urine and feces. Excretion of silver by these routes may be a measure of mean daily intake, but since this view is based largely on the clinical use of silver nitrate and silver sulfadiazine used in burn wound therapy, its true relevance in the metabolism of silver used in the wider context of medical devices is questionable.

Argyria is the most widely publicized clinical condition associated with silver accumulation in blood and soft tissues. It commonly occurs in individuals exposed to high levels of silver occupationally (metallurgy, photography, and mining industries), or consuming or inhaling silver hygiene products (including colloidal silver products) for long periods. Silver is absorbed into the body and deposited in the perivascular regions of the skin and other soft tissues as black granules of silver sulfide or silver selenide. The resulting slate grey discoloration of the skin occasionally associated with melanogenic changes, is semi-permanent and cosmetically undesirable but is not known to be life-threatening.[10]

Although the antimicrobial properties of silver have been known for centuries, we have only recently begun to understand the mechanisms by which silver inhibits bacterial growth. One of the ways that antimicrobial silver can inhibit bacteria is through protein inactivation. It is thought that silver atoms bind to thiol groups (-SH) in enzymes and subsequently cause the deactivation of enzymes. Silver forms stable S-Ag bonds with thiol-containing compounds in the cell membrane that are involved in transmembrane energy generation and ion transport. (see Figure 3) [12]

It is also believed that silver can take part in catalytic oxidation reactions that result in the formation of disulfide bonds (R-S-S-R). Silver does this by catalyzing the reaction between oxygen molecules in the cell and hydrogen atoms of thiol groups: water is released as a product and two thiol groups become covalently bonded to one another through a disulfide bond.[13] The silver-catalyzed formation of disulfide bonds could possibly change the shape of cellular enzymes and subsequently affect their function.

The silver-catalyzed formation of disulfide bonds can lead to changes in protein structure and the inactivation of key enzymes, such as those needed for cellular respiration.[13] It is hypothesized that silver

ions bind to the 30S ribosomal subunit, deactivating the ribosome complex and preventing translation of proteins.[16] The proteins that were found to be down-regulated upon treatment with Ag^+ serve important functions to the cell: succinyl-coenzyme A synthetase, an enzyme involved in the TCA cycle, catalyzes the conversion of succinyl-CoA to succinate while phosphorylating ADP to produce ATP;[14] fructose bisphosphate aldolase is an enzyme involved in glycolysis that catalyzes the breakdown of fructose-1,6-bisphosphate into glyceraldehyde 3-phosphate and dihydroxyacetone phosphate;[14]; MalK is a cytoplasmic membrane-associated protein involved in the transport of maltose.[15] In one way or another, all of these proteins play a role in energy and ATP production for the cell, so the decreased expression of any one of these proteins could lead to cell death.[16]

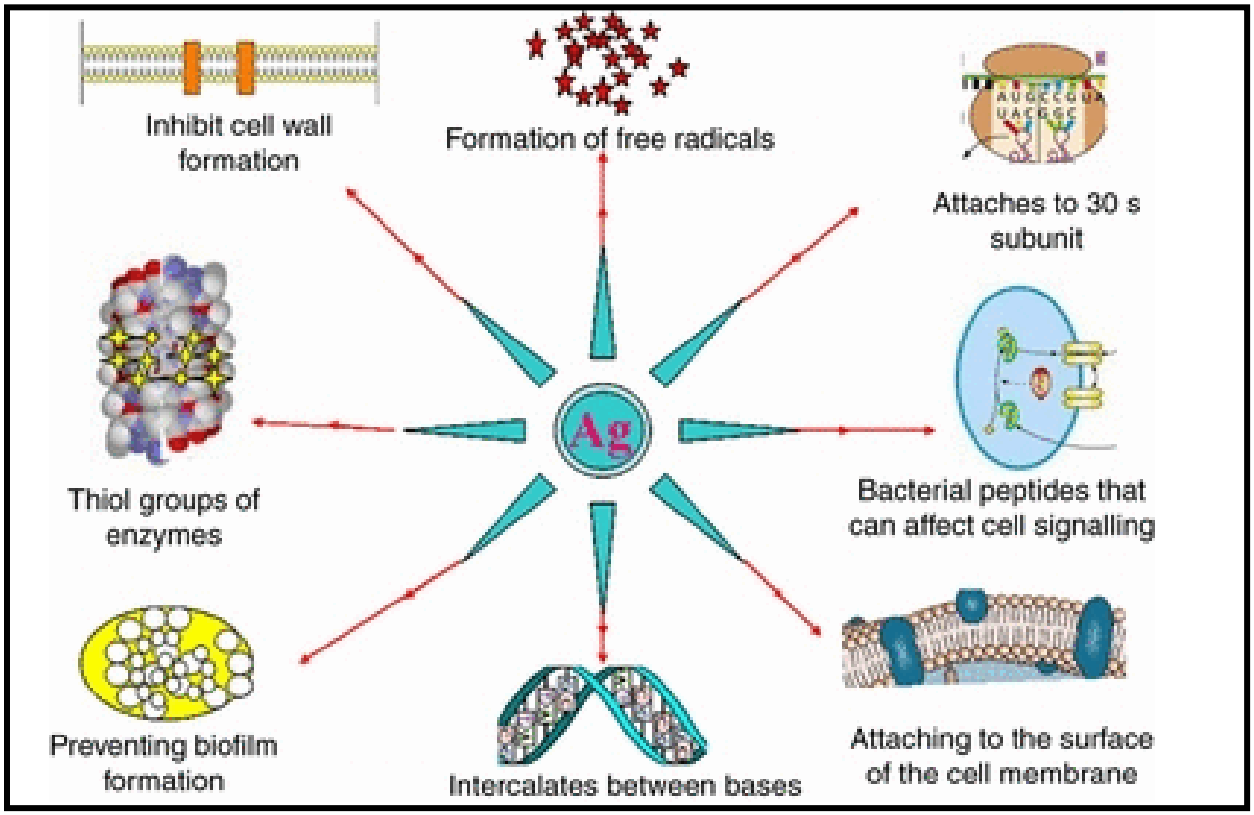


Figure 3. Silver nanoparticles showing multiple bactericidal actions.

DNA association is one of the theoretical mechanisms of the antimicrobial activity of silver in that Ag^+ enters the cell and intercalates between the purine and pyrimidine base pairs disrupting the hydrogen bonding between the two anti-parallel strands and denaturing the DNA molecule.[12] Although this has yet to be proved, it has been shown that silver ions do associate with DNA once they enter the cell.[17]

Most of the proposed mechanisms involve silver entering the cell in order to cause damage. How would a metal like silver, or its ionized form Ag^+, get across the hydrophobic cellular membrane to access the cytoplasm? From the perspective of a transmembrane protein, the silver ion simply appears to be a particle of certain size with a +1 charge. It is possible that silver ions get access to the interior of cells through transmembrane proteins that normally function to transport ions other than silver ions. Transmembrane proteins such as CopB-ATPase from *Enterococcus hirae* have been shown to be able to transport silver ions although its putative function is a copper transporter.[18] This proves that there are

ways for silver to be transported across the cell membrane even though specific silver transporters may not exist.

In order for silver to have any antimicrobial properties, it must be in its ionized form. Silver in its non-ionized form is inert,[19] but contact with moisture leads to the release of silver ions.[20] Thus, all forms of silver or silver containing compounds with observed antimicrobial properties are in one way or another sources of silver ions (Ag^+); these silver ions may be incorporated into the substance and released slowly with time as with silver sulfadiazine, or the silver ions can come from ionizing the surface of a solid piece of silver as with silver nanoparticles.

Feng *et al.* (2000) conducted a study to observe the effects of silver ions on gram-positive and gram-negative bacteria, namely *Staphylococcus aureus* and *Escherichia coli*.[11,21] They treated cells with silver nitrate, $AgNO_3$, which is a source of Ag^+ in aqueous environments, and looked at the structural and morphological effects of these silver ions on the cells. The cells were exposed to $AgNO_3$ for 4-12 hours before being prepared for microscopy. The cell was then fixed and sliced with an ultramicrotome to produce ultrathin sections for transmission electron microscopy (TEM). They observed that cells exposed to the Ag^+ ions seemed to have activated a stress response that led to the condensation of DNA in the center of the cell. They also observed cell membrane detachment from the cell wall, cell wall damage, and electron dense granules outside and, in some instances, inside the cell. It was proposed that condensation of DNA occurred as a protective measure in order to protect the genetic information of the cell, [21] however condensation of DNA could also prevent cell replication by preventing the DNA from being accessed by transcriptional enzymes such as DNA polymerase. The electron dense granules that formed inside and outside the cell were extracted and subjected to X-ray microanalysis to determine their composition. It was discovered that the granules were in part composed of silver and sulfur. This finding supports the idea that silver inactivates proteins by binding to sulfur-containing compounds. [12] It was also observed that when treated with Ag^+, *E. coli*, a gram-negative bacterium, sustained more structural damages than the gram-positive *S. aureus*.[21]

It is important to note that the efficacy of silver ions is delegated to both gram-positive and gram-negative bacteria. Gram-positive do show slightly more resiliency to silver's effect by virtue of their numbers, even though the efficacy is excellent. There are two explanations as to why gram-positive bacteria are less susceptible to Ag^+ than gram-negative bacteria. The first involves the charge of peptidoglycan molecules in the bacterial cell wall. Gram-positive bacteria have more peptidoglycan than gram-negative bacteria because of their thicker cell walls, and because peptidoglycan is negatively charged and silver ions are positively charged, more silver may get trapped by peptidoglycan in gram-positive bacteria than in gram-negative bacteria.[22] The decreased susceptibility of gram-positive bacteria can also simply be explained by the fact that the cell wall of gram-positive bacteria is thicker than that of gram-negative bacteria.

It has also been shown that treating cells with silver leads to cell shrinkage and dehydration.[19] The images (Figure 4) show that cells that sustained extensive damage eventually ended up with cell wall and cell membrane damage. Damage to the cell membrane could lead to the leaking of cytoplasm from the cell, which would result in dehydrated and shrunken cells as shown by the SEM images. Because of the way silver works on metabolic activity and its ability to breach the cell wall, microbes are not likely to become immune to these effects the way that they do with organic antimicrobials or antibiotics.

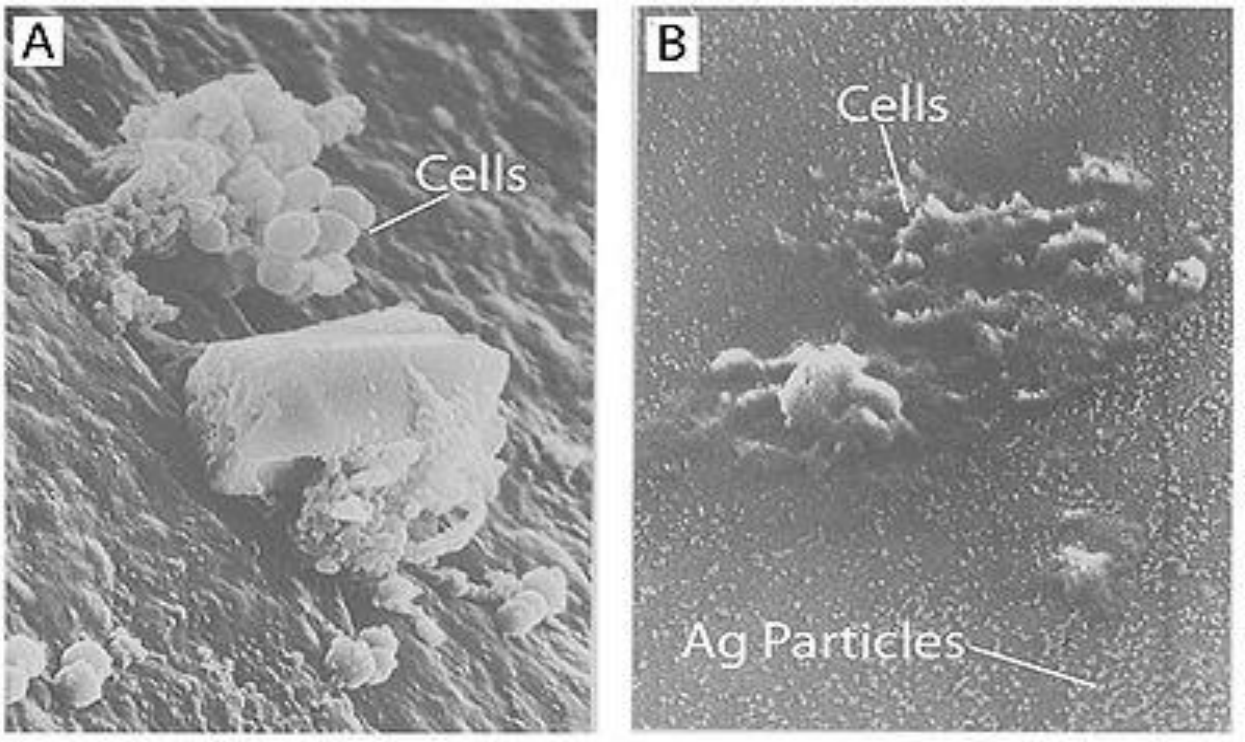


Figure 4. Treatment with silver leads to dehydration of microbial cells. A) *Staphylococcus aureus* without silver treatment as found on a catheter. B) *Staphylococcus aureus* on a silver-containing material with micro dispersed silver particles throughout the matrix. Both images were captured using scanning electron microscopy. Notice the shrunken appearance of the cells.

The constant, metered delivery of silver ions is obviously important. With regard to antimicrobial powder coated surfaces, this release happens conditionally, based on the amount of moisture present. Moisture, which is necessary for the proliferation of bacteria and mold, facilitates the tempo of release because it creates an ion exchange, commonly with nitrogen and/or sulfur, thus supplying the surface sufficiently with silver. This surface will continue to have antimicrobial efficacy between cleanings with disinfectant. Each cleaning reveals new supplies of silver ion which are exposed as the coating is wiped down. Therefore, the coating has effective antimicrobial properties as long as the coating is present.

Why are Antimicrobial Surfaces Important?

An antimicrobial surface contains an antimicrobial agent that inhibits the ability of microorganisms to grow on the surface of a material. Such surfaces are becoming more widely investigated for possible use in various settings including clinics, industry, and even the home. Antimicrobial surfaces are functionalized in a variety of different processes. A coating may be applied to a surface that has a chemical compound, such as glass containing silver ions, which is toxic to many microorganisms. The most common and most important use of antimicrobial coatings has been in the healthcare setting for sterilization of medical devices to prevent hospital associated infections, which have accounted for almost 100,000 deaths in the United States.[6] Gordon, Inc. offers this important property via powder coating for any of its architectural metal components.

There are a number of products on the market that have antimicrobial properties engineered into their part or system. For example, there are manufacturers of jetted tubs that utilize silver ion compounds in the plastic plumbing components to prevent mold from forming between uses. There is also a great number of Kitchen products that utilize this property. While each of these products contributes to a cleaner environment, the antimicrobial property is isolated to the treated component. For this reason, all-encompassing health claims cannot be made.

It is important to point out that many of the compounds discussed in this paper only have efficacy against some viruses. As we are currently enduring an ongoing pandemic which involves the novel coronavirus, this is a fact worthy of mention. This is not to say that antimicrobials as discussed in this context are without utility. In fact, these materials can have a positive effect at the local level where viruses are prevalent. It is known that as the human body fights off a virus, particularly one of which it has no immunity, the body and immune system become overworked and can lose some of the ability to fight certain microorganisms that it normally resists.

Hospitalizations as a result of the pandemic have skyrocketed which creates a need for exceptionally microbe-free environments. A coronavirus patient would have an exceptionally hard time fighting a staph infection while trying to recover from the virus. In fact, some viruses actually use bacteria as a vehicle for replication. The goal here is to provide the most sterile environment possible for the healthcare facility. This concept can be expanded to public places where people accumulate in mass, such as, restaurants, hotels, public washrooms, casinos, locker rooms, schools, offices, convention centers, etc.

The use of antimicrobial compounds in coatings, or any other medium for that matter, will not prevent disease from occurring. This can also be said for the use of bleach or any other disinfectant that is used for the purpose of cleaning. The reasonable goal here is to reduce the number of microbes from the surface which could lead to a reduction of infections as a result of contacting said surface.

The architectural metal components that are made by Gordon, Inc., are used in a variety of applications. Many of these applications can certainly benefit from antimicrobial properties. Ceiling and Wall Systems, for instance, that are used in either Healthcare Facilities, High-traffic Public Areas, or in Cleanroom

Environments can offer antimicrobial protection over a high percentage of the room's surfaces which can contribute to a healthier environment. It is important to note that antimicrobial surfaces must be cleaned as frequently as dictated by the use of the environment. These surfaces are not a replacement for cleaning but offer efficacious antimicrobial performance between cleanings.

It is often asked, when this subject matter is presented, "How long does the antimicrobial property last, and how is it verified?" This is a natural question once an understanding is formed of how these compounds work. Logically, there *are* a finite number of silver ions that can be deployed and for each cell that is dealt with, a few hundred ions are consumed. There is research that indicates that even dying bacteria absorbs silver ions and once they are dead, the silver ions cause the dead bacteria to become lethal to nearby bacteria, in effect, poisoning the environment. Think of it as a "zombie" bacterium.

Based on the prescribed loading of silver ions in a powder coating, the actual number of ions available for microbial efficacy can be calculated. Based on these calculations, it is estimated that there are 37,450,000 silver ions per cubic micron of coating. This same volume would be filled by a only three staphylococcus cells! This is precisely why silver ion containing materials have such great residual efficacy and are gaining in popularity in many other applications.

There are more than thirty-five companies that are manufacturing antimicrobial compounds with this functionality. With the great importance placed on these compounds for performance, it is imperative that sound testing be carried out, and that different conditions are tested to verify the performance. In the next section we will discuss different test methods and some test results from a couple of laboratories that have done analysis on various materials, including powder coatings.

How are Antimicrobial Powder Coatings Tested?

Antimicrobial testing must be carried out in an accredited microbiology laboratory. One of the preferred test methods for assessing antimicrobial efficacy is JIS Z 2801/ISO 22196.[23] Figure 5 shows the steps associated with this test method. This test uses a gram-positive strain of bacteria, *Staphylococcus aureus,* and a gram-negative strain, *Escherichia coli*. Using the two particular types can allow the results to be extrapolated across all bacteria, based on the cell wall composition and the functionality of the silver ion and its activity.

The preparation of the test is very important to preserve the integrity of the results. Sterilization immediately before the inoculation step is critical to ensure precise microbe counts by preventing contamination. A well-equipped, sterile environment is mandatory to properly execute this type of work. This is one of the many reasons why it is necessary to have an accredited microbiology laboratory perform this type of testing.

Accredited laboratories are also needed because the bacteria used for this testing are very infectious and are not available to coating laboratories. Special handling is necessary when infectious microbes are being tested as well as sterilization equipment to prevent contamination of test specimens or infection of technicians.

Another test method that is recognized is ASTM E 2180-01, Standard Test Method for Determining the Activity of Incorporated Antimicrobial Agent(s) In Polymeric or Hydrophobic Materials. This test method has more scope whereby not only the antimicrobial efficacy determined, but also the shelf-life of the antimicrobial compound. Later in this section, there will be published test results that utilized this test method.

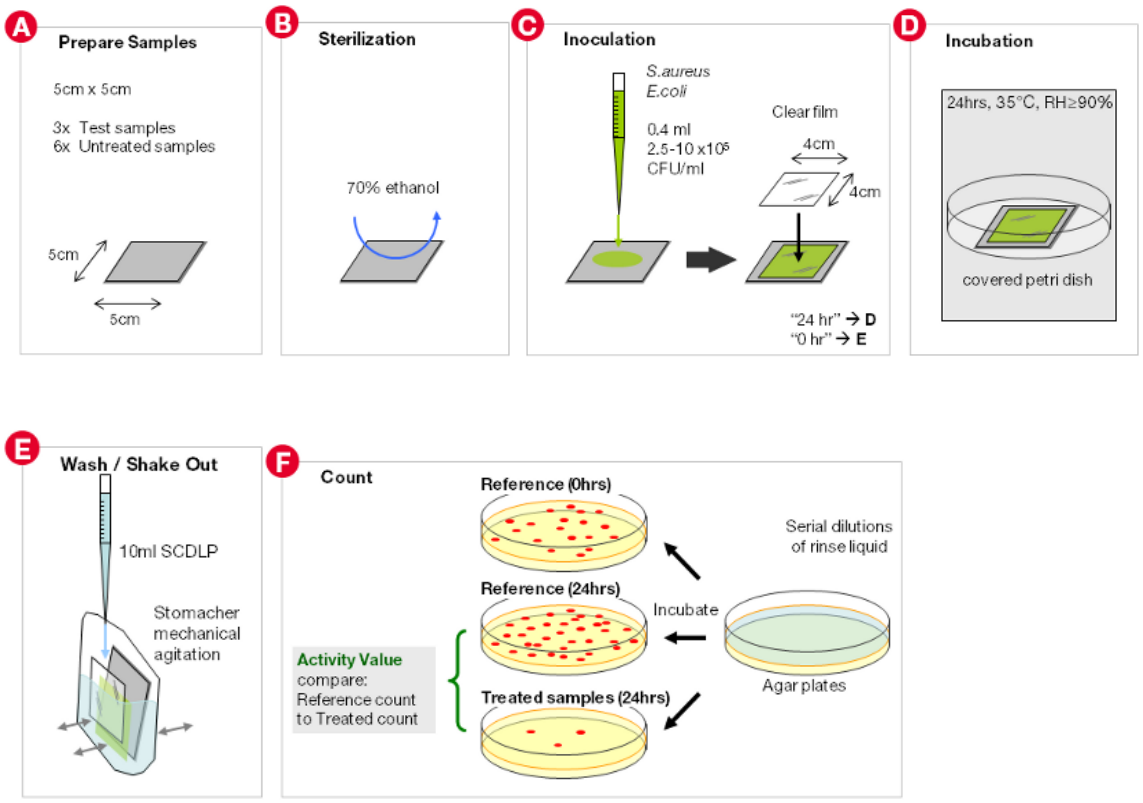
Regardless of the test method used, it is crucial that a control sample be run for each iteration of coating that is tested. The reason for this is to ascertain if any other component in the coating [other than the silver ion compound] is contributing to the antimicrobial efficacy. Test results are always stated in terms of percent reduction. Some bacteria and mold can be reduced by 99.9999%, which is only the survival of 1 cell per million. This is remarkably effective!

The testing of coatings, especially powder coatings, is typically executed using the same techniques that are use for plastics. This is a favorable scenario due to the fact that plastics, and moreover, antimicrobial plastics, are such a dominant segment of the economy compared to powder coatings. This creates more than adequate testing capacity, and hopefully, will create a standard for antimicrobial efficacy that can be applied uniformly to all products.

JIS Z 2801/ISO 22196

Measurement of Antibacterial Activity on Plastics Surfaces (Plastics) [23]

This is an internationally recognized test method for evaluating the antibacterial activity of treated plastic materials (and other non-porous surfaces of products) to inhibit or kill the growth of test microorganisms.



Standardized test organism is inoculated onto the surface of test material. The standard specifies an incubation period of 24 hours, but other time periods can be accommodated. Surviving microorganisms are counted to evaluate the antimicrobial activity of the test material.

Counts are determined before and after incubation. Using a formula provided in the standard, the log of the difference between the 2 counts is determined to give a measurement of antimicrobial activity. [23]

Organisms used in this method: *Staphylococcus aureus* and *Escherichia coli*

Figure 5. Chart showing the steps involved with test method JIS Z 2801/ISO 22196. (courtesy of Microbe Investigations Switzerland)

The table on the following page (Figure 6) shows results of an antimicrobial substance known as Ionpure, which is a specially structured glass particle that contains silver ions. The results displayed in the table show the visual effect of the reduction of each bacterium tested in the respective petri dish. It also shows how loading percentage has an effect on the reduction of bacteria in the test. (Note: Ionpure is a silver ion compound that is glass-based, manufactured by Ishizuka of Japan)

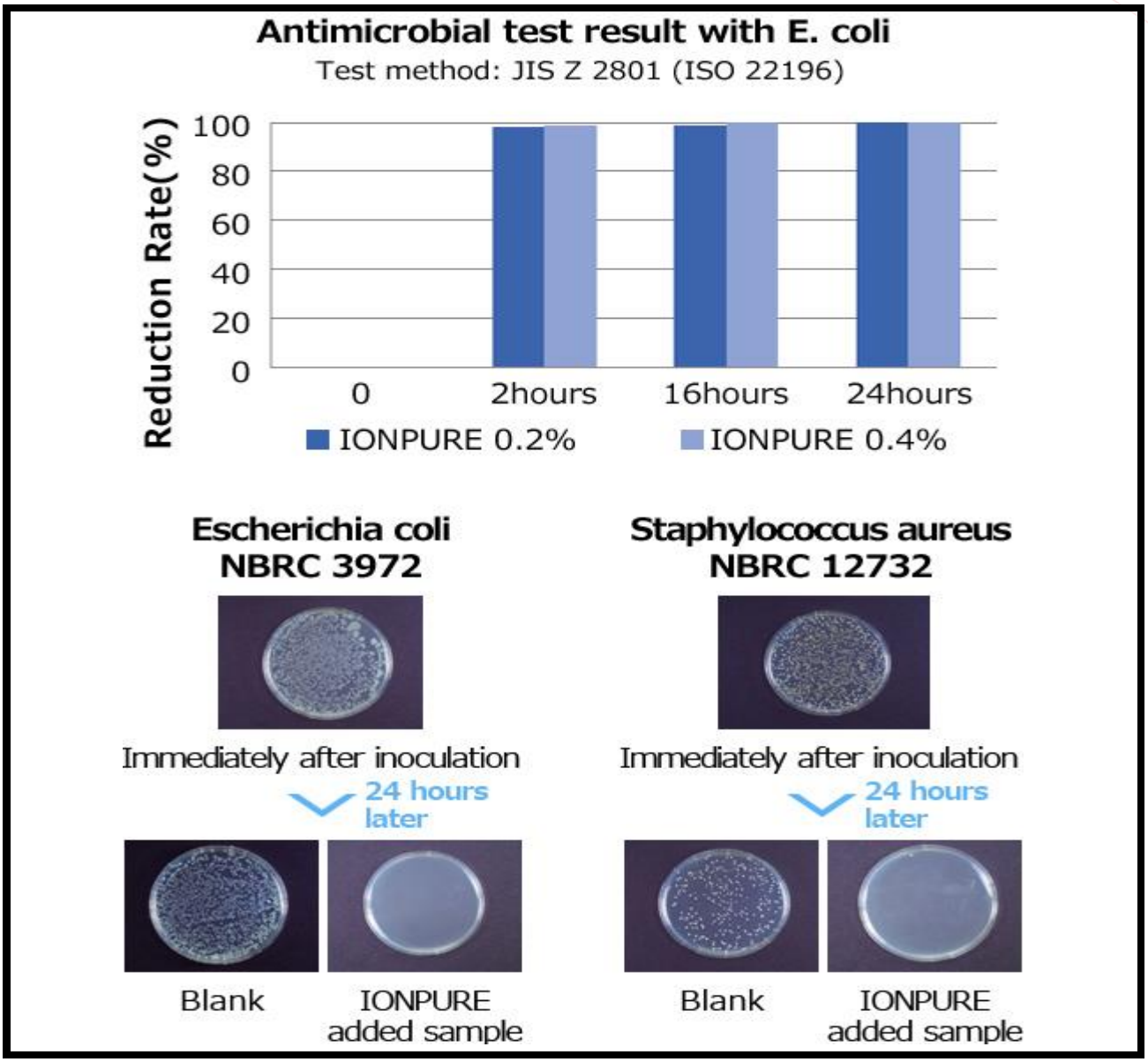


Figure 6. Table and chart showing results of a thermoplastic film utilizing Test method JIS Z 2801/ISO22196. (Courtesy of Ishizuka, Japan)

On the following page (Figure 7) shows a table that shows antimicrobial efficacy of powder coated samples as tested against three different species of bacteria. The table shows cell reduction after 2 hours, 8 hours, and 24 hours.

Sample	Start 0 Hour	After 2 hours	After 8 Hours	After 24 hours
Untreated Powder Coating (control) (*Escherichia coli*)	130,000	220,000	1,300,000	2,800,000
Antimicrobial-containing Powder Coating (*Escherichia coli*)	130,000	85,000 34.61% reduction	170 99.87% reduction	< 20 > 99.99% reduction
Untreated Powder Coating (control) (*Staphylococcus aureus*)	150,000	200,000	290,000	450,000
Antimicrobial-containing Powder Coating (*Staphylococcus aureus*)	150,000	63,000 58.00% reduction	62,000 58.67% reduction	< 20 > 99.99% reduction
Untreated Powder Coating (control) (*Pseudomonas aeruginosa*)	4,700,000	5,000,000	26,000,000	65,000,000
Antimicrobial-containing Powder Coating (*Pseudomonas aeruginosa*)	4,700,000	840,000 82.13% reduction	< 20 > 99.99% reduction	< 20 > 99.99% reduction

Figure 7. Table showing results utilizing Test method ASTM E 2180-01. (Courtesy of Biosan Laboratories, Inc.)

It is also relevant to display the efficacy of silver ion compounds on different types of fibers. This application has been a strong market for athletic wear for a number of years. Antimicrobial fibers for textiles and specialty materials have a function in one of the products that Gordon, Inc. produces. Sound fleece is a textile product that is used in acoustical products such as ceiling planks, wall sections, and sound baffles. In conjunction with an antimicrobial coating, the antimicrobial sound fleece would offer one hundred percent antimicrobial protection of the assembly.

Figure 8 on the following page shows the efficacy data of polypropylene and polyethylene terephthalate fibers. The results are shown to reflect durability after 50 wash cycles compared to an unwashed sample. There is also a control sample that does not have the silver ion antimicrobial compound added. The washed samples have the same reduction in bacteria as does the unwashed sample which is a testament to the “toughness” of the compound. The release of silver ions is very controlled and remains limited to the bacteria-rich environment of which it is designed.

It is important to note that the release of the silver ions is not triggered by moisture alone. If that were the case, then the washed fibers would have zero efficacy, especially after 50 wash cycles. The release of silver ions will only occur when there is an ion exchange available, such as in a microbe rich environment, or an opportunity for the silver to bond to a protein, which is necessary for metabolic function in microbes. If the silver ion binds to the protein, the cell will not be able to survive.

Polypropylene Fiber treated with Ionpure.

Sample	Number of Cells		Reduction Rate (%)
	Beginning	18 Hours Later	
Control	3×10^4	1×10^7	--
PP Fiber with Ionpure (non-washed)	3×10^4	$<2\times10^2$	>99.33%
PP Fiber with Ionpure (50 wash cycles)	3×10^4	$<2\times10^2$	>99.33%

Polypropylene Fiber treated with Ionpure.

Sample	Number of Cells		Reduction Rate (%)
	Beginning	18 Hours Later	
Control	3×10^4	2×10^7	--
PET Fiber with Ionpure (non-washed)	3×10^4	$<2\times10^2$	>99.33%
PET Fiber with Ionpure (50 wash cycles)	3×10^4	4×10^2	>98.66%

Figure 8. Table and chart showing results of a different fiber compositions in the presence of *Escherichia coli* utilizing Test method JIS Z 2801/ISO22196. This test shows the durability of the compound relative to efficacy.

As the aforementioned testing results show, the efficacy of the silver ion compounds is excellent. Depending on the microbe, the shape of the curve can vary, but typically the variance after 16-24 hours is minimal. Even with the overwhelming evidence of how well these compounds work, there are many limitations on what claims can be made. The next section will explain how the EPA regulates these compounds and show some of the inequities between types of antimicrobial products. It is important for parties at every tier of the supply chain to understand how the regulations work and what claims are allowed to be made relative to the subject product.

Regulation of Claims Associated with Antimicrobials

The Environmental Protection Agency (EPA) has jurisdiction over all pesticides, more specifically, antimicrobial pesticides. The constituent ingredient that provides antimicrobial efficacy is typically registered. This registration enables the initial product and any subsequent use of that product in or on another product the ability to be called antimicrobial. The stipulation is that the antimicrobial protection claimed cannot extend beyond the article itself. In other words, no public health claim can be expressed as a consequence of the antimicrobial article. For example, a room with four walls coated with an antimicrobial powder coating cannot be claimed, either implicitly or explicitly, that it creates a safe environment whereby a person could not be infected by a pathogen.

There are many more restrictions on public health claims that are enforced by the EPA; to display a few:

1. A claim for control of specific microorganisms or classes of microorganisms that are directly/indirectly pathogenic to man (or both man and animals)
2. A claim of “antibacterial,” “bactericidal,” or “germicidal” activity or references in any context to activity against germs or human pathogenic organisms implying public health related protection is made.
3. A claim for the product as a fungicide against fungi infections or fungi pathogenic to man, or the product does not clearly indicate it is intended for use against non-public health fungi.
4. A claim to control the spread of allergens through the inhibition or removal of microorganisms such as mold or mildew.
5. A non-specific claim that the product will beneficially impact or affect public health by pesticidal means at the site of use or in the environment in which applied.
6. An unqualified claim of “antimicrobial” activity.

There are some allowances for claims such as:

- Antibacterial
- Bactericidal
- Germicidal
- Kills pathogenic bacteria
- Effective against E. coli and Staphylococcus
- Reduces the risk of food-borne illness from bacteria
- Provides a germ-resistant surface
- Provides a bacteria-resistant surface
- Surface kills common gram positive and negative bacteria
- Surface controls both gram positive and negative bacteria
- Surface minimizes the growth of both gram positive and negative bacteria
- Reduces risk of cross-contamination from bacteria
- Controls allergy causing microorganisms
- Improves indoor air quality through the reduction of microorganisms

This group of claims can be exercised, if and only if, the treated article is registered as a pesticide product.

The agency, however, has made some progressive allowances for copper and copper alloys. The EPA found that copper alloys kill more than 99.9% of disease-causing bacteria within just two hours when cleaned regularly. Copper and copper alloys are unique classes of solid materials as no other solid touch surfaces have permission in the U.S. to make human health claims (EPA public health registrations were previously restricted only to liquid and gaseous products). The EPA has granted antimicrobial registration status to 355 different copper alloy compositions.

Interestingly, cleaning products can use strong language such as kills, eliminates, etc. in conjunction with their products. Even more interesting, most of these products have zero residual activity and must be used repeatedly to keep surfaces free of microbes. Even though antimicrobial powder coated surfaces have shown in laboratory testing to deactivate (kill) bacteria, mold and fungi, it is illegal to make those claims without registering as a pesticidal product.

In the context of antimicrobial powder coated articles, the number of registrations would most likely be numerous and impractical to register in aggregate. Thus, it has been a long-standing position in the industry to use tempered language with regard to claims and let the science and test results do the talking.

Glossary of Terms

ADP – Adenosine diphosphate, also known as adenosine pyrophosphate (APP), is an important organic compound in metabolism and is essential to the flow of energy in living cells. ADP consists of three important structural components: a sugar backbone attached to adenine and two phosphate groups bonded to the 5-carbon atom of ribose. The diphosphate group of ADP is attached to the 5' carbon of the sugar backbone, while the adenosine attaches to the 1' carbon.

ATP – Adenosine triphosphate is an organic compound that provides energy to drive many processes in living cells, e.g. muscle contraction, nerve impulse propagation, and chemical synthesis. Found in all known forms of life, ATP is often referred to as the "molecular unit of currency" of intracellular energy transfer. When consumed in metabolic processes, it converts either to adenosine diphosphate (ADP) or to adenosine monophosphate (AMP). Other processes regenerate ATP so that the human body recycles its own body weight equivalent in ATP each day. It is also a precursor to DNA and RNA, and is used as a coenzyme.

Bacteria – Typically a few microns in length, bacteria have a number of shapes, ranging from spheres to rods and spirals. Bacteria were among the first life forms to appear on Earth, and are present in most of its habitats. Bacteria inhabit soil, water, acidic hot springs, radioactive waste,[4] and the deep biosphere of the earth's crust. Bacteria also live in symbiotic and parasitic relationships with plants and animals.

Cell wall – A cell wall is a structural layer surrounding some types of cells, just outside the cell membrane. It can be tough, flexible, and sometimes rigid. It provides the cell with both structural support and protection, and also acts as a filtering mechanism. Cell walls are present in most prokaryotes, in algae, fungi and eukaryotes including plants but are absent in animals. A major function is to act as pressure vessels, preventing over-expansion of the cell when water enters. The composition of cell walls varies between species and may depend on cell type and developmental stage. Algae possess cell walls made of glycoproteins and polysaccharides such as carrageenan and agar that are absent from land plants. In bacteria, the cell wall is composed of peptidoglycan. Fungi possess cell walls made of the N-acetylglucosamine polymer chitin.

Chromista – A biological kingdom consisting of some single-celled and multicellular eukaryotic organisms, which share similar features in their photosynthetic organelles (plastids). It includes all protists such as some algae, diatoms, oomycetes, and protozoans whose plastids contain chlorophyll *c*.

Cytoplasm – In cell biology, the cytoplasm is all of the material within a cell, enclosed by the cell membrane, except for the cell nucleus. The main components of the cytoplasm are cytosol – a gel-like substance, the organelles – the cell's internal sub-structures, and various cytoplasmic inclusions. The cytoplasm is about 80% water and usually colorless.

Efficacy – Refers to the "effectiveness" or ability of an antimicrobial compound to achieve maximum response in therapeutic effect or beneficial change in a clinical environment.

Enzyme – Proteins that act as biological catalysts (biocatalysts). Catalysts accelerate chemical reactions. The molecules upon which enzymes may act are called substrates, and the enzyme converts the substrates into different molecules known as products. Almost all metabolic processes in the cell need enzyme catalysis in order to occur at rates fast enough to sustain life. Enzymes typically utilize the suffix *-ase* in their nomenclature.

Eukaryotes – Organisms whose cells have a nucleus enclosed within membranes, unlike prokaryotes (Bacteria), which have no membrane-bound organelles. Eukaryotic cells typically contain other membrane-bound organelles such as mitochondria. Unlike bacteria, eukaryotes may also be multicellular and include organisms consisting of many cell types forming different kinds of tissue. Animals and plants are the most familiar eukaryotes.

Extrusion – Used in the manufacture of powder coatings, as well as many types of plastics, foods, pharmaceuticals, etc. An extruder is a complex machine that homogenously mixes multiple constituent components by imparting shear forces in the presence of heat sufficient to convert solid compounds into a liquid paste as a continuous process. Solid materials enter a feed port, travel laterally through a series of heated zones while being mixed by rotary screws, and ultimately exiting the machine (typically) in the form of a molten paste.

Gram-positive (Gram-negative) – Gram staining differentiates bacteria by the chemical and physical properties of their cell walls. Gram-positive cells have a thick layer of peptidoglycan in the cell wall that retains the primary stain, crystal violet. Gram-negative cells have a thinner peptidoglycan layer that allows the crystal violet to wash out on addition of ethanol. They are stained pink or red by the counterstain, commonly safranin or fuchsine.

Ion – An atom or molecule that has a net electrical charge. Since the charge of the electron (considered negative by convention) is equal and opposite to that of the proton (considered positive by convention), the net charge of an ion is non-zero due to its total number of electrons being unequal to its total number of protons. A cation is a positively charged ion (silver for example), with fewer electrons than protons, while an anion is negatively charged, with more electrons than protons. Because of their opposite electric charges, cations and anions attract each other and readily form ionic compounds.

Milling – The final process of manufacturing powder coating. Once extruded material is cooled into thin, brittle sheets, it can be kibbled into small chips which are subsequently pulverized in an air-classifying mill to a predetermined particle size. The success of this process depends greatly on the material's friability. Many antimicrobial compounds cannot withstand this process which requires different methods of incorporation.

Motility – The ability of an organism to move independently, using metabolic energy.

Oxidative phosphorylation – The metabolic pathway in which cells use enzymes to oxidize nutrients, thereby releasing the chemical energy of molecular oxygen, which is used to produce ATP. During oxidative phosphorylation, electrons are transferred from electron donors to electron acceptors such as

oxygen in redox reactions. These redox reactions release the energy stored in the relatively weak double bond of O_2, which is used to form ATP.

Peptidoglycan – Polymer consisting of sugars and amino acids that forms a mesh-like layer outside the plasma membrane of most bacteria, forming the cell wall. Peptidoglycan serves a structural role in the bacterial cell wall, giving structural strength, as well as counteracting the osmotic pressure of the cytoplasm. Peptidoglycan is also involved in binary fission during bacterial cell reproduction. Peptidoglycan forms around 90% of the dry weight of gram-positive bacteria but only 10% of gram-negative strains.

Prokaryotes – A unicellular organism that lacks a membrane-bound nucleus, mitochondria, or any other membrane-bound organelle Prokaryotes are asexual, reproducing without fusion of gametes. The first organisms are thought to have been prokaryotes.

Protein – Large biomolecules, or macromolecules, consisting of one or more long chains of amino acid residues. Proteins perform a vast array of functions within organisms, including catalyzing metabolic reactions, DNA replication, responding to stimuli, providing structure to cells, and organisms, and transporting molecules from one location to another. Proteins differ from one another primarily in their sequence of amino acids. Proteins are essential parts of organisms and participate in virtually every process within cells.

TCA cycle – Short for tricarboxylic acid cycle; also known as the citric acid cycle (CAC) or the Krebs cycle – is a series of chemical reactions used by all aerobic organisms to release stored energy through the oxidation of acetyl-CoA derived from carbohydrates, fats, and proteins, into adenosine triphosphate (ATP) and carbon dioxide. In eukaryotic cells, the citric acid cycle occurs in the matrix of the mitochondrion. In prokaryotic cells, such as bacteria, which lack mitochondria, the citric acid cycle reaction sequence is performed in the cytosol with the proton gradient for ATP production being across the cell's surface (plasma membrane) rather than the inner membrane of the mitochondrion.

Transcriptional enzyme – The first of several steps of DNA based gene expression in which a particular segment of DNA is copied into RNA (especially mRNA) by the enzyme RNA polymerase.

Virus – A submicroscopic infectious agent that replicates only inside the living cells of an organism. Viruses can infect all types of life forms, from animals and plants to microorganisms, including bacteria. Viruses are found in almost every ecosystem on Earth and are the most numerous types of biological entity.

Zeolite – Microporous, aluminosilicate minerals commonly used as commercial adsorbents and catalysts. They are used in inorganic antimicrobial compounds as a carrier for metal ions.

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