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Improving the Quality of the Indoor Environment Utilizing Desiccant-Assisted Heating, Ventilating, and Air Conditioning Systems

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1. Introduction

Throughout history, diverse cultures and societies have appreciated the importance of a clean and healthy environment (Bardana, Montanaro et al. 1988). In western societies today, most people spend over 90% of their time indoors (Teichman 1995; EPA 2003). Reports involving buildings with indoor air-related problems have appeared increasingly in the medical and scientific literature, although this problem has been with humans for centuries. Sick building syndrome (SBS), a common term for symptoms that result from individuals' exposure to poor IAQ (IAQ), was first recognized as an important problem that affects occupants in certain buildings in 1982. The first official study of SBS to examine more than one structure was published in 1984 (Finningan, Pickering et al. 1984). SBS has been difficult to define, and no single cause of the malady has been identified (Hodgson 1992). Early studies showed that many of the reported causes of SBS included undesirably high levels of known respiratory irritants such as nitrogen and sulfur dioxides, hydrocarbons, and particulates (National Academy of Sciences 1981), known or suspected carcinogens such as asbestos, radon, formaldehyde, and tobacco smoke (Sterling 1984), or chemicals released by new building materials. Although fungal spores are ubiquitous in the indoor and outdoor environments, they are now generally accepted as important causes of respiratory allergies (Solomon 1975; Bernstein 1983). Although no single cause for the symptoms induced by poor IAQ likely exists, the presence of fungi, spores, and fungal growth in sick buildings has become consistently associated with this problem (Miller 1992; Mishra 1992; Cooley 1998).
Since Biblical times, indoor fungal contamination and IAQ have been a cause for concern in society. Leviticus 14:33-45, in the Old Testament, states that a house needs to be cleaned and ridded of mildew to be clean and free of mold (Heller, Heller et al. 2003). If the house cannot be cleaned, then it is to be torn down. This is similar to the manner in which IAQ issues associated with fungal contamination are addressed today. Air pollution became an

important environmental issue during the industrial revolution, and several instances of deadly environmental air pollution are cited in the literature. In the early 1900s, building design and construction underwent radical change in the United States; the introduction of air conditioning with cooling coils and forced ventilation, new construction materials, new lighting and heating standards, insulation, and similar advances changed the way buildings were designed and constructed. The new construction designs and methods allowed architects and engineers to build quality structures at lower costs. Schools of engineering and architecture in the United States then began to teach the new building designs and construction methods to students. Thus, thousands of years of collective architectural and engineering design experience, specifically natural ventilation design, were erased from the educational system in the United States.

World War II was a pivotal point in IAQ. At approximately the same time as building design and construction was experiencing radical change, American society also experienced radical change. America began to transform from an agricultural economy wherein the majority of time was spent outdoors, to a service and manufacturing economy, where the majority of time was spent indoors. Since 1945, a phenomenal transformation has occurred: Americans and people in other industrialized nations now spend more than 90 percent of their time indoors (Teichman 1995; EPA 2003). The Arab Oil Embargo of 1973-74 and the resulting energy supply shortages dramatically changed the public's attitude toward environmental control, because building energy usage had a monetary impact on every American. The energy crisis resulted in a tighter building design that produced more energy-efficient homes by closing the windows, redesigning the buildings, circulating re-heated and/or re-cooled air, and reducing the amount of fresh outside air brought into buildings. This "tight" building design resulted in an improvement of buildings and HVAC system energy efficiencies. This improvement in efficiency, however, was paralleled by an increase in SBS complaints. SBS is a term used to describe situations in which building occupants experience health and comfort effects that appear to be linked to time spent in a building, but for which no specific illness or cause can be identified. Indicators of SBS include headache; eye, nose, or throat irritation; dry cough; dry or itchy skin; dizziness and nausea; difficulty in concentrating; fatigue; sensitivity to odors; and other symptoms. Another important indicator was the relief of symptoms when complainants leave the building for extended periods of time (EPA 1991).

The first study to compare indoor versus outdoor fungal morphology was conducted in 1904 by Saito in Japan (Saito 1904); this work was followed by Rostrup in Denmark (Rostrup 1908) and Peyronel in Italy (Peyronel 1919). Since the 1930s, medical specialists in the allergy and immunology community recognized molds as being allergenic and capable of both exacerbating asthma and sensitizing patients (Bernton 1930; Flood 1931; Credille 1933; Conant 1936). With increasing awareness that poor IAQ may generate a variety of deleterious effects on human health, IAQ has become a serious public health concern (Samet 1990; Mishra 1992; Passon 1996; Hodgson, Morey et al. 1998; Sudakin 1998; Hagmann 2000; King and Auger 2002; Karunasena 2005; Karunasena E, Larrañaga MD et al. 2010). It has been estimated that more than 30% of the buildings in developed countries suffer from poor IAQ (World Health Organization 1983; Smith 1990). The Occupational Safety and Health Administration (OSHA) estimated that 30 to 70 million U.S. workers are affected by SBS (Bureau of National Affairs 1992).

Moisture problems have been encountered with increasing frequency both in family housing and in the workplace in the U.S. and Europe (Reijula 1996). Persistent water leaks

and moist building materials inevitably lead to the growth of fungi and bacteria in these buildings. Several epidemiological studies suggested that dampness and fungal problems are present in 20% to 50% of modern homes (Dales 1991; Brunekreef 1992; Jaakkola 1993; Spengler 1994; Verhoeff 1995). Not only are dampness and fungi risk factors in the association between indoor dampness and respiratory symptoms (Hodgson, Morey et al. 1985; Dales 1991; Dales 1991b; National Academy of Sciences 1993; Flannigan 1994; Spengler 1994; Hodgson, Morey et al. 1998; Husman, Meklin et al. 2002), but damp homes tend to have higher levels of fungi than non-damp homes (Platt 1989; Verhoeff 1992). In addition, poorly maintained heating, ventilation, and air conditioning (HVAC) systems have been recognized as sources of microorganisms, including fungi.

Fungi are well known allergens that cause allergic rhinitis, allergic asthma, and hypersensitivity pneumonitis when inhaled (Salvaggio 1981; Tarlo 1988; Burge 1989; Flannigan 1994). Fungi also produce volatile organic compounds (VOCs) including alcohols, aldehydes, and ketones, which often produce moldy odors and can cause symptoms such as headaches, eye, nose and throat irritation, and fatigue (Tobin 1987; Flannigan 1991). Fungi also produce toxic metabolites called mycotoxins. Mycotoxins have been identified indoors or on materials indoors by several authors (Croft 1986; Hodgson, Morey et al. 1998; Nielsen, Hansen et al. 1998; Richard, Platnerr et al. 1999; Croft, Jastromski et al. 2002). Mycotoxins produced by *Stachybotrys chartarum* have been implicated in producing non-allergic respiratory symptoms in humans (Croft 1986; Johanning 1996; Andersson 1997; Croft, Jastromski et al. 2002) and have been shown to cause significant damage to cells of the neurological system in concentrations found indoors (Karunasena E, Larrañaga MD et al. 2010).

At present, no single environmental factor or group of factors has been established as the cause of SBS. Although fungal contamination in indoor environments has been shown to produce allergies in building occupants (Lehrer 1983; Licorish 1985; Verhoeff 1995), the role of fungi in SBS has become increasingly controversial. Numerous theories have been put forward (Mendell 1993). Along with the VOC theory, a heightened neurogenic inflammatory response to low-level chemical exposures has been suggested (Meggs 1993; Karunasena E, Larrañaga MD et al. 2010), while other theories have focused on particulates (Salvaggio 1994a) and physical factors (Levin 1995). Inadequate ventilation is a factor in all of these theories. Investigators who are more skeptical have emphasized the roles of psychosocial factors, stress, and gender (Stenberg 1994; Salvaggio 1994b; Bachmann 1995).

Today, children spend most of the day indoors, and because dampness in buildings has increased over the last decade, relationships have been identified between an increase in children's health symptoms, dampness, and fungal spores (Dill 1996; Li 1997; Garrett, Rayment et al. 1998). Children who attend school in buildings with dampness and fungal contamination have been shown to suffer higher rates of respiratory infections (Koskinen 1995). The literature suggests a strong association between the presence of fungal growth indoors and SBS (Cooley 1998). The Centers for Disease Control states that the inhalation of fungal spores inside buildings can cause allergic rhinitis, hypersensitivity pneumonitis, and exacerbate asthma (Redd 2002). Although associations have been made, far more research related to SBS, building-related illness (BRI), and IAQ is needed. Hodgson, et al., maintain that undesirable moisture levels indoors represent a public health concern inadequately addressed by building, health, or housing codes (Hodgson, Morey et al. 1998).

In warm and humid climates, conventional HVAC systems are incapable of adequately controlling humidity and simultaneously meeting the minimum fresh air requirements

specified by the American Society for Heating, Refrigerating, and Air Conditioning Engineers' (ASHRAE) Standard 62, Ventilation for Acceptable IAQ. The bulk of a building's moisture load is carried by the incoming ventilation air, and simply drying the ventilation air will provide excellent humidity control at minimal cost (Harriman and Kittler 2001; Larrañaga, Beruvides et al. 2008). Drying the ventilation air via desiccant based cooling is a cost effective method of humidity control. A separate dedicated outdoor air system with humidity control is the simplest method and may be the only reliable method of meeting Standard 62 (Mumma 2001; Larrañaga, Beruvides et al. 2008). Controlling humidity is crucial for human comfort, minimizing adverse health effects associated with high humidity, and maximizing the structural integrity of buildings. The use of a desiccant pre-conditioner apparatus can improve the humidity control capabilities of HVAC systems arising from inherent evaporator coil limitations and can accommodate the minimum outdoor air ventilation rates specified by Standard 62 (Meckler 1994; Larrañaga, Beruvides et al. 2008).

Since the mid to late 1980s, desiccant based cooling systems have found increased applications as humidity control devices for non-industrial structures like schools, homes, hospitals, and commercial buildings (Hines 1992c; Harriman III, Witte et al. 1999; Larrañaga, Beruvides et al. 2008). Several authors have stated that the use of active desiccants enhances the quality of the indoor air by helping to maintain comfort criteria (temperature, humidity and ventilation) (Meckler 1994; Kovak 1997; Fischer and Bayer 2003), removing particulates and bioaerosols from the air (Hines 1992a; Kovak 1997), and removing chemical pollutants from the air (Hines 1992c; Popescu and Ghosh 1999). Several investigators explored the ability of solid and liquid desiccant materials to remove environmental tobacco smoke, particulates, radon, organic vapors, carbon dioxide, and several microorganisms responsible for the majority of nosocomial infections, including several bacteria and *Aspergillus niger,* from the airstream. Popescu and Ghosh used a fixed bed adsorber to simulate the operation of a rotary desiccant wheel, and showed that carbon dioxide and organic vapors were successfully removed by the desiccant materials (Popescu and Ghosh 1999). Hines, et al., used both fixed bed adsorbers in a column configuration for solid desiccants (Hines 1992a) and a packed bed absorber-stripper system for liquid desiccants (Hines 1992b) in their studies. Hines, et al., studied the desiccant removal capabilities of these column-type adsorbers and absorbers on carbon dioxide, volatile organic compounds (Hines 1992b), airborne particulates, environmental tobacco smoke, several bacteria, and *Aspergillus niger* (Hines 1992a). Kovak, et al., conducted a laboratory and field study of the capabilities of a solid-desiccant dehumidifier in removing seven microorganisms responsible for nosocomial infections (Kovak 1997).

This study quantified the removal capabilities of a rotary wheel solid-desiccant dehumidifier at removing selected IAQ-related fungal organisms from the airstream. While the above-mentioned authors studied the removal capabilities of solid and liquid desiccants and one rotary wheel solid desiccant dehumidifier, none explored the ability of a rotary wheel solid desiccant dehumidifier to remove IAQ-related fungal species from the air. Rotary wheel solid desiccant dehumidifiers in the honeycomb configuration are the most appropriate dehumidifier configuration for air-conditioning applications (Pesaran 1994). The use of active desiccation in warm and humid climates would result in energy savings from a reduction in latent cooling and an increase in sensible cooling, offsetting initial purchase costs (Dolan 1989; Pesaran 1994; Larrañaga, Beruvides et al. 2008).

Indoor environmental quality has been an issue throughout history. The interactions of a number of technological discoveries and historical events have resulted in the construction of buildings that make people sick. Every industrialized nation in the world has experienced an increase in asthma in the last 30 years. Asthma is an affliction of the industrialized world, and is not a prominent illness in third-world countries (Vogel 1997). The term sick-building syndrome was first used in the 1980s, when illnesses associated with buildings began surfacing throughout the industrialized world. SBS is a societal and public health issue that has become prevalent in today's world with a negative impact on the world's economy.

2. The economic impact of poor IAQ

The incidences of illnesses related to building occupancy have brought about a number of financial penalties, ranging from lower worker productivity to expensive lawsuits (Addington 2000). Poor IAQ has a negative effect on productivity, worker health, and morale. Direct evidence established in the literature stated that characteristics of buildings and indoor environments can directly affect worker health and productivity. Estimates (in 1996 dollars) of annual savings and productivity gains included $6 to $14 billion from reduced respiratory disease; $2 to $4 billion from reduced allergies and asthma; $15 to $40 billion from reduced symptoms of sick building syndrome; and $20 to $200 billion from direct improvements in worker performance. Building characteristics and indoor environments have been linked to SBS experienced by building occupants. The most common reported sufferers of SBS are office workers and teachers, who make up approximately 50 percent of the total workforce (64 million workers). SBS symptoms include irritation of the eyes, nose, skin and upper respiratory tract, increased airway infections, dizziness, nausea, headache, fatigue, bleeding from the nose, and lethargy. Cognitive impairment, memory loss, permanent lung damage, and other physiological effects have been correlated to SBS. Psychosocial factors are also known to influence the symptoms of SBS. Building factors such as the amount of fresh air ventilation, indoor lighting levels including sunlight, levels of chemical and microbial contamination, and indoor temperature and humidity have been shown to influence SBS symptoms (Gordon, Johanning et al. 1999; Fisk 2000).

SBS symptoms hinder work. Symptoms also can cause not only absences from work, but also visits to doctors and costly emergency medical services. The investigations, maintenance, relocation, legal fees, and insurance costs associated with SBS quickly rise to astronomical levels, and impose a societal burden. The quantification of SBS costs is extremely difficult, due to economic and psychosocial factors, decreases in productivity, legal costs, and other influences. However, several attempts have been made at quantification of the costs of SBS based on the Gross Domestic Product (GDP) associated with office-type-work. The GDP of the United States in 1996 was $7.6 trillion. On the basis of an estimated two percent decrease in productivity due to SBS symptoms for office-type-work, which has a GDP of $3.8 trillion, the annual nationwide cost of SBS symptoms is $76 billion. The potential financial benefits of improving U.S. indoor environments exceed costs by a factor of 18 to 47 (Bayer 2000). While poor IAQ places a heavy economic burden on the workplace, poor IAQ can also have a negative impact on school-aged children, and teachers (Handal, Leiner et al. 2004).

2.1 Asthma as epidemic

Mold and moisture indoors is a significant risk factor for asthma and the US Environmental Protection Agency identifies mold and moisture indoors as asthma triggers (Environmental Protection Agency 2010). Since 1970, a three-fold increase occurred in the incidence of asthma in the United States: 7 million cases in 1970 vs. 20 million cases in 2000. Persons with asthma collectively have more than 100 million days of restricted activity and 470,000 hospitalizations annually (Weiss 1992). Asthma is the most common chronic childhood disease, affecting 6.3 million children. 1 in 10 school-aged children has asthma (Environmental Protection Agency 2010), and the rate is rising more rapidly in children of preschool age than in any other age group. In 2000, there were nearly 2 million emergency room visits and approximately 500,000 hospitalizations due to asthma. Asthma symptoms that are not severe enough to require an emergency room physician visit can still be severe enough to prevent a child with asthma from living a fully active life. Asthma is the leading cause of school absenteeism due to chronic illness. During the past 20 years, the number of school absence days due to asthma has more than doubled. The CDC estimates 14 million school days were missed due to asthma in 2000 (EPA 2003).

The economic impact of asthma is staggering; During 1994, total US costs of asthma were $10.7 billion (Weiss, Sullivan et al. 2000), yearly treatment costs alone approach $6 billion (Cookson 1999), and asthma costs 5,000 deaths yearly with no signs of leveling off (Vogel 1997). The roots of asthma may be traced to heating of the bedrooms in homes, tight building design, and air conditioning. Forced air ventilation allowed homes to be heated or cooled throughout at all times of the year. Prior to the industrial revolution, homes were designed with a central room with heating capabilities (i.e. kitchen and living room) and plumbing. The surrounding rooms, most commonly bedrooms, were not heated, and would freeze through the cold months of the year. This yearly cycle of freezes in bedrooms allowed beddings to freeze, killing dust mites. Few indoor environments routinely freeze today. Thus, dust mites survive throughout the year in carpets and beddings, and are able to affect those with asthma. Heating and air conditioning system design has re-circulated the indoor air to maintain efficiencies, decreasing the amount of fresh air available in buildings.

2.2 The economics of poor IAQ and schools

Teachers and school-age children also suffer from SBS. One in five U.S. schools exhibits IAQ problems, and studies linking specific environmental conditions to student performance indicate impaired performance of students. A study of 627 Swedish secondary school pupils reported "impaired performances were more common in schools with lower air exchange rates, higher relative humidities, and higher concentrations of respirable dust, formaldehyde, VOCs, and total bacteria or molds. A relationship was demonstrated between subjective reports of impaired mental performance, measured indoor air pollutants, and low air exchange rate" (Bayer 2000). A similar study of 12 schools within the Denver, CO metropolitan area indicated an increased prevalence of nasal congestion, sore throat, headache, dustiness complaints, and red and watery eyes in schools with certain ventilation system types (Kinshella, Van Dyke et al. 2001). In a similar study of 85 schools in Canada, it was shown that children with allergies who displayed allergic-type symptoms during school were disproportionately in the below-average category for academic achievement (Landrus 1990). Several other studies demonstrated a link between student absenteeism and IAQ factors. Additionally, there seemed to be a link between unsatisfactory IAQ and the proportion of a school's students from low-income households.

IAQ and SBS appeared especially important in schools because (1) children are developing physically and affected by pollutants to a greater degree than adults, (2) the number of children with asthma has risen approximately 49 percent since 1982, (3) children below the age of 10 have three times as many colds as adults, (4) poor IAQ can lead to drowsiness, headaches, lack of concentration, and other symptoms, and (5) children have a higher rate of metabolism than adults and may ingest or inhale more air and surface contaminants than adults (Bayer 2000). Schools face separate epidemics: an epidemic of deteriorating facilities and an epidemic of asthma among children (Bascom 1997). Asthma is the principal cause of school absences, accounting for 20 percent of lost school days in elementary and high school (Richards 1986). Richards also states that allergic disease (nasal allergy, asthma, and other allergies) is the number one chronic childhood illness. It has been clearly established that SBS and poor IAQ affect productivity in a negative way. The factors associated with IAQ interact in a very complex relationship that sometimes requires extensive and diverse knowledge, experience, and diversity to solve. Ventilation, however, plays a key role as the underlying factor for SBS in the modern, sealed building with a controlled indoor environment (Cooley 1998).

2.3 Economic incentives for improving IAQ

In some cases, improving IAQ to acceptable levels can be quite expensive and uneconomical. In rare instances, structures are demolished rather than repaired or remediated because of poor IAQ. Potential savings from changes in building factors, that produced a 10 to 30 percent reduction in symptoms and associated costs, projected an annual savings of $2 to $4 billion, in addition to reducing the psychosocial and societal costs. Three general approaches for reducing allergy and asthma by changes in buildings are currently recognized: (1) control the indoor sources of the allergens and chemical compounds that cause symptoms or initial sensitization, (2) use cleaning systems to decrease the indoor concentrations of the relevant pollutants, and (3) modify buildings and IAQ in a manner that reduces viral respiratory infections among occupants (Fisk 2000).

Potential savings from changes in building factors creating a 20 to 50 percent reduction in symptoms and associated costs in office buildings projected an annual productivity increase on the order of $15 to $38 billion (Fisk 2000). Strong evidence existed that good IAQ can effectively increase health and productivity and the cost benefits associated with improving IAQ exceeded the cost of improving IAQ by a factor of 18 to 47. "For the United States, the estimated potential annual savings plus productivity gains, in 1996 dollars, are approximately $40 billion to $250 billion" (Fisk 2000). This evidence justified changes in (1) the components of building codes affecting IAQ and (2) company and institutional policies related to IAQ, (3) building design, operation, and maintenance to incorporate maintaining and promoting a desirable IAQ.

Fischer concluded that the payback period associated with a desirable indoor environmental quality is probably very short (Fischer 1996). He indicated that the many benefits listed would be recognized year after year, whereas the costs associated with providing the desirable indoor environmental quality are a one-time expense with minimal maintenance costs. The expected benefits—which included reductions in absenteeism and health care costs, positive impacts on productivity, alertness, drowsiness, allergies, and illness, avoidance of property damage and remediation, and reduced maintenance costs—quickly exceeded the initial expense associated with an improved indoor environment (Bayer 2000).

3. Causes of poor IAQ and desiccation as an IAQ control strategy

Indoor dampness, water damage, and fungi have been associated with respiratory complaints (Martin 1987; Andrae 1988; Brunekreef 1989; Dales 1991; Dales 1991b; Brunekreef 1992; Summerbell 1992; Jaakkola 1993; Joki 1993; Husman, Meklin et al. 2002), and with both allergic and non-allergic respiratory disease (Salvaggio 1981; Lehrer 1983; Licorish 1985; Flannigan 1994; Spengler 1994; Verhoeff 1995; Jarvis and Morey 2001) in several industrialized nations. Asthma was associated with 'damp houses and fenny countries' three centuries ago by Sir John Floyer (Sakula 1984). In a study of 48 U.S. schools, Cooley, et al., associated the presence of propagules of *Penicillium* and *Stachybotrys* on building surfaces with SBS (Cooley 1998). In a survey of 59 homes selected on the basis of previously measured mold levels in 400 houses, White correlated measurements of mold growth and immunological reactions of occupants, noting that lymphocytes from children are chronically activated, and immuno-regulation may be altered in households with mold growth (White 1995). The presence of moisture damage in schools was identified as a significant risk factor for respiratory symptoms in children based on data from microbial IAQ studies in 24 schools (Meklin, Husman et al. 2002) and in the home (Hyvärinen, Pekkanen et al. 2002), and airborne *Penicillium* and *Aspergillus* species was identified as a risk factor for asthma, atopy, and respiratory symptoms in children (Garrett, Rayment et al. 1998). In a population-based incident case-control study in South Finland of 521 adults with newly diagnosed asthma and 932 controls, Jaakkola, et al., found that 35.1% (95% confidence interval, 1.0%-56.9%) of the adult-onset asthma cases were related to workplace mold exposure indoors and that indoor mold problems constitute an important occupational health hazard (Jaakkola, Nordman et al. 2002). It is unlikely that the number of associations in several different countries is a result of chance. It is more likely these associations represent a combination of factors leading to poor ventilation, moisture damage, fungal contamination, and poor IAQ because of systemic and synergistic effects of contaminants within modern built environments (Passon 1996). One important building parameter in controlling indoor moisture and mold growth is the HVAC system, which if not properly designed, maintained, or operated, can cause poor IAQ.

3.1 HVAC systems as a cause of poor IAQ and desiccation as an IAQ control strategy

HVAC systems are essential to modern life and can provide healthy and comfortable indoor environments when properly installed, operated, and maintained (Batterman 1995). Sietz categorized the primary factors leading to building-related illness (BRI), and found that 53% of 529 IAQ evaluations conducted by NIOSH from 1971 through 1988 were associated with inadequate ventilation (Seitz 1990). NIOSH attributed more than half (52%) of the SBS cases to unsuitable facility ventilation systems (Bayer 2000). Additionally, conventional HVAC systems cannot adequately dehumidify air in warm and humid climates (Bayer 1992a; Fischer 1996; Davanagere 1997; Larrañaga, Beruvides et al. 2008) and it is not economically feasible to use only materials that are not susceptible to moisture damage. A systemic relationship between the HVAC system, outdoor air, and indoor environment exists when indoor relative humidities are high. A properly designed, functioning, and operating HVAC system can have a significant positive impact on reducing the number of SBS symptoms experienced within buildings.

The application of a control strategy that aids in removing organic materials and microorganisms from the air, while introducing fresh air into a building, can improve the

IAQ of a building and eliminate many problems associated with ventilation and lack of fresh air in buildings. Bayer suggested that IAQ improves when using active humidity control and continuous ventilation in schools (Bayer 2000). In a study of 10 schools in Georgia, Bayer states that of the five schools having conventional HVAC systems, none supplied outside air at the ASHRAE recommended 15 cfm/person. The schools having desiccant systems were delivering as much as three times more outside air, while maintaining equal or better control of the indoor relative humidity than the conventional systems. The average total volatile organic compound (TVOC) concentrations tended to be lower in schools having desiccant-based systems. The school showing the highest air exchange rate utilized a rotary desiccant system, and had the lowest carbon dioxide, TVOC, and airborne microbial concentrations, and the lowest average indoor relative humidity (Bayer 2000). In Phase II of the same project, Fischer and Bayer stated that increasing the air ventilation rate from 5 to only 8 cfm/student challenged the ability of the conventional systems to maintain the space relative humidity below the ASHRAE and ACGIH recommended 60% level. Increasing the ventilation rate of the conventional systems to the required 15 cfm/student allowed the space relative humidities routinely to exceed 70%. These data explained why all of the conventional HVAC system schools were designed and/or operated with only 6 cfm/student of outdoor air or less. The decreased ventilation rates were in direct response to the performance limitations of the conventional cooling equipment and contributed to the poor IAQ within the schools. Furthermore, the schools served by the conventional HVAC systems experienced absenteeism at a 9% greater rate than those served by the desiccant systems (Fischer and Bayer 2003). Kumar and Fisk proposed that the energy cost of providing additional ventilation may be more than offset by the savings that result from reduced employee sick leave, and that increasing ventilation rates above the minimum rates specified in ANSI/ASHRAE Standard 62, Ventilation for Acceptable IAQ, can yield substantial benefits, including the reductions of the incidence of allergy and asthma in building occupants (Kumar and Fisk 2002).

The general approaches for reducing allergy and asthma by changes in buildings are: (1) control the indoor sources of the allergens and chemical compounds that cause symptoms or initial sensitization, (2) use cleaning systems to decrease the indoor concentrations of the relevant pollutants, and (3) modify buildings and IAQ in a manner that reduces viral respiratory infections among occupants (Fisk 2000). Utilizing desiccant treatment to pretreat fresh air and maintain the desired airflows created benefits for building occupants by providing a means to meet all three general approaches for reducing allergy and asthma in buildings. The use of desiccation as an IAQ control strategy provided other benefits including an increase in sensible cooling and a decrease in latent cooling at the cooling coils.

IAQ studies found that molds, or bioaerosols, were primary link to building-related illness, infections, toxic syndromes, and hypersensitivity diseases (Kovak 1997). Outdoor air parameters can be controlled actively by pre-treating outdoor air prior to its entering a building. Studies have shown that forced desiccant treatment of air has been effective in reducing airborne levels of tobacco smoke and volatile organics (Hines 1992c; Kovak 1997; Popescu and Ghosh 1999). The objective of this research was to determine the effectiveness of a titanium dioxide/silica gel catalytic dehumidification system in removing IAQ-related bioaerosols from the air. The research consisted of subjecting a laboratory setup of the desiccation system to airborne concentrations of IAQ-related bioaerosols. Its success proved that adapting dehumidification technology for use in HVAC systems will allow for moisture control and removal of IAQ-related organisms from the air stream, and offered a viable

control strategy for preventing moisture damage and mold growth in buildings. Furthermore, utilization of active desiccation in humid climates results in energy savings from a reduction in latent cooling and an increase in sensible cooling, offsetting initial purchase costs while providing an economic benefit.

Hines, et al., (1992), Kovak, et al., (1997), and Popescu and Ghosh (1999) showed that forced desiccant treatment of air effectively reduced airborne levels of bacteria, fungi, particulates from environmental tobacco smoke, and VOCs. Hines showed that a packed bed adsorber can act as a filter for airborne particulates by removing between 22% and 73% of particulate matter associated with environmental tobacco smoke (Hines 1992a). Kovak, et al., showed median reductions after exposure to desiccant based air conditioning (DBAC) systems in three field studies of 39%-64% for bacteria and 32%-72% for fungi (Kovak 1997). In laboratory tests, Kovak et al. showed an average reduction of 38% of seven organisms associated with nosocomial infections after exposure to a DBAC system (Kovak 1997). Popescu and Ghosh showed removal efficiencies of a desiccant bed to be 35% for formaldehyde, 70% for toluene, 29% for carbon dioxide, and 54% for 1,1,1-tricchloroethane using a packed bed adsorber configuration.

The above authors investigated removal capabilities of desiccant treatments in other configurations than this research utilized. For example, Hines et al. (1992) studied the desiccant setups in a packed bed filter-like configuration. Popescu and Ghosh (1999) simulated a rotating desiccant wheel using an experimental system consisting of a fixed bed adsorber, which acted as a filter. Kovak, et al., (1997) exposed a desiccant wheel to biological organisms that were both associated with nosocomial (hospital-induced) infections and inherently heat sensitive.

Fig. 1 shows a desiccant unit installed in a school in south Texas for the purposes of (1) drying the school, (2) preventing the structure from becoming wet, (3) reducing the amount of latent cooling by the cooling coils, (4) creating a dew point of 45 °F to prevent condensation at the cooling coils, within the HVAC unit, and within the building itself, and (5) providing fresh pre-conditioned air for the interior space. Most school facilities utilize packaged HVAC equipment designed for inexpensive, efficient cooling. This type of equipment is not designed to handle the continuous supply of outdoor air necessary to comply with ASHRAE-62, Ventilation for Acceptable IAQ. As a result, these schools are likely to experience IAQ problems (Fischer 1996; Larrañaga, Beruvides et al. 2008).



Fig. 1. Desiccant unit installed in a south Texas school to provide pre-conditioned fresh air for ventilation.

The desiccant setup in Fig. 1 is depicted in the flow diagram in Fig. 2. This unit is designed to provide the school with 100% outdoor make-up air while maintaining the indoor dew point below 45°F (7°C.). The use of 100% fresh make-up air helps maintain the building at positive pressure to minimize unplanned moisture infiltrations into the building. The desiccant wheel was constantly rotating and adsorbing moisture from the air stream on the process side, while moisture was removed from the wheel on the regeneration side. This provided a constant adsorption medium with no phase change. Heat is necessary to release the moisture from the desiccant wheel, which results in heating of the airstream and an energy penalty. However, the use of active desiccation saves energy costs by: 1) providing an enhanced occupant comfort at a lower cost, 2) improved humidity control resulting in sensible versus latent cooling, 3) equipment expenditures by allowing the downsizing of the evaporator coil and condensing units for comparable design loads, 4) allowing independent temperature and humidity controls, and 5) allowing higher temperature set points (Meckler 1994).

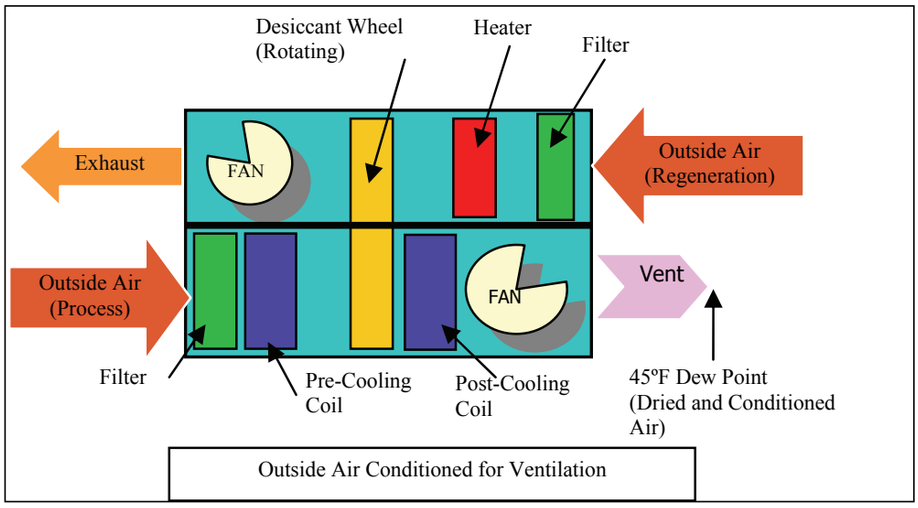


Fig. 2. Depiction of desiccant unit for treatment of 100% outside air with no treatment of return air from the building. This setup is typical of large commercial buildings or schools.

In units used for 100% outside air for ventilation (Fig. 2), or continuous ventilation, the outside air (process) is first filtered, cooled by the pre-cooling coil, dehumidified by the desiccant wheel, cooled again by the post-cooling coil, and delivered to the building's interior. This configuration does not allow for air within the building to be re-circulated, providing continuous fresh air to the system. Although the 100% make-up air configuration conditions more air, using more energy, than the typical desiccant setup depicted in Fig. 3 , it is preferred in very hot and humid climates for the protection of the building and building systems from moisture infiltration, condensation, and latent heat loads of occupants.

4. Materials and methods

There are five typical configurations for desiccant dehumidifiers: liquid spray tower, solid packed tower, rotating horizontal bed, multiple vertical beds, and rotating honeycomb (Harriman III 2002c). The most typical method of presenting solid desiccants to a high volume air stream is to impregnate the material into a lightweight honeycomb-shaped matrix

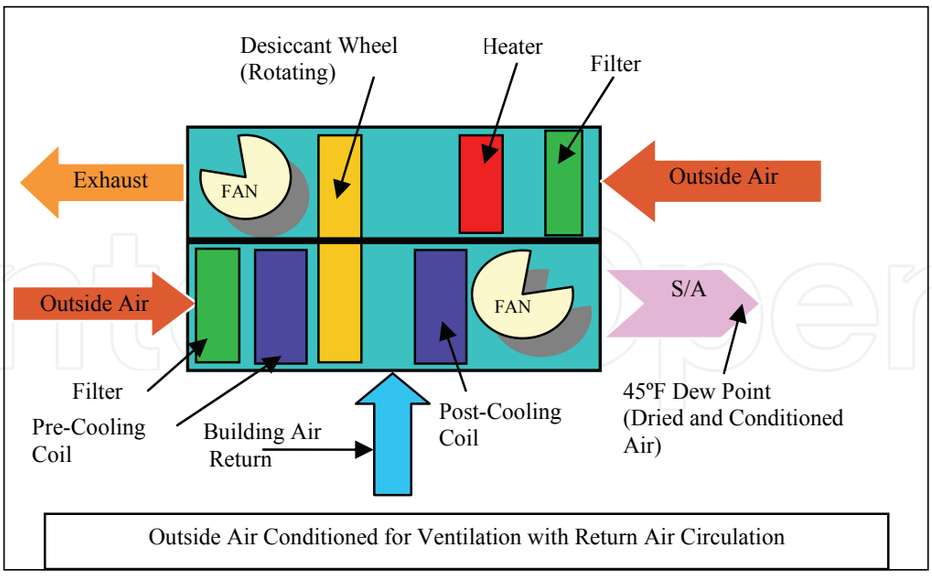


Fig. 3. Typical desiccant setup with return air from the building treated by the Post-Cooling coil. This setup is typical of small commercial buildings, schools, and residential buildings.

that is formed into a wheel (Harriman III, Witte et al. 1999). The rotating honeycomb wheel is a finely divided desiccant impregnated into a semi-ceramic structure, maximizing the surface area of the desiccant material. The appearance of the honeycomb wheel resembles corrugated cardboard that has been rolled up into the shape of a wheel. The air passes through the flutes formed by the corrugations, and the wheel rotates through the process and reactivation airstreams. The flutes served as individual desiccant-lined air ducts, which maximizes the surface area of the desiccant presented to the air stream. The rotating honeycomb wheel design has several advantages. The structure is lightweight and very porous. Different types of desiccants can be arranged into a honeycomb wheel configuration for different applications. The design allowed for laminar flow within the individual flutes, reducing air pressure resistance compared to packed beds. This allowed the honeycomb wheel to operate efficiently for low dew point and high capacity applications. The honeycomb wheels are very light, and their rotating mass is very low compared to their high moisture removal capacity. The result is an energy efficient unit (Harriman III 2002c). The design is simple, reliable, and easy to maintain. The design is the most widely installed of all desiccant dehumidifiers in ambient pressure applications (Harriman III 2002c). Additionally, the honeycomb design is the most appropriate dehumidifier configuration for air-conditioning applications (Pesaran 1994). A working desiccant honeycomb unit with environmental chambers at the outlets of both the regeneration side and process side of the unit was utilized to determine removal efficiencies. See Fig. 4.

The desiccant unit was modified with an additional heater (factory installed by Munters) and temperature controller (Omega CN132) to allow the operating temperature of the regeneration cycle (cycle that removes moisture from the wheel) to be varied between 100° (38°C) and 360° F (182°C). This allowed testing of the wheel at various increments of temperature. Spores were introduced using a 6-jet Collison nebulizer, a world standard for aerobiology research, that allowed for the aerosolization of fungal conidia for the purposes of testing the removal capabilities of the unit. The Collison nebulizer was operated at 40

psig, which generated a liquid generation rate of 16.5 ml/hr, allowing the experimenter to introduce a known concentration of fungi per volume of water as an aerosol into the test mechanism. For example, a fungal concentration of $1.25x10^5$ spores/ml provided an aerosol generation rate of $3.44x10^4$ spores per minute, allowing the experimenter to generate a known and constant airborne fungal concentration. Pressure was applied to the nebulizer with a Husky (model DK710700AV) Air Compressor.

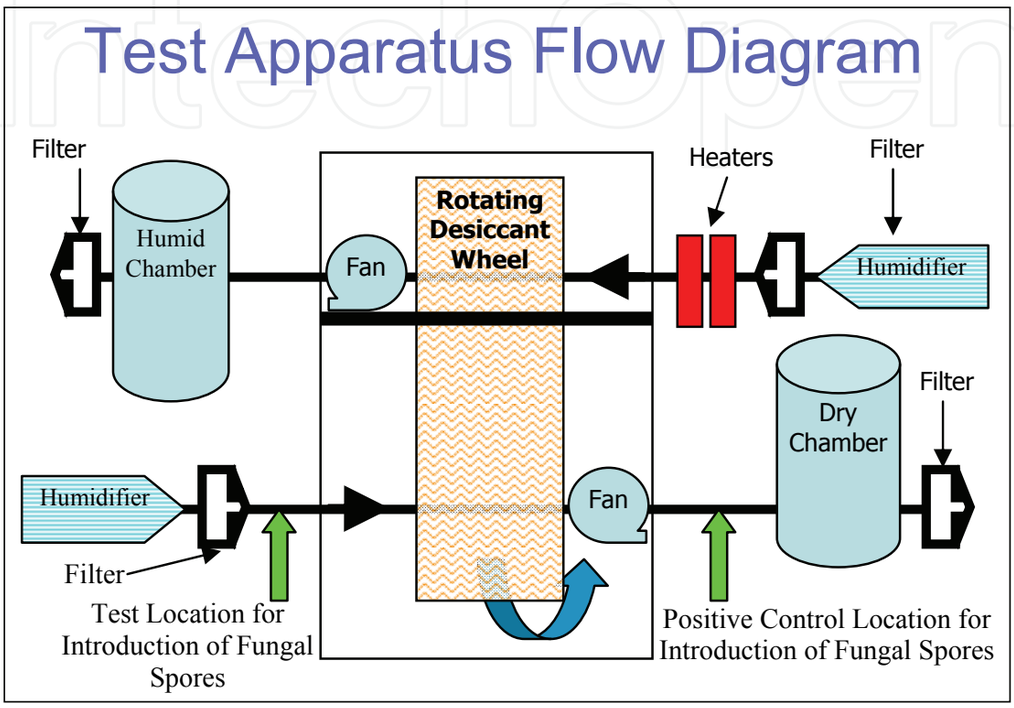


Fig. 4. Munters Dew-150 Desiccant Wheel Test Setup

The air was filtered with a HEPA Capsule prior to entering the Collison nebulizer. All microorganisms were concentrated, cultured, and speciated into a liquid solution. Lyophilization, a freeze-drying method under a vacuum, was used to concentrate spores (Virtis Freezemobile 6, Gardiner, NY). The organisms were then re-suspended in a known quantity of sterile water, and the concentration of spores determined through direct microscopic examination using a hemocytometer. The concentration was then manipulated by adding more water or spores to achieve the desired concentrations. The resulting fungal spore concentrates were frozen at -80°C. The test apparatus consisted of the Munters Dew 150 Desiccant Dehumidifier, four DeLonghi Dap-130 air purifiers with true high efficiency particulate air filters capable of capturing 99.97% of particles as small as 0.3 microns, and two environmental chambers (See Fig. 4). The environmental chambers were made of two 5-foot pieces of 24" agricultural high-pressure water pipe sealed at both ends with Plexiglas. Access doors were cut into each chamber, shelves installed, and a four plug-115V electrical outlet was installed to provide power for the sampling instruments. Each environmental chamber was sprayed twice with a Staticide ESD Clear Permanent Static Dissipative Coating to minimize the potential for electrostatic interference during the experiment. The environmental chambers were connected through metal duct to both the regeneration outlet (humid) and process outlet (dry) to permit the air exiting the desiccant unit to be sampled.

All air supplied to the desiccant unit was pre-filtered to remove microorganisms and other particulates from the air for quality control purposes. The air was again filtered upon leaving the environmental chamber so that microorganisms were not unnecessarily introduced into the laboratory. The air filters were modified to accept ducting so that the air could be supplied directly to the desiccant unit and filters and vice versa. Filters were connected to the apparatus via 5" flex duct and are maintained under slightly positive pressure. Air supplied to the process air inlet was humidified to 60% relative humidity using a Holmes Cool Mist Humidifier (model HM3655) to simulate a humid environment.

Air sampling within the environmental chambers was conducted using Andersen Microbial Impactors and Allergenco MK-3 Microbial Air samplers. Samples were analyzed by microscopic analysis for total count or visual count readings for culturable samples. All culturable samples were cultured with potato dextrose agar. Data were analyzed using a two-factor analysis of variance with equal replication. The treatments were temperatures ranging from 60°-360° F (16°-182°C) at intervals of 100 °F (38°C). Temperature settings were determined based on the following information:

1. 60 °F (16°C) –Setting the desiccant unit at this temperature allows the unit to operate without heat and isolates the desiccant wheel from the effect of temperature. At this temperature, the desiccant wheel can be saturated so that no desiccation is occurring.
2. 160 °F (71°C) –Units utilizing low cost surplus heat generated from indirect sources such as steam boilers, engine-cooling jackets, refrigeration condensers, exhaust air, steam condensate, water heaters, etc., may operate at 160°F or less. The regeneration air must be either hotter or dryer than the process air (Harriman III 1999 p.28), allowing the desiccant unit to operate at lower temperatures. Using indirect energy sources can accomplish this task without the energy penalty of heating the regeneration air. These units are not suitable for low dew-point applications.
3. 260°F (127°C) –This temperature was chosen within the range necessary for low dew point applications, which may require reactivation temperatures as high as 250°F (121°C) to 275°F (135°C) (Harriman III, Humidity Control Design Guide, p. 211).
4. 360°F (182°C) –Setting the desiccant unit at this temperature allowed the unit to maximize the heat applied to the regeneration air stream and isolated effects due to temperature. At this temperature, the desiccant wheel could not be saturated by humid air and desiccation was maximized. Commercial desiccant units typically operate between 180°F (82°C) and 225°F (107°C) (Harriman III 1999 p. 29) and do not typically operate at this temperature.

To conduct an ANOVA for data generated by the two instruments (Allergenco™ and Andersen), a total of [(10 replications x 4 temperature settings x 3 tests (P, T1, T2) x 2 instruments) + (2 negative control samples x 2 chambers x 4 temperature settings x 2 instruments)] = a minimum of 272 samples must be taken per organism to complete each experiment. To test the three microorganisms *Aspergillus niger, Cladosporium cladosporioides*, and *Penicillium chrysogenum*, 816 samples must be taken, analyzed, and interpreted. Many simulation studies suggest that, generally, the central limit theorem holds for n>30 (Ott 1993), allowing the use of normal distributions in the analysis of data. If these data were shown to be non-normal and did not meet the assumption of normality via transformation, a non-parametric two-factor ANOVA was to be used. Non-normal data obtained from a two-factor experimental design should be analyzed non-parametrically by an extension of the Kruskal-Wallis test for single-factor analysis (Zar 1974), allowing the research hypotheses to remain unchanged.

4.1 Hypotheses

The general hypothesis stated that the active desiccant wheel removes statistically significant concentrations of airborne IAQ-related bioaerosols from the air supplied to a building. The sampling mechanism dictated whether results are expressed as viable or total number of spores per cubic meter of air. Viable particulate samplers are used to collect and assay airborne concentrations of aerobic species of culturable bacteria and fungi. All inertial impactors that use solid media produce data in colony forming units (CFU) (Ness 1991). A CFU is a viable fungal spore or bacterium capable of producing a mass of organisms, or colony that originates from a single cell or spore.

Data generated from the Andersen Impactor are expressed in CFU/m^3. Table 1 summarizes the testable hypothesis that this research will investigate from the data generated using the Andersen Impactor. Intertial slit impactors like the Allergenco MK-3 Microbial Air Sampler collect total concentrations of both viable and non-viable bioaerosols from the air. No distinction can be made between viable and non-viable airborne concentrations using slit impactors. The data generated by the Allergenco MK-3 Microbial Air Sampler are expressed as a total concentration of spores/m^3. Table 1 summarizes the testable hypothesis that this research will investigate from the data generated using the Allergenco MK-3 Microbial Air Sampler.

5. Results and analyses

A total of 816 samples were taken to complete the experiment. Tests for normality showed that several of the data sets did not meet the assumption of normality and several data sets contained outliers. When concerned over the normality effect and outliers, a separate ANOVA should be performed on both the original data and the ranks; should the two procedures differ, use of the rank transformation ANOVA is preferred because it is less

Testable Hypothesis for Data Generated by the Andersen Impactor		
Hypothesis	**Test Statistic**	**Variables** (airborne concentrations in colony forming units/m^3)
Hypothesis 1: No interaction between temperature and viable airborne fungal concentrations.	Interaction	Temperature is the temperature settings for each test. μ_P is the mean of the airborne concentrations of the positive control. μ_{T1} is the mean of the airborne concentrations of the dry-chamber test.
Hypothesis 2: No difference on the airborne concentration of viable spores due to temperature.	H1: $\mu_{T1} = \mu_P$ Ha: $\mu_{T1} \neq \mu_P$	μ_P is the mean of the airborne concentrations of the positive control. μ_{T1} is the mean of the airborne concentrations of the dry-chamber test.
Hypothesis 4: No difference on the airborne concentration of viable spores due to exposure to the desiccant wheel.	H1: $\mu_{T1} = \mu_P$ Ha: $\mu_{T1} \neq \mu_P$	μ_P is the mean of the airborne concentrations of the positive control. μ_{T1} is the mean of the airborne concentrations of the dry-chamber test.

Table 1. Summary of Testable Hypotheses for Data Generated by the Andersen Impactor.

Testable Hypothesis for Data Generated by the Allergenco MK-3 Microbial Air Sampler		
Hypothesis	**Test Statistic**	**Variables** (airborne concentrations in spores/m^3)
Hypothesis 1: No interaction between temperature and total airborne fungal concentrations.	Interaction	Temperature is the temperature settings for each test. μ_P is the mean of the airborne concentrations of the positive control. μ_{T1} is the mean of the airborne concentrations of the dry-chamber test.
Hypothesis 3: No difference on the airborne concentration of total spores due to temperature.	H1: $\mu_{T1} = \mu_P$ Ha: $\mu_{T1} \neq \mu_P$	μ_P is the mean of the airborne concentrations of the positive control. μ_{T1} is the mean of the airborne concentrations of the dry-chamber test.
Hypothesis 5: No difference on the airborne concentration of total spores due to exposure to the desiccant wheel.	H1: $\mu_{T1} = \mu_P$ Ha: $\mu_{T1} \neq \mu_P$	μ_P is the mean of the airborne concentrations of the positive control. μ_{T1} is the mean of the airborne concentrations of the dry-chamber test.

Table 2. Summary of Testable Hypotheses for Data Generated by the Allergenco MK-3 Microbial Air Sampler.

likely to be distorted by non-normality and unusual observations (Montgomery 2001). This experimental analysis was completed using a two-factor ANOVA for both the original and the ranked data. The results of the two analysis differed in several instances, specifically in differences in temperature and groups (control versus test).

5.2 Andersen impactor

Tests for normality were conducted to help determine protocols necessary for data analysis. The Kolmogorov-Smirnov (K-S) goodness of fit test was employed because it is particularly useful when sample sizes are small and when no parameters have been estimated. A large p-value indicates a good fit, while a small p-value indicates a poor fit (Banks 2001). Nine of the 12 *Aspergillus niger* data sets failed to meet the assumption of normality. Eight of 12 *Cladosporium cladosporioides*-Andersen Impactor and 4 of 12 *Penicillium chrysogenum*-Andersen Impactor data sets did not meet the assumption of normality. One two-factor ANOVA per organism tested was conducted for the data generated using the Andersen Impactor. The ANOVAs for each organism are described below.

5.2.1 *Aspergillus niger*-Andersen impactor data analysis

Post hoc analysis using the Student-Newman-Keuls (SNK) test for rank value showed that measured airborne concentrations were not significantly different at any of the four temperature settings. The SNK grouping for the positive control (μ_P) vs. dry chamber test (μ_{T1}) vs. humid chamber test (μ_{T2}) showed that the controls were significantly different from the dry chamber and humid chamber results at each temperature setting. The power of the *Aspergillus niger*-Andersen Impactor analysis for control vs. dry and humid chamber results is greater than 0.99.

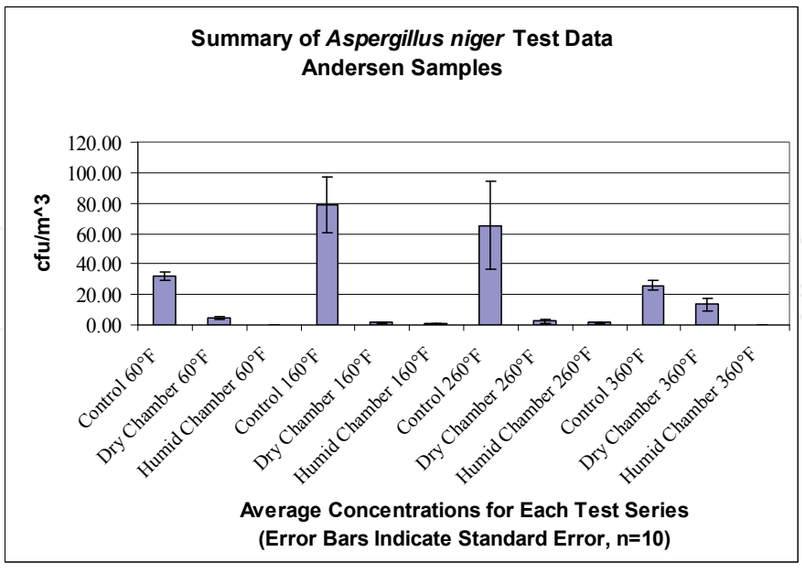


Fig. 5. Average airborne concentrations for *Aspergillus niger*-Andersen Impactor tests.

The results showed that there was interaction between that humid chamber and dry chamber data sets, there was no difference in the ranks due to temperature, and there was a significant difference between the mean ranks of the positive control (μ_P) and the mean ranks of the dry chamber tests (μ_{T1}) and humid chamber tests (μ_{T2}). Interaction occurred at the 160 °F (71°C) and 260 °F (127°C) between the dry chamber data ranks and the humid chamber data ranks. See Fig. 6 . The mean removal efficiencies are shown in Fig. 7 and can be described by the equation 'y = $-0.0561x^3 + 0.2612\ x^2 - 0.2687x + 0.9153$' with a correlation coefficient (R^2) of one.

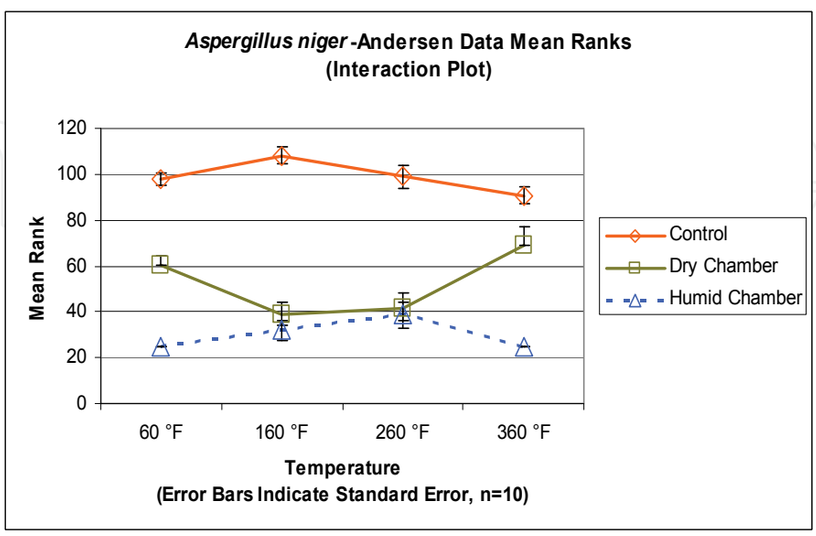


Fig. 6. Interaction Plot for the *Aspergillus niger*-Andersen Data Mean Ranks.

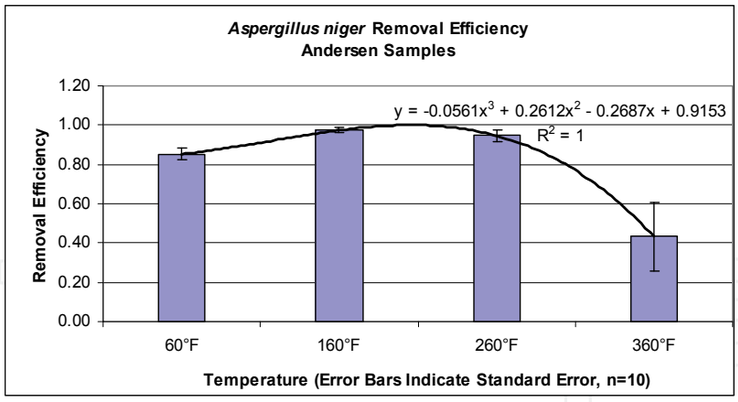


Fig. 7. *Aspergillus niger* Removal Efficiencies for Andersen Samples

5.2.2 Cladosporium cladosporioides-Andersen impactor data analysis

Post hoc analysis using the Student-Newman-Keuls (SNK) test for rank value showed that measured airborne concentrations were not significantly different at either of the four temperature settings. The SNK grouping for the positive control (μ_P) vs. dry chamber test (μ_{T1}) vs. humid chamber test (μ_{T2}) showed that the controls were significantly different from the dry chamber and humid chamber results at each temperature setting. The power of the *Cladosporium*-Andersen Impactor analysis for control vs. dry and humid chamber results is greater than 0.99. Fig. 8 summarizes the *Cladosporium cladosporioides*-Andersen Impactor data sets. These data show the mean airborne concentrations of the positive control versus the dry and humid chamber tests at each temperature setting. The results showed that there was no interaction, there was no difference in the mean ranks due to temperature, and there was a significant difference between the mean ranks of the positive control (μ_P) and the mean ranks of the dry chamber test (μ_{T1}) and humid chamber results (μ_{T2}). The mean removal efficiencies are shown in Fig. 9 and can be described by the equation 'y = $-0.0053x^3 + 0.0475x^2 - 0.3278x + 1.18$' with a correlation coefficient (R^2) of one.

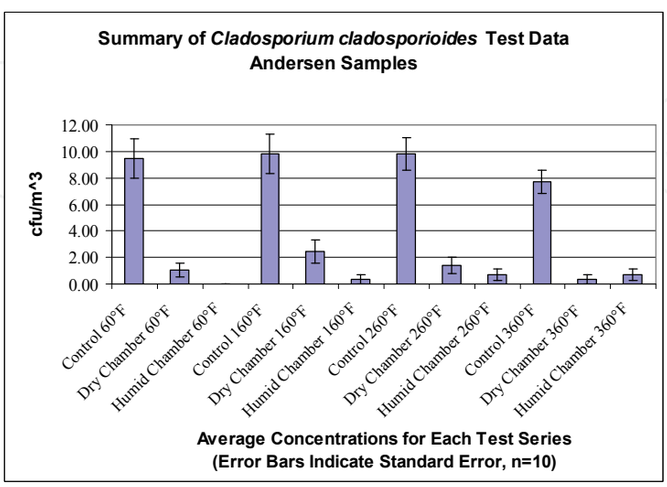


Fig. 8. Average airborne concentrations for *Cladosporium cladosporioides*-Andersen Impactor tests.

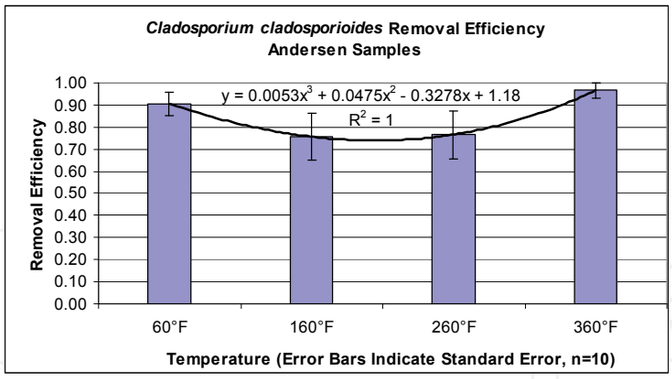


Fig. 9. *Cladosporium* removal efficiencies for Andersen samples

5.2.3 *Penicillium chrysogenum*-Andersen Impactor Data Analysis

Post hoc analysis using the Student-Newman-Keuls (SNK) test for rank value showed that measured airborne concentrations were not significantly different at any of the four temperature settings. The SNK grouping for the positive control (μ_P) vs. dry chamber test (μ_{T1}) vs. humid chamber test (μ_{T2}) showed that the controls were significantly different from the dry chamber and humid chamber results at each temperature setting. The power of the *Penicillium chrysogenum*-Andersen Impactor analysis for control vs. dry and humid chamber results is greater than 0.99. Fig. 10 summarizes the *Penicillium chrysogenum*-Andersen Impactor data sets. These data show the mean airborne concentrations of the positive control versus the dry and humid chamber tests at each temperature setting. The results showed that there was no interaction, there was no difference in the ranks due to temperature, and there was a significant difference between the mean ranks of the positive control (μ_P) and the mean ranks of the dry chamber test (μ_{T1}) and humid chamber tests (μ_{T2}). The mean removal efficiencies are shown in Fig. 11 and can be described by the equation 'y = -0.0728x³ + 0.5584x² – 1.3065x + 1.5574' with a correlation coefficient (R^2) of one.

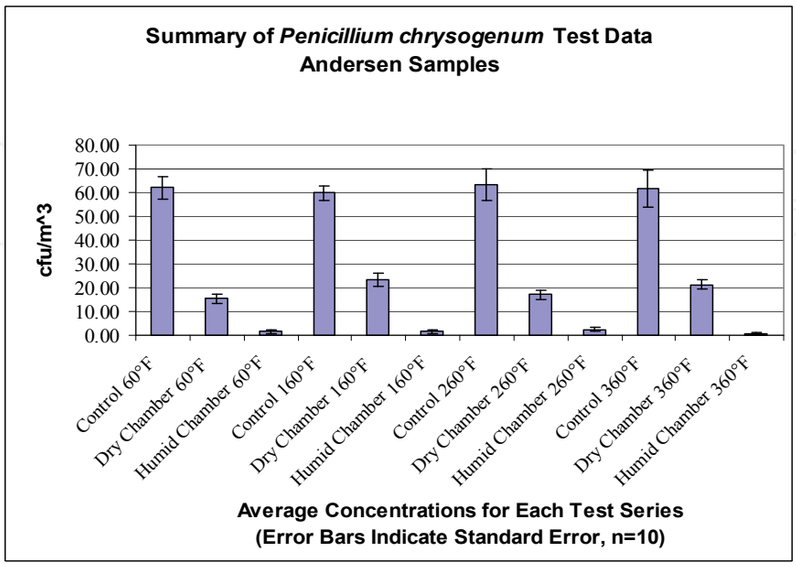


Fig. 10. Average airborne concentrations for *Penicillium chrysogenum* Andersen Impactor tests.

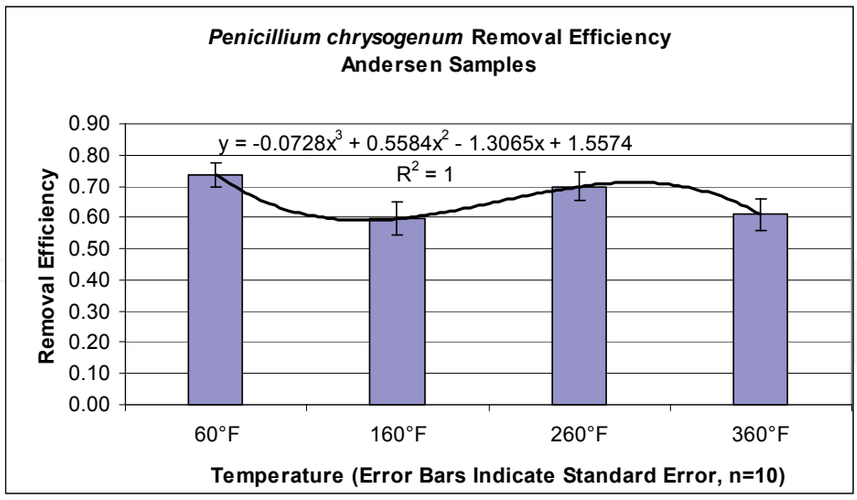


Fig. 11. *Penicillium chrysogenum* Removal Efficiencies for Andersen Samples

5.2.4 Combined removal efficiencies for andersen impactor data

The combined removal efficiencies of the *Aspergillus niger, Cladosporium cladosporioides, and Penicillium chrysogenum* data sets are summarized in Fig. 12 .

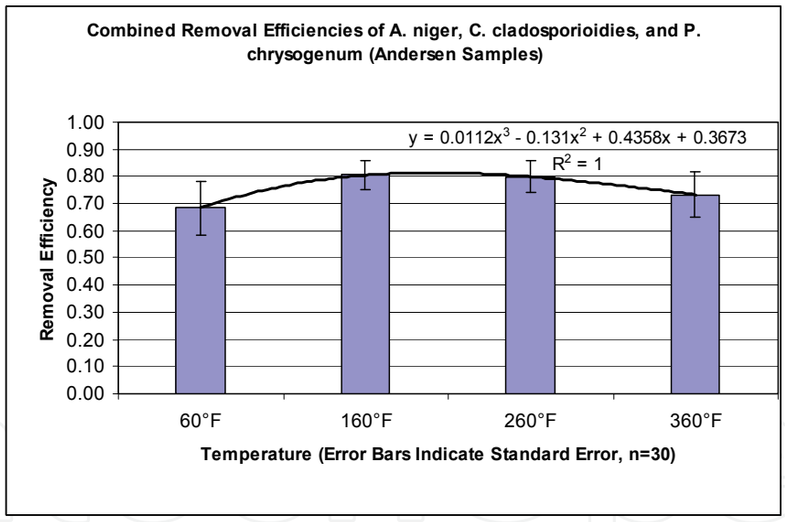


Fig. 12. Combined removal efficiencies of the *Aspergillus niger, Cladosporium cladosporioides, and Penicillium chrysogenum* –Andersen Impactor data sets.

5.3 Allergenco MK-III microbial air sampler

Tests for normality were conducted to help determine protocols necessary for data analysis. The K-S goodness of fit test was employed because it is particularly useful when sample sizes are small and when no parameters have been estimated. A large p-value indicates a good fit, while a small p-value indicates a poor fit (Banks 2001). Seven of the 12 *Aspergillus niger* data sets failed to meet the assumption of normality. Six of 12 *Cladosporium cladosporiodies*-Allergenco Microbial Air Sampler and 6 of 12 *Penicillium chrysogenum*-

Allergenco Microbial Air Sampler data sets did not meet the assumption of normality. One two-factor ANOVA per organism tested was conducted for the data generated using the Allergenco Microbial Air Sampler. The ANOVAs for each organism are described below.

5.3.1 *Aspergillus niger*-Allergenco microbial air sampler data analysis

Post hoc analysis using the SNK test for rank value showed that measured airborne concentrations were not significantly different at 160°F (71°C) and 260°F (127°C) or at 60°F (16°C) and 360°F (182°C). The two temperature groupings (160°F (71°C) and 260°F (127°C), 60°F (16°C) and 360°F (182°C)) were also statistically different. The SNK grouping for the positive control (μ_P) vs. dry chamber test (μ_{T1}) vs. humid chamber test (μ_{T2}) showed that the controls were significantly different from the dry chamber and humid chamber results at each temperature setting. The power of the *Aspergillus niger*-Andersen Impactor analysis for a temperature effect is 0.825, while the power of the analysis for control vs. dry and humid chamber results is greater than 0.99. Fig. 13 summarizes the *Aspergillus niger*-Allergenco Microbial Air Sampler data sets. These data show the mean airborne concentrations of the positive control versus the dry and humid chamber tests at each temperature setting. The results showed that there was interaction between that humid chamber and dry chamber data sets, there were differences in the ranks due to temperature, and there was a significant difference between the mean ranks of the positive control (μ_P) and the mean ranks of the dry chamber test (μ_{T1}). The interaction occurs at 160 °F (71°C) between the dry and humid chamber mean ranks. The mean removal efficiencies can be described by the equation 'y = $0.0662x^3 - 0.5048\ x^2 + 1.1476x + 0.1393$' with a correlation coefficient (R^2) of one. See Fig.s 4.10 AND 4.11.

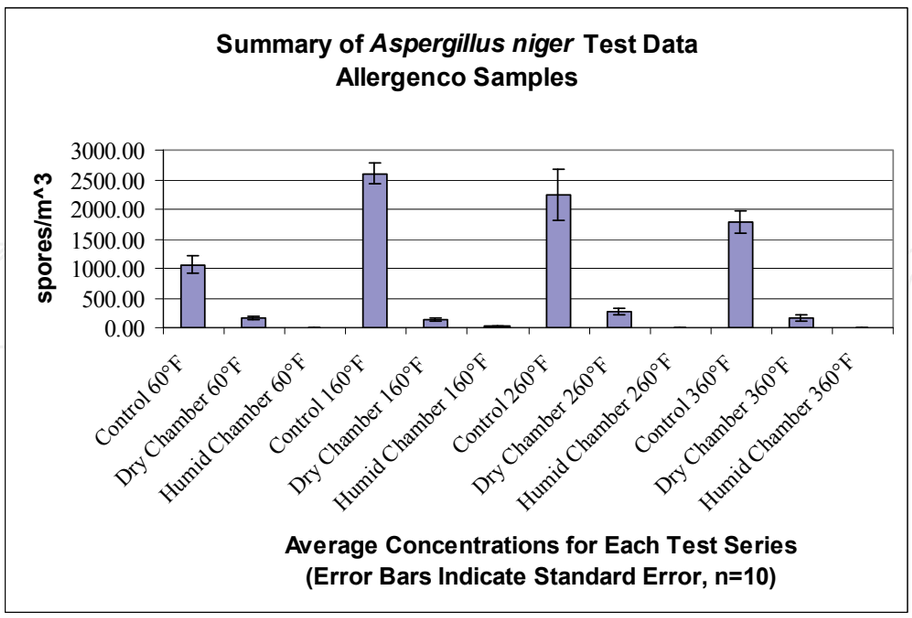


Fig. 13. Average airborne concentrations for *Aspergillus niger*-Allergenco Microbial Air Sampler tests

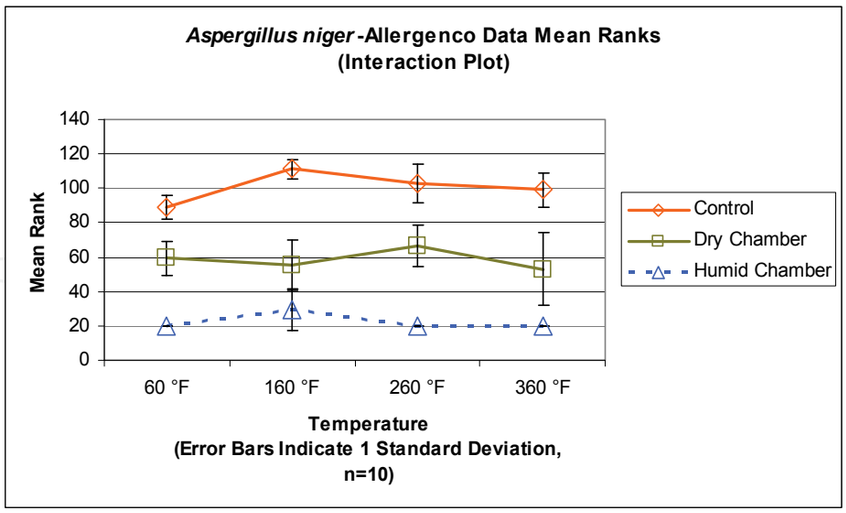


Fig. 14. Interaction Plot for the *Aspergillus niger*-Allergenco Microbial Air Sampler Data Mean Ranks.

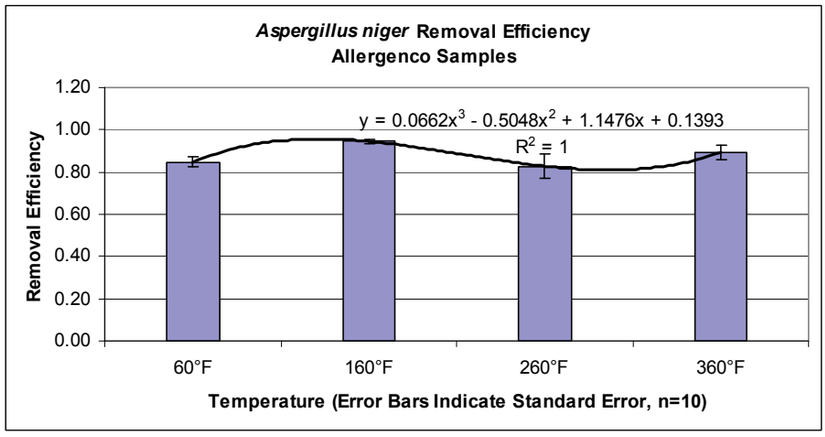


Fig. 15. *Aspergillus niger* Removal Efficiencies for Allergenco samples.

5.3.2 Cladosporium cladosporioides-Allergenco

Post hoc analysis using the SNK test for rank value showed that measured airborne concentrations were not significantly different. The SNK grouping for the positive control (μ_P) vs. dry chamber test (μ_{T1}) vs. humid chamber test (μ_{T2}) showed that the controls were significantly different from the dry chamber and humid chamber results at each temperature setting. The power of the *Cladosporium cladosporioides*-Allergenco Microbial Air Sampler analysis for control vs. dry and humid chamber results is greater than 0.99. Fig. 16 summarizes the *Cladosporium cladosporioides*-Allergenco Microbial Air Sampler data sets. Post hoc analysis using the SNK test for rank value showed that measured airborne concentrations were not significantly different at the four temperatures. The results showed that there was interaction between the dry chamber and humid chamber data sets, there was no difference in the ranks due to temperature, and there was a significant difference between the mean ranks of the positive control (μ_P) and the mean ranks of the dry (μ_{T1}) and humid chamber tests (μ_{T1}).

The mean removal efficiencies are shown in Fig. 17 and is described by the equation 'y = $-0.033x^3 + 0.22x^2 - 0.4149x + 0.9267$' with a correlation coefficient (R^2) of one.

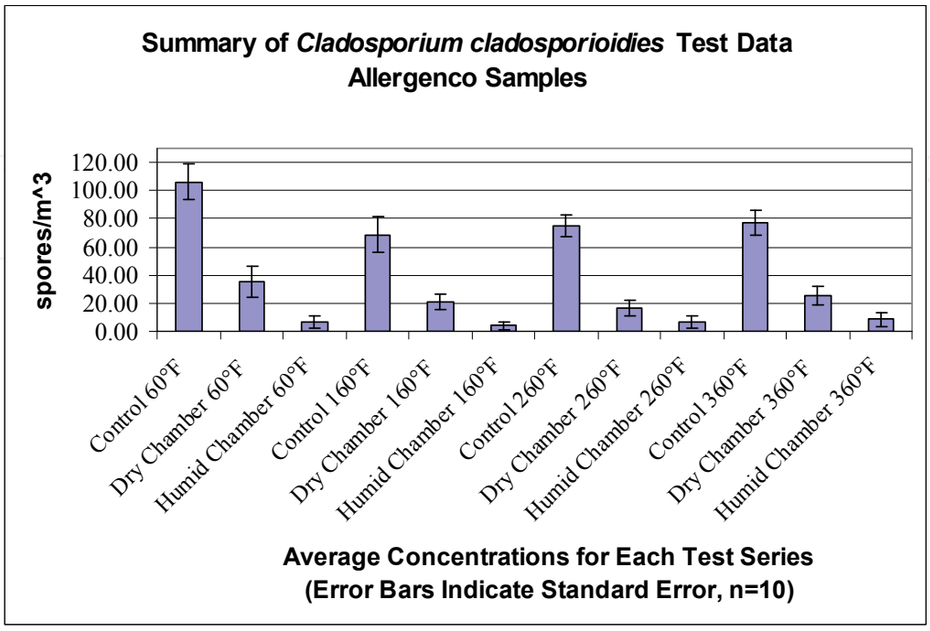


Fig. 16. Average airborne concentrations for *Cladosporium cladosporioides*–Allergenco Microbial Air Sampler tests.

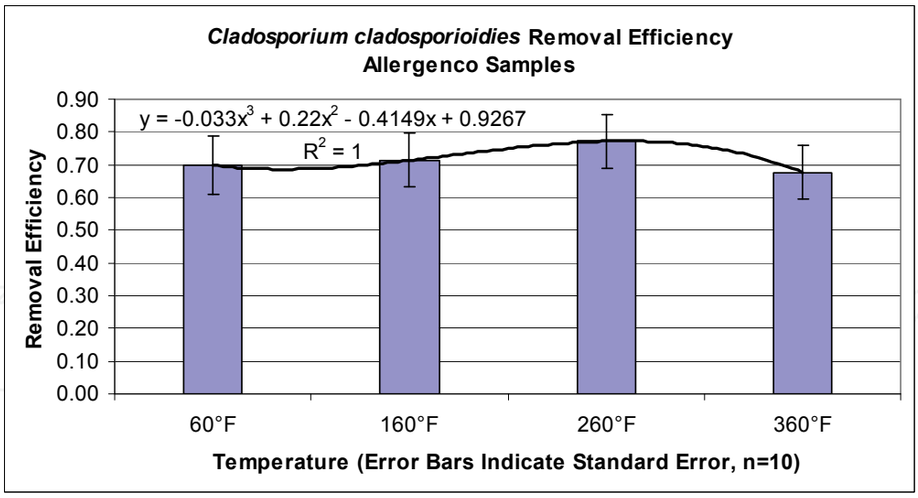


Fig. 17. *Cladosporium cladosporioides* Removal Efficiencies for Allergenco Samples.

5.3.3 *Penicillium chrysogenum*-Allergenco microbial air sampler data analysis

Post hoc analysis using the SNK test for rank value showed that measured airborne concentrations were significantly different at 360°F (182°C). The three remaining temperatures (60°F (16°C), 160°F (71°C), and 260°F (126°C)) were not statistically different. The SNK grouping for the positive control (μ_P) vs. dry chamber test (μ_{T1}) vs. humid chamber test (μ_{T2})

showed that the controls were significantly different from the dry chamber and humid chamber results at each temperature setting. The power of the *Penicillium chrysogenum*-Andersen Impactor analysis for a temperature effect was 0.55, while the power of the analysis for control vs. dry and humid chamber results was greater than 0.99. Fig. 18 summarizes the *Penicillium chrysogenum*-Allergenco Microbial Air Sampler data sets. The results showed that there was no interaction between that humid chamber and dry chamber data sets, there was a difference in the ranks due to temperature, and there was a significant difference between the mean ranks of the positive control (μ_P) and the mean ranks of the dry chamber test (μ_{T1}). The mean removal efficiencies are shown in Fig. 19 and can be described by the equation 'y = $0.0844x^3 - 0.7017x^2 + 1.9039x - 0.9933$' with a correlation coefficient (R^2) of one.

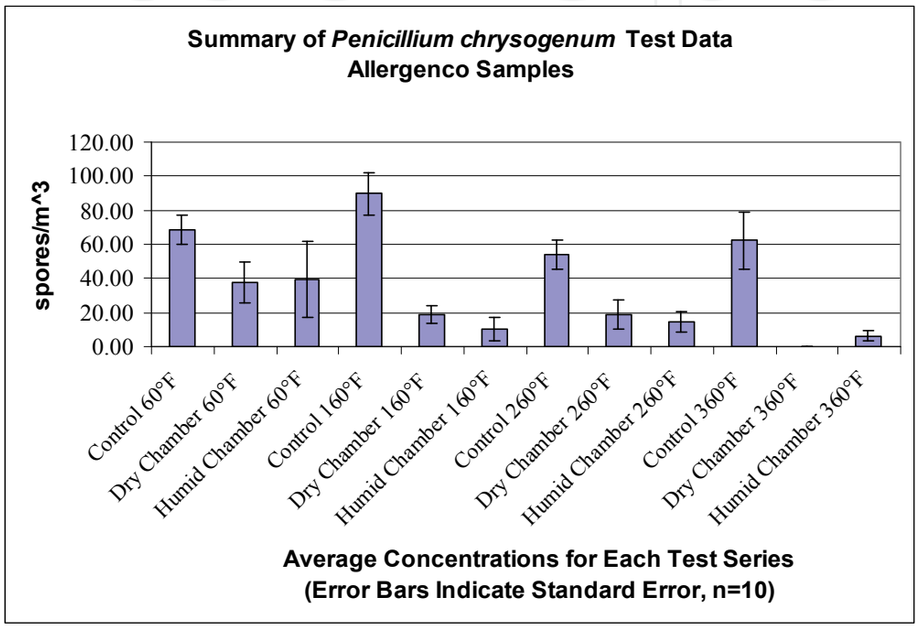


Fig. 18. Average airborne concentrations for *Penicillium chrysogenum*–Allergenco Microbial Air Sampler tests.

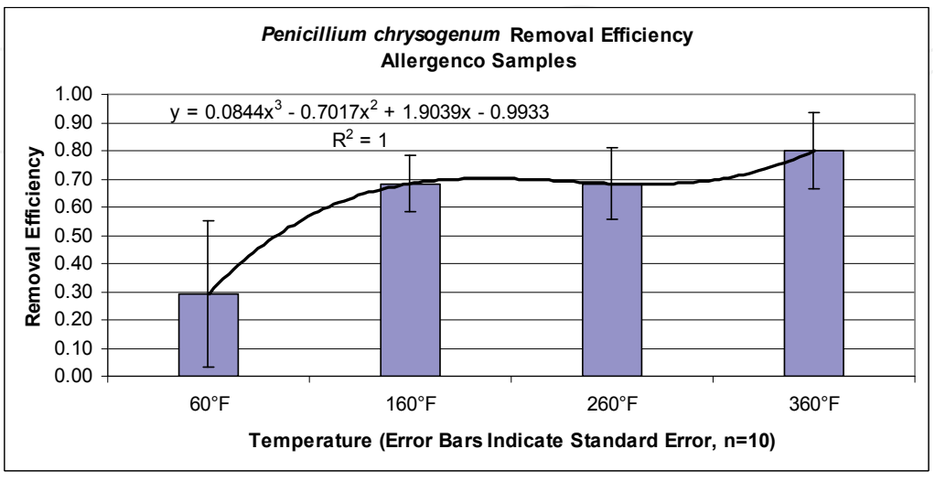


Fig. 19. *Penicillium chrysogenum* Removal Efficiencies for Allergenco Samples

5.4 Combined removal efficiencies for Andersen impactor data

The combined removal efficiencies of *Aspergillus niger, Cladosporium cladosporioides*, and *Penicillium chrysogenum* are summarized in Fig. 20 and can be explained by the polynomial regression equation 'y = -0.0132x^3 + 0.0912x^3 – 0.1913x + 0.8744' with a correlation coefficient of one.

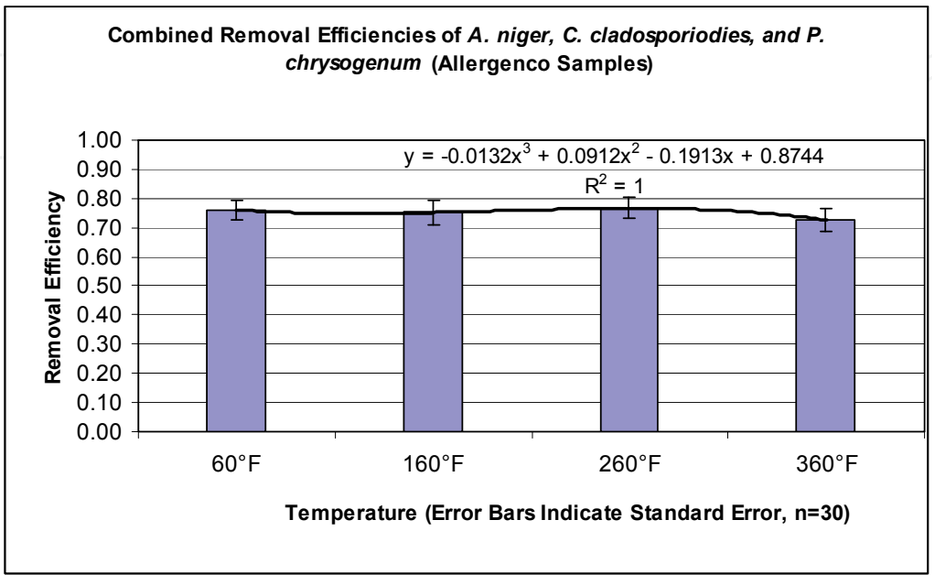


Fig. 20. Combined removal efficiencies of the *Aspergillus niger, Cladosporium cladosporioides, and Penicillium chrysogenum*–Allergenco Microbial Air Sampler data sets.

6. Summary of findings

The overall results of the hypothesis testing are summarized in Table 3. In all cases, the positive control (μ_P) was significantly greater than the dry chamber (μ_{T1}) results. Differences in temperature were found with the *Aspergillus niger* and *Penicillium chrysogenum* Allergenco data sets. Interaction was found within the *Aspergillus niger* data sets for both the Andersen Impactor and Allergenco Microbial Air Sampler.

Interaction of the *Aspergillus niger* data sets occurred in both cases between the mean ranks of the dry and humid chambers (μ_{T1} and μ_{T2}). Significant interaction did not occur between the mean ranks of the positive control and the mean ranks of the dry chamber test ($\mu_{P>}\mu_{T1}$), which were the parameters of interest when determining removal efficiencies and airborne concentrations delivered indoors. Differences due to temperature were identified within the *Aspergillus niger*-Allergenco Microbial Air Sampler data sets. See Table 3 above for the SNK grouping. A difference in temperature was also identified by the *Penicillium chrysogenum*-Allergenco Microbial Air Sampler data analysis with a statistical power (P) is 0.55, which is less than the commonly accepted value of 0.8. This means that there is 55% confidence that the temperature effect exists and a 45% confidence that the temperature effect does not exist. See the SNK grouping in Table 3 above. This indicates that the desiccant wheel may be more efficient at removing *Penicillium chrysogenum* spores from the airstream at 360°F (182°C). In both cases, the temperature difference occurred at one or both of the extremes of

the temperature settings; the *Aspergillus niger*-Allergenco Microbial Air Sampler analysis showed that the total spore concentrations at 60°F (16°C) and 360°F (182°C) were different from those concentrations at 160°F (71°C) and 260°F (127°C), and the *Penicillium chrysogenum*-Allergenco Microbial Air Sampler analysis showed that the total spore concentrations at 360°F (182°C) were different from those concentrations found at 60°F (16°C), 160°F (71°C), and 260°F (127°C).

7. Discussion

The purpose of this research was to determine if the desiccant wheel was effective at removing statistically significant concentrations of IAQ-related microorganisms from the air it supplies to a building. In addition, the capabilities of the desiccant wheel at removing airborne concentrations of IAQ-related microorganisms at four separate temperature settings were explored. The purpose of exploring the removal capabilities at different temperature settings was to establish the mechanism of spore removal and generate prediction models of airborne removal efficiencies for the two sampling methods and three organisms tested. In two of the six two-factor analyses of variance, a temperature effects were significant.

In one instance the *Aspergillus niger*-Allergenco Microbial Air Sampler analyses showed that the mean of the ranks at 60°F (16°C) and 360°F (182°C) (60°F (16°C) and 360°F (182°C) were not statistically different) were statistically different from the mean of the ranks at 160°F (71°C) and 260°F (127°C) (160°F (71°C) and 260°F (127°C) were not statistically different). Both the 60°F (16°C) and 360°F (182°C) temperature settings were designed as controls to help determine the mechanism of spore removal by the desiccant wheel. This lack of a temperature effect between the two control temperatures indicates that the mechanism of removal was likely a mechanical filtration effect unaffected by the increasing magnitude of adsorption created by an increase in the reactivation temperature. This premise was supported by five of the six analyses. In the second instance of a significant temperature difference, the *Penicillium chrysogenum*-Allergenco Microbial Air Sampler analyses showed that the mean rank of the airborne concentrations at 360°F (182°C) was significantly different from the mean ranks at 60°F (16°C), 160°F (71°C), and 260°F (127°C), which were not statistically different (P=0.55). With a statistical power less than 0.8, however, the difference does not maintain the confidence necessary to validate the temperature effect. Therefore, the mechanism of removal appeared to be a mechanical filtration of spores resulting in a decrease in the airborne concentrations of viable and total concentrations of *Aspergillus niger*, *Cladosporium cladosporioides*, and *Penicillium chrysogenum* through the process air stream of the desiccant unit. The desiccant unit removed significant airborne concentrations of both viable and total spores for the three organisms in each of the six analyses. The results of this study showed that the desiccant unit significantly reduces the airborne concentrations of these organisms introduced into the indoor environment.

8. Conclusion

This study aimed to quantify the removal capabilities of a rotary wheel (honeycomb) solid-desiccant dehumidifier at removing selected IAQ-related fungal organisms from the airstream. For each organism, the reductions in airborne concentrations delivered to the dry chamber were significant. These results support the findings of several authors who have

stated that the use of active desiccant technology enhances the quality of the indoor air by helping to maintain comfort criteria (temperature, humidity and ventilation) (Meckler 1994; Kovak 1997; Fischer and Bayer 2003), removing particulates and bioaerosols from the air (Hines 1992a; Kovak 1997), and removing chemical pollutants from the air (Hines 1992c; Popescu and Ghosh 1999). This study demonstrates the ability of the desiccant unit to remove IAQ-related microorganisms from the air. In addition, the study shows the removal capabilities are significant at the four temperatures tested. The ability of active desiccants to remove particulates, bioaerosols, chemical pollutants, and water vapor from the airstream delivered to a building provides a unique opportunity to view active desiccant technology as a viable control strategy for enhancing and maintaining a favorable IAQ in cooling climates.

Mold and other factors related to damp conditions indoors are linked to increased asthma symptoms in asthmatics and coughing, wheezing, and upper respiratory tract symptoms in otherwise healthy people; and damp indoor conditions may be associated with the onset of asthma, as well as shortness of breath and lower respiratory illness in otherwise healthy children. The Institute of Medicine calls for studies that compare various ways to limit moisture or eliminate mold growth indoors and to evaluate whether interventions improve the health of occupants. This study provides a foundation for exploring the feasibility of integrating desiccation technologies into existing HVAC system design for cooling climates for improving the IAQ within the built environment.

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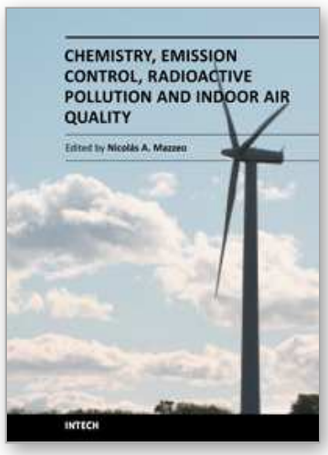
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The atmosphere may be our most precious resource. Accordingly, the balance between its use and protection is a high priority for our civilization. While many of us would consider air pollution to be an issue that the modern world has resolved to a greater extent, it still appears to have considerable influence on the global environment. In many countries with ambitious economic growth targets the acceptable levels of air pollution have been transgressed. Serious respiratory disease related problems have been identified with both indoor and outdoor pollution throughout the world. The 25 chapters of this book deal with several air pollution issues grouped into the following sections: a) air pollution chemistry; b) air pollutant emission control; c) radioactive pollution and d) indoor air quality.

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