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Submitted by

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DEDICATION

I would like to dedicate my thesis to my mother who always believed in me, supported me, and encouraged me during my whole life. If it was not for her sacrifice and her prayers, I could never be able to stay where I am standing today.

I also dedicate this thesis to my family including my wife, my two sons, and my in-laws, whose support and sacrifice enabled me to achieve one of my biggest goals in life.

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I would like to thank all the professors at Medical University of Ohio, whose knowledge encouraged me for three years to drive five hours in order to participate in classes.

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TABLE OF CONTENTS

INTRODUCTION

Background

Chemical laboratory hoods (chemical hoods) are important engineering control devices in research laboratories. Although chemical hoods have been in use for years, testing their performance is still a challenge for designers, manufacturers, and especially users. The ANSI/AIHA Z9.5-1992 (American National Standards Institute/American Industrial Hygiene Association, Laboratory Ventilation Standard) hood performance testing standard is often utilized. Using this method, the hood face is equally divided into grids. The air velocity is measured at the center of each of these grids using a velocity meter. An average face velocity is then calculated from the individual air velocities.

Unlike the ANSI/AIHA Z9.5 -1992 (ANSI-1992), the Occupational Safety and Health Administration (OSHA) standard (Occupational Exposure to Hazardous Chemicals in Laboratories, 29CFR 1910.1450), does not require any specific average face velocity. OSHA does mandate that all local exhaust ventilation, including chemical hoods, be functioning properly (OSHA does not define the functioning criteria)

Another method, the ANSI/ASHRAE 110-1995 (American National Standards Institute / American Society of Heating, Refrigerating, and Air Conditioning Engineers, Method of Testing Performance of Laboratory Fume Hoods) has been developed using tracer gas to test the chemical hood containment rather than average face velocity. The new ANSI/AIHA Z9.5-2003 standard (ANSI-2003) recommends a containment test method, such as the ASHRAE 110 test, be used for chemical hood performance evaluation.

Statement of Problem

The ANSI/ASHRAE 110-1995 (ASHRAE 110) tracer gas testing method was introduced in 1995 as an alternative to the traditional face velocity test method. In the ANSI-1992 test, the chemical hood performance is measured with the average face velocity, while in the ASHRAE 110 test method face velocity is not used. The ASHRAE 110 test method consists of several steps. The first step includes a local smoke test with smoke-generating substances such as smoke tubes. The second step includes releasing large volumes of smoke into the chemical hood with a smoke machine. In the third step, sulfur hexafluoride (SF6) tracer gas flows into the chemical hood through a specially constructed "ejector" and a detector (usually an infrared spectrophotometer) measures the SF6 concentrations outside the hood.

In 2003, ANSI issued a revised standard that stated adequate face velocity is necessary, but is not the only criterion to achieve acceptable performance of chemical hoods. This standard further states that face velocity alone is an inadequate indicator of the chemical hood performance and recommends a containment test method such as the ASHRAE 110 to be used in its place. The ASHRAE 110 test is an expensive test method that requires about $ 20,000 equipment and about $20 tracer gas for each chemical hood testing. One ASHRAE test requires approximately two hours. A thorough on-line search of the different institutions website (universities in particular) indicated that the ANSI-1992 method is still a popular method for the chemical hood performance evaluation since it only requires 10-15 minutes and about $2,000 equipment.

Additionally, the ANSI-1992 method does not always detect problems found using the ASHRAE 110 method. The case studies below provide examples of this issue.

Case 1

In 2002, a newly installed chemical hood was tested with the ASHRAE 110 test method. The initial test indicated an adequate average face velocity and therefore the chemical hood passed according to the ANSI-1992 criteria. However, this chemical hood failed the ASHRAE 110 test. Tracer gas testing indicated that high concentrations of the tracer gas could be detected even when the hood sash was in a fully closed position. After ruling out several possible scenarios, it was found that the hood exhaust stack was too close to the building air intake. The released tracer gas in the hood was re-entrained through the air intake and returned to the lab. Without the tracer gas test and by relying only on the face velocity results, the hood could have been in service and caused an over-exposure to chemical hazards.

Case 2

During another ASHRAE 110 test on a chemical hood in the hazardous material waste facility, high concentrations of the tracer gas were detected in the room. Investigation revealed that the hood exhaust duct had ruptured outside the room. Since the room pressure was kept negative to the outside, tracer gas was drawn back into room, causing the test failure. The chemical hood average face velocity was again adequate based on the ANSI-1992 method.

Case 3

In 2001, the ASHRAE 110 test was performed on 95 variable air volunme chemical hoods (VAV). Of these 95, four chemical hoods met the ANSI-1992 requirements, but failed to meet the ASHRAE 110 test criteria. It was found that the VAV control system on these four hoods was not functioning properly, resulting in a 15-30 second delay in adjusting the average face velocity. During this delay, face velocity was very low, causing the gas to leak form the hood into the room, and therefore causing the test failure.

Objectives

1. Determine whether the test results from the ASHRAE 110 and the ANSI-1992 methods were significantly different for the 484 tests performed on chemical hoods.
2. Determine whether the test results from the ASHRAE 110 and the ANSI-1992 methods were significantly different by hood type.
3. To identify possible predictors of the ASHRAE 110 test outcome for both variable air volume (VAV) and constant air volume (CAV) chemical hoods using logistic regression analysis.

Null Hypothesis

There is no significance difference between the test outcomes from the ASHRAE 110 and the ANSI-1992 methods

LITERATURE REVIEW

Types of Chemical Laboratory Hoods

The history of the chemical hoods can be traced back to Thomas Edison (Walters, 2001). Edison's chemical hood relied on the chimney effect to exhaust the toxic gases and vapors to the outside air. In general, chemical hoods are designed to capture, contain, and exhaust chemical gases/vapors to the outdoor environment (Deluca, 2003). The three types of hoods available for this study were:

Hood Testing

The ANSI -1992 method recommends that each chemical hood maintain an average face velocity of 80-120 fpm. Additionally, each individual measurement needs to be within 20% of the average.

There is a disagreement among different organizations about the adequate face velocity settings. This disagreement was cited in Neuman (2001) study as the weakness of the face velocity test. Neuman compared the chemical hood face velocity settings recommended by organizations such as OSHA, California OSHA (Cal. OSHA), National Research Council (NRC), Scientific Equipment and Furniture Association (SEFA), National Institute of Health (NIH), National Institute of Occupational Safety and Health (NIOSH), and American Conference of Governmental Industrial Hygienists (ACGIH). This comparison indicated that recommended face velocity among different organizations varies from a minimum of 60 feet per minute (fpm) to a maximum of 150 fpm *(Table I)*. OSHA does not mandate any specific face velocity for a chemical hood, but recommends an adequate face velocity range of 60-100 fpm (29 CFR 1910.1450(e)(3)(iii) and 29 CFR 1910.1450 App A).

Table I: **Chemical Hood Face Velocity Recommended by Several Organizations**

Organization	Face Velocity
OSHA	Should be "adequate," typically 60 to 100 fpm
Cal. OSHA	100 fpm (150 fpm for certain substances)
NRC	80 to 100 fpm (120 fpm for certain substances)
SEFA	100 (range of 75 to 125 fpm)
NIH	100 fpm
NIOSH	100 to 150 fpm
ACGIH	60 to 100 fpm

Some universities have also developed their own internal chemical hood certification programs, which are not consistent with the ANSI-1992 criteria. The Stanford University (2001) requires face velocity of 80 fpm at 15", with no individual measurement less than 70 fpm. The University of Toledo (2004) has established a target average face velocity of 100 fpm as acceptable face velocity.

In a historical perspective of laboratory chemical hoods by First (2003), the status of their structural design, operating characteristics, safety, energy conservation, and certification methods were studied. The major conclusions in this study were as follows:

1. In terms of hood design, by the end of the 1950s, hood designers were able to overcome the major hood design problems, and were able to develop hoods with minimum turbulent and acceptable capture.
2. New hood test methods were incomplete.
3. New designers have learned to conserve energy and cost.

4. Different organizations have recommended different face velocity settings, causing confusion among health and safety professionals and ventilation system designers about adequate face velocities.

First concluded that none of the current hood test protocols, including ASHRAE 110 and ANSI-1992, is able to estimate the risk associated with using a chemical hood. First also stated that the standard tests are only tools to differentiate between the well-designed hoods and hoods with inappropriate design.

In a study by Hampl (1984), a new technique using sulfur hexafluoride tracer gas (SF_6) was developed to evaluate the efficiency of the "local exhaust hoods." The major advantages of this method were explained as the "ability to measure directly the efficiency and minimum chance of cross contamination during the test" since SF_6 does not naturally exist in the air. This study was conducted prior to ASHRAE 110 being published.

Hitchings (1995) compared the ASHRAE 110 containment test and the traditional face velocity test results. The study explained that the best way to determine the exposure to chemicals during use of a chemical hood would be personal sampling, which is not feasible due to both cost and time. The second best way mentioned in this study was using ASHRAE 110 test method. After testing more than 160 chemical hoods, the author found a correlation of 15% between the tracer gas containment level and face velocity.

Hitchings (1996) used the ASHRAE 110 test method as a "total quality management (TQM) tool" to evaluate and improve "laboratory fume hood performance." In this study on the 46 chemical hoods, 50% of the chemical hoods with adequate face velocities based on the ANSI-1992, failed to meet the ASHRAE 110 criteria. Based on this finding, the author concluded that “face velocity alone is a very poor indicator of chemical hood containment” and it should be replaced with the ASHRAE 110 test method. This finding is in keeping with the Maupins stud (1998) that compared the ASHRAE 110 and the ANSI-1992 test methods and concluded that face velocity was not an accurate indicator of chemical hood performance.

Greenly (1999) studied the containment of occupied and unoccupied laboratory chemical hoods using both the ASHRAE 110 and the ANSI-1992 methods. This research studied the effect of the face velocity, sash height and hood loading on the hood containment for different sizes of the chemical hoods. While face velocity was kept within the ANSI-1992 requirements, 67% of the chemical hoods failed the containment test. The study concluded that although face velocity was an important factor in hood performance, it could not be considered as the only factor for hood performance evaluation. Greenly (2000) performed a similar study and concluded that factors other than face velocity may affect the chemical hood performance.

Ekberg (2000) used the ASHRAE 110 method to determine required response time for VAV hood controllers. This study concluded that if a VAV control system is not able to re-establish the face velocity within 1-2 sec after the hood sash is opened, an increased outward leakage of tracer gas would happen. Without using a containment test method such as ASHRAE 110, the hood failure due to late response of the control system cannot be detected. The face velocity test is just a static measurement, unable to detect defects such as control system response in VAV systems.

At the Environmental Protection Agency’s (EPA) “laboratories for the 21st century” conference (1999), Hichings presented the result of testing 366 chemical hoods using both the ASHRAE 110 and ANSI-1992 test methods. While 51% of the hoods at this study met the ANSI-1992 criteria, only 29% of the hoods passed the ASHRAE 110 test.

In June 1998, the Howard Hughes Medical Institute held a workshop on the performance of the chemical hoods. The report of the workshop was later published by DiBerandinis (2003). The workshop brought 24 experts in the field of laboratory chemical hoods to study the differences between the current test methods for the chemical hood performance evaluation. In the final statement of the workshop, the experts stated that face velocity alone is not a good predictor of hood containment.

Smith (2004) compared the results of the ANSI-1992 and the ASHRAE 110 tests on 1,671 chemical hoods. Test results indicated that 15% of the laboratory hoods operating at average face velocities between 80 - 120 fpm did not meet the ASHRAE 110 test method requirements. In addition, 51% of the hoods running at average face velocities below 80 fpm failed the ASHRAE 110 test method. The author stated that unlike the ANSI-1992 test, the ASHRAE 110 test method is able to evaluate the effects of the factors such as improper chemical hood / ventilation system design on hood performance.

Following the findings from several studies, in January 2003, the ANSI -2003 laboratory ventilation standard recommended that an adequate face velocity was necessary, but not the only criterion to achieve acceptable chemical hood performance and should not be used as the only performance indicator. As an alternative, the standard recommends a containment test such as the ASHRAE 110 test method. The ANSI-2003 standard also recommends that periodic face velocity test be performed to check any deviation form the benchmark face velocity (face velocity at which the chemical hood passed the containment test). Some of the governmental and non-governmental institutions have adopted the ASHRAE 110 test protocol for the chemical hood testing. National Institute of Health (NIH), California OSHA, and Scientific Equipment and Furniture Association (SEFA) are the major institutions, which have adopted the ASHRAE 110 test method or a modified form of this standard.

MATERIAL

In a 4-year study (2001-2004), a total of 484 ASHRAE 110 tests were performed on chemical hoods. The same number of the tests was performed using the ANSI-1992 method (on same chemical hoods). The chemical hoods included in this study were located in research laboratories, located at a large university in Northeast Ohio. There were three types of the chemical hoods tested in this study:

1. *Constant Air Volume hood (CAV)* or standard hood has a constant exhausted air regardless of the sash height. Therefore, the face velocity of a CAV hood is inversely proportional to the sash height, so that the lower the sash height, the higher the face velocity. CAV hoods are hoods with an average designed face velocity of 100 foot per minute (fpm) at a 25 inch sash opening (or fully open).
2. *Variable Air Volume hood* (VAV) is a hood with a control system that maintains a relatively constant face velocity (100 fpm) at all sash openings. As sash height is decreased, a control valve will close a damper and maintain a constant face velocity.
3. *Low flow hood* is newer designed CAV hood with an average face velocity of 60-70 fpm at fully open sash position (25”-30”). The main purpose of this new design is to reduce the energy cost through reducing the quantity of conditioned exhaust air.

The majority of these chemical hoods were between 4 to 8 feet wide with a maximum sash opening between 25 to 30 inches.

Equipment

All equipment was maintained and used in accordance with the manufactures’ instructions.

- Disposable Dräger air current tubes no. CH25301 and squeeze bulb.
- Anemometer: Two TSI hot wire anemometers, Model 8360, for hood face velocity measurement.
- A Gem Sound large volume smoke generator model 970-1269.
- Printer: A small TSI portable printer model 8925 to print velocity data from anemometers.
- MIRAN Sapphire 205B Series IR spectrophotometer and accessories, including charger and connecting cables and hoses.
- An ASHRAE 110 test mannequin with a tripod, adjustable to different heights.
- A gas diffuser (ejector) with a standard orifice, designed to release 4 liters per minute (4 L/min) of gas at 30 pounds per square inch (PSI). Diffuser was purchased from the Exposure Control Technologies, Inc.
- Sulfur Hexafluoride (SF_6) gas cylinder.
- Miscellaneous items such as stickers for operable sash height marking, tape measure, fog fluid, forms, particulate and chemical cartridges for instrument protection and zero adjustment, and a cart for equipment setup and transportation.

METHODS

Experimental Procedures

Experimental procedures were based on the ASHRAE 110 (tracer gas) and the ANSI-1992 (face velocity) test methods. For Low Flow hoods, face velocity test was performed based on the university internal operating procedure (IOP) at which 60 fpm is considered as adequate face velocity. Each of the individual tests on a chemical hood at different sash heights was considered as an independent new test in the study. Based on the university chemical hood program, the minimum sash opening was 15 in and if the hood could not pass the test at this height, it was rated as "inoperative." Experimental process included the following steps:

Step One: Face Velocity Measurement

Using a factory calibrated TSI hot wire anemometer, average face velocity was measured at either a fully open or 25 in sash height (in year 2003, test protocol was changed form measurement at 25 in to fully open). Sash openings were equally divided into 9 grids for 4 ft and 5 ft hoods (width) and 12 grids for more than 5 ft width. Face velocity was measured at the center of each grid by holding the probe in the plane of the hood face. For each measurement, the probe was held until an accurate reading, without fluctuation, could be measured. Each individual measurement and the average face velocity calculated by the anemometer were stored in the measuring device. A listing of these measurements was printed and the hood number and sampling date were recorded on the printout.

Step Two: Local Visualization Test

Once the face velocity was measured, a local visualization test was conducted to determine air movement patterns within the hood. First, both ends of a Dräger air current tube were opened and one end inserted into a rubber squeeze bulb. Smoke was then run under the air foil (an inward angled metal frame at the bottom of the chemical hood face opening to minimize turbulence and to provide smooth air movement into the hood), along the walls, in an 8 in diameter circle inside the chemical hood on the back wall, around the face opening (6 in inside the hood), and along the equipment inside the chemical hood. If any smoke escaped form the chemical hood, the chemical hood failed the test. When a chemical hood failed, the sash was lowered 5 in and the test was repeated again, starting with step one.

Step Three: Large Volume Visualization Test

Once a hood passed the local visualization test, a large volume smoke test was performed. Using a 4 in diameter flexible hose, a large volume of smoke was released 6 in behind the sash within the hood. If smoke escaped from hood, the chemical hood failed the test. When a chemical hood failed, the hood sash was lowered 5 inches and the test was repeated starting from step one. If the sash was already at 15 inches, the chemical hood was posted as inoperative and testing was discontinued.

Step Four: Static Tracer Gas Test

After the chemical hood passed all previous steps at a specific sash height, the static tracer gas test was performed to continue on hood containment assessment. First, the tracer gas ejector was placed inside the chemical hood, 12 in from the left wall of the hood and 6 in from the sash *(Figure 1)*. The sample probe of the spectrophotometer was connected through the mannequin's breathing zone with the mannequin standing outside the chemical hood in line with the ejector. The mannequin height from the center of the probe to the hood work surface was always kept at 18 in and the distance between the probe and hood sash was 3 in. In accordance with the ASHRAE 110 method, the SF_6 tracer gas was released at 4L/min rate, inside the hood for five minutes while the spectrophotometer continuously sampled for tracer gas through the probe in the mannequin's breathing zone. When the 5 min average concentrations for SF_6 was equal or less than 100 parts per billion (PPB) at the left location (ASHRAE 110 requirement), tracer gas ejector was moved to the center of the hood and 6 in behind the sash with the mannequin standing outside the hood in line with ejector. Mannequin's height and distance from the sash was adjusted same as the left location. Then tracer gas was released for another 5 min while the spectrophotometer continuously sampled for SF_6 through the probe in the mannequin's breading zone. When the five minutes average concentrations for SF_6 was equal or less than 100 PPB at the center location, test was performed at the right side of the chemical hood. For right location, ejector was placed inside the hood, 12 in from the right wall of the hood and 6 in behind the sash. The mannequin was kept also outside the hood in line with the ejector, at same height and distance (from sash) as the left and center location. Tracer gas was released inside the hood for another 5 min while the spectrophotometer continuously measured for SF_6 through the probe in the mannequin's breathing zone.

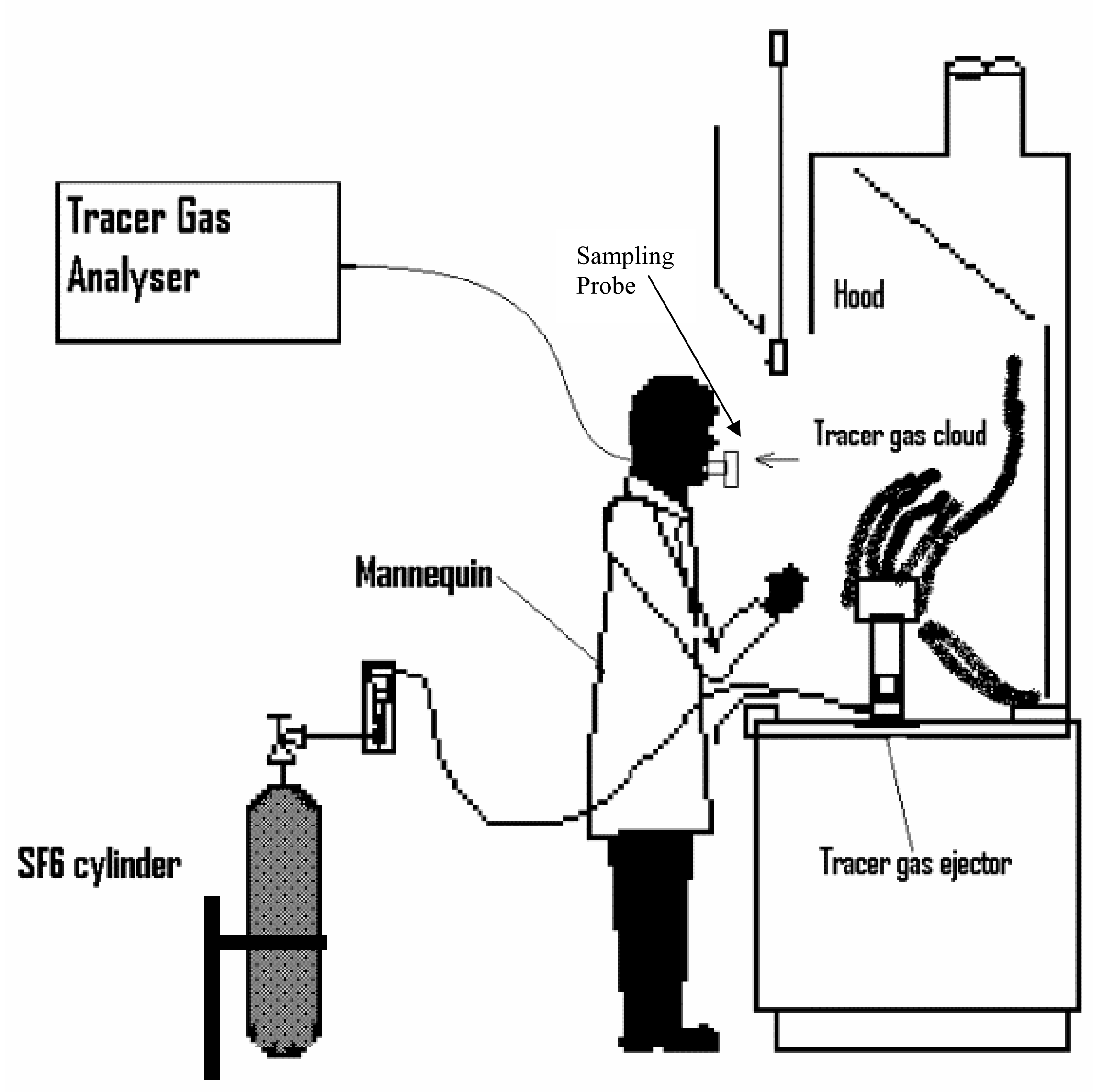

Figure1: The ASHRAE 110 Test Setup.

When the 5 min average concentrations for SF_6 was equal or less than 100 PPB at the right location, hood passed the static test. When a chemical hood failed the static test at any of left, center, or right locations, the sash was lowered 5 in and the test was repeated starting from step one. If the sash was already at 15 in, the hood was posted as inoperative and testing was discontinued (*Figure 2*).

Step Five: Dynamic Tracer Gas Test

Once a chemical hood passed all phases of the static tracer gas test at a particular sash height (15 in or above), a dynamic tracer gas test was conducted then as the final step for the hood certification. For the dynamic test, the ejector was placed inside the hood at the center location. As in static test, the mannequin was placed outside the hood in line with the ejector. In the first phase of the dynamic test, the sash was fully closed and SF_6 was released inside the hood for 2 min. Then the sash was raised up (to the sash height at which previous phases of test were successfully completed) while SF_6 continued to flow for another 2 min. This cycle was repeated twice more through a total of three closed and three open positions. The dynamic test then ended with a final 2 min with the sash in the closed position. If the average SF_6 concentration at any step of the dynamic test exceeded 100 PPB, the chemical hood failed and test was repeated starting from step one with the sash height 5 in lower. If the sash height was already at 15 in, the hood was posted as inoperative and testing was discontinued.

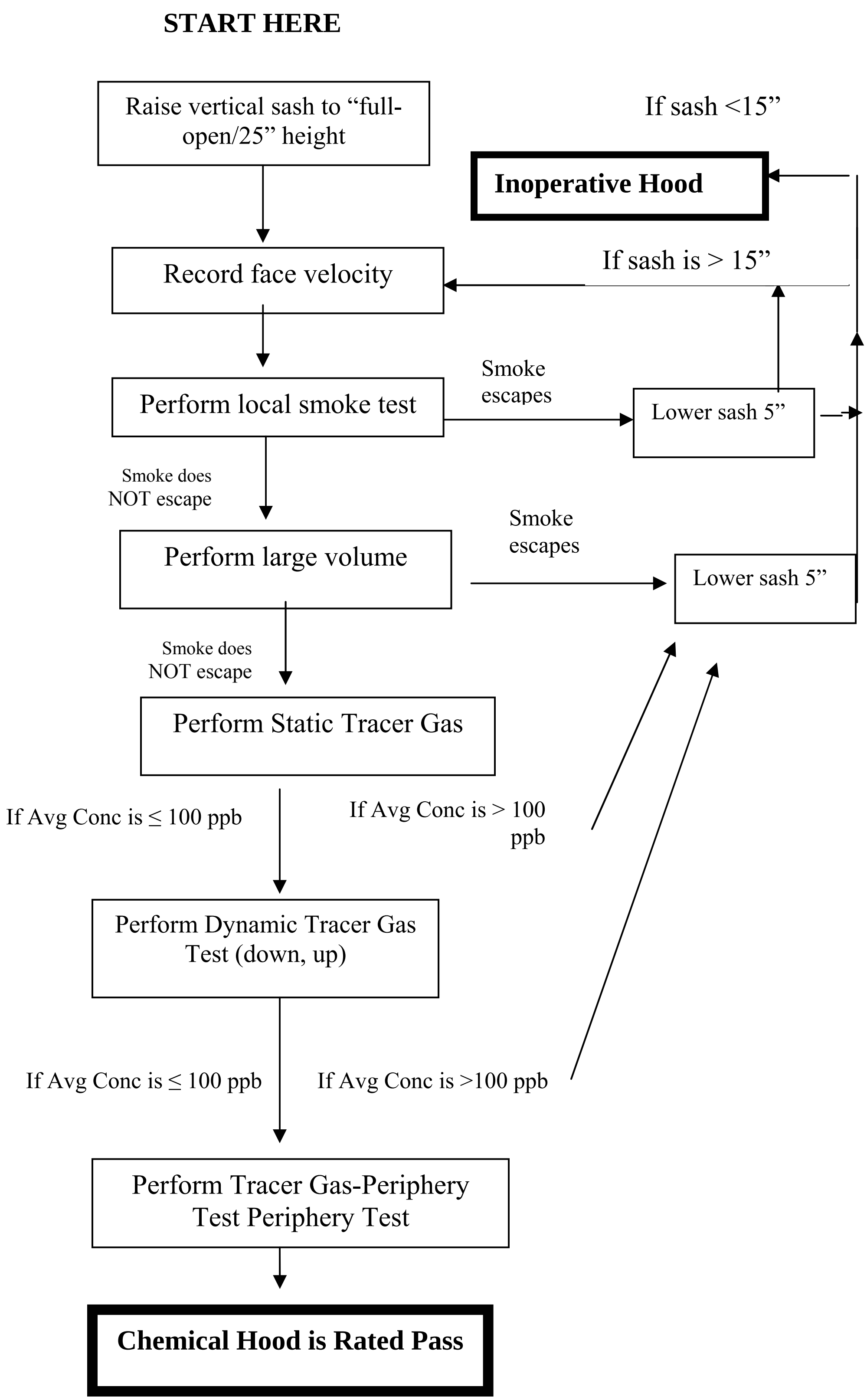

Figure 2: The ASHRAE 110 Test Flow Chart

Other Data Collection

During each test, there were several other recorded observations. A peripheral tracer gas test was one of these observations at which the mannequin was removed and the ejector was placed at the center of the hood. While tracer gas was releasing, the sample probe was traversed around the hood periphery and 1 in outside the hood for two minutes. The maximum leak concentration and location of the leak was recorded. According to the ASHRAE 110 test standard, the peripheral test result is only used to study the movement of the gas around the hood periphery and has no value for hood performance evaluation. Other observations such as type of the chemical hood, cross drafts, existence of the air foil, and location of the air diffusers in the room were manually recorded and entered in the database.

Data Entry

All collected data were manually entered in the FileMaker Pro, version 6.0-2001 database. The quality and accuracy of the data was controlled by internal audits and an annual audit by an external safety committee. Before using the database for the current study, all hard copies were matched with the data in computer to make sure that there were no mistakes during data entry. All incomplete tests were excluded from the study.

Data Analysis

A database containing the hood information was exported from FileMaker Pro version 6.0-2001 to Microsoft Excel and coded for statistical analysis. This database included the chemical hood number and type (VAV, low flow, and CAV), the ASHRAE 110 test outcome (pass/fail), average face velocity, four face velocity categories (<80 fpm, 80-120 fpm, 121-150 fpm, and >150 fpm), and the ANSI-1992 test outcome (pass/fail). The database was imported then into the SPSS 10.0 (Statistical Packages for the Social Sciences) software for statistical analysis.

Initially, descriptive statistics were calculated, including the mean, minimum, and maximum of the average face velocities. These descriptive statistics were calculated separately for each of the individual hood types as well as for the CAV and VAV chemical hoods combined. The combined CAV and VAV variables could be then compared to results presented at other studies.

Additionally, the chi-square/Fishers Exact tests were used to determine the difference between the ASHRAE 110 test outcome (pass/fail) and the ANSI-1992 test outcome (pass/fail) for each of the individual hood types as well as for the VAV and CAV hoods combined. For each analysis, the difference between the two test methods was considered "significant," if the significance level (P value) was less than 0.05.

In the last statistical analysis, the logistic regression was used to determine significant predictors of the ASHRAE 110 test outcome for both CAV and VAV hoods. Logistic regression was used also to determine the best models for the ASHRAE 110 test outcome prediction. In this analysis, the ASHRAE 110 outcome (pass/fail) was considered as dependent variable while the ANSI-1992 outcome (pass/fail), velocity values (fpm), and categorized velocities (< 80 fpm, 80-120 fpm, 121-150 fpm, and > 150 fpm) were independent variables. To select the best prediction model, the following regression analysis outputs were used:

1. Model chi-square test was used to conclude the overall model significance. The model chi-square test compares the difference between each model, with a simple model with only intercept (all coefficients are zero). The P value indicates the statistical significance of this difference. A model was considered significant if significance level (P value) was less than 0.05.
2. Using the significance level (P value), significance of individual independent variables (ASHRAE 110 test outcome predictors) was found in each model. A variable was considered significant if P value was less than 0.05.
3. Using the Cox & Snell R square value, models fit (how well does the model fit the data) was determined. The closer the values of R square to one (maximum value), the better the fit of the model.
4. Standard error for regression coefficient (β) was used to select the best prediction model. Smaller standard errors mean more confidence in the precise coefficients estimation.
5. The likelihood ratio test (LR) was used to judge between competing models:

$$LR = \frac{-2\text{Log Likelihood}_{reduced} - (-2\text{ Log Likelihood}_{full})}{df}$$

Where:

$-2\text{LogLikelihood}_{reduced}$ = -2 log likelihood for model with one independent variable
$-2\text{ LogLikelihood}_{full}$ = -2 log likelihood for model with two independent variable
d.f = Degree of freedom

LR was compared to a chi square critical value with 1 degree of freedom (3.84 at p=0.05). If LR was greater than 3.84, it was concluded that the full model significantly explained the model better than the reduced model with only one variable.

RESULTS

Sample Description

A total of 968 tests were performed on chemical hoods located at a large university in Northeast Ohio, 484 using the ASHRAE 110 method and 484 tests the ANSI -1992 method on the exact same hoods. Each set of 484 tests included 108 tests on Low Flow chemical hoods (22.3%), 201 tests on VAV chemical hoods (41.5%) and 175 tests on CAV chemical hoods (36.2%), as shown in *Table II*. The face velocity for the Low Flow chemical hoods ranged from 48 fpm to 96 fpm with a mean (standard deviation) of 67 fpm (11 fpm). The face velocity for the VAV chemical hoods ranged from 47 fpm t0 183 fpm with a mean (standard deviation) of 110 fpm (24 fpm). For CAV chemical hoods, the face velocity ranged from 57 fpm to 197 fpm with a mean (standard deviation) of 111 fpm (29 fpm). *Table* III summarizes these face velocities.

Test Outcomes

1. VAV hoods

Overall, a failed test was recorded for 36 (18%) of the 201 tests on the VAV hoods using the ASHRAE 110 criteria. Using the ANSI-1992 criteria, a failed test was recorded for 104 (52%) of the 201 tests on VAV chemical hoods. These results are shown in *Table IV* and in *Figure 3*.

Table II: **Frequency Distribution by type of Chemical Laboratory Hood for Each Set of 484 Tests**

Chemical Laboratory Hoods	**Frequency**	**Percent (%)**
Low Flow chemical laboratory hoods	108	22.3
VAV chemical laboratory hoods	201	41.5
CAV chemical laboratory hoods	175	36.2
Total of chemical laboratory hoods	484	100

Table III: **Face Velocity distribution by Type of Chemical Laboratory Hood**

Chemical Laboratory Hoods	**Mean (sd)**	**Minimum (fpm)**	**Maximum (fpm)**
Low Flow chemical laboratory hoods	67 fpm (11 fpm)	48	96
VAV chemical laboratory hoods	110 fpm (24 fpm)	47	183
CAV chemical laboratory hoods	111 fpm (29 fpm)	57	197

Table IV: **Distribution of 201 VAV Chemical Laboratory Hoods Meeting the ASHRAE 110 and the ANSI-1992 Test Criteria**

Testing Criteria	**Pass (%)**	**Fail (%)**
ANSI-1992	97 (48%)	104 (52%)
ASHRAE 110	165 (82%)	36 (18%)

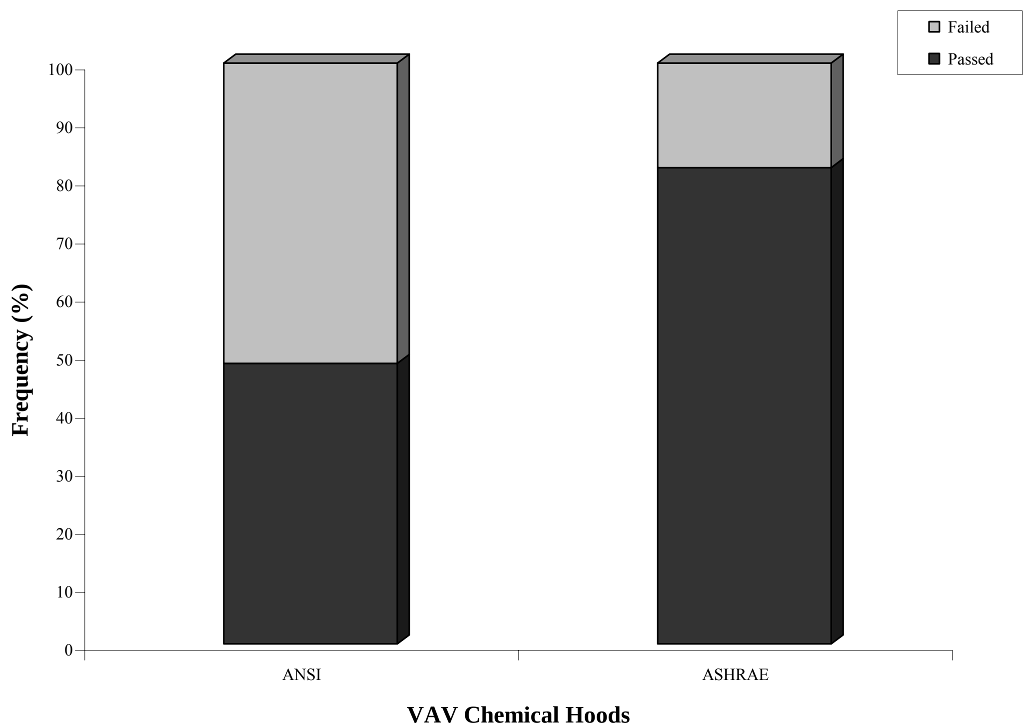

Figure 3: ANSI-1992 and the ASHRAE-110 Tests outcomes For 201 VAV Chemical Laboratory Hoods

For the 201 test outcomes from the ASHRAE 110 method and from the ANSI – 1992 method, 74 (37%) passed both sets of criteria while 13 (6%) failed both sets of criteria. *Table V* displays the 2 x 2 contingency table created to compare these test outcomes. Non-agreement for the two methods came from 91 tests passed using the ASHRAE 110 test criteria but not the ANSI -1992 criteria and from 23 tests that passed using the ANSI-1992 criteria but not the ASHRAE 110 criteria. The chi test for homogeneity for this 2 x 2 contingency table found a statistically significant difference in the test results between the two methods (χ = 4.248, $0.025<p<0.05$) as shown in *Table V*.

Table V. **Chi Test for Homogeneity Among VAV Hoods**

ASHRAE 110	**ANSI-1992**		***χ^2 and P***
	Pass (%)	Fail (%)	
Pass (%)	74 (37%)	91 (45%)	χ^2= 4.248 0.025<P<0.05 *
Fail (%)	23 (11%)	13 (6%)	

* Statistically significant since P<0.05

Separating the average face velocity for each of the 201 tests resulted in 13 (6%) tests having an average face velocity under 80 fpm, 138 (69%) having an average face velocity between 80 and 120 fpm (the ANSI-1992 recommended range), 35 (17%) having an average face velocity between 121 and 150 fpm, and 15 (8%) having an average face velocity greater than 150 fpm. *Table VI* and *Figure 4* display these frequency distributions. *Table VI* also displays the frequency distribution of each average face velocity category by ASHRAE 110 test outcome. For VAV hoods with average face velocities ranged 80-120 fpm, 80% (110 of 138) passed the ASHRAE 110 testing method, while only 38% (5 of 13) of the hoods with average face velocities less than 80 fpm passed the ASHRAE 110 testing method. These results are shown graphically in *Figure 5.*

Table VI: **Frequency Distribution for VAV Chemical Hoods of the ASHRAE 110 Test Outcomes by Face Velocity Category**

ASHRAE Outcome	**Face Velocity (fpm)**				
	<80 (%)	**80-120 (%)**	**121-150 (%)**	**>150 (%)**	**Total**
Passed	5 (38%)	110 (80%)	35 (100%)	15 (100%)	165 (82%)
Failed	8 (61%)	28 (20%)	0	0	36 (18%)
Total Hoods	13 (6%)	138 (69%)	35 (17%)	15 (8%)	201 (100%)

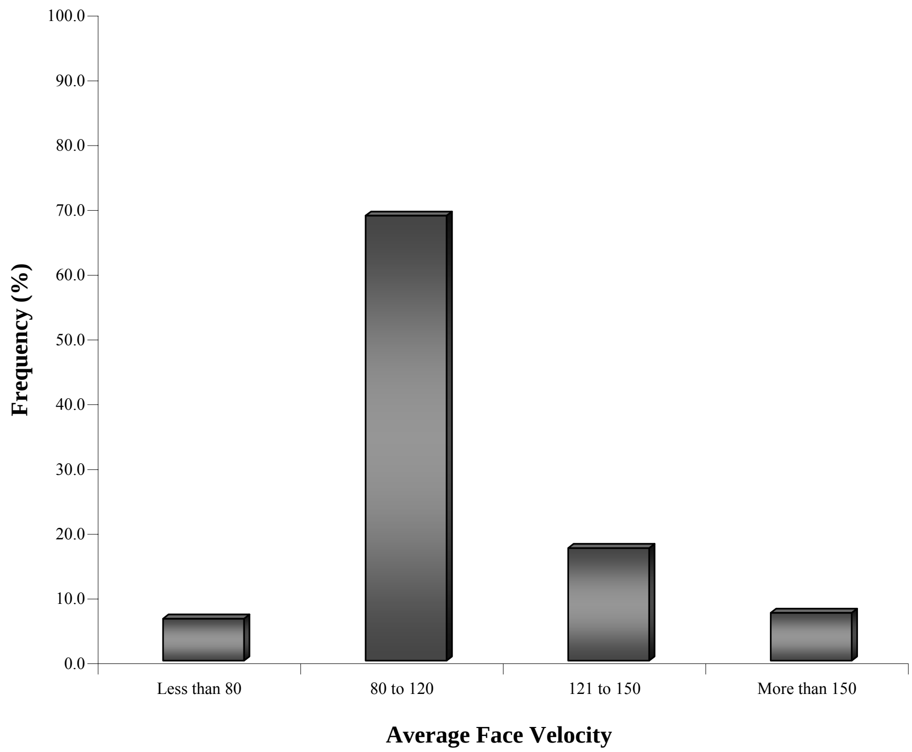

Figure 4: Frequency Distribution for VAV Chemical Hoods by Average Face Velocity Category.

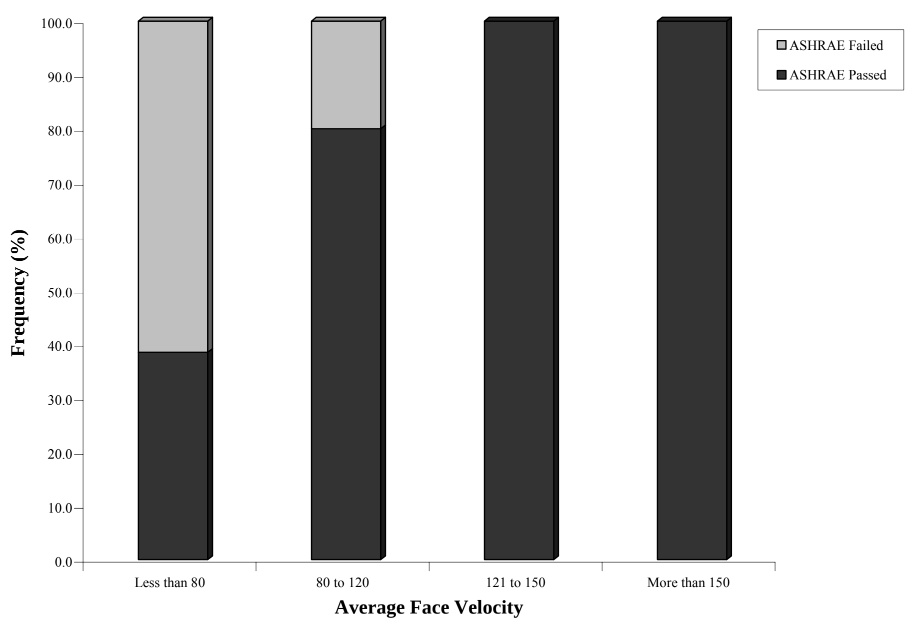

Figure 5: Cumulative Frequency for VAV Chemical Hoods Based on ASHRAE 110 for VAV Chemical Hoods by Average Face Velocity Category

In logistic regression analysis for VAV chemical hoods, the ASHRAE 110 test outcome was considered as dependent variable. The ANSI-1992 test outcome (ANSI), face velocity value (velocity), and face velocity categories (velcat) were also considered as independent variables. For single independent models (e. g., ASHRAE = Velocity), the analysis result indicated that all three independent variables (one independent variable in each model) were significant predictors of the ASHRAE 1110 test outcome ($P<0.05$). The chi-square test of model significance also indicated that all three models were statistically significant. Comparing the regression analysis results for these three models, it was revealed that ASHRAE = ANSI model had the smallest Cox & Snell R square value, an indication of the model fit. Analysis did not indicate any significance difference between ASHRAE = Velocity and ASHRAE = Velcat models for ASHRAE 110 test outcome prediction. However, the ASHRAE = Velocity model had smaller standard error for regression coefficient (B). Smaller standard errors mean more confidence in the precise coefficients estimation. Negative regression coefficient for ASHRAE = ANSI model indicated that there was an inverse relationship between independent and dependent variables in this model. To develop mathematical equation for each model, logistic regression prediction formula was used:

$$\text{Log}\ (p/1\text{-}p) = b_{0} + (b_1\ x_1) + (b_2\ x_2) + \ldots + (b_k\ x_k)$$

Where:

P is probability of Y=1 (ASHRAE pass)
b_0 is constant or intercept
$b_{1\text{-}k}$ are the coefficients of predictors (independent variables)
$x_{1\text{-}k}$ are independent variables

The results of logistic regression analysis for single independent models are shown in *Table VII.*

Table VII: **Results of Logistic Regression Analysis for Dependent Variable: ASHRAE 110 in VAV Chemical Hoods (single independent variable)**

Models	*Independent Variables*	*Independent variables significance (P)* [7]	*B*[4]	*Standard Error*[5]	*C*[6]	*Model Significance (P)*[7]	*R square*[8]	*-2 Log*[9]
Velocity[1]	Velocity	**0.000**	0.062	0.013	-4.827	**0.000**	0.149	156.454
ANSI[2]	ANSI	**0.041**	-0.777	0.381	1.946	**0.038**	0.021	184.628
Velcat[3]	Velcat	**0.000**	2.239	0.524	-3.025	**0.000**	0.139	158.795

1. Face velocity values
2. ANSI-1992 test outcome
3. Four velocity categories
4. Regression coefficient of predictor (independent) variables
5. Standard error for coefficient
6. Constant or intercept
7. Significance level of chi-square test
8. Cox & Snell R square
9. -2 log likelihood for the model

Table VIII: **Results of Logistic Regression Analysis for Dependent Variable: ASHRAE 110 in VAV Chemical Hoods (combined effects of independent variables)**

Models	*Independent Variables*	*Independent variables Significance (P)*	*B*	*Standard Error*	*C*	*Model Significance (P)*	*R square*	*-2Log*
Velocity + Velcat	Velocity	**0.048**	0.041	0.021				
	Velcat	0.206	1.007	0.796	-4.746	**0.000**	0.156	154.794
ANSI + Velocity	ANSI	0.051	-0.839	0.458				
	Velocity	**0.000**	0.07	0.016	-5.059	**0.000**	0.167	152.302
ANSI + Velcat	ANSI	0.094	-0.797	0.475				
	Velcat	**0.000**	2.544	0.619	-3.091	**0.000**	0.153	155.665

***Table IX:* Results of Logistic Regression Analysis for Dependent Variable: ASHRAE 110 in VAV Chemical Hoods (interaction)**

Models	*Independent Variables*	*Independent variables Significance (P)*	*B*	*Standard Error*[5]	*C*	*Model Significance (P)*	*R square*	*-2 Log*
Velcat *Velocity	(Velcat *Velocity)	**0.000**	0.016	0.004	1.865	**0.000**	0.158	154.448
ANSI * Velocity	(ANSI* Velocity)	0.064	-0.007	0.004	1.894	0.061	0.017	185.441
ANSI *Velcat	(ANSI *Velcat)	**0.038**	-0.39	0.1	1.954	**0.034**	0.022	184.467

Applying the data from *Table VII,* the logistic regression equations were developed to express the relationship between independent and dependent variables:

For model ASHRAE = Velocity: ASHRAE = -4.827 + (0.062 * Velocity)

For model ASHRAE = ANSI: ASHRAE = 1.946 + (-0.777 * ANSI)

For model ASHRAE = Velcat: ASHRAE = -3.025 + (2.239 * Velcat)

In multivariable logistic regression models (with two independent variables), the chi-square test of overall model significance indicated that all three models were statistically significant ($P<0.05$). In ASHRAE = Velocity + Velcat and ASHRAE = ANSI + Velocity models, only velocity was found a significant ASHRAE 110 test outcome predictor. In ASHRAE = ANSI + Velcat model, only Velcat was found as a significant predictor. The Cox & Snell R square value for model fit did not reveal any difference between these three models. However, the Velocity + Velcat model had the lowest standard error for regression coefficients among other models. The results of the multivariable logistic regression analysis are shown in *Table VIII*. Applying the data from *Table VIII,* the logistic regression equations were developed to express the relationship between independent and dependent variables:

For model ASHRAE =Velocity + Velcat: ASHRAE = -4.746 + (0.041 * Velocity_1) + (1.007 * Velcat)

For model ASHRAE = ANSI + Velocity: ASHRAE = -5.509 + (-0.839 * ANSI) + (0.07 * Velocity)

For model ASHRAE = ANSI + Velcat: ASHRAE = -3.091 + (-0.797 * ANSI) + (2.544 * Velcat)

In interaction models, the chi-square test of overall model significance indicated that the ASHRAE = ANSI x Velocity model was not statistically significant. The interaction of ANSI and velocity (independent variable) was not a significant predictor in this model as well (P>0.05). Test of the overall model significance indicated that both ASHRAE = Velcat x Velocity and ASHRAE = ANSI x Velcat interaction models were statistically significant. Interaction of the independent variables in both models were also found significant (P<0.05). However, the Cox & Snell R square value indicated that the Velcat x Velocity interaction model was a better fit. Using the likelihood ration test (LR), the ASHRAE = Velocity (reduced model) and the ASHRAE = Velcat x Velocity competing models were compared to find the best fit model. The LR test revealed that adding Velcat to model did not improve the significance of prediction (LR<3.84) and ASHRAE =Velocity was more significant prediction model. The results of the interaction logistic regression analysis are shown in *Table IX*. Applying the data from *Table IX,* the logistic regression equations were developed to express the relationship between independent and dependent variables:

For model ASHRAE =Velocity * Velcat: ASHRAE = 1.865 + (0.016 * (Velocity * Velcat))

For model ASHRAE = ANSI *Velocity: ASHRAE = 1.894 + (-0.007 * (ANSI * Velocity))

For model ASHRAE = ANSI * Velcat: ASHRAE = 1.954 + (-0.397 * (ANSI * Velcat))

2. CAV chemical hoods

Overall, a failed test was recorded for 30 (17%) of the 175 tests on CAV chemical hoods using the ASHRAE 110 criteria. Using the ANSI-1992 criteria, a failed test was recorded for 119 (68 %) of the 175 tests on CAV chemical hoods. These results are shown in *Table X and Figure 6.*

For the 175 test outcomes from the ASHRAE 110 method and from the ANSI – 1992 method, 50 (29%) passed both sets of criteria while 24 (14%) failed both sets of criteria. *Table XI* displays the 2 x 2 contingency table created to compare these test outcomes. Non-agreement for the two methods came from 95 tests passed using the ASHRAE 110 test criteria but not the ANSI -1992 criteria and from 26 tests that passed using the ANSI-1992 criteria but not the ASHRAE 110 criteria. The chi test for homogeneity for this 2 x 2 contingency table did not find a statistically significant difference in the test results between the two methods (χ = 2.4, p= 0.122) as shown in *Table XI* .

Separating the average face velocity for each of the 175 CAV chemical hood tests resulted in 19 (11%) tests having an average face velocity under 80 fpm, 102 (58%) having an average face velocity between 80 and 120 fpm (the ANSI-1992 recommended range), 35 (20%) having an average face velocity between 121 and 150 fpm, and 19 (11%) having an average face velocity greater than 150 fpm. *Table X and Figure 7* display these frequency distributions. *Table XII* also displays the frequency distribution of each average face velocity category by ASHRAE 110 test outcome. For CAV hoods with average face velocities ranged 80-120 fpm, 84% (86 of 102) passed the ASHRAE 110 testing method, while only 58% (11 of 19) of the hoods with average face velocities less than 80 fpm passed the ASHRAE 110 testing method. These results are shown graphically in *Figure 8.*

Table X: **Distribution of 175 CAV Chemical Laboratory Hoods Meeting the ASHRAE 110 and the ANSI-1992 Test Criteria**

Testing Criteria	**Pass (%)**	**Fail (%)**
ANSI-1992	56 (32%)	119 (68%)
AHSRAE 110	145 (83 %)	30 (17%)

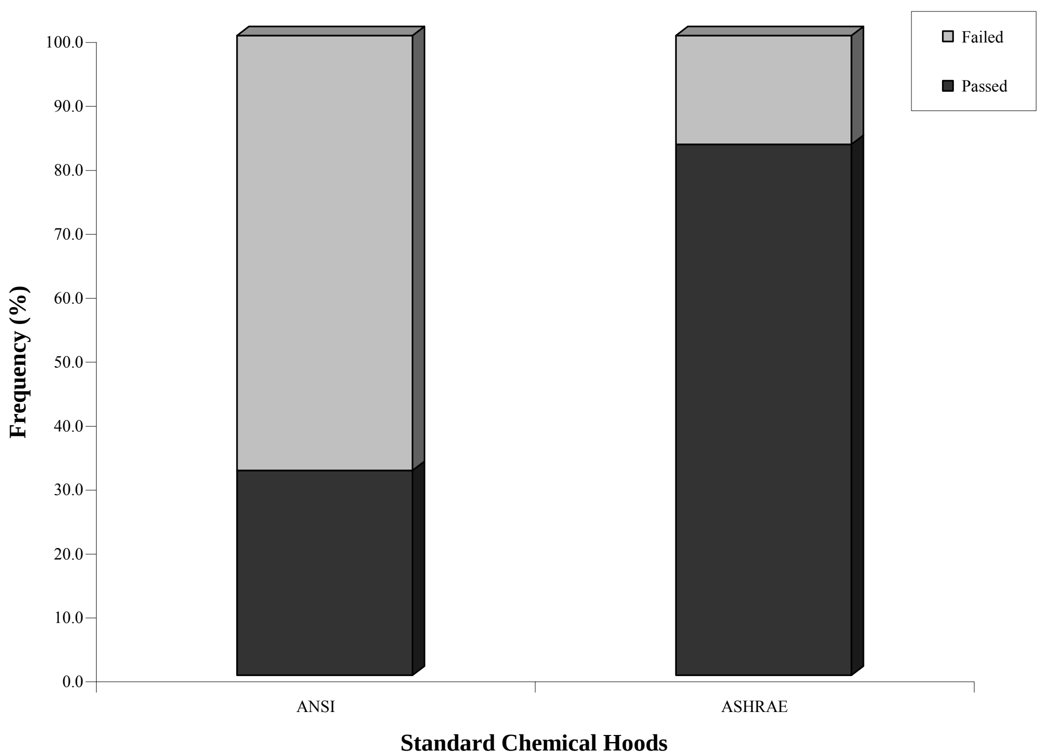

Figure 6: **ANSI-1992 and the ASHRAE-110 Tests Outcomes for 175 CAV Chemical Laboratory Hoods**

Table XI. **Chi Test For Homogeneity Among CAV Hoods**

ASHRAE 110	**ANSI-1992**		χ^2 ***and P***
	Pass (%)	Fail (%)	
Pass (%)	50 (29%)	95 (54%)	χ^2= 2.4
Fail (%)	6 (3%)	24 (14%)	P= 0.122

Table XII: **Frequency Distribution for CAV Chemical Hoods of the ASHRAE 110 Test Outcomes by Face Velocity Category**

Met ASHRAE Criteria	**Face Velocity (fpm)**				
	<80 (%)	**80-120 (%)**	**121-150 (%)**	**>150 (%)**	**Total**
ASHRAE Passed	11 (58%)	86 (84%)	29 (83%)	19 (100%)	145 (83%)
ASHRAE Failed	8 (42%)	16 (16%)	6 (17%)	0	30 (17%)
Total Hoods	19 (11%)	102 (58%)	35 (20%)	19 (11%)	175 (100%)

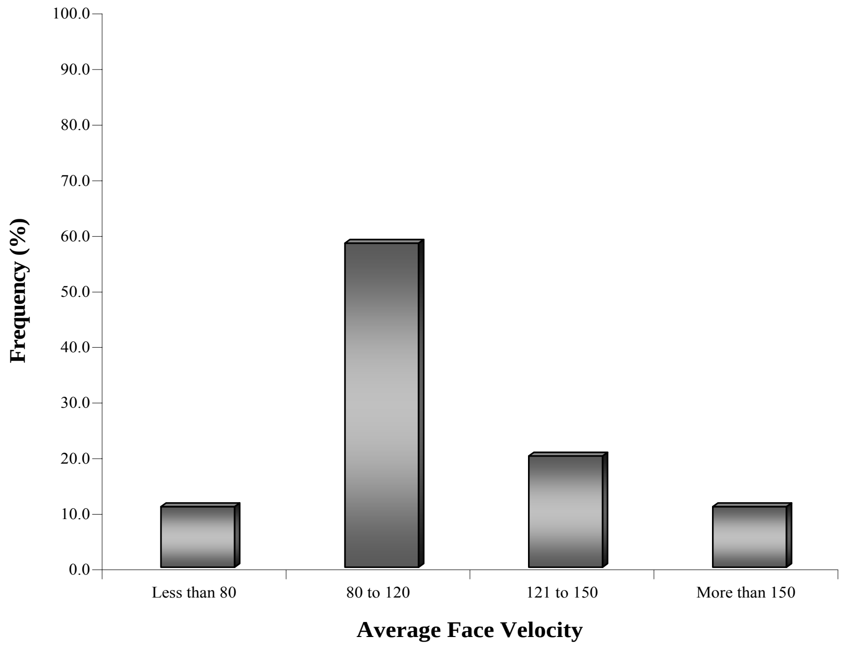

Figure 7: Frequency Distribution for CAV Chemical Hoods by Average Face Velocity Category.

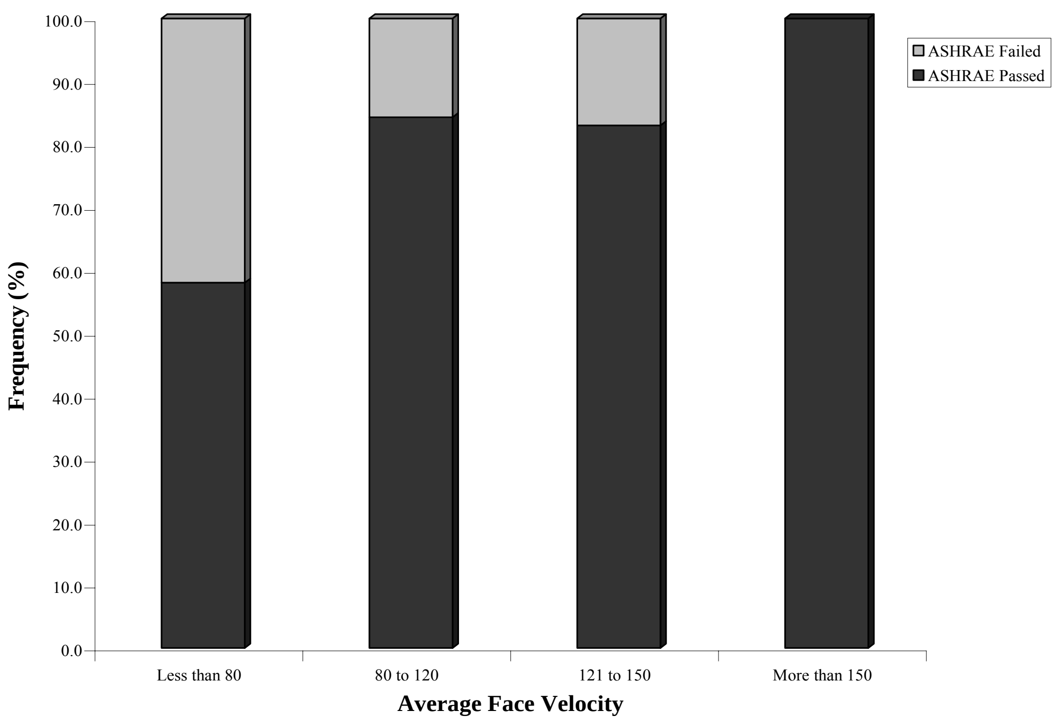

Figure 8: Cumulative Frequency for CAV Chemical Hoods Based on ASHRAE 110 for VAV Chemical Hoods by Average Face Velocity Category.

As for VAV chemical hoods, in logistic regression analysis for CAV chemical hoods the ASHRAE 110 test outcome was considered as dependent variable. The ANSI-1992 test outcome (ANSI), face velocity value (velocity), and face velocity categories (velcat) were also considered as independent variables. The analysis results indicated that in a single independent model (ASHRAE = ANSI), ANSI was not a significant predictor of the ASHRAE 1110 test outcomes ($P>0.05$). The chi-square test of model significance also indicated that the overall ASHRAE = ANSI model was not statistically significant. The chi-square test of model significance indicated that both ASHRAE = Velocity and ASHRAE = Velcat models were statistically significant. Comparing the regression analysis results for ASHRAE = Velocity and ASHRAE = Velcat models, it was revealed that both velocity and velcat were significant ASHRAE 110 predictors in a single independent model ($P<0.05$). However, the ASHRAE =Velocity model had larger Cox & Snell R square value (test of model fit) and smaller standard error for regression coefficient (B). Smaller standard errors mean more confidence in the precise coefficients estimation. To develop mathematical equation for each model, logistic regression prediction formula was used:

$$\text{Log}\ (p/1\text{-}p) = b_0 + (b_1\ x_1) + (b_2\ x_2) + \ldots + (b_k\ x_k)$$

Where:

P is probability of Y=1 (ASHRAE pass)
b_0 is constant or intercept
$b_{1\text{-}k}$ are the coefficients of predictors (independent variables)
$x_{1\text{-}k}$ are independent variables

The results of logistic regression analysis for single independent models are shown in *Table XIII.*

Table XIII: **Results of Logistic Regression Analysis for Dependent Variable: ASHRAE 110 in CAV Chemical Hoods (single independent variable)**

Models	*Independent Variables*	*Independent variables Significance (P)* [7]	*B* [4]	*Standard Error* [5]	*C* [6]	*Model Significance (P)* [7]	*R square* [8]	*-2 Log* [9]
Velocity[1]	Velocity	**0.015**	0.02	0.008	-0.559	**0.009**	0.038	153.515
ANSI[2]	ANSI	0.128	0.744	0.489	1.376	0.109	0.015	157.784
Velcat[3]	Velcat	**0.021**	0.688	0.297	0.052	**0.013**	0.035	154.141

1. Face velocity values
2. ANSI-1992 test outcome
3. Four velocity categories
4. Regression coefficient of predictor (independent) variables
5. Standard error for coefficient
6. Constant or intercept
7. Significance level of chi-square test
8. Cox & Snell R square
9. -2 log likelihood for the model

Table XIV**: Results of Logistic Regression Analysis for Dependent Variable: ASHRAE 110 in CAV Chemical Hoods (combined effects of independent variables)**

Models	*Independent Variables*	*Independent variables Significance (P)*	*B*	*Standard Error*	*C*	*Model Significance (P)*	*R square*	*-2 Log*
Velocity + Velcat	Velocity	0.297	0.014	0.014				
	Velcat	0.570	0.269	0.473	-0.518	**0.028**	0.067	153.164
ANSI + Velocity	ANSI	**0.042**	1.008	0.479				
	Velocity	**0.005**	0.022	0.008	-1.053	**0.003**	0.064	148.851
ANSI + Velcat	ANSI	**0.045**	0.992	0.495				
	Velcat	**0.007**	0.748	0.279	-0.367	**0.005**	0.060	149.583

***Table XV*: Results of Logistic Regression Analysis for Dependent Variable: ASHRAE 110 in CAV Chemical Hoods (interaction)**

Models	*Independent Variables*	*Independent variables significance (P)*	*B*	*Standard Error*	*C*	*Model Significance (P)*	*R square*	*-2Log*
Velcat *Velocity	(Velcat *Velocity)	**0.023**	0.004	0.002	0.611	**0.009**	0.038	153.571
ANSI * Velocity	(ANSI* Velocity)	0.153	0.007	0.005	1.389	0.134	0.013	158.105
ANSI *Velcat	(ANSI *Velcat)	0.128	0.372	0.244	1.376	0.109	0.015	157.784

Applying the data from *Table XIII,* the logistic regression equations were developed to express the relationship between independent and dependent variables:

For model ASHRAE = Velocity: ASHRAE = -0.559 + (0.02 * Velocity)

For model ASHRAE = ANSI: ASHRAE = 1.376 + (0.744 * ANSI)

For model ASHRAE = Velcat: ASHRAE = 0.052 + (0.688 * Velcat)

In multivariable logistic regression models (with two independent variables), all three models were statistically significant. However, in ASHRAE = Velocity + Velcat model, none of the independent variables were statistically significant (P>0.05). While there were no differences in overall model significance and individual independent variables significance for two ASHRAE = ANSI + Velocity and ASHRAE = ANSI + Velcat models, there were relatively larger Cox & Snell R square value (test of model fit) and smaller standard errors for coefficients in ANSI + Velocity model. Using the likelihood ration test (LR), the ASHRAE = Velocity (reduced model) and the ASHRAE = ANSI + Velocity competing models were compared to find the best fit model. The LR test revealed that adding ANSI to model improved the significance of prediction (LR>3.84) and ASHRAE =ANSI +Velocity was more significant prediction model. The results of the multivariable logistic regression analysis are shown in *Table XIV*. Applying the data from *Table XIV,* the logistic regression equations were developed to express the relationship between independent and dependent variables:

For model ASHRAE =Velocity + Velcat: ASHRAE = -0.518 + (0.014 * Velocity) + (0.269 Velcat)

For model ASHRAE = ANSI + Velocity: ASHRAE = -1.053 + (1.008 * ANSI) + (0.022 * Velocity)

For model ASHRAE = ANSI + Velcat: ASHRAE = -0.367 + (0.992 * ANSI) + (0.748 * Velcat)

In interaction models for CAV chemical hoods, the chi-square test of model significance indicated that only ASHRAE = Velcat x Velocity model was statistically significant. This model also was the only interaction model with significant independent variable ($P<0.05$). Analysis results also revealed that ASHRAE = Velcat x Velocity model had the highest Cox & Snell R square value (test of model fit) among other interaction models. The results of the interaction logistic regression analysis are shown in *Table XV* Applying the data from *Table XV,* the logistic regression equations were developed to express the relationship between independent and dependent variables:

For model ASHRAE =Velocity * Velcat: ASHRAE = 0.611 + (0.004 * (Velocity * Velcat))

For model ASHRAE = ANSI *Velocity: ASHRAE = 1.389 + (0.007 * (ANSI * Velocity))

For model ASHRAE = ANSI * Velcat: ASHRAE = 1.376 + (0.372 * (ANSI * Velcat))

<u>3. Low flow hoods</u>

Overall, a failed test was recorded for 35 (32%) of the 108 tests on low flow hoods using the ASHRAE 110 criteria. Using the university face velocity criteria (IOP), a failed test was recorded for 6 (6 %) of the 108 tests on Low flow chemical hoods. These results are shown in *Table XVI and Figure 9.*

Since expected variables (number of the fail/pass outcomes) in this test were less than five, was used to study the difference between two types of the test methods. The statistical analysis did not indicated any significant difference (P= 0.085) between the ASHRAE 110 and the ANSI-1992 test outcomes *(Table XVII).*

For the 108 test outcomes from the ASHRAE 110 method and from the university face velocity criteria, 71 (66%) passed both sets of criteria while 4 (4%) failed both sets of criteria. *Table 13* displays the 2 x 2 contingency table created to compare these test outcomes. Non-agreement for the two methods came from only two tests passed using the ASHRAE 110 test criteria but not the university face velocity criteria (IOP) and from 31 tests that passed using the university face velocity criteria (IOP), but not the ASHRAE 110 criteria. The Fisher's Exact test for homogeneity for this 2 x 2 contingency table (since expected values in 2 x 2 table were less than five, The Fisher's Exact test was used) did not find a statistically significant difference in the test results between the two methods (P= 0.085) as shown in *Table XVII.*

Table XVI: **Distribution of 108 Low Flow Chemical Laboratory Hoods Meeting the ASHRAE 110 and the University (IOP)* Test Criteria**

Testing Criteria	**Pass (%)**	**Fail (%)**
University Face Velocity (IOP)	102 (94%)	6 (6%)
ASHRAE 110	73 (68%)	35 (32%)

* University Internal Operating Procedure for Low Flow hoods at which 60 fpm was considered adequate face velocity

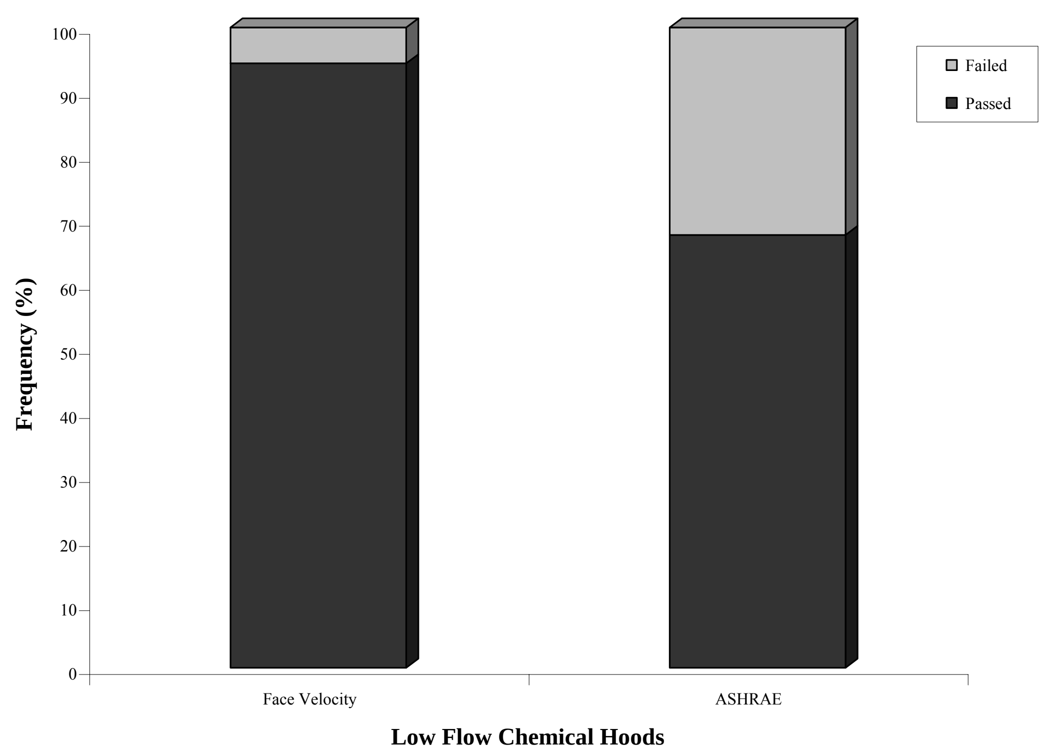

Figure 9: **University Face Velocity (IOP) and the ASHRAE-110 Tests Outcomes for 108 Low Flow Chemical Laboratory Hoods**

Table XVII. **Fisher's Exact Test for Homogeneity among Low Flow Hoods**

ASHRAE 110	IOP*		*P value*
	Pass (%)	Fail (%)	
Pass (%)	71 (66%)	2 (2%)	P= 0.085
Fail (%)	31 (29%)	4 (4%)	

* University Internal Operating Procedure for Low Flow hoods at which 60 fpm was considered adequate face velocity

4. VAV and CAV chemical hoods

Overall, a failed test was recorded for 66 (18%) of the 376 tests on VAV and CAV hoods combined, using the ASHRAE 110 criteria. Using the ANSI-1992 criteria, a failed test was recorded for 223 (59 %) of the 376 tests on VAV and CAV chemical hoods. These results are shown in *Table XVIII and Figure 10.*

For the 376 test outcomes from the ASHRAE 110 method and from the ANSI – 1992 method, 124 (33%) passed both sets of criteria while 37 (10%) failed both sets of criteria. *Table XIX* displays the 2 x 2 contingency table created to compare these test outcomes. Non-agreement for the two methods came from 186 tests passed using the ASHRAE 110 test criteria but not the ANSI -1992 criteria and from 29 tests that passed using the ANSI – 1992 criteria but not the ASHRAE 110 criteria. The chi test for homogeneity for this 2 x 2 contingency table did not find a statistically significant difference in the test results between the two methods (χ= 3.4, p=0.128) as shown in *Table XIX.*

Separating the average face velocity for each of the 376 VAV and CAV chemical hood tests resulted in 32 (8%) tests having an average face velocity under 80 fpm, 240 (64%) having an average face velocity between 80 and 120 fpm (the ANSI-1992 recommended range), 70 (19%) having an average face velocity between 121 and 150 fpm, and 34 (9%) having an average face velocity greater than 150 fpm. *Table XX* and Figu*re 11* display these frequency distributions. *Table XX* also displays the frequency distribution of each average face velocity category by ASHRAE 110 test outcome. For VAV and CAV chemical hoods with average face velocities ranged 80-120 fpm, 82% (196 of 240) passed the ASHRAE 110 testing method, while only 50% (16 of 32) of the hoods with average face velocities less than 80 fpm passed the ASHRAE 110 testing method. These results are shown graphically in *Figure 12.*

Table VXIII: **Distribution of 376 VAV and CAV Chemical Laboratory Hoods Meeting the ASHRAE 110 and the ANSI-1992 Test Criteria**

Testing Criteria	**Pass (%)**	**Fail (%)**
ANSI-1992	153 (41%)	223 (59%)
AHSRAE 110	310 (82%)	66 (18%)

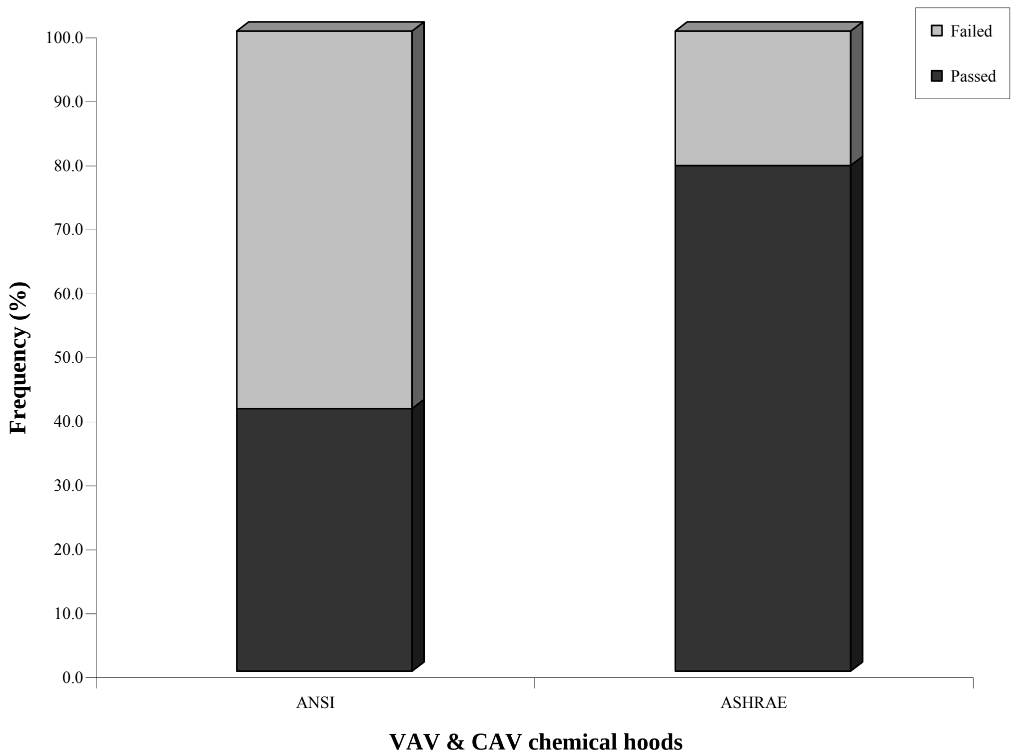

Figure 10: **ANSI-1992 and the ASHRAE-110 Tests Outcomes for 376 VAV and CAV Chemical Laboratory Hoods**

Table XIX: **Chi test for Homogeneity among VAV and CAV Chemical Hoods**

ASHRAE 110	**ANSI-1992**		***χ^2 and P***
	Pass (%)	Fail (%)	
Pass (%)	124 (33%)	186 (49%)	χ^2= 3.4
Fail (%)	29 (8%)	37 (10%)	P= 0.128

Table XX: **Frequency of the ASHRAE 110 Test Outcomes for VAV & CAV Chemical Hoods by Face Velocity**

Met ASHRAE Criteria	Face Velocity (fpm)				
	<80 (%)	**80-120 (%)**	**121-150 (%)**	**>150 (%)**	**Total**
ASHRAE Passed	16 (50%)	196 (82%)	64 (91%)	34 (100%)	310 (82%)
ASHRAE Failed	16 (50%)	44 (18%)	6 (9%)	0	66 (18%)
Total Hoods	32 (8 %)	240 (64%)	70 (19%)	34 (9.0%)	376 (100%)

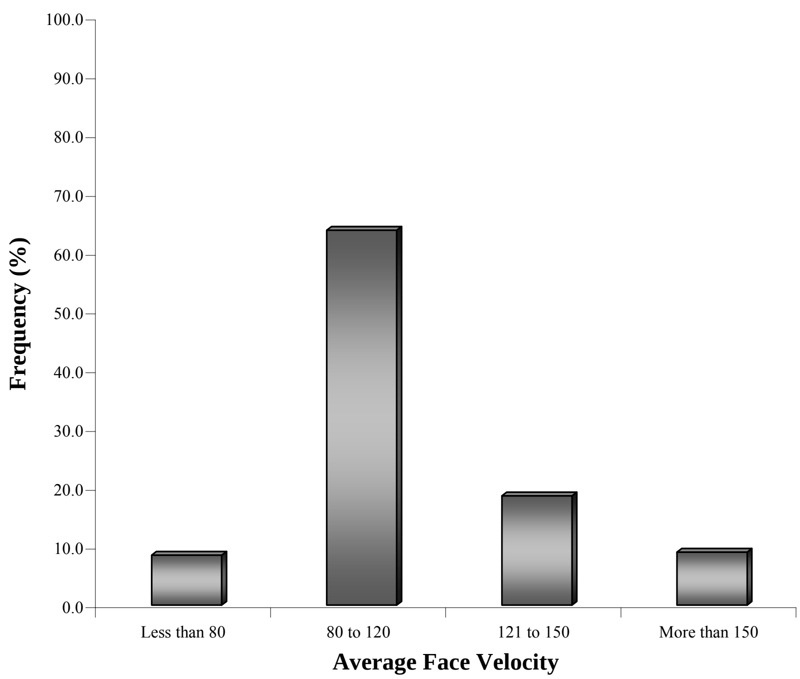

Figure 11: **Frequency of the VAV & CAV Chemical Hoods by Average Face Velocity**

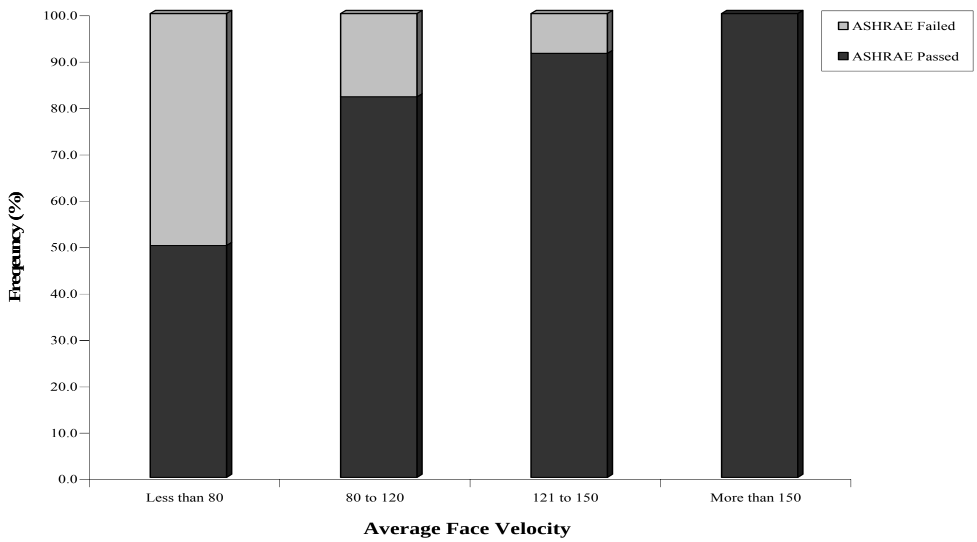

Figure 12: **ASHRAE 110 Outcomes for VAV & CAV Chemical Hoods by Average Face Velocity**

DISCUSSION

Summary of Results

Of 484 tests, 101 tests (20.9%) failed the ASHRAE 110 and 383 tests (79.1%) were rated as “pass.” The statistical analysis revealed a significant difference between the face velocity and the ASHRAE 110 test results for VAV hoods (P=0.038).

The difference between the two test methods were found approaching statistical significance for low flow hoods (P= 0.085) and non-significant for CAV hoods (P= 0.122). Test results indicated that at average face velocities between 80 -120 fpm, 20.0% of the VAV hoods and 16% of the CAV hoods failed to meet the ASHRAE 110 test criteria.

Logistic regression analysis revealed that in different regression models, significant predictors of the ASHRAE 110 test outcome were different by hood type (CAV and VAV chemical hoods). For VAV hoods, the ASHRAE = Velocity model appeared to be the best model for ASHRAE 110 test outcome prediction. For CAV hoods, the multi independent variable ASHRAE = ANSI +Velocity model appeared to be the best ASHRAE 110 test prediction model.

Other than the statistical analysis, three case studies revealed the ability of the ASHRAE 110 test method to identify defects of the chemical hood and other parts of a local exhaust ventilation system.

Interpretation

The statistical analysis was performed to study the difference between the face velocity and the ASHRAE 110 test results. Analysis was performed for each of the VAV, Low Flow, and CAV chemical hoods separately and VAV and CAV hoods combined. Pearson chi-square or Fisher's Exact test (for Low Flow hoods) showed a significant difference between ASHRAE 110 and face velocity test results only for VAV hoods. This finding can be explained by complexity of the VAV systems. A control valve in VAV hoods system adjusts the face velocity in such a way that face velocity is kept constant regardless of the sash height. During the tracer gas dynamic test (once sash was moved from closed to open position), it was found that some control systems had 10-30 sec delay time to adjust the face velocity. This time delay usually triggered the tracer gas leak from hood and failed the ASHRAE 110 test. Face velocity test was not able to recognize this defect and therefore chemical hood was rated as "operable" based on the face velocity test results. These results indicate that using ASHRAE 110 method is more critical for VAV hoods performance evaluation than other types of the chemical hoods.

The statistical analysis (Fisher's Exact test) indicated that ASHRAE 110 and face velocity test results for low flow hoods are approaching statistical different (p= 0.085). Considering the fact that low flow hoods in this study were the smallest sample group (n=108), an increased sample size may contribute to more significant difference between two types of the tests.

From 240 VAV and CAV hoods that met the ANSI -1992 requirements (average face velocity 80-120 fpm), 18% (n=44) failed the ASHRAE 110 test method. The ASHRAE 110 fail rate for VAV and CAV hoods was 28% (n=28) and 16% (n=16), respectively. These findings indicate the importance of a containment-base test method (e.g., ASHRAE 110) for hood performance evaluation, particularly for the VAV hoods. Without implementing the ASHRAE 110 test method, 18% of the chemical laboratory hoods would be still in use, while they were not able properly contain and exhaust the hazardous chemicals to the outside environment.

At higher average face velocities (121-150 fpm, and more than 150 fpm), VAV hoods showed an improved containment. All VAV hoods with average face velocities of 121-150 and above 150 fpm (n=50) passed the ASHRAE 110 test. CAV hoods showed an increased ASHRAE 110 failing rate at average face velocities of 121-150 fpm (17.0%, n=6), but had no ASHRAE 110 test fail at face velocities above 150 fpm (n=19). These findings indicate that high face velocity is a more important risk factor for CAV hoods performance than for VAV hoods.

At average face velocities below 80 fpm, 50.0% of the VAV and CAV hoods (n=16) failed the ASHRAE 110 test. This failure rate was higher for the VAV hoods (61.6%) compare to the CAV hoods (42.0%). This finding indicates that for both VAV and CAV hoods, average face velocities below 80 fpm will increase the risk of hood containment failure.

While based on the university face velocity test criteria (IOP) low flow hoods had the highest passing rate (94%) among other types of the hoods, they showed the lowest passing rate (68%) for ASHRAE 110 test criteria. This finding indicates that the university internal operating procedure (IOP) for low flow hoods was not able to evaluate chemical hood performance and better face velocity settings were required for low flow hoods. This IOP sets the average 60 fpm at sash fully open position as the target face velocity and accepts up to 10% lower velocities (54 fpm) as the face velocity reading error.

For both VAV and CAV chemical hoods, average face velocities above 150 fpm did not contribute to any tracer gas leak. All VAV and CAV chemical hoods running at average face velocities above 150 fpm passed the ASHRAE 110 test and were found "operable." This finding contradicts both the ANSI-1992 and ANSI-2003 standards at which average face velocities above 150 is suggested as a contributor to turbulence and hood containment failure.

In general, when face velocity test (based on the ANSI-1992 method for VAV and CAV hoods, and university IOP for low flow hoods) was used, chemical hoods failing rate was considerably higher (47.0% failure) than the ASHRAE 110 test method (21% failure). Reducing the number of the inoperative hoods, can decrease the maintenance /repair costs and increase the number of the operable chemical hoods, which are usually a necessary control device for research laboratories. A cost benefit analysis may be able to justify using of the relatively expensive ASHRAE 110 test method (cost is usually considered as a disadvantage of the ASHRAE 110 method).

Logistic regression analysis for VAV and CAV chemical hoods revealed that model significance, independent variables (predictors) significance, and overall model fit differed based on the type of the chemical hoods.

For VAV chemical hoods, the ASHRAE = Velocity model was pointed out the best model for the ASHRAE 110 test outcome prediction. Among significant models with significant independent variables, this model was selected for relatively larger Cox & Snell R square value (test of model fit) and smaller standard error of the regression coefficients. Selection of this model also was based on the likelihood ration test (LR) for competing models. While all multi independent variable models for VAV hoods were found statistically significant, only one independent variable in each model was significant.

For CAV chemical hoods, the multi variable regression model ASHRAE = ANSI + Velocity was appeared to be the best model for the ASHRAE 110 test outcome prediction. Among significant models with significant independent variables, this model was selected for relatively larger Cox & Snell R square value (test of model fit) and smaller standard error of the regression coefficients. Selection of this model also was based on the likelihood ration test (LR) for competing models.

While face velocity is one of the most important predictors for hood performance and the ASHRAE 110 test outcome, there are other factors affecting the ASHRAE 110 test outcome. Cross draft was one of these factors found to affect the hood performance. ANSI-2003 states that cross draft velocities more than 50% of the hood average face velocity will adversely affect the hood containment. In several cases, chemical hoods with adequate face velocities and high cross drafts failed the ASHRAE 110 test. Same hoods passed the ASHRAE 110 test at same face velocities, after the cross draft was eliminated or reduced. Hood loading was another important factor affecting hood performance. A chemical hood loaded with bottles, boxes, and large instruments was more likely to fail the ASHRAE 110 test, though average face velocity was within the acceptable levels. The cross draft and loading effect observations are not included in this study. Since the ASHRAE 1110 test procedure is essentially based on the smoke and tracer gas test results, other important data such as hood loading, cross drafts, and hood dimensions were not collected during this study and they could not be included for regression analysis.

Comparison

A thorough review of several literatures could not point out any study at which the ASHRAE 110 and the face velocity test methods were compared in different types of the VAV, CAV, and Low Flow laboratory chemical hoods. To my knowledge, this study represents the first attempt to evaluate the relationship between the ASHRAE 110 and the face velocity tests for different types of laboratory chemical hoods.

In a study by Smith (2004), the face velocity and the ASHRAE 110 tests results were compared in a total of 1,671 chemical laboratory hoods. For total hoods (VAV and CAV) running at average face velocities below 80 fpm, the current study found a 50% failure for the ASHRAE 110 test. This finding is in keeping with the Smith study that showed a 51% failure for the ASHRAE 110 test. The current study and the Smith study found that at face velocities ranging 80-120 fpm, the ASHRAE 110 test failure rates were 18% and 15%, respectively. This study demonstrated that at average face velocities of 121-150, the ASHRAE 110 failure rate was 8.6% whereas it was 11% in the Smith study. Furthermore, the present study was not able to find any ASHRAE 110 test failure at face velocities above 150 fpm, as Smith's study has reported a 3% failure of the ASHRAE 110 test.

It is important to note that Smith (2004) used the tracer gas containment as the only criteria for rating (pass/fail) a laboratory chemical hood. However, in the current study, both large volume smoke and tracer gas tests (both tests are part of the ASHRAE 110 test method) were used to rate a laboratory chemical hood.

Hitchings' study (1996) on 39 chemical laboratory hoods with average face velocities ranging 85-115 indicated a 28% failure for the ASHRAE 110 tracer gas test (after several corrections on the local ventilation system). This failure rate is considerably higher than findings in both the current and Smith's studies.

Present study has indicated a significant difference between the face velocity and the ASHRAE 110 test results for VAV hoods. As it was explained in case 3, part of this difference stems from the fact that some VAV control systems were not fast enough to adjust the face velocity after the sash was raised in a dynamic tracer gas test. Ekberg's (2000) study of the required response time for VAV hoods indicated an increase in tracer gas leak when the face velocity (air flow) was not established within 1-2 sec. This finding is in keeping with present study that showed several ASHRAE 110 test failures due to late (10-30 sec) face velocity re-establishment in VAV hoods.

The results of a 3-year study of the 366 chemical laboratory hoods by Volin (1998) showed poor smoke containment (using both smoke tubes and dry-ice water baths) at face velocities below 84 fpm and above 130 fpm. For face velocities below 85, the ASHRAE 110 test results in the current study are similar to Volin's findings. At average face velocities above 130 fpm, the present study is contrary to the findings in the Volin's study and shows an improvement in chemical hood performance.

CONCLUSION

Implication

In general, ASHRAE 110 test lowered the number of the inoperative CAV and VAV chemical hoods from 223 (59%) based on the ANSI-1992 test criteria to 66 (18%). This decrease in number of the inoperative chemical hoods decreased the maintenance costs in long term. ASHRAE 110 test also revealed local ventilation system (including chemical hoods) design and installation defects.

This study revealed that low flow hoods had the highest face velocity test pass (94.4%), and the lowest ASHRAE 110 pass (67.7%). This indicates that establishing safe low face velocity ranges requires more study.

For VAV chemical hoods, the ASHRAE = Velocity model appeared to be the best model to predict the ASHRAE 110 test outcome. For CAV chemical hoods the ASHRAE = ANSI + Velocity model appeared to be the best model for the ASHRAE 110 test outcome prediction.

Limitations

1. Effect of the sash height in ASHRAE 110 test outcome was not considered in this study.
2. Large volume smoke test is a subjective test and there is no specific standard for volume, flow rate and type of the smoke.
3. Factors such as cross drafts, hood location, and hood loading were not considered in this study.

4. Statistical limitations to logistic regression analysis. Logistic regression has less stringent requirements, does not require normally distributed variables, and does not assume linearity of relationship between the independent and independent variables. As another limitation, logistic regression analysis is able to demonstrate only an association, not a cause-and-effect relationship between variables.

Recommendations for Future Studies

1. Comparison between the large volume smoke test and the tracer gas test outcomes is necessary to find if the outcomes of these two tests are significantly different.
2. Establishing a peak level for tracer gas leak seems necessary.
3. To improve the accuracy of the ASHRAE-110 test method, further studies are required to determine the relationship between a tracer gas leak concentration and human exposure.
4. Further studies are required to test the significant models to determine how well they can predict the ASHRAE 110 test outcomes. This includes comparison of the ASHRAE 110 test outcome, with predicted test outcome using regression models (for each single chemical hood). It also will be necessary to collect enough data to find if models are better predictors for specific types and sizes of chemical hoods.

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Appendix A: MSDS for SF6

R Codes:	R44
	R20
S Codes:	S23 S51 S9 S7

Risk Statements:

- Risk of explosion if heated under confinement.
- *Inhalation may produce health damage*.*

* (limited evidence)

Safety Statements:

- Do not breathe gas/fumes/vapor/spray.
- Use only in well ventilated areas.
- Keep container in a well ventilated place.
- Keep container tightly closed.

PERSONAL PROTECTIVE EQUIPMENT FOR INDUSTRIAL/COMMERCIAL ENVIRONMENTS




Appendix B: Data Collection Form

PI
Building
Room#
Hood#
Hood manufacturer
Date
Hood type
Sash @ fully open
Sash stop
Air foil
Alarm
Controls
Loading
Housekeeping
Face velocity @ fully open
Face velocity @ 25"
Face velocity @ 20"
Face velocity @ 15"
Local visualization @
L.V.Rating
L.V. Dead air
L.V. Reverse air
Large Volume Visual. @ 6" from sash @
L.V.V. Rating
L.V.V. Air patterns
Tracer gas test @
Cylinder leakage
Background
Periphery test @
Leak location

Appendix C: Sample Data Printout from Analyzer

MIL 420 424 9-12-05

MIRAN SapphIRe-DL SITE REPORT 12Sep05 15:2

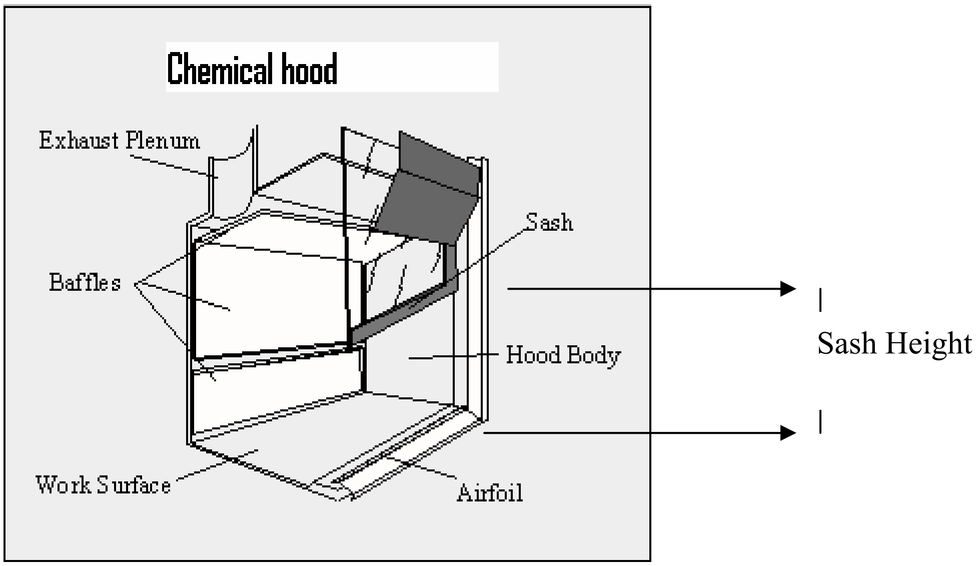
SITE: MIL

MIL-420-1

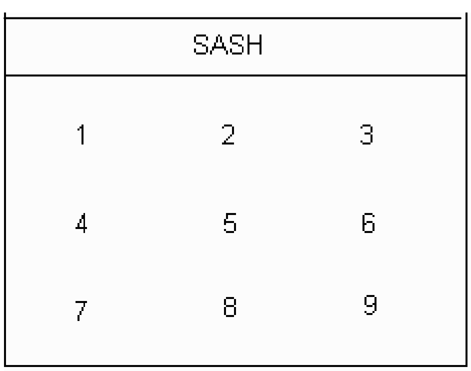
LOCATION	DATE/TIME	SF6 HRL: 4000 ppb MAX	MIN	AVG	FLAGS
LEFT-FO	12Sep05 11:36:10	13	6	10	...
CENTER-FO	12Sep05 11:43:12	16	11	12	...
RIGHT-FO	12Sep05 11:49:31	13	8	10	...

LOCATION	DATE/TIME	SF6 HRL: 4000 ppb MAX	MIN	AVG	FLAGS
1-C-FO	12Sep05 11:54:42	8	4	6	...
2-O-FO	12Sep05 11:56:47	6	2	4	...
3-C-FO	12Sep05 11:58:51	4	1	2	...
4-O-FO	12Sep05 12:00:55	3	0	1	...
5-C-FO	12Sep05 12:03:00	1	-1	0	...
6-O-FO	12Sep05 12:05:04	1	-4	0	...
7-C-FO	12Sep05 12:07:09	0	-4	-1	...
PERIPHERY-FO	12Sep05 12:09:57	-2	-7	-3	...

Appendix D: Chemical Hood Description



Picture: A chemical hood with adjustable vertical sash. Sash height is measured as the vertical distance from hood work surface to the sash edge.



Picture: Nine reading points for the face velocity.

ABSTRACT

A total of 484 tests were performed on chemical laboratory Hoods (chemical hoods), using the ANSI/AIHA Z9.5-1992 (American National Standard Institute / American Industrial Hygiene Association, Laboratory Ventilation Standard) test method (ANSI-1992). Same numbers of the tests were performed on same chemical hoods, using the ANSI/ASHRAE 110-1995 (American National Standards Institute/American Society of Heating, Refrigerating, and Air Conditioning Engineers, Method of Testing Performance of Laboratory Fume Hoods) test method (ASHRAE 110). The three types of chemical hoods available for this study were Constant Air Volume (CAV), Variable Air Volume (VAV), and Low Flow. Overall, CAV hoods had the highest passing rate for the ASHRAE 110 (83%) followed by VAV hoods (82%) and low flow hoods (68%). The X^2 test for homogeneity found a statistically significant difference between the test outcomes (pass/fail) of the ASHRAE 110 and the ANSI-1992 methods (X^2 = 4.248, P=0.038) for VAV hoods only. Overall, 18% of the CAV and VAV chemical hoods tested in the 80-120 feet per minute (fpm) average face velocities, failed to meet the ASHRAE 110 test criteria. If the ANSI-1992 test method was performed alone, 18% of the chemical hoods would be certified while they were not able to meet the ASHRAE 110 criteria.
Logistic regression analysis for VAV and CAV chemical hoods revealed that for VAV chemical hoods, the ASHRAE = Velocity model and for CAV chemical hoods, the multi variable regression model ASHRAE = ANSI + Velocity were appeared to be the best model for the ASHRAE 110 test outcome prediction.