Comparison of Efficacies of Current Methods for Troubleshooting Industrial Exhaust Ventilation Systems to a Proposed New Method

BY

Ann Pinsky

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Master's Thesis

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Abstract

Comparison of Efficacies of Current Methods for
Troubleshooting Industrial Exhaust Ventilation
Systems to a Proposed New Method

by Ann Pinsky

Chairperson of the Supervisory Committee: Professor Steven E. Guffey
Department of Environmental Health

Industrial exhaust ventilation systems are designed to minimize worker exposure to airborne contaminants. For ventilation systems to operate effectively and to protect workers from harmful exposures, air drawn into the fan must be distributed among the hoods at predetermined (target) airflows. Over time systems age, incurring damage, obstructions, leaks and other alterations that skew the airflow distributions so that some hoods receive less than their target airflows. The ability to swiftly detect alterations ("troubleshooting") and restore systems to their previous working condition is therefore crucial for worker protection.

Two methods used to identify alterations that produce shifts in airflow distribution are long-standing, the Industrial Ventilation method (IVM) and the hood static pressure method. In use, it is assumed in both methods that a decrease in hood static pressure (SPH) indicates a new obstruction, but an increase in SPH does not. However, one could broaden the method and assume that an increase also can indicate a new obstruction, thus creating what is called here "One-Sided" and "Two-Side" Hood Static Pressure methods.

A third method is proposed by Guffey. It incorporates a variant of the hood static method and introduces two more diagnostic tests: ratios of static pressures (variable called "SPratio") and equivalent loss coefficients ("X-values") which are kinetic power loss coefficients for any volume. Previous laboratory studies have demonstrated the superiority of X-values in locating obstructions that have been deliberately placed in systems. This is important because shifts in airflow are generally due to obstructions. However, to determine values of X requires a time-consuming velocity pressure traverse. Therefore, it would be convenient to use

static pressures as screening tools to reduce the number of cases where X-values must be determined.

In this study of an eleven branch ventilation system, static pressures were measured downstream of the hood (SPH), at the end of the branch (SPend), and at a location between the hood and end of the branch (SPmid). Velocity pressures were measured by a Pitot traverse at a convenient location in each branch. Cases where the change in X exceeded a specified threshold were deemed "obstructed." A screening test was deemed "positive" if the change in its variable value(s) exceeded a given threshold. A "true positive" for a method occurred when the value of X for a branch changed by more than a given X-threshold and the value of the method variable changed by more than its threshold. Thresholds for X were tested at values ranging from 0.05 to 0.6 and thresholds for each screening test's variable were varied from 0.0 to 0.6. A family of receiver operating characteristic (ROC) curves were drawn at each threshold for X. Performance for each screening tool was judged in part by area under the ROC curve.

The results of this study were that in every case the areas under the ROC curves (indicating superior combinations of sensitivity and specificity) were higher for the SPratio Method and the "Two-Sided SPH" method and were very low for the IVM method and the "One-Sided SPH" method. One reason the IVM method and One-Sided SPH method performed poorly was because they ignored obstructions upstream of the SPH measurement location. There was little difference between Two-Sided SPH method and SPratio with high values of X. At moderate changes in X, (e.g., ≤30%) the SPratio method was clearly superior to all the other methods. Therefore, SPratio method is the best screening tool at finding moderate obstructions. For very substantial obstructions, the Two-Sided SPH method would be adequate.

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List of Abbreviations

Q	airflow (cubic feet per minute: cfm)
V	velocity (feet per minute: ft/min)
VP	mean velocity pressure at a cross-section
df	density factor: ratio of actual density to standard density
A	cross-sectional area of a duct (square feet)
Fen	entry loss coefficient at a junction
SP	mean static pressure at a cross-section (inches water gauge)
SPH	hood static pressure at a cross-section just downstream of a hood
SPend	static pressure measured at a cross-section just upstream of the junction
SPmid	static pressure measured at a cross-section between SPH and SPend
SPratio	static pressure ratio = $\frac{SPH}{SP_{end}}$
TP	mean total pressure at a cross-section = SP + VP
LP	power lost (i.e., dissipated to heat) for the volume is the difference between the sum of the powers of the flows entering and sum of the powers exiting the volume, plus any external powers added in-between
KP	kinetic power passing through a reference cross-section = (Q)(VP)
X	kinetic power loss coefficient for a volume = $\frac{LP}{KP}$
Xhood	kinetic power loss coefficient for a hood $= -\frac{TP_{hood}}{VP_{branch}}$
Xmid	kinetic power loss coefficient for the mid location in a branch, $X_{mid} = -\frac{TP_{mid}}{VP_{branch}}$ Xend kinetic power loss coefficient for a branch, $X_{end} = -\frac{TP_{end}}{VP_{branch}} = -(\frac{SP_{end} + VP_{branch}}{VP_{branch}})$

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I. INTRODUCTION

Industrial exhaust ventilation systems are designed to minimize worker exposures to airborne contaminants. For ventilation systems to operate effectively and to adequately protect workers from potentially harmful exposures, air drawn into the fan must be distributed among the hoods at predetermined (target) airflows. Over time systems age, incurring damage, obstructions, leaks and other alterations that skew the airflow distributions so that some hoods receive less than their target airflows. The ability to swiftly detect alterations ("troubleshooting") and restore systems to their previous working conditions is therefore crucial for worker protection.

There are three methods currently used to identify alterations that produce shifts in airflow distribution. Two of the methods have been used for decades: 1) the method recommended in Industrial Ventilation (1995), and 2) comparison of changes in hood static pressure values. More recently, Guffey proposed a procedure that incorporates a variant of the hood static pressure method and introduced two more diagnostic tests: ratios of static pressures (using a variable called "SPratio") and equivalent loss coefficients (using a variable called "X").

For branch ducts, the value of X is equivalent to a velocity pressure coefficient for the entire branch. Spann (1993) demonstrated in a ventilation laboratory that values of X varied little (<5%) even with profound changes in airflow due to changes in fan speed. Colvin (1993) found that the X value for a given branch changed little when substantial obstructions were placed in other branches, but did change substantially in value when obstructions were deliberately placed in the branch itself. Taken together, these two studies demonstrated that values of X had high diagnostic value in determining whether and to what degree a duct has been obstructed or has otherwise experienced a change in resistance to flow.

However, determining the value of X for a branch requires a time-consuming velocity pressure traverse. Taking static pressure readings is much faster. It would be ideal if hood static pressures (SPH) or some combination of pressure readings alone could always correctly diagnose whether or not a branch is substantially obstructed. In fact, a static pressure method could still save time and effort even if it were suitable only for use as a first-pass screening tool, leaving determination of X-values to decide the ambiguous cases.

This study seeks to determine which static pressure method is most useful as a screening tool.

II. BACKGROUND

Description of Ventilation Systems

Industrial exhaust ventilation systems are designed to protect workers from exposures to contaminants in the workplace. Ventilation systems play a crucial role in safeguarding health in the workplace by capturing contaminants at the source of generation and drawing the contaminated air into the hood face away from the operators' breathing zone. Hoods are designed to capture contaminated air generated from routine shop activities such as tool grinding and woodworking. The air travels from the hoods into the branches (See Figure 1). The branches in turn join a series of connecting ducts called submains. The submains ultimately join a large central "main" duct from where the air flows directly to the fan or air-cleaning-device. The air-cleaning device removes contaminants from the air. Downstream of the fan the air passes through the "stack" and into the atmosphere.

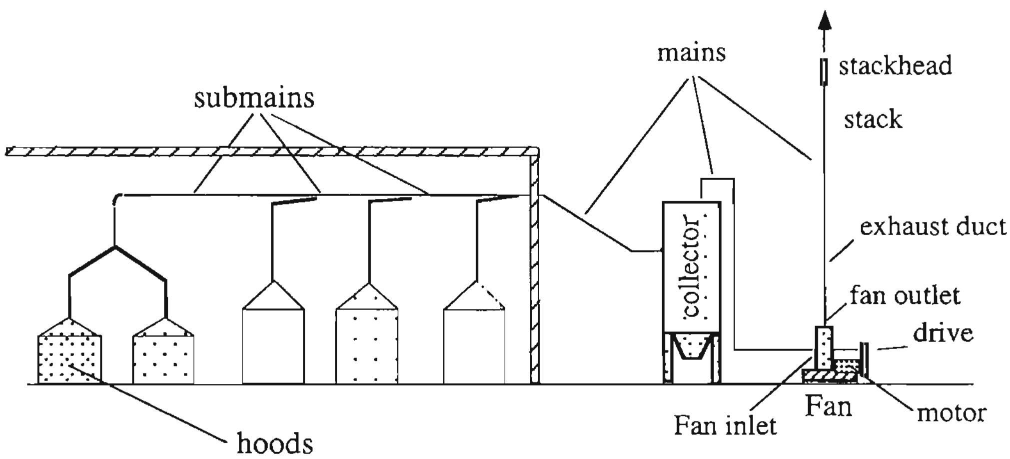

Figure 1. Parts of a ventilation system

Importance of Troubleshooting

For ventilation systems to operate efficiently while adequately protecting workers from contaminant exposures that are potentially injurious to health, air drawn into the fan must be distributed among the branches at predetermined (target) airflows. However, ventilation systems live perilous lives. Within their working lifetime, they are likely to incur damage, obstructions, leaks and multiple alterations that can skew airflow distributions so that some branches receive less than their target airflows while other branches receive excessive airflows. In addition, unauthorized (and even authorized) system alterations sometimes inadvertently compromise system effectiveness, including those systems intended to protect workers from heavy metals and other highly toxic contaminants. Therefore, it is highly desirable to discover significant changes as they occur ("troubleshooting") and, if possible, restore the altered volumes to their previous conditions, ("maintenance").

Finally, it is not enough to find all problems early on and correct them expeditiously. One must do so efficiently, wasting as little time and money as possible. It can be costly to attempt to remove obstructions. In some cases, the search can damage the ducts. If internal inspection reveals that, in fact, no alteration actually occurred, then the search may have consumed time, effort, money, credibility, and "good-will" for nothing. Thus, a good troubleshooting method must not only reliably discover problems, it must also reliably reject cases where alterations have not occurred.

Inadequacy of Worker Complaints and Visual Inspection

It is possible to discover adverse changes to systems by observing their effects on contaminant control. For example, one might assume a branch has been altered because of a worker's complaints about exposure or visible emissions from the hood. However, this strategy would all too frequently discover problems only when they were both severe and obvious. A sharply reduced flow could escape detection for long periods if the escaping contaminants were neither visible nor obnoxious. Even visible and obnoxious exposures could continue for lengthy periods before complaints and visible indications finally elicited a response.

There are good reasons for such time lags. For one, complaints can occur even when there has been no change in the exposure level or the ventilation performance. Indeed, complaints may occur when no change to exposure has occurred. For another, visible emanations and complaints can be the result of poor work practices and may not be related to *changes* in ventilation. In such cases, inspecting the inside of ducts would be a waste of time.

For those reasons, ventilation texts have emphasized visual inspection (Brandt, 1950; Cutter, 1976). Instead of waiting for complaints, one could routinely inspect the fan, air-cleaner, and the ducts for signs of alterations. The hope is that visual inspection will reveal alterations before their effects become severe enough to be obvious or to generate complaints. However, visually inspecting ventilation systems is often difficult. Systems can be large in extent and it can be difficult to get close enough to portions of some ducts to inspect them closely. Worse, alterations within a duct usually are not visible externally.

Ventilation Measurements in Troubleshooting

NIOSH (1978) recommended measuring hood velocities and airflows to troubleshoot ventilation systems. The National Safety Council (1980) also listed periodic measurements of airflows and pressures among its essential tests. Burton (1995) proposed a series of performance standards and recommended guidelines for testing of exhaust ventilation systems. He states:

> "Routinely test and monitor every process/tool exhaust system for required performance after installation. Periodic testing programs might include daily checks of the hood static pressure, quarterly face velocity testing and annual containment tests."

It is doubtful that many companies perform daily checks of hood static pressures or, for that matter, velocities and airflows — probably because such checks would be dauntingly time-consuming. Perhaps due to personnel and cost limitations, systems generally tend to be monitored on an ad hoc basis as problems arise. According to Guffey (1994), only a minority of industrial exhaust ventilation systems are regularly evaluated by any method, possibly due to the sense that the time and effort required to monitor is not worth the effort. If, for example, practitioners found that traditional methods of interpreting static pressure changes often led to fruitless searches for non-existent alterations, they could easily conclude that it was better to wait for other evidence of problems (e.g., complaints).

There is some reason to believe that traditional methods may not provide sufficient guidance. The first is the difficulty of finding any published case studies where the methodologies have been applied systematically with success (to be fair, there appear to be no studies that show lack of success, either). The second is conceptual: a change in fan performance or a modification anywhere in the system will cause changes in static pressures and flows throughout the system. Thus, it would seem likely that a change in pressure at a hood would be an uncertain indicator of an alteration in the branch serving that hood.

Troubleshooting Methods Employing Measured Values

Although it is clear that visual inspection and complaints are inadequate, it remains to be seen whether traditional methods or newer methods of interpreting changes in pressures are adequate troubleshooting tools. In the following sections, the traditional methods and the newer methods are discussed.

For the purposes of this study, one of the newer methods (X-value Method) will be used as the "gold" standard against which the performance of other test variables are evaluated. The basis for this choice and the characteristics of X-values are discussed next.

Definition of Power Loss Coefficients (X)

A power loss coefficient (X) is a unitless ratio of the lost power (energy dissipated to heat) for the volume divided by a reference (usually downstream) kinetic power (Guffey, 1994).

$$X = \frac{LP}{KP} \qquad (1)$$

Where: LP = power "lost" for the volume
KP = kinetic power passing through a reference cross section (generally the exit cross-section)

Although, X can be determined for any continuous section of a ventilation system, this study was limited to use values of X for individual branches. For submains and more complex portions of a ventilation system, the computation for a value of X can be complicated, but for the simple cases of an entire branch or a hood (see Figure 2), the computation of X simplifies to a familiar relationship:

$$X_{branch} = -\frac{TP_{end}}{VP_{branch}} \qquad (2)$$

$$X_{hood} = -\frac{TP_{hood}}{VP_{branch}} \qquad (3)$$

Where: TP = mean total pressure
VP = mean velocity pressure at a cross-section

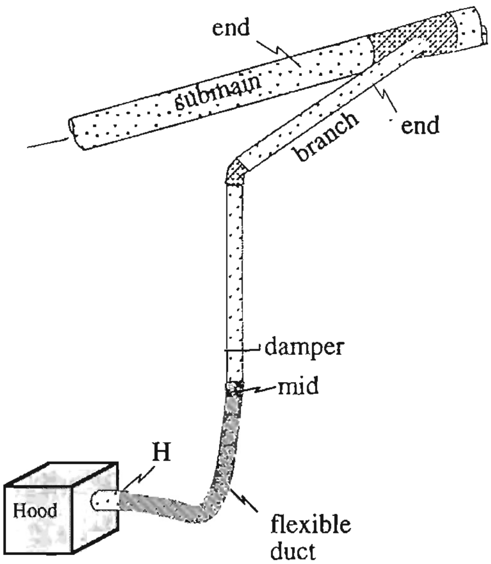

Figure 2. Measurement locations in ducts

Initial baseline values of pressures and airflows are measured at selected locations (see Figure 2), followed by later readings taken when a suspected change in the system has occurred. On comparison of initial and final values, a relative change in X is generally indicative of an alteration to the corresponding section of the system. The magnitude of the change in X is directly proportional to the extent of the alteration; that is, the greater the alteration, the more substantial is the relative change to X. Conversely, if the suspected volume had experienced no alterations, X would remain constant.

Therefore, if changes in X are observed between consecutive measurement rounds, an obstruction may have occurred or departed in the intervening period. It also follows that once an obstruction is removed and the branch is restored to its previous condition, X should return to its original value.

Justifications for Employing X-Values as Final Diagnostic Tests

For this study relative changes in X-values are treated as known, quantifiable indicators of obstructions in branches. Specifically, values of X are used to determine true positives and negatives. Since X is not a binary variable, "true" and "false" are defined by exceedance of a threshold value of X (i.e., $X_{threshold}$).

There are three reasons X-values are employed as final diagnostic tools in this study. First, the X-values employed in the study are computationally identical to the most fundamental calculations employed to predict pressures in new system design. Equation 3 is familiar because it is identical to the computation for a "velocity pressure coefficient" for losses. Velocity pressure coefficients due to elbows, hoods, and most other components in an exhaust ventilation system are computed using this same relationship. Equation 2 has the same form and could be considered as equivalent to a velocity pressure coefficient for the totality of the components in a branch.

Second, laboratory studies have shown the values of X for a hood and an entire branch to be highly repeatable and to be directly related to known changes to that specific branch. Spann (1993) demonstrated that X-values changed little with dramatic shifts in airflow in the absence of an obstruction or other alteration. Colvin (1993) deliberately placed obstructions in some ducts and not others. He found that the change in X due to a given obstruction in a given branch was highly repeatable. When the obstruction was removed, the value of X returned to the original value. A very substantial obstruction in one duct had negligible effect on the value of X found in other branch ducts. He observed that no X-values varied from initial values by more than 7% and no static pressure ratio values varied by more than 5% if no obstruction was currently in that branch duct. Colvin's results suggest that the resolution of X-values may be as low as 7% and the resolution of SPratios may be as low as 5%.

Third, changes in X can be associated with shifts in airflow distribution (Guffey, June 1993):

$$\frac{Q_b}{Q_a} = \left(\frac{df_a}{df_b}\right)\left(\frac{A_b}{A_a}\right)\sqrt{\frac{1 - X_a + F_{en_a}}{1 - X_b + F_{en_b}}} \qquad (4)$$

Where: df = ratio of actual to standard density

A = cross-sectional area

F_{en} = entry loss coefficient at a junction

Equation 4 (See Appendix G) also can be used to determine a desirable threshold for action for changes in X. As has been shown elsewhere (Hoppe, 1995), a 17% change in the relative values of Xa and Xb, where Xa is the power loss coefficient for Branch "a" and Xb is the power loss coefficient for Branch "b" which meet at a junction, would be associated with no more than 5% shift in the relative airflow through ducts a and b. Since a change in airflow of 5% is generally considered to be worthy of notice (IVM 1995), a shift in an X-value of 20% would be a reasonable threshold for intervention.

As an additional plus, if one determines values of X for more than one portion of a branch, there is a means to discover some measurement errors. This arises from the fact (Guffey, 1994) that a change in a part should be reflected by the value for the whole. In this study, for example, if there is a change in Xhood there also should corresponding changes in Xmid and Xend values (see Figure 2). If a change in Xhood is not reflected in the value of Xend, then either SPH or SPend is incorrect and both should be re-measured.

The calculation of X, however, requires a time-consuming velocity pressure traverse. For that reason, a quicker method could be a useful even if it were not highly specific. The following sections describe troubleshooting methods that do not require velocity pressure traverses.

Static Pressure Ratio

The static pressure ratio (SPratio) is computed from:

$$SP_{ratio} = \frac{SPH}{SP_{end}} \tag{5}$$

Where: SPH = static pressure measured downstream of the hood

SPend = static pressure measured near the end of the branch upstream of the junction

The static pressure ratio (SPratio) of hood to end is related to values of X by the following equation:

$$\frac{SPH}{SP_{end}} = \frac{X_{hood} + 1}{X_{end} + 1} \tag{6}$$

Where: Xhood = power loss coefficient for the hood

Xend = power loss coefficient for the branch

As can be inferred from Equation 6, (See Appendix G) the ratio of SPH to SPend cannot vary unless Xhood, Xend, or both change. Therefore, as with a change in X, a change in SPratio from one measurement period to another may indicate an alteration. Limitations arise in cases where the hood resistance accounts for nearly all of the branch's resistance (i.e., SPratio≈1). If this were to occur, the SPratio would change little if an obstruction appeared upstream of the SPH measurement location. Likewise, if an obstruction were to occur downstream of the hood, it would have to be very large to cause any significant change. Nevertheless, SPratios do not require time-consuming Pitot traverses and can be measured very quickly and conveniently, a significant advantage in the field.

I V M Manual Method as Published

The method proposed by Industrial Ventilation: A Manual of Recommended Practice (IVM) is a "commissioning" (new system checkout) procedure. The procedure requires that after verifying fan performance, air-cleaning-device efficiency, and duct dimensions, one would compare observed static pressures to corresponding values predicted from the system design variables (e.g., duct lengths, types and number of elbows, etc.). The predicted static pressures are computed using published loss coefficients and the computation procedure described in IVM.

Once the expected static pressures were computed, one would then measure static pressures in each branch, one branch at a time. If the hood static pressure (SPH) for a given branch is greater than or equal to the predicted value, that branch is assumed to be free of problems. If SPH is lower than predicted, one then measures the static pressure farther downstream in the branch. If the downstream static pressure is higher than expected, an alteration is assumed to have occurred between the two measurement locations in the branch.

The Vent Manual acknowledges that the method has limited application and notes that "It is intended as an initial verification of the design computations and contractor's construction in new systems, but it may be used also for existing systems when design calculations are available or can be recomputed" (Industrial Ventilation, 1995).

There are several difficulties in applying this method:

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There are several difficulties in applying this method:

1. If taken literally, the fan must be producing the predicted total system airflow - an unlikely event. Although most fans may be adjusted to within 5 or 10% of desired total airflows without great difficulty, only fans driven by a variable frequency drive can be easily adjusted to outputs within 2 or 3% of desired airflows. Furthermore, the fan rotation rate may be appropriate as installed, yet the airflow could be off due to poor installation or alteration.

2. The method assumes that loss coefficients developed from testing new unused components would be the same as components in older, aging systems that have suffered the wear and tear of prolonged use. There are no data published in the literature to support this assumption. As shown by Hoppe (1995), the observed sum of coefficients for branches in two 3-year old systems deviated from values predicted from loss coefficients by more than 25% in over half the branches.

3. Real systems often have components for which the IVM and other sources provide no suggested coefficients or for which sources disagree. Examples of the former are flexible ducts with bends in them, many (perhaps most) hood designs, and non-standard elbows and fittings. For components that have been tested, recommended loss coefficients vary widely with the sources. For example, until 1995, the IVM values and ASHRAE Fundamentals (1995) for a common elbow geometry (radius/diameter=2, 5 section) were 0.27 and 0.19, respectively. Later editions of IVM adopted the ASHRAE values while later editions of <u>Fundamentals</u> moved on to new values.

4. The original design data is generally lost within a few years after installation.

5. Systems frequently are not installed exactly as designed, often for good reason. Furthermore, a system often is substantially altered within a year of installation and sees many more alterations as the years go by. For this reason, it is crucial that one correctly predict pressures and flows based on the "as-installed" system, not on original design. This requires careful descriptions of each fitting and length of duct — a process so tedious and time-consuming that practitioners very seldom do it for any reason.

6. It assumes that alterations always produce increases in resistance and that alterations are never upstream of the hood measurement location (H), (see

Figure 2). Thus, it should fail to discover cases where the resistance to flow has increased upstream of H or has decreased downstream of H.

A Modified IVM Method

The IVM method relies on the availability of accurate loss coefficients for every component in a system. It assumes that design calculations are error-free and that the system layout is still in complete conformity with the original design. In addition, the method requires that the fan convey precisely the design airflow, even if the system has experienced substantial modifications.

The chances of any of these requirements being met is poor. The chances that all are met in a system that has been in service for several years is probably near zero. For that reason, the IVM method is impractical for most systems as stated. However, it is feasible to execute the following procedure:

1. Instead of computing SPH and junction pressure from loss coefficients and design variables, measure the hood pressure 3 duct diameters downstream of the hood and the junction pressure 3 duct diameters upstream of the junction fitting (SPend).

2. If at some later time new measurements show that SPH has fallen by more than some threshold value ($SPH_{threshold}$), remeasure SPend. If it has not increased, assume no change to the branch duct.

3. If SPH has fallen more than $SPH_{threshold}$ and SPend has increased by any amount, assume an obstruction is present between SPH and SPend.

This procedure represents the ideal IVM case where the system originally behaved exactly as predicted in every particular. This procedure may still fare poorly under the following conditions:

1. An obstruction is upstream of the SPH measurement location.

2. The resistance to flow has decreased since the last set of measurements.

3. The fan airflow through the branch has increased due to a flow change in the system and the branch has experienced an alteration.

"One-Sided" Hood Static Pressure"

What is called here the "One-sided" Hood Static Pressure method ("One-Sided" SPH) is the most commonly employed troubleshooting approach used in the field. In this method, the current static pressure measured downstream of the hood is compared to previously measured values. If SPH has decreased (but not increased) from the previous measurement, there may have been a modification to the branch or to a downstream submain. This method is described or referred to in most ventilation texts. However, there are no published guidelines describing what constitutes an event substantial enough to warrant intervention.

While it is true that a modification to a branch will change SPH, it is also true that any modification at any location in a ventilation system also will shift airflow distributions that change static pressures at every point in the system. Thus, it can be expected that even under circumstances where there has been no modification to the "suspected" branch, changes in SPH may occur. Such changes may be accountable to a slipped fan belt, alterations to other ducts, or leaks elsewhere in the system, etc. While SPH may be sensitive to shifts in airflow distribution, it is also highly nonspecific and could be expected to produce many false positive outcomes if the threshold for intervention were low. There are also situations where alterations may occur upstream of the hood measurement location and affect SPH.

"Two-Sided" Hood Static Pressure (Modification of One-Sided Hood Static Pressure)

There is no inherent reason one must ignore cases where SPH increases. By investigating the cases where the static pressure measured near the hood both increases and decreases, it may be possible to reduce the number of false negatives. This certainly will improve sensitivity. The tradeoff is a reduced specificity as the number of false positives will increase according.

Analysis of SPratio, One-Sided SPH, Two-Sided SPH and IVM Methods as Screening Tools

This study evaluated the validity of using static pressures as initial screening tools to reduce the number of cases where equivalent loss coefficients (i.e., X-values) must be determined. The candidate screening tools were discussed in preceding sections and are summarized in Table 1. The tests for positive indication for each method are summarized in Table 2.

Table 1. Troubleshooting Variables as Diagnostic Screening Tools

Method	Variable	Comment
Static Pressure Ratio	SPH/SPend	An increase in the ratio is assumed to indicate an increase in resistance to flow upstream of the hood or a decrease downstream of the hood. A decrease in the ratio indicates the converse.
Two-Sided SPH	SPH	An obstruction is assumed to be downstream of the hood when SPH decreases and upstream of the hood when SPH increases.
One-Sided SPH	SPH	An obstruction is assumed to be located in any branch where SPH has fallen. This method ignores cases where SPH has increased.
*IVM	SPH, SPend	A new obstruction is assumed to be located downstream of the hood and upstream of the end if SPH has fallen and SPend has increased. This method ignores all other cases, including those where SPH has increased.

*Industrial Ventilation (1995)

Table 2. Screening Tools

Variables	Relative Change Computed as:	Test of Whether a Relative Change is a Positive Indication	Values of Thresholds Employed
Xend	$\frac{abs(X_{end} - X_{end\,Previous})}{X_{end\,Previous}}$	|% Change| ≥ Xend Threshold	0.02, 0.04, ... 0.1, 0.2, 0.3, ... 0.6
SPratio	$\frac{abs(SP_{ratio} - SP_{ratio\,Previous})}{SP_{ratio\,Previous}}$	|% Change| ≥SPratio Threshold	0.1, 0.2, ... 0.6
One-Sided SPH	$\frac{SPH - SPH_{Previous}}{SPH_{Previous}}$	% Change ≤ – SPH Threshold	0.1, 0.2, ... 0.6
Two-Sided SPH	$\frac{abs(SPH - SPH_{previous})}{SPH_{previous}}$	|% Change| ≥ SPH Threshold	0.1, 0.2, ... 0.6
IVM	$\frac{SPH - SPH_{Previous}}{SPH_{Previous}}$ and, $\frac{SP_{end} - SP_{end\,Previous}}{SP_{end}}$	% Change ≤ – SPH Threshold and, % Change SPend > 0	0.1, 0.2, ... 0.6

"Previous" indicates values determined from the previous round of measurements. If it is not "previous", then it refers to the current round.

Treatment of Sensitivity and Specificity

The cost of a false positive is unwarranted and pointless intervention. The cost of a false negative is failure to intervene where needed, possibly leading to excessive exposure to workers.

For this study a false negative occurs when the test variable indicates the absence of an alteration for a case when the X-value indicates that an alteration is indeed present (see Table 2). A false positive occurs when the test variable indicates the presence of an alteration while the X-value indicates there is no change from the previous measurement period.

Ideally, the perfect test variable would have 100% sensitivity and 100% specificity when testing for outcome. This is rarely the case. In fact, as the threshold for positive change is increased (increasing the test's specificity) the number of false negatives generally increases, reducing sensitivity (the ability of the test to discriminate positive outcomes). It is also the case that when the threshold for positive change is decreased (increasing the test's sensitivity) the number of false positives generally increases, reducing specificity (the ability of the test to discriminate negative outcomes).

For each test variable, there is a trade off between sensitivity and specificity. That tradeoff is a policy issue that should be decided based on the relative costs of false negatives and false positives. In the case of a screening tool (e.g., SPratios) the cost of a false positive is not exorbitant (do a Pitot traverse and compute X), while the cost of a false negative could be excessive worker exposures. Given those costs, in this study it is assumed that the consequences of having false negatives are crucial and, therefore, the tradeoff is heavily weighted towards sensitivity.

Proposed Troubleshooting Approach Using Screening Tests

Figure 3 schematically represents a diagnostic means of identifying obstructions in branches. This is discussed in detail in the conclusions.

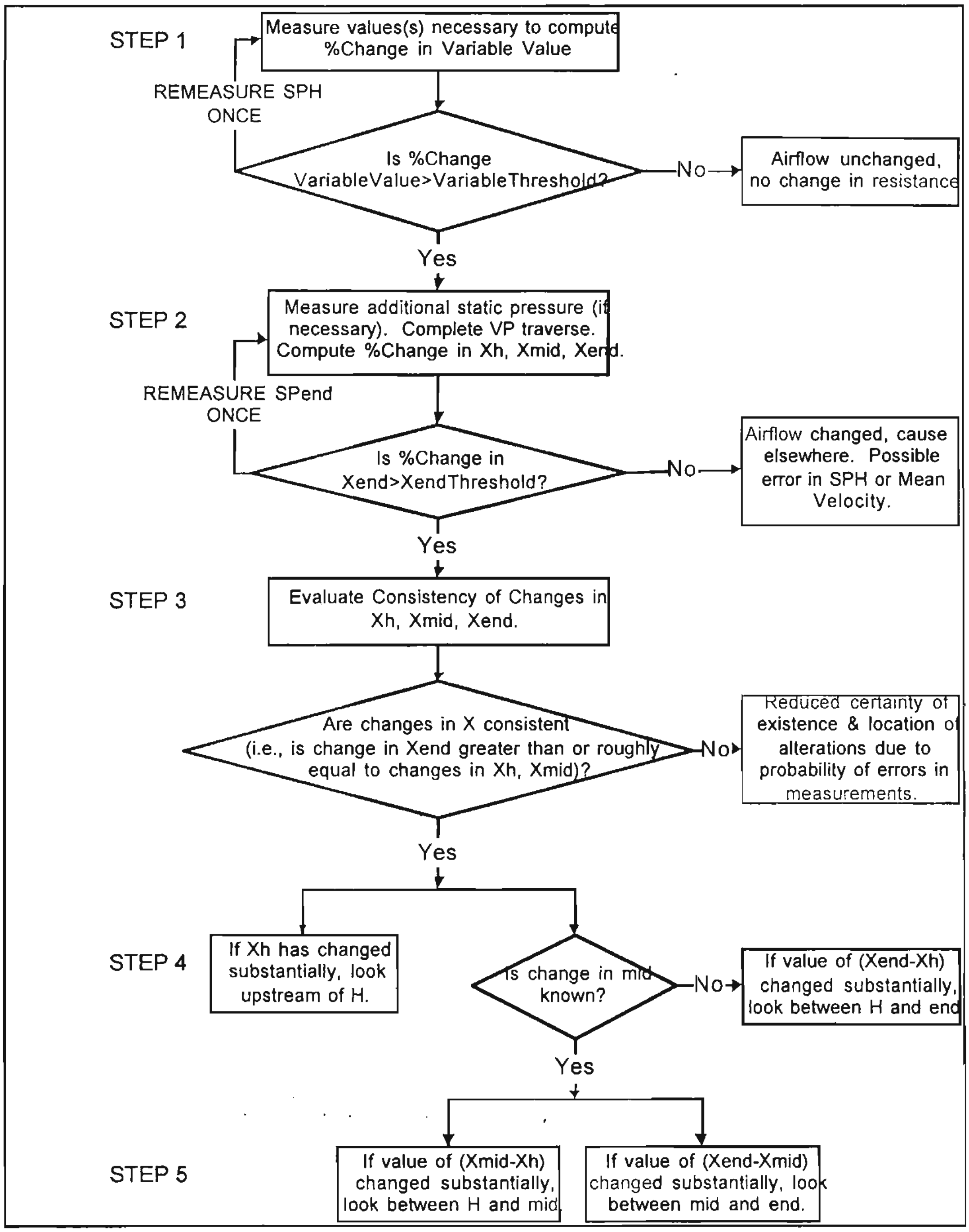


Figure 3. Proposed troubleshooting approach

III. HYPOTHESES

Stated in plain language, this study is intended to determine if any of the variables (i.e., Static Pressure Ratio, One-Sided SPH, Two-Sided SPH, and IVM) are superior screening tools in detecting alterations (e.g., obstructions) when testing exhaust ventilation systems. Superior performance will be judged by a higher area under a receiver operator curve and by greater specificity at an acceptable level of sensitivity (e.g., 90%).

True cases will be assigned based on whether or not the relative value of Xend exceeds a given threshold of change (e.g., ≥20%). Sensitivity is defined as the number of true positive outcomes divided by total positive outcomes. Specificity is defined as the number of true negative outcomes divided by the total negative outcomes.

The following specific hypotheses will be tested:

NULL HYPOTHESIS: H_O

All of the screening tools have the same areas under the ROC curves.

ALTERNATE HYPOTHESIS: H_A

Some screening tools have more area under the ROC curves than others.

NULL HYPOTHESIS: H_O

At a given level of sensitivity (e.g., 90%), all methods have equal specificities.

ALTERNATE HYPOTHESIS: H_A

Some screening tools have a higher specificity than others at a given level of sensitivity (e.g., 90%).

IV. MATERIALS AND METHODS

Apparatus

Ventilation System

Initially, eight ventilation systems located at The Boeing Company's Aircraft Manufacturing Facilities at the Kent Space Center in Kent, Washington were reviewed for the study. The "Model Shop" was selected for the study for the following reasons:

- Measurement locations were physically accessible in a safe manner for repeated measurements.
- The system was in current, heavy use to effectively test the troubleshooting methodologies.
- The system was located at a convenient geographical location to allow for repeated on-site visits during the two year longitudinal study.
- Original contractor drawings of the system from facilities were made available.

Layout and Description

The Model Shop is used primarily for making prototypical models of airplanes that are under current testing. The majority of the activity involves wood cutting and sanding using multiple types of saws and sanders. Some metal cutting also occurs. The ventilation system is composed of eleven branches and a Rotoclone type fan/air cleaning unit (See Appendix C). Each branch contains a damper readily adjustable by shop personnel. All but two of the branches are constructed completely or in part with flexible duct.

The shop is quite active. Wood dust is commonly suspended in the room air and lying on working surfaces. Wood chips, metal ribbons, and other debris are swept daily from the shop floor into one of the branches used as a floor sweep.

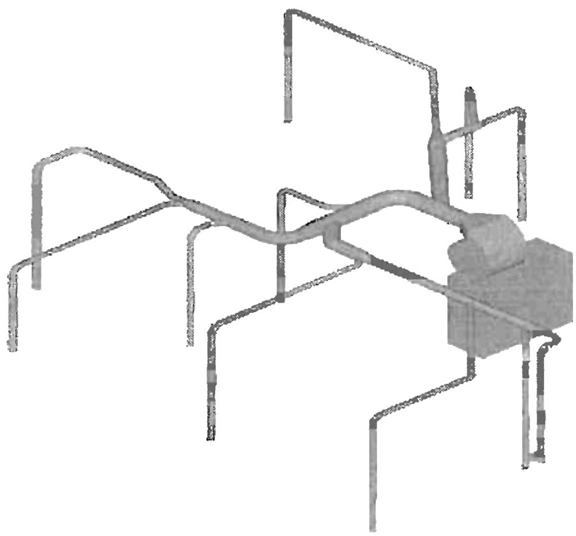
Dampers and flexible ducts introduced complications to the study protocol. As dampers and branches could be moved at will, (even when readings were in progress), it was not always possible to track changes with complete certainty between measurements rounds. As any change to any branch affects the measured pressures and flows to that branch and to the entire ventilation system, photographs of branches were generally taken prior to measurements to document the precise branch orientations.

It was determined that detailed records of past measurement histories had not been kept, although some information was available.

System Characterization

The dimensions of the Model Shop (see Figure 4) were measured, including internal duct diameters, lengths of runs (measured from centerline to centerline), junction angles, taper angles, and number of elbows per branch. Branches were numbered from 1 to 11, beginning with the most upstream branch.

With this information, drawings were prepared which designated the ID numbers for the branches and the pressure measurement locations. Changes of measurement locations or system modifications between measurement rounds were noted on the drawings as they occurred.



System Configuration

Airflow	14,000 acfm
Velocity	>3,500 ft/min
No. Hoods	11

Figure 4. Model Shop layout

Instruments

The instruments were used to read pressure and flow measurements were the Alnor CompuFlow ElectroManometers (Model 8530 D-I) with an accuracy of ±1% and resolution of 0.01 inches water gauge (Alnor, 1990) and the Dwyer Air Velocity

Meter (Model No. 400-10) with an accuracy of ± 2% and resolution of 0.01 inches water gauge (Dwyer Instruments, 1991).

All measurements were taken using Dwyer 1/8" and 3/8" Pitot tubes complying with AMCA and ASHRAE specifications (Dwyer Instruments, 1989). Pitot tubes were connected to the digital manometers using 1/4" ID, 1/16" wall thickness Tygon® tubing. Traverse devices designed by Guffey (1990) were mounted on the ducts and used to measure velocity pressures and some center-line static pressures For other static pressure measurements, the Pitot tube was inserted by hand to centerline and held perpendicular to the duct.

Dry and wet bulb temperatures were measured with a Bendix Psychron (Model No. 566) with an accuracy of ± 1% and resolution of 1 °F. Barometric pressure was measured with a Precision Micro Barometer (Model PMB-1) with an accuracy of ± 0.45% and resolution of 0.001 inches Hg. Temperatures and barometric pressures were measured prior to each round and were used to calculate air density.

Calibration

Initial calibration of the Meriam Wall-Mounted 4" Inclined Manometer (model No. 40HE35WM) and the Alnor CompuFlow® ElectroManometer (Model 8530D-I) was done in October 1994 by Hoppe (1995) using a Dwyer Hook Gage (Series 1425) with 0.001 inches water gauge ("w.g.) resolution as the primary standard. A subsequent calibration of the Alnor CompuFlow® ElectroManometer and a Dwyer Air Velocity Meter (Model No. 400-10) was done using the Meriam Wall-Mounted Inclined Manometer.

For calibration, the Alnor CompuFlow® ElectroManometer and the Dwyer Air Velocity Meter were connected via Tygon® tubing via a manifold to a Meriam hand pump (model No. B34348). Pressures ranging form 0.10-4.00 "w.g. were applied. Readings from both instruments were recorded and compared.

The calibration data for the Alnor instrument had an R^2 value of 0.9999 and a gain of 0.0090 when compared to the Meriam inclined manometer. For the most part, the Alnor calibration readings were slightly lower than the Meriam. The percent change ranged from 0% to a maximum value of 2.7% at 0.75" w.g. The Dwyer had an R^2 value of 1.0000 and a gain error of 0.0016, with the greatest deviation among calibration values being 1% at 1.0" w.g. These errors are trivial when compared to average changes in pressures of 20% or greater that were investigated in this study. Typical pressures were generally higher than 1.0" w.g.

Complete calibration data can be found in Appendix A.

Statistical Software

Statistical analysis for this study was completed using Data Desk®, version 4.2c, software by Data Description, Inc., Ithaca, New York.

Methods

Measurements

One-eighth-inch holes were drilled into the ventilation ducts at predetermined locations and plugged with plastic plugs or covered with duct tape. These measurement locations were labeled with identification numbers using black or red marker pens. Photographs were taken of each branch for the majority of the rounds to establish the physical orientation of each branch for comparison purposes between rounds.

Procedures When Taking Measurements

Prior to each round of measurements all dampers were checked and adjusted to baseline positions (generally fully-open). It took from 1 to 3 hours to complete an entire round of measurements. The shop was generally in operation during this period, so employees were asked not to tamper with the system adjustments. It was otherwise routine for them to move flexible ducts or open dampers to improve ventilation at the work stations. Sometimes workers forgot and moved ducts or adjusted dampers while measurements were taken on other ducts.

When possible IVM recommendations were followed in selecting measurement locations. Generally, velocity pressure traverses were taken at least 7 duct diameters downstream and 3 duct diameters upstream of known obstructions, elbows, hoods, or any system components that could produce non-symmetric velocity contours (ACGIH, 1995). If such locations were not available, two perpendicular traverses were performed at the same cross-section and the mean velocities averaged In most cases, static pressures were measured 3 duct diameters upstream of the junction fittings and 3 duct diameters downstream of the joiner connecting the hood to the duct branch.

Even when conditions met IVM recommendations, two perpendicular velocity pressure traverses were taken on each branch except in cases where 1) system geometry did not permit a second traverse diameter, and 2) where the specific branch was suspected to have zero airflow. In the latter case, one perpendicular velocity pressure traverse was taken to confirm the no-flow condition. Velocity pressure traverses were also taken at selected locations on submains, the main system duct, and on the stack to confirm the total system airflow.

For cases where measurement conditions were not ideal, the best available measurement locations were selected. The general the range of distances that were selected are indicated in Table 3.

Table 3. Pressure Measurement Locations in Branches

Measurement	Number of duct diameters distance from elbows, hoods, and junction fittings	
	Downstream	Upstream
SPH	2-4	----
SPend	>4	>1
SPmid	>4	>1
VP	≥7	>2

Measurements began at the most upstream branch from the fan and proceeded in the direction of the fan. Initially, all pressure readings were recorded on a data collection form and were later transcribed into a computer spreadsheet file.

Over the course of the study data collection evolved into a more computerized method driven by the need to reduce time and reduce transcriptions errors. Field data were typed directly into a Toshiba Portege 3400 laptop computer or a Hewlett Packard 100LX palmtop computer using HV_MEAS ventilation software (version 1.0) developed by Guffey (1995, Manual for Heavent) for surveying and troubleshooting ventilation systems. From inputted static and velocity pressures, HV_MEAS computed airflows, static pressure ratios, and X-values. With HV_MEAS it was possible to consolidate all measured and computed values from all rounds and output through to one computer file. That file was imported into a software program (Data Desk) for statistical analysis.

In the later rounds, direct data acquisition became available. This technological advancement allowed for instantaneous data input and comparison in the field of measured pressures and airflows from multiple rounds collected on previous dates. Because the earlier rounds involved data transcription by hand, some rounds had transcription errors while the latter rounds were error free.

The interiors of branches and submains were videoed with a borescope during two rounds. Photographic documentation of the alterations of all branches were taken whenever possible. It was beyond the scope of this study to document alterations in overhead submains.

V. STUDY DESIGN

For troubleshooting variables to be useful, they must change when alterations are present in a duct and remain "reasonably" stable if there are no alterations to the duct.

This study was a passive longitudinal study in that no deliberate alterations were made to the branches. The purpose of the study was to evaluate the relative performance of the troubleshooting variables (i.e., One-Sided SPH, Two-Sided SPH, SPratios, and IVM) as diagnostic screening tools.

Pressures and airflows were measured at an initial unaltered (i.e., baseline) condition of the Model Shop ventilation system. At approximately 3-month-intervals, pressures and airflow measurements were repeated. The current round of measurements was compared to the previous consecutive round for a total of twelve rounds.

The relative percent changes in the tested troubleshooting variable values and the X-values were computed between consecutive rounds. An assignment of a branch as "altered" or "not altered" was designated based on whether $|\%\Delta X| > X_{threshold}$. An assignment of positive or negative for each test variable was based on whether or not it had exceeded its threshold value i.e.:

$|\%\Delta SPH| \geq SPH_{threshold}$ for Two-Sided SPH Method;

$\%\Delta SPH \leq -SPH_{threshold}$ for One-Sided SPH Method;

$|\%\Delta SPratio| \geq SPratio_{threshold}$ for SPratio Method; and,

$\%\Delta SPH \leq -SPH_{threshold}$ and $\%\Delta SPend > 0$ for the IVM Method.

Assignments of true positive, false positive, true negative, and false negative were made at each $X_{threshold}$ and were evaluated over a range of variable thresholds. Sensitivities and specificities were computed and ROC curves were drawn for each method.

Although initial discussion begins with the Preliminary Studies, they were completed after the Main Study was concluded. Data from the Preliminary Studies were incorporated in the analysis of the Main Study. A total of three preliminary studies were completed. Two of the studies are described here (i.e., Study 1 and

Study 2). The results of Study 3 are described in Appendix F. A brief description of the studies objectives is provided in Table 4 below.

Table 4. Studies Objectives

Study	Purpose
Preliminary Study 1	Effects of changing airflows on static pressures, SPratios, and X-values
Preliminary Study 2	Observe effects of deliberately placed obstructions in branches on Static pressures, SPratios, and X-values
Main Study	Determine the relative effectiveness of One-Sided SPH, Two-Sided SPH, SPratios, and IVM Methods as initial screenings tools to identify alterations in branches

Preliminary Studies

Study 1: Reduced Airflow Effects on SPratios

The intent of this study was to investigate changes in pressures in branches that occurred as fan airflow was changed from one level to another and no alterations were made. No alterations to the branches were made deliberately as part of the study. However, as will be discussed, workers innocently made alterations that were unknown to the researchers until later. Fan performance was reduced by removing an inspection plate upstream of the fan. After pressures and flows were measured, all measurements were then repeated with the inspection plate in place.

Study 2: Inserted Obstructions with Measured Static Pressures and Airflows

The intent of this study was to investigate how well the screening tests could predict the presence or absence of alterations deliberately placed in some branches by facilities personnel. In this study, however, Pitot traverses were performed in addition to measurement of static pressures, allowing computation of X-values.

Three rounds of measurements were taken within two days. The first round (i.e., round 1) established baseline values of measured pressures and airflows. In the second round (i.e., round 2) pressures and airflows were measured with deliberate alterations in place. Rounds 1 and 2 were measured on the same day. On the second round (i.e., round 2) pressures and airflows were measured with deliberate alterations in place. Rounds 1 and 2 were measured on the same day. On the second day, (approximately 24 hours later) each "suspected" branch was partially disassembled and examined to confirm the presence or absence of an obstruction. If an obstruction was detected, it was removed and the branch was then restored to its original (baseline) configuration. A third round of measured pressures and airflows (i.e., round 3) was taken in the restored system and these values were compared to the values measured in the baseline round.

Main Study

A round (i.e., all branches) of measurements of pressures and flows was repeated at approximately three month intervals during a 23-month period for a total of 5 rounds. At the end of each round of measurements, data from each branch were evaluated. A change in resistance (i.e., X-values) indicated an alteration. Where possible individual branches were disconnected and visually examined. If foreign material was found in the branches, they were then cleaned, reconnected, and the static pressures were remeasured. Photographs were taken of branches in multiple rounds to document their spatial orientation between measurement periods. Although helpful in noting large changes in the branches orientations, the photographs could not discriminate subtle changes that could affect static pressures or shifts in airflow.

Although data was collected to troubleshoot the entire system, this study is limited to the analysis of pressures and airflows for branches only. Submains and junctions are beyond the scope of this study and are left for future researches.

This study also excluded cases where the velocity pressures were very low (i.e., <0.1 inches w.g.) because they would display a large variability and were of little interest (see Table 5). The larger values of velocity pressure allowed a more confident determination of X-values which were the standard from which the screening tools were evaluated. Excluding the cases where the velocity pressures were less than 0.1 inch w.g. also excluded cases where the SPratio was equal to zero or one. As such cases were indicative of an almost complete blockage to flow, further restricting cases to where the SPratio>0.2 eliminated the cases of very low airflow.

Table 5. Data Filter

Selector Filter	Total Cases by Branch ID Number
None	132
VPavg>0.001	99
VPavg>0.1	86
VPavg>0.1 and VPavgPrev>0.001	66
VPavg>0.1 and VPavgPrev>0.1	62
VPavg>0.1 and VPavgPrev>0.1 and SPH>0.002	61
VPavg>0.1 and VPavgPrev>0.1 and SPH>0.2	61
VPavg>0.1 and VPavgPrev>0.1 and SPH>0.2 and SPH/SPend>0.002	61
VPavg>0.1 and VPavgPrev>0.1 and SPH>0.2 and SPH/SPend>0.2	61

VI. RESULTS AND DISCUSSION

Preliminary Studies

Study 1: Reduced Airflow

Since SPratio and X-values are independent of changes in airflow, these variables should remain relatively constant with changing airflow conditions. Static pressures, however, are very sensitive to changes in airflow and so one would expect significant percent changes in SPH values between rounds. This study investigated the stability of static pressures, SPratios, and X-values with changes in system airflows. The results of this study are summarized in Tables 6, 7 and 8.

The overall results indicated that when the system airflow was reduced by about 8%, the SPratios varied at most by 8% with the majority of branches changing by less than 1%. The largest deviation in X-values was 10% and the majority of branches experienced less than a 4% change in X-values. The SPH values decreased by 15% to 20% in those branches with unobstructed airflow.

As one would expect, when pressures were very low, minor deviations in measured values can cause large percentage changes in the computed values. For example, in branch 1 values of SPH and SPmid were very low due to a closed damper downstream of the mid location. Consequently, relatively high changes in the SPratio values for Hood/end (21.9%) and Mid/end (16.2%) were computed between the two rounds when no alteration had occurred. The resultant X-values for Xhood (25.1%) and Xmid (19.8%) were also high due to the very low velocity pressures in the branch upstream of the damper.

Xend (0.7%) remained relatively constant. This suggests that the screening test methods may be unreliable when static pressures are very low and the X-values may be unreliable when velocity pressures are very low.

Branch 2 also experienced excessively large percent changes in the computed values (i.e., 50% to 100%) due to low pressures and low airflow near the hood and mid locations in the branch. Initially unknown to the author, a downstream damper was innocently closed between rounds by a shop workman. This was a physical modification to the branch and, as such, a violation of the study design assumptions which intended that the system would experience no alterations other than changes in airflow.

In branch 11, an unexpected fast accumulation of wood debris downstream of the hood between rounds 1 and 2 caused an increased resistance near the hood. This was reflected in the increased SPratios for Hood/Mid and Hood/End and the X-values.

With the exception of the specific situations addressed above, the results of this study have demonstrated the stability of X-values and SPratios in the absence of true alterations and with changes in airflow, and the large changes that occurred in SPH with changes in airflow, when no alterations had occurred in the branches. The magnitude of changes that may be expected for Xhood and Xend due to random measurement error or subtle alterations was less than 10%.

Table 6. SPH and SPratio for Branches With Normal and With Reduced Airflow Conditions for Study 1

Branch No.	SPH1 "w.g.	SPH2 "w.g.	SPmid1 "w.g.	SPmid2 "w.g.	SPend1 "w.g.	SPend2 "w.g.	SPratio1 H/End	SPratio2 H/End	SPratio1 H/Mid	SPratio2 H/Mid	SPratio1 Mid/End	SPratio2 Mid/End
1	0.10	0.16	0.13	0.18	4.13	4.93	0.03	0.03	0.81	0.85	0.03	0.04
2	0.00	1.91	0.00	3.83	4.12	4.84	0.00	0.40	--	0.50	0.00	0.79
3	1.10	1.26	3.64	4.14	3.91	4.44	0.28	0.28	0.30	0.30	0.93	0.93
4	2.48	2.88	2.91	3.35	3.73	4.55	0.67	0.63	0.85	0.86	0.78	0.74
5	2.07	2.44	2.85	3.38	3.77	4.22	0.55	0.58	0.73	0.72	0.76	0.80
6	3.75	4.01	3.63	4.18	3.83	4.38	0.98	0.92	1.03	0.96	0.95	0.95
8	1.95	2.47	3.46	4.33	3.94	4.71	0.50	0.52	0.56	0.57	0.88	0.92
9	1.97	2.37	3.97	4.74	3.85	4.63	0.51	0.51	0.50	0.50	1.03	1.02
10	1.37	1.70	3.62	4.46	3.70	4.56	0.37	0.37	0.38	0.38	0.98	0.98
11	1.70	1.83	2.62	3.41	4.23	5.13	0.40	0.36	0.65	0.54	0.62	0.67

Subscript 1 designates round with reduced airflow conditions

Subscript 2 designates round with normal airflow conditions

rences for SPH, SPratios, and Q for Branches
Reduced Airflow Conditions for Study 1

%Change SPratio Hood/End	%Change SPratio Hood/Mid	%Change SPratio Mid/End	%Q, acfm
21.9	4.1	16.2	8
99.7	--	100.0	38
1.1	0.7	0.1	6
-5.1	0.9	-6.0	8
5.0	-0.6	5.6	9
-6.9	-7.7	0.6	7
5.5	1.1	4.5	7
0.0	0.8	-0.7	8
0.8	0.8	-0.0	9
-12.6	-20.9	6.9	7

in values was caused by a damper adjustment

Branches With Normal and With Reduced Airflow Conditions

Xmid1	Xmid2	Xend1	Xend2	%Change Xhood (1-2)	%Change Xmid (1-2)	%Change Xend (1-2)
3.68	4.59	150.00	149.00	25.1	19.8	-0.7
---	4.08	230.00	516.00	100.4	---	55.4
4.88	4.90	5.32	5.32	2.2	0.4	0.0
5.39	5.20	7.19	7.43	-2.8	-3.7	3.2
6.87	6.72	9.41	8.64	-3.1	-2.2	-8.9
29.60	29.40	31.30	30.90	-8.9	-0.7	-1.3
8.95	9.69	10.30	10.60	9.6	7.6	2.8
11.80	11.80	11.40	11.50	1.3	0.0	0.9
6.98	7.12	7.16	7.31	3.8	2.0	2.1
2.59	3.08	4.80	5.14	-11.8	15.9	6.6

round with reduced airflow
round with normal airflow
by workman

Study 2: Inserted Obstructions with Measured Static Pressures and Airflows

If there is no alteration to a given branch, SPratios and X-values should remain constant for that branch. If an obstruction is inserted in a branch, the SPratios and X-values should change to reflect the changed resistance to flow. By contrast, static pressures should respond not only to alterations in the given branch, but also to alterations anywhere in the system.

In study 2, a person not part of the study inserted obstructions in some branches between rounds 1 and 2. The obstructions were removed between rounds 2 and 3. As shown in Tables 9, 10 and 11, five of the eleven branches contained deliberately inserted obstructions and six branches remained unaltered from baseline conditions. The magnitude of the percent changes in X-values and SPratios was proportional to the size of the alterations. If an obstruction was in the hood (e.g. branch 2), the percent change in SPH was positive, reflecting an increased hood resistance (see Table 10). If an obstruction occurred downstream of the hood (i.e., in four out of five cases where deliberate obstructions were detected), the percent change in SPH was negative due to a reduced airflow through the hood. The positive increase in the magnitude of SPH when an obstruction is upstream of the hood measurement location is important since the One-Sided SPH and IVM methods assume that increases in SPH are always benign.

Several cases occurred in which poor measurement conditions at the hood produced unexpected and possibly misleading results. A case in point is branch 8 (See Table 10), where large negative changes in SPH and the SPratio values (H/mid and H/end) falsely indicated an obstruction between the hood and mid locations in the duct. However, in-spite-of the large negative change in Xhood, the lack of change in Xmid and Xend contraindicated an alteration and a measurement error in SPH was suspected. The use of Xhood and Xend together caught the measurement error. A similar error in SPH reading is also believed to have occurred with branch 11.

When the obstructions were removed in round 3 (See Table 11), it was expected that the SPH, SPratios, and X-values would return to their baseline values and this was generally the case with some exceptions. Branch 2 had an erroneously high measured SPH value which was again attributed to a poor measurement location at the hood. This may have accounted for the high SPratio values (i.e., H/mid and

H/end) and the high Xhood value which was inconsistent with the low Xmid and Xend values.

Branch 3 experienced no deliberate alterations. The large percent changes in Xhood, Xmid, and Xend, with the relatively insignificant percent changes in static pressures and SPratios were attributed to measurement errors when taking velocity pressure readings. Such readings were suspected to have occurred in round 1, as this same pattern was observed in both rounds 2 and 3.

Branch 11 had a high percent change in Xhood value and inconsistently low Xmid and Xend values in rounds 2 and 3. For this branch, the relatively high values of SPH and SPratio values (i.e, H/mid, and H/end) with unexpectedly low SPmid, SPend and M/end were indicative of a measurement error in SPH.

Xend varied by less than 7% and Xhood varied by less than 31% in the absence of any known alterations to the given ducts (i.e., round 2). After all known alterations were removed and the ducts were restored to their original configurations (i.e., round 3), Xend varied by less than 9% and Xhood varied by less than 25% when considering all branches. In both scenarios, Xend was far more stable. In Table 10, Xend changed more than SPH when an alteration occurred and less than SPH when it did not occur.

This study demonstrated that SPratios and X-values can reliably detect alterations in the branches and that there were no differences in efficacy in SPH and SPratios. Xend was more stable than Xhood, the SPratios, or SPH mainly because SPH measurements often had to be taken in poor measurement locations such as near elbows and in flexible ducts. The volatility of the hood measurement location is a real phenomenon in the field. In cases where obstructions were trivially small (such as branch 9), the percent changes in all test variables were difficult to discriminate from random fluctuations. Distinguishing between actual and suspected alterations underscores the difficulty in conducting a "controlled" study in a system in active use.

Table 9. Values Before Insertion of Obstructions for Study 2

	Static Pressures			SPratio Values			X-Values		
ID	SPH "w.g.	SPmid "w.g.	SPend "w.g.	H/mid	M/end	H/end	Xhood	Xmid	Xend
1	2.20	2.79	4.81	0.79	0.58	0.46	2.78	3.79	7.25
2	2.13	3.52	4.34	0.61	0.81	0.49	9.11	15.7	19.6
3	1.08	3.69	4.04	0.29	0.91	0.27	0.92	5.57	6.20
4	2.68	3.08	3.96	0.87	0.78	0.68	4.44	5.25	7.03
5	2.33	3.61	4.00	0.65	0.90	0.58	4.85	8.06	9.00
6	4.07	3.88	4.11	1.05	0.94	0.99	31.0	29.5	31.3
7	4.07	--	4.02	--	--	1.01	--	--	--
8	2.16	3.88	4.29	0.56	0.90	0.50	5.48	10.6	11.9
9	2.04	4.15	4.15	0.49	0.99	0.49	5.19	11.6	11.7
10	--	--	4.08	--	--	--	--	--	7.60
11	1.36	2.91	4.62	0.47	0.63	0.29	0.72	2.67	4.80

Table 10. Percent Change of Troubleshooting Variables From Initial Conditions to Conditions With Inserted Obstructions in Place for Study 2

	%Change Static Pressures			%Change SPratio Values			%Change X-Values			
D	SPH	SPmid	SPend	H/mid	M/end	H/end	Xhood	Xmid	Xend	Inserted Obstructions
1	-18.2	20.4	-1.7	-32.1	22.4	-16.6	-13.3	78.1	36.8	2.5"X0.4"X6.0" wood, between H and Mid, substantial
2	35.7	10.2	3.7	23.1	6.3	30.8	104.2	61.1	50.5	3" diameter tape, upstream of H, substantial
3**	2.8	--	5.0	-2.0	0.0	-1.9	-15.3	-6.3	-6.3	no
4	-22.8	13.0	5.6	-31.6	7.1	-26.9	-7.7	44.2	32.3	tape across galvanized steel duct adjacent to flex, between H and Mid, substantial
5	- 9.9	-17.5	5.0	9.3	-21.3	-14.1	-14.0	-2.6	33.8	damper half closed, downstream of mid, moderate
6	4.2	4.9	3.9	-0.7	1.0	-0.3	-4.2	-3.4	-4.5	no
7	3.9	--	4.0	--	--	0.0	--	--	--	no
8*	-13.0	2.8	3.5	-15.4	-0.6	-15.9	-18.6	0.0	0.0	no
9	-1.0	2.7	4.6	-3.7	-0.6	-4.3	-0.4	3.4	5.1	0.4"X1.5"X6" wood, between H and Mid, slight
10	--	--	--	--	--	--	--	--	4.1	no
11*	17.6	3.1	3.5	14.1	-0.3	13.9	30.7	-1.5	-0.8	no

*Likely that SPH measurement was incorrect since would have expected the large percent change in Xhood to be followed by equally large or greater percent changes in Xmid and Xend.

**Likely velocity pressure measurement was incorrect since percent changes in X-values are not confirmed by percent changes in static pressures and SPratios.

Table 11. Percent Change of Troubleshooting Variables From Initial Conditions to Conditions With Inserted Obstructions Removed for Study 2

	%Change Static Pressures			%Change SPratio Values			%Change X-Values		
ID	SPH	SPmid	SPend	H/mid	M/end	H/end	Xhood	Xmid	Xend
1*	5.0	-2.9	-1.7	8.0	-1.2	6.8	7.9	-2.6	-0.8
2*, **	-14.1	-0.0	-1.4	-14.0	1.4	-12.8	-18.9	-3.8	-5.1
3***	-1.9	-1.4	-1.7	-0.7	0.4	3.4	-15.7	-8.3	-8.7
4*	-3.0	-3.6	-1.0	0.6	-2.6	-2.1	-3.8	-4.4	-1.3
5*	-3.0	-1.7	-1.5	-1.2	-0.1	-6.0	3.7	5.2	5.3
6	-2.9	-0.3	-1.2	-2.7	1.0	-1.7	-5.5	-2.7	-3.5
7	-1.7	--	-1.2	--	--	-0.4	--	--	--
8	--	--	--	--	--	--	--	--	--
9*	4.9	-1.4	0.0	6.3	-0.2	6.2	3.3	-3.4	-3.4
10	--	--	-0.7	--	--	--	--	--	-2.0
11**	-5.9	-1.4	-2.2	-4.5	0.8	-3.7	-24.5	-7.9	-8.1

*Inserted Obstruction Removed

**Likely that SPH measurement was incorrect since would have expected the large percent change in Xhood to be followed by equally large or greater percent changes in Xmid and Xend.

***Likely velocity pressure measurement was incorrect since percent changes in X-values are not confirmed by percent changes in static pressures and SPratios.

The three preliminary studies have demonstrated that changes in Xend and SPratios varied by less than 9% and Xmid varied by less than 8% in branches with no known alterations. As small, unapparent changes in the branches may have caused changes in Xend, it is possible that the true resolution of Xend may be lower than observed. Xhood was more volatile than Xend and varied by as much as 31% when branches were not deliberately altered. In the absence of any known alterations and constant airflow conditions, SPH changed by less than 6% and with reduced airflow SPH changed as much as 35%. This reflected the volatility of SPH in the absence of any physical changes to the system.

In those cases where an error in SPH was suspected, it was often attributable to poor measurement locations such as near elbows and junctions (See Tables 10 and 11). Whenever possible, the most stable measurement locations were selected. The SPratio was computed by dividing SPH by SPend. It is conceivable that SPend could have contributed some error to the SPratio value as well. However, the SPend values were generally less variable due to more favorable measurement locations. These studies showed that SPratio values varied equally with Xend.

In cases of known alterations, changes in Xend were greater than changes in SPH. In the absence of known alterations, changes in Xend were less than changes in SPH (See Table 12). This experimentally supports the assumption that X is reliably related to alterations and is, therefore, a good standard.

Main Study

The Preliminary Studies all involved interventions by the investigators. The Main Study was completely passive, involving observations of changes in each branch's airflow, SPH, SPratio, and X values. The data collection was the same.

The traverse velocity pressures, SPH, SPmid, and SPend all were measured for each branch for each round of data collection. The only changes to resistance were those produced by normal work routines; they were not controlled by the researcher. The percent change in each troubleshooting metric (e.g., One-Sided SPH, Two-Sided SPH, SPratio, IVM, and Xend for each branch) was calculated from measurements taken in the immediately *preceding round* and in the *current* *round* using the equations defined in Table 2. Each branch and round combination was considered a separate case.

Ranges of thresholds were employed for each screening tool and for Xend. If the change in a screening tool exceeded the screening tool's specified threshold, then the screening tool was judged to have made a positive indication. If the change in Xend exceeded the specified threshold for Xend, then a actual change in resistance (i.e., an "alteration") was judged to have occurred. If, for example, a screening tool indicated positive when the X-value indicated positive, the outcome for that screening tool was deemed to be a true positive. False positives, false negatives, and true negatives were similarly defined and sensitivities and specificities calculated (See Appendix D).

Selection of Appropriate Xend Thresholds

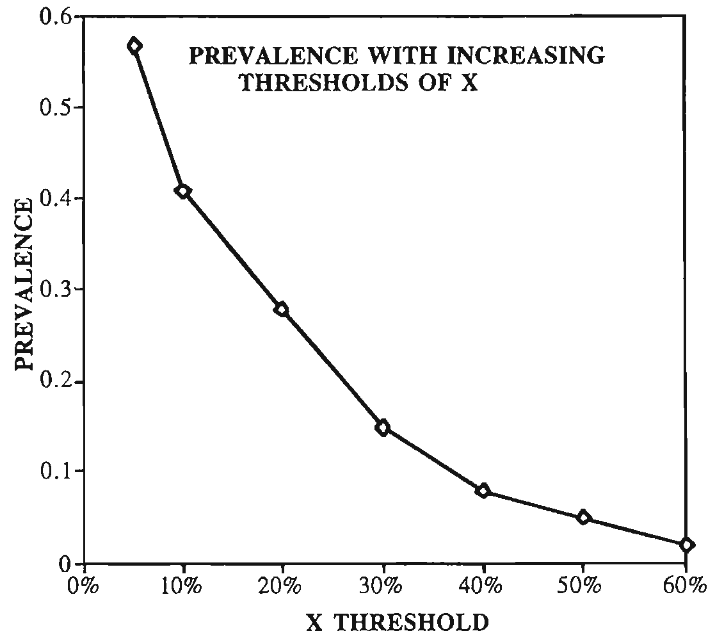


Figure 5. Positive outcomes with increasing thresholds of X

Figure 5 shows that with increasing thresholds of X the prevalence (number of positive outcomes per total number of cases) decreased precipitously. That is, at higher thresholds of X, fewer and fewer alterations were deemed to be "proven" alterations. It is important to understand that an "alteration" could occur upstream or downstream of H (SPH measurement location) and that the appearance and disappearance of an obstruction both constituted "alterations."

The changes in resistance represented a mix of obstructions, a fraction of which occurred by chance upstream of the hood measurement location and the rest occurred downstream of the hood. Alterations in the hood were due to obstructed inlet conditions, changes in flexible duct orientations, etc. The fact that some obstructions did occur upstream of the hood is important since the One-Sided SPH test ignores increases in hood static pressures, which were demonstrated in Study 2 to be associated with obstructions upstream of H.

As shown in Figure 5, an $X_{threshold}$ of 10% was exceeded in 41% of the cases. An in $X_{threshold}$ of 5% was exceeded in 57% of the cases. Colvin's study referred to earlier in the background discussion had determined that changes in X of up to 7% will occur even in the absence of any alterations to the ducts due to random measurement errors. This suggests that many of the positive outcomes detected at $X_{threshold}$=5% in this study may have been due simply to random variability, when in actuality there had been no physical change or alteration occurring in those cases. It is also possible but not proven, that some of the small changes were due to real events that were too subtle to discover.

What, then, is a reasonable threshold to measure positive outcomes? Hoppe's work showed that a 17% change in X caused a substantial change in airflow. Since, that value is much greater than the resolution of X, the author suggests that a 20% change in X is a reasonable threshold to label outcomes positive. However, thresholds of 10%, 20%, 30%, 40%, 50%, and 60% were employed in the following analyses.

Performance of Screening Tools in the Main Study

Evaluation of ROC Curves

Figures 6 through 11 display the ROC curves for each proposed screening tool at selected thresholds of X. Better performance is indicated by an ROC curve that is higher and to the left in the ROC space. That is, greater areas under the ROC curves are indicative of superior combinations of sensitivity and specificity.

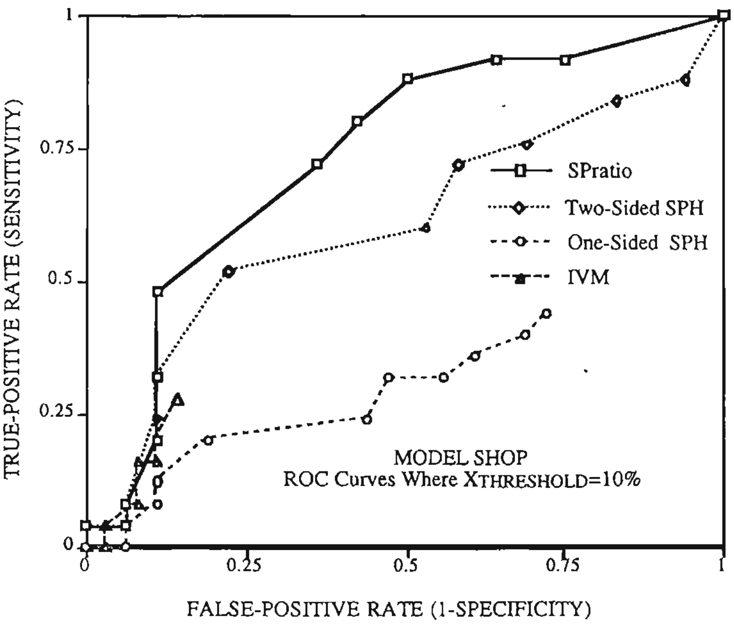


Figure 6. ROC curve where XThreshold=10%

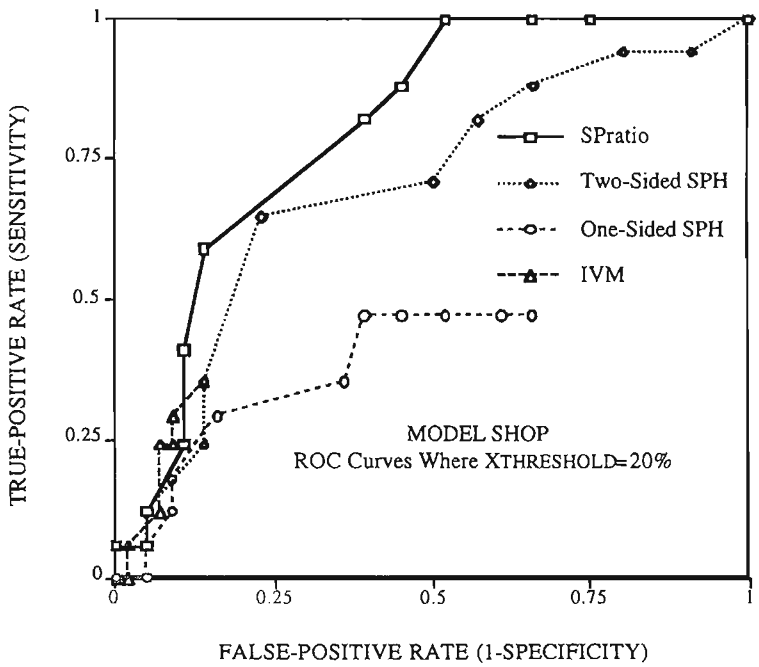


Figure 7. ROC curve where Xthreshold=20%

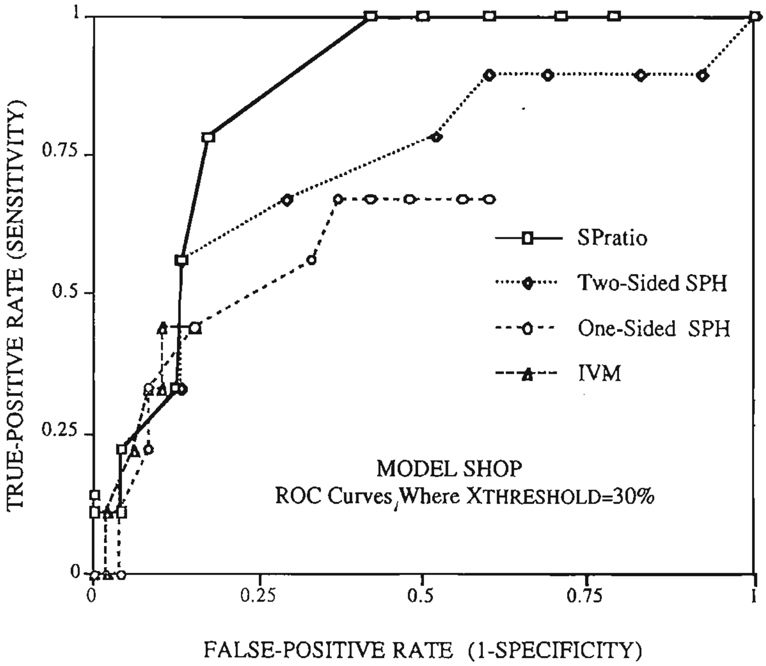


Figure 8. ROC curve where XThreshold=30%

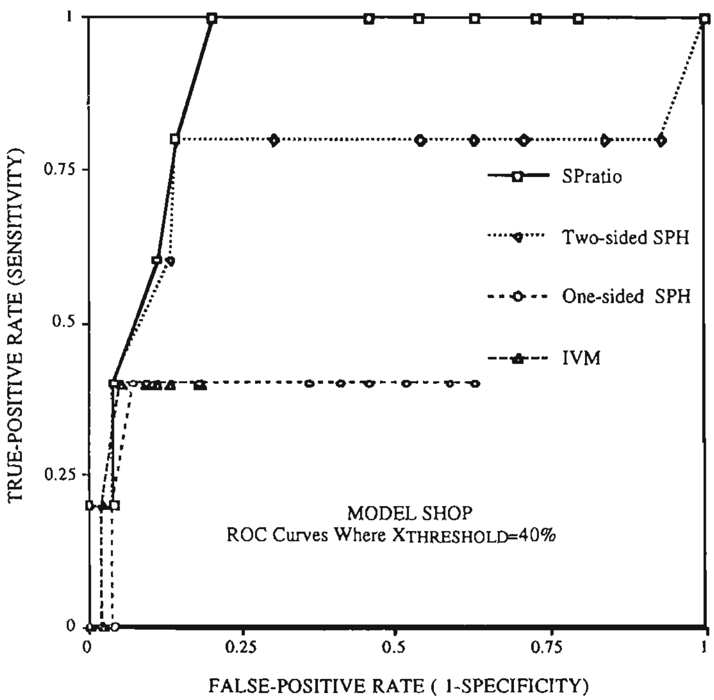


Figure 9. ROC curve where XThreshold=40%

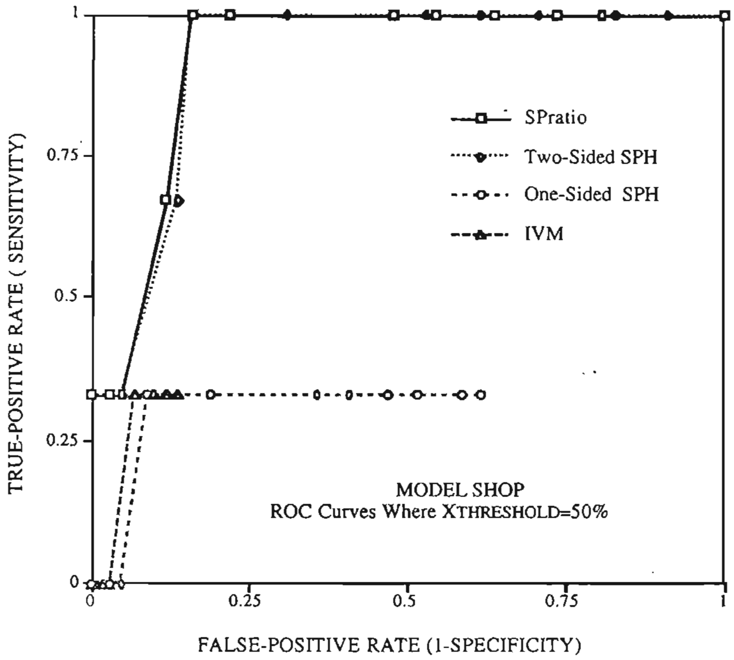


Figure 10. ROC curve where XThreshold=50%

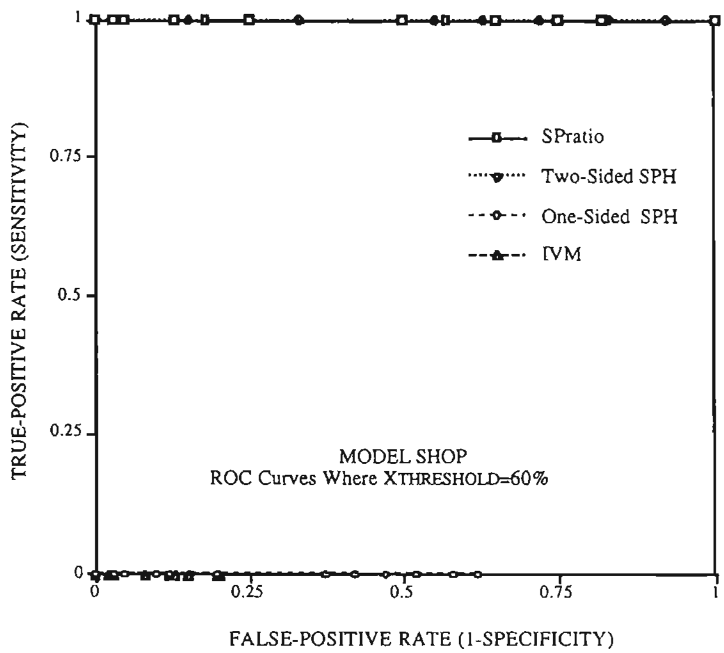


Figure 11: ROC curve where XThreshold=60%

Figure 12 shows the relationship between selected thresholds of X and the areas under the ROC curves for SPratio, One-Sided SPH, Two-Sided SPH, and IVM.

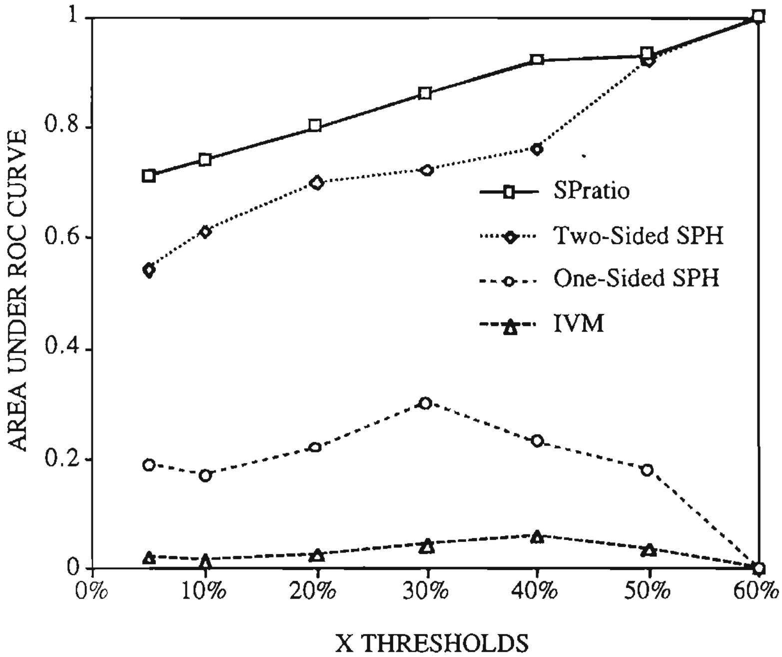


Figure 12. Area under ROC curves at selected thresholds of X

Analysis of the ROC curves indicated that, in general, the larger the obstructions the better the ability of the SPratio and the Two-Sided SPH methods to detect positive outcomes. SPratio performed better than Two-Sided SPH in detecting moderate alterations in the branch that occurred between H and End locations. For very large obstructions SPratio and Two-Sided SPH detected alterations equally well.

Increasing values of X threshold produced increasing True-Positive Rates for SPratio and for Two-Sided SPH. It is not surprising that both methods are more likely to correctly identify larger alterations than smaller alterations. What may be surprising is that One-Sided SPH and IVM methods do not consistently show improved accuracy with higher thresholds of X. This is due to the fact that both methods ignore increases in hood static pressure, which are strongly associated with obstructions upstream of H. One would expect that sensitivity would increase monotonically with increasing thresholds of X. The erratic changes in True Positive Rates are due to the fact that the mix of obstruction locations (upstream or downstream of H) varied with increasing values of X. Thus, the maximum sensitivity for One-Sided SPH and IVM cannot exceed the fraction of obstructions located downstream of H. For the same reason, even for a threshold of zero for One-Sided SPH or IVM, the False-Positive Rate cannot equal unity for these tools.

One-Sided SPH and IVM methods' abilities to detect alterations in the branch were very poor even with the greatest threshold values. Substantial obstructions occurring in the hood were missed completely. Figure 13 below represents a plot of changes in Xhood with changes in SPH. With some minor exceptions, as ΔXh increases ΔSPH also increases. This suggests that many of the cases identified in this study as negative may have represented obstructions occurring at the hood. This is significant because the One-Sided SPH and IVM methods would not have detected these cases and would have labeled them as false negative outcomes. In fact, as Figure 13 shows, all but one of the false negative outcomes for One-Sided SPH were cases where SPH increased.

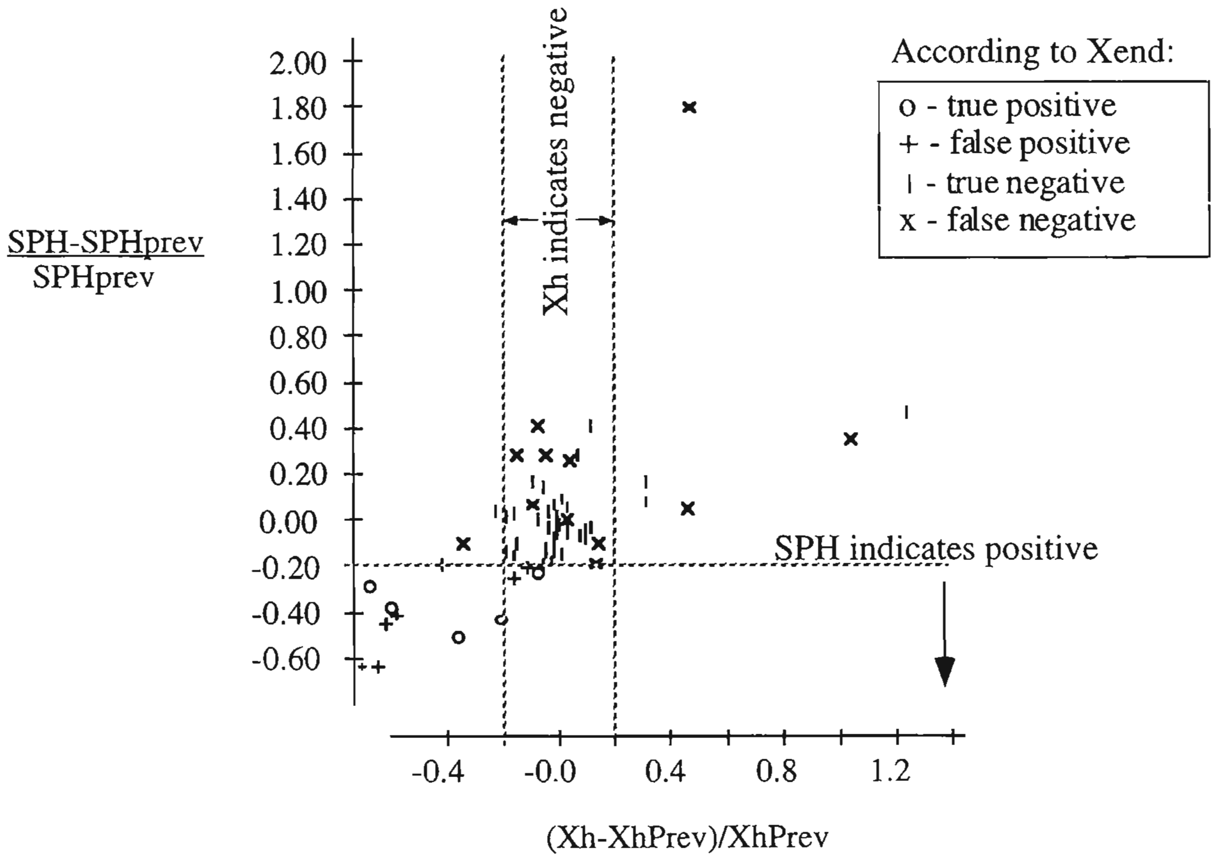


Figure 13. Change in SPH with change in Xhood

Evaluation of Sensitivity and Specificity of Screening Tools at X=20% Threshold in the Main Study

In this study, it is assumed that comparison of Xend values is a generally highly sensitive and specific method of identifying alterations. It is also assumed that the cost of determining Xend is modest compared to the consequences of either overlooking alterations or attempting to disconnect ducts to discover nonexistent alterations. Finally, since the proposed screening test methods do not involve taking a Pitot traverse, each is both faster and more convenient than determining X values. Hence, the screening tests should be employed for final diagnosis only if experimentation demonstrates that their sensitivity and specificity is nearly as good as that afforded by Xend comparisons.

As shown in Figures 6 through 11, none of the proposed tests produces nearly 100% sensitivity at very low False-Positive Rates (e.g., 10%). In each case, the price of high sensitivity is a substantial fraction of costly fruitless searches. Hence, these tools can serve, at best, as screening tools to reject the more obvious negative cases and identify others as requiring determination of changes in Xend.

The sensitivity that one is willing to accept is a policy issue. The choice of sensitivity can be a basis for selecting a threshold for each screening tool. Once the thresholds are established, the associated specificities also can be determined. It can also be the basis of determining which screening tools are the most useful.

Let us select 90% sensitivity as a reasonable choice. A 90% sensitivity (i.e., 10% false negatives), corresponds to a threshold of 8% for SPratio method and a threshold of 5% for the Two-Sided SPH method (See Figure 14). At these respective thresholds, SPratio achieved a 55% specificity and Two-Sided SPH achieved a 35% specificity (See Figure 15).

As seen in Figure 14, the One-Sided SPH and the IVM methods did not achieve 90% sensitivity at any threshold. At the 10% threshold for example, the One-Sided SPH method achieved a 35% sensitivity and the IVM method achieved a 25% sensitivity. Even with a zero threshold both these methods would have missed more than half of the alterations because, as mentioned above, they did not detect cases where SPH increased and are, therefore, eliminated from further discussion.

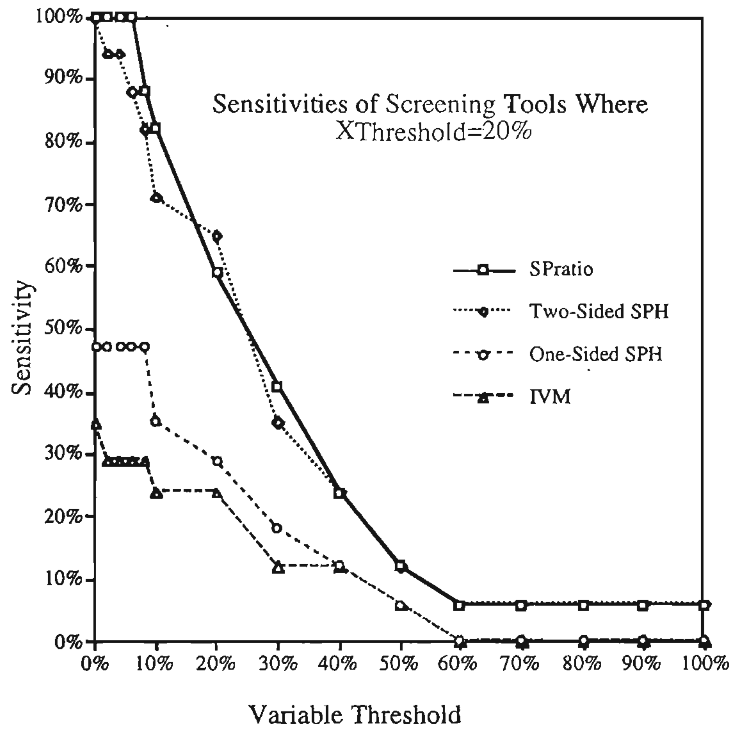


Figure 14. Relationship of Sensitivity with increasing variable thresholds

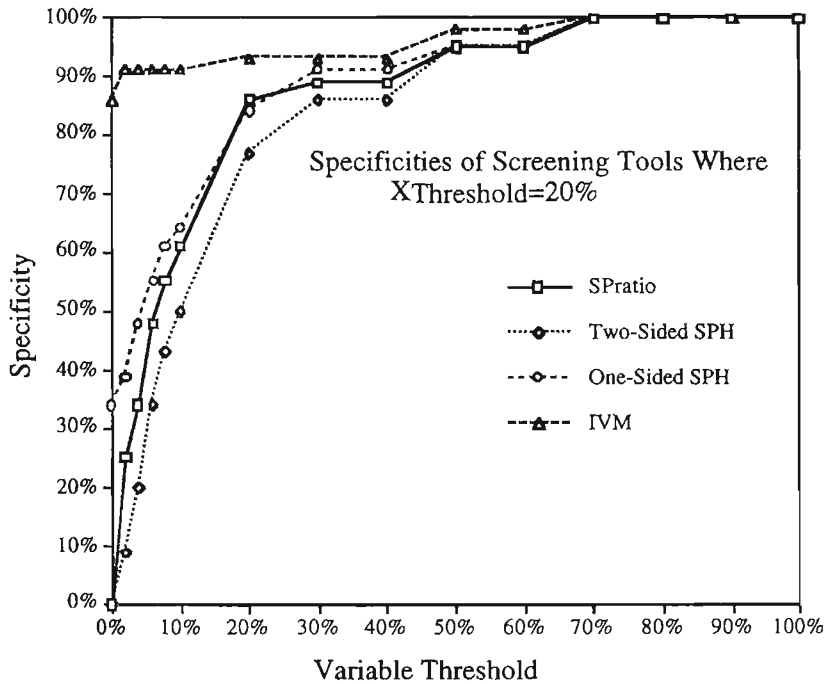


Figure 15. Relationship of Specificity with increasing variable thresholds

The recommended thresholds and the associated specificities for each method at 90% sensitivity and change in X>20% is shown in Table 12.

Table 12. Recommended Thresholds and Associated Specificities for Screening Tools Given 90% Sensitivity and Change in X=20%

Screening Tools	Threshold	Specificity
SPratio	8%	55%
Two-Sided SPH	5%	35%
* One-Sided SPH	---	---
*IVM	---	---

* Could not achieve 90% Sensitivity with this data

Evaluation of Efficacy of Screening Tools at Selected Variable Thresholds with 90% Sensitivity and X=20% Threshold in the Main Study

A good screening tool reduces the number of cases requiring in-depth investigation while rejecting few true cases. From Figures 16 and 17 we see that for SPratios at the recommended threshold of 8%, the method had 4% false negatives (i.e., rejected 4% of the actually positive cases) and 38% false positives (i.e., accepted 38% of the actually negative cases). At a 5% threshold the Two-Sided SPH method had 3% false negatives and 35% false positives.

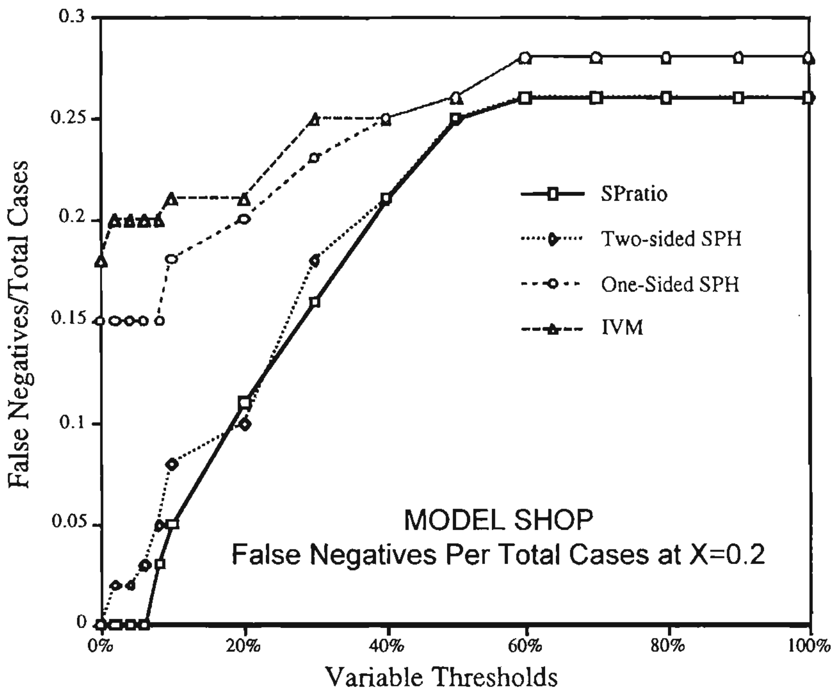


Figure 16. Relationship of false negatives per total cases with increasing variable thresholds

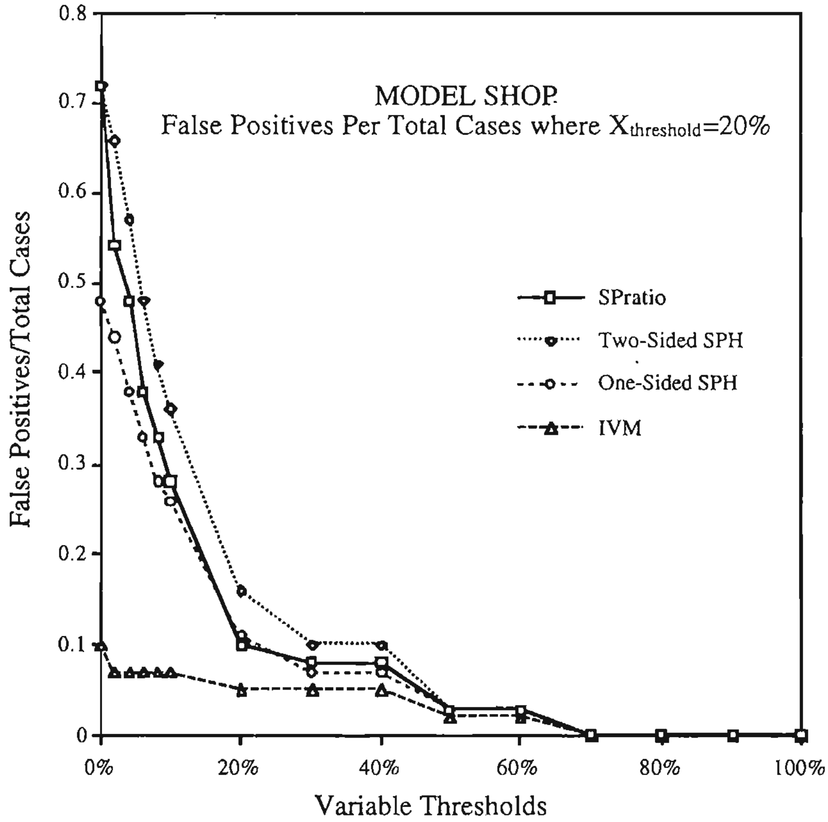


Figure 17. Relationship of false positives per total cases with increasing variable thresholds

VII. CONCLUSIONS

A simple, quick method to diagnose ventilation system problems could be of great benefit to ventilation practitioners. SPratios provided the best performances at every $X_{threshold}$, but there was little difference between Two-Sided SPH and SPratio in discovering dramatic changes (e.g., $X_{threshold}$ >40%) for this data. Thus, for very substantial obstructions producing large changes in airflow, Two-Sided SPH was an adequate screening tool for this data. For moderate changes in $X_{threshold}$ (e.g. ≤30%), SPratio was a better screening tool for these data. The IVM and One-Sided SPH performed poorly at all thresholds of X and were not useful screening tools.

RECOMMENDED DIAGNOSTIC APPROACH

Figure 18 is a schematic representation of a decision tree which utilizes the troubleshooting variables described in this study to effectively identify alterations in working industrial exhaust ventilation systems.

In this method the hood static pressure is measured and the percent change is calculated. Because it is difficult to always avoid error, a substantial change in SPH should merit immediate re-measurement. If the magnitude percent change is less than the threshold value (e.g., 5%) no action is necessary as the airflow has not changed. If the percent change is greater than the threshold value, one should measure the static pressures at the mid or end locations (or both) and compute the percent changes in the static pressure ratios.

If the percent change in SPratios is less than the threshold value (e.g., 8%), the change in airflow was most likely caused by a change elsewhere in the system. If the percent change was greater than the threshold value, one should do a Pitot traverse and compute percent changes in Xhood, Xmid, and Xend.

If the percent change in the Xend is less than its threshold value (e.g., 20%), the change in airflow may have been caused by a change elsewhere in the system or there may have been a measurement error in the hood static pressure or mean velocity. If a measurement error is suspected, the SPend value and the velocity should be remeasured. Otherwise, if Xend is greater than its threshold, evaluate the individual changes in Xhood, Xmid, and Xend.

As mentioned earlier, the properties of the X-values require that any changes in Xend be equal to the sum of changes to the section of the branch (i.e., ΔXend$\geq\Delta$Xhood+Δ(Xmid-Xhood). If ΔXend is substantially smaller than the sum of individual changes, then the value of SPH, SPmid, or SPend was incorrect either in the previous round or the present round. If the relationships between Xhood, Xmid and Xend are consistent, then by evaluating where changes in X-values increase and decrease it should be possible to precisely locate alterations in branches.

Caveats

It remains to be seen if the SPratio is a better screening test than Two-Sided SPH in other active ventilation systems. In addition, these findings assume that when other tests disagree with X-value indications, it is the X-values that should be believed. That assumption should be tested much more thoroughly in other studies before it is accepted as fact.

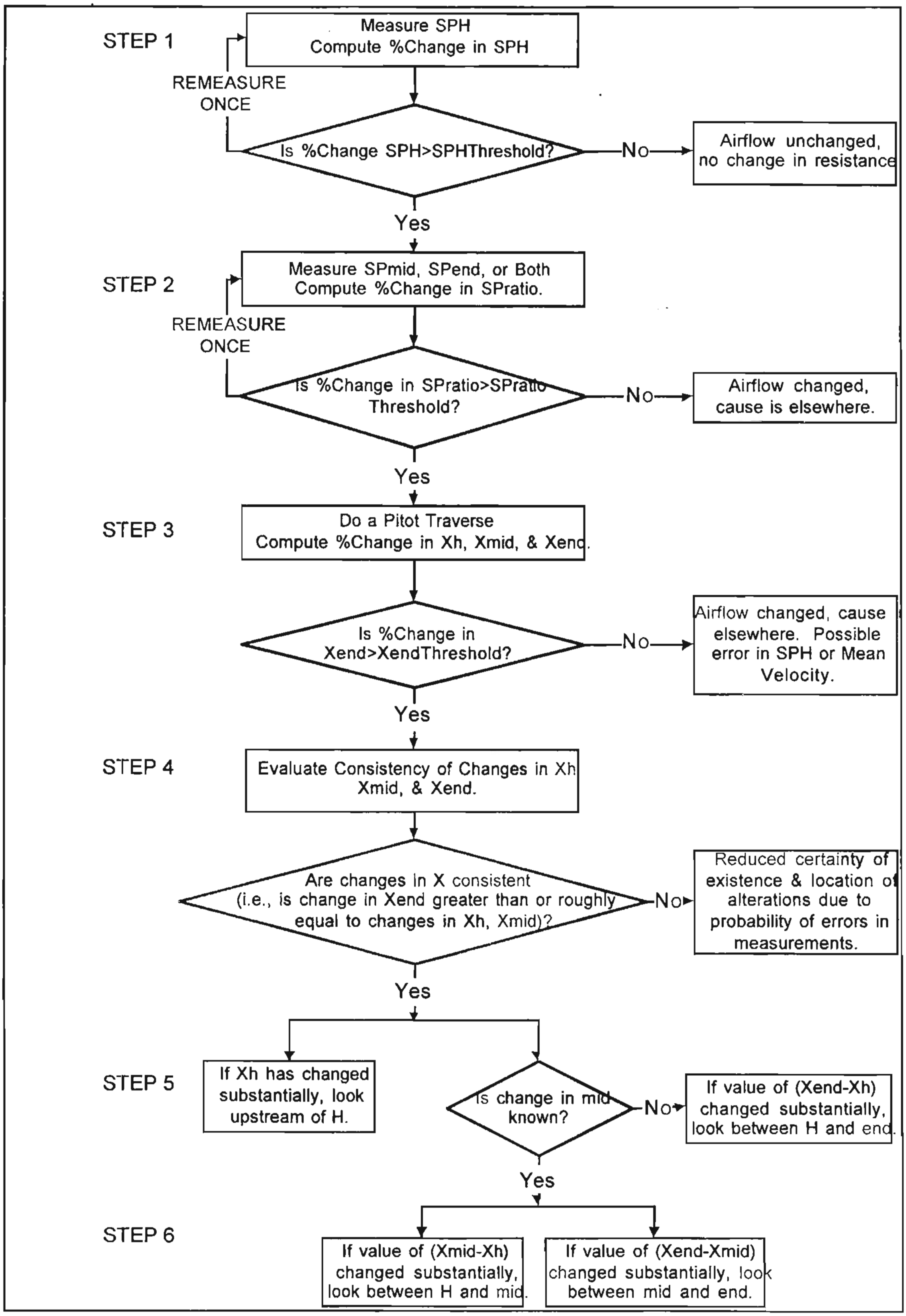


Figure 18. Decision tree to identify alterations in a branch

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APPENDIX A: CALIBRATION DATA

Alnor ElectroManometer & Merian Inclined Manometer Calibration
(Taken from Hoppe, M.S. Thesis, 1995)

This data is provided courtesy of Jeanne Schlichtman Hoppe who completed this calibration.

Location: Northlake laboratory
Instrument: Dwyer Hook Gauge No. 1425
Date: 941012
Temp: 19° C

Instrument	Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	Pt 7	Pt 8	Pt 9	Pt 10
Hook V	0.00	0.10	0.15	0.20	0.25	0.30	0.50	0.75	1.00	2.00
Hook P	0.00	0.10	0.10	0.20	0.25	0.30	0.50	0.75	1.00	2.00
Alnor Digital	0.02	0.20	0.30	0.40	0.49	0.60	1.00	1.50	2.00	3.98
Dwyer Digital	0.00	0.20	0.29	0.39	0.50	0.60	1.00	1.49	1.99	3.99
Meriam Inclined	0.00	0.20	0.29	0.40	0.50	0.61	1.01	1.50	2.03	3.98

Alnor ElectroManometer & Dwyer Inclined Manometer Calibration

Location: Northlake laboratory
Instrument: Meriam 4" Inclined Manometer
Model No. 40HE35WM
Serial No. 149990CI

Date: 950709

Instrument	Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	Pt 7	Pt 8	Pt 9	Pt 10
Meriam Inclined	0.0	0.25	0.50	0.75	1.0	1.5	2.0	2.5	3.0	3.5
Alnor Digital	0.0	0.25	0.50	0.73	0.99	1.49	1.99	2.49	2.98	3.53

Date: 950709

Instrument	Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	Pt 7	Pt 8	Pt 9	Pt 10
Meriam Inclined	0.0	0.25	0.50	0.75	1.0	1.5	2.0	2.5	3.0	3.5
Dwyer Inclined	0.0	0.25	0.50	0.75	0.99	1.5	2.0	2.5	3.0	3.5

APPENDIX B: VENTILATION SYSTEM CHARACTERIZATION DATA

Model Shop 18:23 Bldg.
FAN ID:(AAF Skimmer) American Air Filter/14" Diameter/10HP
Air Cleaner: Roto-Clone Dynamic Precipitator

ID	Type	ID ColUp	ID LatUp	Galv Steel Dia (inches)	Galv Steel Length (inches)	Flex Duct Dia (inches)	Flex Duct Length (inches)	#90 degree Elbows	Damper	Comments
1	Branch	--	--	6	297.25	6	34	2	yes	
2	Branch	--	--	5	256.143	4	138	2	yes	
15	SUBMAIN	1	2	8	44	--	--	--	--	
3	Branch	--	--	5	161.5	5	10	1.5	yes	
20	SUBMAIN	15	3	9	88.75	--	--	--	--	
30	SUBMAIN	40	4	10	57.5	--	--	--	--	
4	Branch	--	--	5	290.8	5	79	1.5	yes	
40	SUBMAIN	50	5	8	112.1	--	--	--	--	
5	Branch	--	--	5	353.75	4	44	1.5	yes	
50	SUBMAIN	7	6	8	54.5	--	--	--	--	
6	Branch	--	--	5	178.1	--	--	0	yes	
7	Branch	--	--	5	172.75	--	--	2	no	
60	SUBMAIN	20	30	14	37.6	0	0	--	--	
8	Branch	--	--	5	195.42	5	72	1.5	yes	
70	SUBMAIN	60	8	14	67.4	0	0	--	--	
80	SUBMAIN	11	90	10	105.22	0	0	--	--	
11	Branch	--	--	5	402	5	106	1.5	yes	
90	SUBMAIN	9	10	8	38.2	0	0	--	--	
9	Branch	--	--	5	179.3	4	55	1	yes	
10	Branch	--	--	5	198.73	4	67	1	yes	
100	MAIN	70	80	14	32	--	--	--	--	
110	Collector Inlet	100	--	14 to 10x24	0	--	--	--	--	
115	Collector	110	--			--	--	--	--	
120	Fan Inlet	115	--	22-14	19	--	--	--	--	reducer
125	FAN	120	--			--	--	--	--	
130	Fan Outlet	125	--	10-18	24	--	--	--	--	expansion
140	STACK	130	--	18	165	--	--	--	--	

APPENDIX C: FIELD DATA

File: MS931020

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Dwyer Inclined Manometer
Date Measured: 10/20/93
Measured by: ap/bb

Site Altitude: 57 Feet Above Sea Level
Tdb: 69 deg F
Twb: 56 deg F
BarP: 30.19 inch Hg
RH: 43%
DenF: 1.0109

ID	Type	Dia	SPH	SPmd	SPend	Vmeas	Qact
1	Branch	6	2.4	–	3.50	2928	584
2	Branch	5	3.4	–	4.40	1672	230
3	Branch	5	2.2	–	4.10	3282	451
4	Branch	5	3.6	–	4.10	1916	263
5	Branch	5	0.1	–	4.30	0	0
6	Branch	5	3.5	–	3.50	1289	177
7	Branch	5	4.4	–	4.20	20	3
8	Branch	5	3.9	–	4.20	2177	299
9	Branch	5	4.1	–	4.10	2291	315
10	Branch	5	3.7	–	4.00	2638	362
11	Branch	5	3.0	–	4.50	3431	471
15	Submain	8	–	–	4.50	–	814
20	Submain	9	–	–	4.50	–	1265
30	Submain	10	–	–	4.30	–	443
40	Submain	8	–	–	4.30	–	180
50	Submain	8	–	–	4.30	–	180
60	Submain	14	–	–	4.50	–	1708
70	Submain	14	–	–	4.50	1642	2007
80	Submain	10	–	–	4.30	2100	1147
90	Submain	8	–	–	4.40	–	677
100	Submain	14	–	–	5.30	–	3156
110	Coll Inlet	14 to 10X24	–	–	–	–	3156
115	Collector	–	–	–	–	–	3156
639	Fan Inlet	22 to 14	–	–	5.70	–	3156
640	Fan	–	–	–	–	–	3156
641	Fan Outlet	10 to 18	–	–	1.30	–	3156
642	Stack	18	–	–	0.01	–	3156

File: MS931020

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Dwyer Inclined Manometer
Date Measured: 10/20/93
Measured by: ap/bb

Site Altitude: 57 Feet Above Sea Level
Tdb: 69 deg F
Twb: 56 deg F
BarP: 30.19 inch Hg
RH: 43%
DenF: 1.0109

ID	Type	Comment
1	Branch	hood connected to plainer
2	Branch	hood connected to band saw/br split in two/one duct closed
3	Branch	hood connected to oliver joiner
4	Branch	hood connected to10 inch table saw
5	Branch	hood connected to spindle sander
6	Branch	hood connected to band saw
7	Branch	hood connected to floor Collector
8	Branch	hood connected to 14 inch table saw
9	Branch	hood connected to belt sander
10	Branch	hood connected to 30 inch sander
11	Branch	hood connected to cross-cut saw
15	Submain	
20	Submain	
30	Submain	
40	Submain	
50	Submain	
60	Submain	
70	Submain	
80	Submain	
90	Submain	
100	Submain	
110	Coll Inlet	
115	Collector	
639	Fan Inlet	
640	Fan	
641	Fan Outlet	SPend=(-)1.3 inch w.g.
642	Stack	SPend=(-)0.01 inch w.g.

File: MS940221

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Dwyer Inclined Manometer
Date Measured: 2/21/94
Measured by: ap/bb

Site Altitude: 57 Feet
Above Sea Level
Tdb: 71 deg F
Twb: 56 deg F
BarP: 29.69 inch Hg
RH: 37%
DenF: 0.9904

ID	Type	Dia	SPH	SPmd	SPend	Vmeas	Qact	Comment
1	Branch	6	2.3	–	3.50	2634	14	
2	Branch	5	0.0	–	4.50	257	35	SPH=0.0
3	Branch	5	2.3	–	4.00	2979	406	
4	Branch	5	1.3	–	3.90	1903	259	
5	Branch	5	2.8	–	3.90	2626	358	
6	Branch	5	3.3	–	3.60	1239	169	
7	Branch	5	4.0	–	4.00	235	32	
8	Branch	5	3.8	–	4.10	2232	304	
9	Branch	5	3.9	–	4.00	2243	306	
10	Branch	5	3.6	–	3.90	2620	357	
11	Branch	5	2.9	–	4.35	3296	449	
15	Submain	8	–	–	4.30	–	50	
20	Submain	9	–	–	4.30	–	456	
30	Submain	10	–	–	4.20	–	819	
40	Submain	8	–	–	4.15	–	559	
50	Submain	8	–	–	4.05	–	201	
60	Submain	14	–	–	4.40	–	1275	
70	Submain	14	–	–	4.40	1828	1579	
80	Submain	10	–	–	4.20	–	1112	
90	Submain	8	–	–	4.30	1888	663	
100	Submain	14	–	–	5.10	–	2692	
110	Coll Inlet	14 to 10X24	–	–	–	–	2692	
115	Collector	–	–	–	–	–	2692	
639	Fan Inlet	22 to 14	–	–	5.60	–	2692	
640	Fan	–	–	–	–	–	2692	
641	Fan Outlet	10 to 18	–	–	2.30	–	2692	
642	Stack	18	–	–	0.26	–	2692	SPend=(-)0.26

File: MS940803
Company: Boeing Company
Proj.: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 8/3/94
Measured by: ap/bb

Site Altitude: 57 Feet Above Sea Level
Tdb: 73 deg F
Twb: 62 deg F
BarP: 29.98 inches Hg
RH: 53%
DenF: 0.9961

ID	Type	Dia	SPH	SPmd	Pend	Vmeas	Qact	Comment
1	Branch	6	2.3	3.03	4.82	2799	550	
2	Branch	5	2.3	3.42	4.44	1194	163	
3	Branch	5	1.4	3.79	4.25	3111	424	
4	Branch	5	1.3	3.76	4.20	1076	147	
5	Branch	5	0.0	0.06	4.27	0	0	Damper closed /no airflow
6	Branch	5	4.2	3.85	4.37	1206	164	
7	Branch	5	0.0	0	4.19	0	0	Floor Sweep /no airflow
8	Branch	5	2.2	3.94	4.31	1860	254	
9	Branch	5	1.9	3.93	4.20	1918	262	
10	Branch	5	1.3	3.68	4.07	2574	351	
11	Branch	5	1.6	2.95	4.54	3369	459	
15	Submain	8	–	–	4.51	–	712	
20	Submain	9	–	–	4.56	–	1132	
30	Submain	10	–	–	4.36	–	311	
40	Submain	8	–	–	4.29	–	164	
50	Submain	8	–	–	4.30	–	164	
60	Submain	14	–	–	4.43	–	1443	
70	Submain	14	–	–	4.54	–	1697	
80	Submain	10	–	–	4.50	–	1072	
90	Submain	8	–	–	4.32	–	613	
100	Submain	14	–	–	5.19	–	2769	
110	Coll Inlet	14 to 10X24	–	–	–	–	2769	
115	Collector	–	–	–	–	–	2769	
639	Fan Inlet	22 to 14	–	–	–	–	2769	
640	Fan	–	–	–	–	–	2769	
641	Fan Outlet	10 to 18	–	–	–	–	2769	
642	Stack	18	–	–	0.293	2268	2763	SPend =(+)0.293

File: MS941117

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 11/17/94
Measured by: ap/bb

Site Altitude: 57 Feet Above Sea Level
Tdb: 72 deg F
Twb: 56 deg F
BarP: 29.88 inches Hg
RH: 34%
DenF: 0.9948

ID	Type	Dia	SPH	SPmd	SPend	Vmeas	Qact
1	Branch	6	2.5	3.05	4.61	2912	572
2	Branch	5	1.9	4.06	4.35	1825	249
3	Branch	5	1.4	3.91	4.26	3278	447
4	Branch	5	0.9	4.07	4.19	1820	248
5	Branch	5	0.0	0.06	4.31	254	35
6	Branch	5	4.0	3.81	4.55	1265	173
7	Branch	5	4.2	4.25	4.24	434	59
8	Branch	5	2.0	3.95	4.31	2117	289
9	Branch	5	2.2	4.01	4.29	2108	287
10	Branch	5	1.3	3.59	4.16	2592	353
11	Branch	5	2.3	3.14	4.55	3130	427
15	Submain	8	–	–	4.35	–	819
20	Submain	9	–	–	4.49	–	1266
30	Submain	10	–	–	3.64	–	514
40	Submain	8	–	–	4.23	–	266
50	Submain	8	–	–	3.97	–	232
60	Submain	14	–	–	4.48	–	1780
70	Submain	14	–	–	4.53	–	1802
80	Submain	10	–	–	4.45	–	1068
90	Submain	8	–	–	4.25	–	641
100	Submain	14	–	–	–	–	2229
110	Coll Inlet	14 to 10X24	–	–	5.34	–	2229
115	Collector	–	–	–	–	–	2229
639	Fan Inlet	22 to 14	–	–	5.63	–	2229
640	Fan	–	–	–	–	–	2229
641	Fan Outlet	10 to 18	–	–	–	–	2229
642	Stack	18	–	–	0.23	2089	2229

File: MS941117

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 11/17/94
Measured by: ap/bb

Site Altitude: 57 Feet Above Sea Level
Tdb: 72 deg F
Twb: 56 deg F
BarP: 29.88 inches Hg
RH: 34%
DenF: 0.9948

ID	Type	Comment
1	Branch	when opened blastgate could hear settled material move out after banging: SPmid=2.75 SPH=2.46
2	Branch	possible settling in flex duct after banging & disconnect/reconn: SPmid=4.08 SPH=1.93
3	Branch	
4	Branch	copious settling (see photo to view duct interior)/after cleanout: SPH=2.6 SPmid=3.07
5	Branch	
6	Branch	a few handfuls wood chips/after cleanout: SPH=4.07 SPmid=4.01
7	Branch	
8	Branch	small amount of sticks stuck inside: SPmid=3.75 SPH=1.74 small amount of settled sticks: SPmid=3.75 SPH=2.12
9	Branch	
10	Branch	
11	Branch	
15	Submain	
20	Submain	
30	Submain	
40	Submain	
50	Submain	
60	Submain	
70	Submain	
80	Submain	
90	Submain	
100	Submain	
110	Coll Inlet	
115	Collector	
639	Fan Inlet	
640	Fan	
641	Fan Outlet	
642	Stack	SPend =(+)0.23 inches w.g.

File: MS950330
Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 3/30/95
Measured by: ap/bb

Site Altitude: 57 Feet Above Sea Level
Tdb: 73 deg F
Twb: 62 deg F
BarP: 29.97 inches Hg
RH: 53%
DenF: 0.9960

ID	Type	Comment
1	Branch	chk: SPH=2.14 SPmd=2.6 SPmd'=2.22:aft: SPH=2.09 SPmd=2.64 damper open : small rattling like dust when cleaned
2	Branch	chk: SPH=1.91 SPm=3.02
3	Branch	spvp=3.50 chk:SPH=1.24 SPm=3.34 aft: clean
4	Branch	SPvp used: chk: SPH=2.33 SPmd=2.725:aft SPH=2.24 SPmd=2.69 small amount of debris removed
5	Branch	SPend=SPvp: chk SPH=2.13 SPmd=3.32/clean
6	Branch	SPvp=3.57: chk SPH=3.65 SPmd=3.44 aft: SPH=3.67 SPmd=3.44 damper inserted between SPH and SPmid location: fair clean
7	Branch	branch permanently closed/floor cleaner
8	Branch	SPvp=3.69: chk SPH=1.76 SPmd=3.48 aft: SPH=2.09 SPmd=3.4 significant trash
9	Branch	chk:SPH=1.65 SPmd=3.7\something rattled:SPH=1.86 SPm=3.68
10	Branch	SPvp= 3.60/chk SPH=1.25 SPmd=3.38\ was clean entrance to hood changed/saw
11	Branch	SPvp=3.38 SPHchk=2.64 \aft clean SPmd=2.61 SPH=1.455 wood chips removed upstr hood
15	Submain	
20	Submain	
30	Submain	
40	Submain	
50	Submain	
60	Submain	
70	Submain	
80	Submain	
90	Submain	
100	Submain	
110	Coll Inlet	
115	Collector	
639	Fan Inlet	
640	Fan	
641	Fan Outlet	
642	Stack	SPend =(+)0.51 inches w.g.

File: MA950627

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 6/27/95
Measured by: ap/bb

Site Altitude: 57 Feet Above Sea Level
Tdb: 70 deg F
Twb: 52 deg F
BarP: 29.92 inches Hg
RH: 25%

Comment: Positive Control/Normal Operating Airflow Levels

ID	Type	Comment
1	Branch	spvp=4.98/damper closed
2	Branch	damper open during meas/later closed by shop
3	Branch	SPvp=4.50
4	Branch	flex duct ds meas pt torn w/large holes
5	Branch	flex duct attached to orbital sander/ previously hanging
6	Branch	SPvp=4.31
7	Branch	VP's all zero
8	Branch	SPvp=4.50
9	Branch	SPvp=4.56
10	Branch	SPvp=4.31
11	Branch	SPvp=3.79
15	Submain	
20	Submain	
30	Submain	
40	Submain	
50	Submain	
60	Submain	
70	Submain	
80	Submain	
90	Submain	
100	Submain	
110	Coll Inlet	
115	Collector	
639	Fan Inlet	
640	Fan	
641	Fan Outlet	
642	Stack	SPend=0.0 screen at end of stack cleaned/restriction gone

File: MB950627

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 6/27/95
Proj: Model Shop 18:23 Bldg.

Site Altitude: 57 Feet Above Sea Level
Tdb: 70 deg F
Twb: 52 deg F
BarP: 29.92 inches Hg
RH: 25%
DenF: 0.9946

Comment: Positive Control/Reduced Airflow Levels (Inspection Plate Upstream of Fan Inlet Removed)

ID	Type	Dia	SPH	SPmd	SPend	Vmeas	Qact
1	Branch	6	0.1	0.128	4.13	664	130
2	Branch	5	0.0	0.0	4.12	537	73
3	Branch	5	1.1	3.64	3.91	3174	433
4	Branch	5	2.5	2.91	3.73	2711	370
5	Branch	5	2.1	2.85	3.77	2426	331
6	Branch	5	3.8	3.63	3.83	1389	189
7	Branch	5	0.0	0	0.00	0	0
8	Branch	5	2.0	3.46	3.94	2377	324
9	Branch	5	2.0	3.97	3.85	2247	306
10	Branch	5	1.4	3.62	3.70	2711	370
11	Branch	5	1.7	2.62	4.23	3443	470
15	Submain	8	–	–	4.04	–	204
20	Submain	9	–	–	3.87	–	637
30	Submain	10	–	–	3.85	–	890
40	Submain	8	–	–	3.93	–	520
50	Submain	8	–	–	3.91	–	189
60	Submain	14	–	–	3.81	–	1527
70	Submain	14	–	–	4.17	–	1851
80	Submain	10	–	–	4.08	–	1146
90	Submain	8	–	–	3.91	–	676
100	Submain	14	–	–	4.42	–	2996
110	Coll Inlet	14 to 10X24	–	–	4.72	–	2996
115	Collector	–	–	–	–	–	2996
639	Fan Inlet	22 to 14	–	–	5.42	–	2996
640	Fan	–	–	–	–	–	2996
641	Fan Outlet	10 to 18	–	–	–	–	2996
642	Stack	18	–	–	0.00	2140	2996

File: MC950629
Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 6/29/95
Measured by: ap/bb/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 72 deg F
Twb: 52 deg F
BarP: 30.02 inch Hg
RH: 21%
DenF: 0.9893

Comment: Positive Control/Inserted Obstructions

ID	Type	Dia	SPH	SPmd	SPend	Vmeas	Qact	Comments
1	Branch	6	0.1	0.18	–	–	–	
2	Branch	5	1.2	2.19	–	–	–	Damper open for Br1 & Br2 readings then closed
3	Branch	5	1.4	4.72	–	–	–	
4	Branch	5	3.2	3.87	–	–	–	
5	Branch	5	1.3	1.99	–	–	–	
6	Branch	5	5.0	4.83	–	–	–	
7	Branch	5	–	–	–	–	–	
8	Branch	5	2.4	4.39	–	–	–	
9	Branch	5	2.6	5.17	–	–	–	
10	Branch	5	0.0	0.068	–	–	–	Damper 80% Closed
11	Branch	5	2.0	3.36	–	–	–	
15	Submain	8	–	–	–	–	–	
20	Submain	9	–	–	–	–	–	
30	Submain	10	–	–	–	–	–	
40	Submain	8	–	–	–	–	–	
50	Submain	8	–	–	–	–	–	
60	Submain	14	–	–	–	–	–	
70	Submain	14	–	–	–	–	–	
80	Submain	10	–	–	–	–	–	
90	Submain	8	–	–	–	–	–	
100	Submain	14	–	–	–	–	–	
110	Coll Inlet	14 to 10X24	–	–	–	–	–	
115	Collector	–	–	–	–	–	–	
639	Fan Inlet	22 to 14	–	–	–	–	–	
640	Fan	–	–	–	–	–	–	
641	Stack	18	–	–	–	–	–	

File: MD950629

Company: The Boeing Company
Project: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 6/29/95
Measured by: ap/bb/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 72 deg F
Twb: 52 deg F
BarP: 30.02 inches Hg
RH: 21%
DenF: 0.9893

Comment: Positive Control/Obstructions Removed

ID	Type	Dia	SPH	SPmd	SPen	Vmeas	Qact
1	Branch	6	0.148	0.18	–	–	–
2	Branch	5	2.9	4.13	–	–	–
3	Branch	5	1.44	4.72	–	–	–
4	Branch	5	3.22	3.87	4.58	–	–
5	Branch	5	2.64	4.38	–	–	–
6	Branch	5	4.96	4.83	–	–	–
7	Branch	5	–	–	–	–	–
8	Branch	5	2.44	4.39	–	–	–
9	Branch	5	2.61	5.13	–	–	–
10	Branch	5	1.72	4.37	–	–	–
11	Branch	5	1.96	3.35	–	–	–
15	Submain	8	–	–	–	–	–
20	Submain	9	–	–	–	–	–
30	Submain	10	–	–	–	–	–
40	Submain	8	–	–	–	–	–
50	Submain	8	–	–	–	–	–
60	Submain	14	–	–	–	–	–
70	Submain	14	–	–	–	–	–
80	Submain	10	–	–	–	–	–
90	Submain	8	–	–	–	–	–
100	Main	14	–	–	–	–	–
110	Coll Inlet	14 to 10X24	–	–	–	–	–
115	Collector	–	–	–	–	–	–
639	Fan Inlet	22 to 14	–	–	–	–	–
640	Fan	–	–	–	–	–	–
641	Stack	18	–	–	–	–	–

File: MD950629

Company: Boeing Company
Proj: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 6/29/95
Measured by: ap/bb/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 72 deg F
Twb: 52 deg F
BarP: 30.02 inches Hg
RH: 21%
DenF: 0.9893

Comment: Positive Control/Obstructions Removed

ID	Type	Comment
1	Branch	
2	Branch	obstruction removed
3	Branch	SPH/SPmid indicates no change/scope shows dust in dwnstr jct damper 50% closed/spvp=4.41
4	Branch	no obstruction observed
5	Branch	sp dstr damper=4.88 initially/after obs rmovd=4.33 no accum near junction
6	Branch	spvp=4.62 no obs obstruction/poss debris accom in bandsaw upstr hood
7	Branch	Floor Sweep/no readings taken
8	Branch	spvp=4.44 no obstr observed/obs w/borescope: section adj to junc clean
9	Branch	no obstr obsvd/spvp=4.5
10	Branch	sp dstr damper =5.29/SPvp=4.33/obstruction removed obstr dwnstr SPmid (between mid & damper)/Damper 80% closed
11	Branch	wood chips removed/little change to static pressures some wood chips on hood screen upstr of SPH/spvp=4.00
15	Submain	Looking upstr w/borescope: junc of br1 &2 are very clean looking dwnstr w/borescopes: wood chips on bottom of duct
20	Submain	observation w/borescope:duct clean/no obst or wood chip accum
30	Submain	
40	Submain	observation w/borescope: no accum upstr/no accum dwnstr
50	Submain	observation w/borescope: upstr some accum/dwnstr no accum
60	Submain	
70	Submain	
80	Submain	Observation w/borescope: some wood chip accum in duct
90	Submain	Obs w/Borescope upstr into Br's 9&10: rags caught on skews
100	Main	Obs w/borescope: no obstr in rect transition of main to fan
110	Coll Inlet	
115	Collector	
639	Fan Inlet	
640	Fan	
641	Stack	

File: MS50918A

Company: The Boeing Company
Project: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 9/18/95
Measured by: ap/seg/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 77 deg F
Twb: 64 deg F
BarP: 30.120 inches Hg
RH: 48%
DenF: 1.0000

Comment: Positive Control/Undisturbed System
System initially examined w/ a borescope, then static pressures & airflows measured

ID	Type	Dia	SPH	SPmd	SPen	Vmeas	Qact
1	Branch	6	2.2	2.79	4.81	3060	601
2	Branch	5	2.13	3.52	4.34	1838	251
3	Branch	5	1.08	3.69	4.04	3000	409
4	Branch	5	2.68	3.08	3.96	2813	384
5	Branch	5	2.33	3.61	4	2527	345
6	Branch	5	4.07	3.88	4.11	1428	195
7	Branch	5	4.07	–	4.02	0	0
8	Branch	5	2.16	3.88	4.29	2311	315
9	Branch	5	2.04	4.15	4.2	2297	313
10	Branch	5	–	–	4.08	2752	375
11	Branch	5	1.36	2.91	4.62	3567	486
15	Submain	8	–	–	4.45	–	851
20	Submain	9	–	–	4.47	–	1260
30	Submain	10	–	–	4.27	–	923
40	Submain	8	–	–	4.25	–	539
50	Submain	8	–	–	4.13	–	195
60	Submain	14	–	–	4.53	–	2183
70	Submain	14	–	–	4.59	–	2498
80	Submain	10	–	–	4.48	–	1175
90	Submain	8	–	–	0	–	688
100	Main	14	–	–	5.14	–	3674
110	Coll Inlet	14 to 10X24	–	–	5.42	–	3674
115	Collector	–	–	–	6.24	–	3674
639	Fan Inlet	22 to 14	–	–	0	–	3674
640	Fan	–	–	–	0	–	3674
641	Stack	18	–	–	0	2268	3674

File: MS50918A
Company: The Boeing Company
Project: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 9/18/95
Measured by: ap/seg/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 77 deg F
Twb: 64 deg F
BarP: 30.120 inches Hg
RH: 48%
DenF: 1.0000

Comment: Positive Control/Undisturbed System
System initially examined w/ a borescope, then static pressures & airflows measured

ID	Type	Comment
1	Branch	spvp=3.50/no obstr's in duct/portion of damper obstructing duct when fully open
2	Branch	spvp=4.34/no obstr's in duct/portion of damper obstructing duct when fully open
3	Branch	damper obstructing 40% of duct when fully open/some wood dust upstr
4	Branch	small piece of wood lodged at elbow of flex duct dwnstr/rect hood entrance visible & clear
5	Branch	no obstr's in duct
6	Branch	some wood dust accum dwnstr
7	Branch	debris accum at grating of floor sweep/opened periodically for floor sweep
8	Branch	wood splinters on corrugated joint & some screws at elbow upstr/wood splinters at damper entrance dwnstr/damper obstructs 20% of duct when fully open
9	Branch	wood chip (4"X4") at elbow of flex dwnstr
10	Branch	wood dust accum at transition of jointer to hood entrance upstr
11	Branch	splinters & wood dust accum at expanded steel mesh grating at face of hood upstr
15	Submain	
20	Submain	
30	Submain	
40	Submain	
50	Submain	
60	Submain	
70	Submain	
80	Submain	
90	Submain	
100	Main	
110	Coll Inlet	
115	Collector	
639	Fan Inlet	
640	Fan	
641	Stack	

File: MS50918B

Company: The Boeing Company
Project: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 9/18/95
Measured by: ap/seg/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 77 deg F
Twb: 64 deg F
BarP: 30.120 inches Hg
RH: 48%
DenF: 1.0000

Comment: Positive Control/Inserted Obstructions (Static Pressures & Airflows Measured)

ID	Type	Dia	SPH	SPmd	SPend	Vmeas	Qact
1	Branch	6	1.8	3.36	4.73	2637	518
2	Branch	5	2.89	3.88	4.5	1537	210
3	Branch	5	1.11	3.87	4.24	3159	431
4	Branch	5	2.07	3.48	4.18	2553	348
5	Branch	5	2.1	2.98	4.2	2270	310
6	Branch	5	4.24	4.07	4.27	1487	203
7	Branch	5	4.23	–	4.18	0	0
8	Branch	5	1.88	3.99	4.44	2350	320
9	Branch	5	2.02	4.26	4.34	2290	312
10	Branch	5	1.6	3.98	4.21	2746	374
11	Branch	5	1.6	3.00	4.78	3642	497
15	Submain	8	–	–	4.58	–	725
20	Submain	9	–	–	4.63	–	1156
30	Submain	10	–	–	4.49	–	858
40	Submain	8	–	–	4.43	–	511
50	Submain	8	–	–	4.33	–	202
60	Submain	14	–	–	4.72	–	2017
70	Submain	14	–	–	4.75	–	2133
80	Submain	10	–	–	4.7	–	1180
90	Submain	8	–	–	4.46	–	685
100	Main	14	–	–	5.25	–	3318
110	Coll Inlet	14 to 10X24	–	–	5.25	–	3316
115	Collector	–	–	–	6.67	–	3316
639	Fan Inlet	22 to 14	–	–	–	–	3316
640	Fan	–	–	–	–	–	3316
641	Stack	18	–	–	–	–	3316

File: MS50918B
Company: The Boeing Company
Project: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 9/18/95
Measured by: ap/seg/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 77 deg F
Twb: 64 deg F
BarP: 30.120 inches Hg
RH: 48%
DenF: 1.0000

Comment: Positive Control/Inserted Obstructions (Static Pressures & Airflows Measured)

ID	Type	Comment
1	Branch	spvp=3.86- expect obstr in mid - correct 2.5x.4x6 normal to
2	Branch	expect obstr. in H- correct: found 3in d tape across h conn
3	Branch	expect nothing- found nothing
4	Branch	expect obstr. in mid- correct: d tape across galv where flex
5	Branch	expect obstr dn of mid// found damper half-closed
6	Branch	expect nothing
7	Branch	expect nothing/SPmid value lost in transcription/floor sweep /no flow
8	Branch	expect SPH error-- correct
9	Branch	expect small in mid-- correct: found .4x1.5x6in laying flat
10	Branch	no SPH , expect <=small -- found nothing
11	Branch	expect meas error SPH -- found nothing
15	Submain	
20	Submain	
30	Submain	
40	Submain	
50	Submain	
60	Submain	
70	Submain	
80	Submain	
90	Submain	
100	Main	
110	Coll Inlet	
115	Collector	
639	Fan Inlet	
640	Fan	
641	Stack	

File: MS50919C

Company: The Boeing Company
Project: Model Shop 18:23 Bldg.
Instrument: Alnor Digital Manometer
Date Measured: 9/18/95
Measured by: ap/seg/rs

Site Altitude: 57 Feet Above Sea Level
Tdb: 71 deg F
Twb: 61 deg F
BarP: 30.115 inches Hg
RH: 56%
DenF: 1.0049

Comment: Positive Control/Obstructions Removed (Static Pressures & Airflows Remeasured)

ID	Type	Dia	SPH	SPmd	SPen	Vmeas	Qact	
1	Branch	6	2.31	2.71	4.73	3039	597	spvp=3.45
2	Branch	5	1.83	3.52	4.28	1866	254	
3	Branch	5	1.06	3.64	3.97	3083	420	
4	Branch	5	2.6	2.97	3.92	2808	383	
5	Branch	5	2.26	3.55	3.94	2445	333	
6	Branch	5	3.95	3.87	4.06	1441	197	
7	Branch	5	4	–	3.97	0	0	Floor Sweep /no flow
8	Branch	5	–	–	–	–	–	Transcribed values lost
9	Branch	5	2.14	4.09	4.15	2315	316	
10	Branch	5	1.45	3.78	4.05	2760	376	
11	Branch	5	1.28	2.87	4.52	3644	497	
15	Submain	8	–	–	4.39	–	851	
20	Submain	9	–	–	4.41	–	1272	
30	Submain	10	–	–	4.24	–	913	
40	Submain	8	–	–	4.11	–	530	
50	Submain	8	–	–	4.09	–	197	
60	Submain	14	–	–	4.5	–	2184	
70	Submain	14	–	–	4.56	–	2184	
80	Submain	10	–	–	4.47	–	1189	
90	Submain	8	–	–	4.28	–	692	
100	Main	14	–	–	5.05	–	3373	
110	Coll Inlet	14 to 10X24	–	–	5.31	–	3373	
115	Collector	–	–	–	6.33	–	3373	
639	Fan Inlet	22 to 14	–	–	–	–	3373	
640	Fan	–	–	–	–	–	3373	
641	Stack	18	–	–	–	–	3373	

APPENDIX D: DEFINITION OF SENSITIVITY AND SPECIFICITY

	%ΔX > X Threshold	%ΔX < X Threshold
%ΔVariable > Variable Threshold	TP	FP
%ΔVariable < Variable Threshold	FN	TN
	Total Positives	Total Negatives

Sensitivity = TP/Total Positives   Specificty = TN/Total Negatives

A %ΔX > Xthreshold indicates the presence of an obstruction and a %ΔX < Xthreshold indicates the absence of an obstruction. The variables evaluated were One-Sided SPH, Two-Sided SPH, SPratios, and IVM Methods. SPratios and Two-Sided SPH measured absolute percent changes. One-Sided SPH and IVM measured relative percent changes. Agreement or disagreement of the Variable outcomes with the outcomes of X constituted truth or falsehood.

APPENDIX E: ANALYSIS OF DATA FOR STUDY 2

Branch 1

SPH decreased (18.2%), SPmid increased (20.4%) and SPend (1.7%) changed minimally, predicting an obstruction between the hood and mid. Further confirmation came from the SPratios of H/mid (32.1%) and H/end (17%) which decreased and Mid/end (22.4%) which increased. A decrease in Xhood (13.3%) and an increase in Xmid and Xend also followed. A piece of wood 2.5"X4"X6" was found normal to the flex duct between the hood and mid locations.

Branch 2

All variables showed positive percent increases suggesting an increased resistance to flow upstream of the hood. The most significant increases were in SPH (35.7%) and Xhood (104.2%) further suggesting that an obstruction was at the hood. A 3" diameter strip of duct tape was observed across the joiner connected the hood to the flex duct.

Branch 3

Static pressures and SPratios exhibited minimal changes predicting no obstruction — none was found.

Branch 4

SPH (22.8%) decreased, SPmid (13%) and SPend (5.6%) increased predicting an obstruction between the hood and mid. A decrease in H/mid (31.6%) and H/end (26.%) while M/end (7.1%) changed less than 10% in a positive direction is consistent with this prediction. Xhood (8%) decreased reflecting a reduced flow upstream of the hood. Xmid (44.2) and Xend (32.3) increased reflecting increased resistance downstream of the hood. Duct tape was found across the galvanized duct at the mid point where the flex duct and galvanized steel duct were connected.

Branch 5

SPH and SPmid decreased and SPend increased, predicting an obstruction between the mid and end of the branch followed by a concurrent decrease in M/end (21.3%) and H/end (14.1%). Xend increased the most percentage wise by 33.8% reflecting an increased resistance downstream of the mid location in the branch. The damper downstream of the mid had been closed halfway.

Branch 6

All variable changed by less than 5%. We expected nothing in the branch and found nothing.

Branch 7

This branch was used as a floor sweep and normally had no airflow. Consequently, velocity pressures were not taken and X-values were not calculated. Both SPH and SPend had less than a 4% relative change and H/mid had a 0% relative change. The variables predicted no obstruction in this branch and this was confirmed.

Branch 8

A 13% decrease in SPH and a concurrent decrease in H/mid and H/end (i.e., approximately 16%) and Xhood (19%), would be a normal indicator of an obstruction between the hood and mid location of the branch. This was not confirmed by Xmid and Xend which exhibited no change. Either there was a measurement error at SPH or the obstruction at the hood was very minor. No obstruction was found.

Branch 9

SPH stayed about the same with a minor increase in SPmid and SPend of approximately 3%. Xhood changed insignificantly (0.4%) while Xmid and Xend increased slightly, approximately 3% to 5%. The variables predicted a small obstruction in the mid. We found a 0.4 X 1.5 X 6.0" piece of wood laying flat along the flex duct.

Branch 10

SPend and Xend increased from 3% to 4%. We predicted a small obstruction or nothing in the branch found nothing.

Branch 11

SPH increased by 17.6% implying an obstruction in the hood. But this increase was not substantiated by any significant increase in SPmid (3.1%) and SPend (3.5) and, both Xmid and Xend changed by less than 2%. A measurement error was suspected for SPH. The duct was then opened to confirm that no obstructions were present.

APPENDIX F: STUDY 3: INSERTED OBSTRUCTIONS WITH MEASURED STATIC PRESSURES

STUDY DESIGN

The intent of this study was to investigate how well the screening tests could identify alterations deliberately placed in branches. Three rounds of measurements were compared. The second round of measurements from Study 1 represented the baseline values for this study (i.e., round 1). As such, rounds 2 and 3 while measured on the same day were completed two days after the baseline values were established. For each round, static pressures were measured at the hood and mid locations. The SPratios (i.e., SPH/SPmid) were computed from these values. Airflows and X-values were not determined in this study.

A person not part of the study agreed to insert obstructions of his choice in whatever branches and at whatever locations in the branches he chose. Measurements were taken while the deliberately inserted obstructions were in place, establishing round 2. Comparison of round 2 values with baseline values (i.e., a change in SPratios) of a given branch indicated the presence or absence of an alteration. The interior of each branch was examined and then restored to its baseline configuration. Follow-up readings were taken in the restored branch (which became round 3) before continuing on to the next downstream branch. Proceeding from upstream to downstream each sequential branch was examined in this manner.

RESULTS AND DISCUSSION

Since SPratios will change in altered branches but are not affected by changing airflows or alterations in other branches, those branches with deliberate obstructions should exhibit changes in SPratios and the SPratios of unaltered branches should remain relatively constant other than possible changes due unanticipated and subtle alterations. Once the deliberately inserted obstructions are removed, the SPratios should return to near baseline values. Measured and calculated values are summarized in Tables 9 and 10.

Branches 2, 5, and 10 contained deliberately inserted obstructions downstream of the hood and had an average percent change in SPratio values of 20% between rounds 1 and 2. Branches that were not deliberately altered and which contained no visible settled material exhibited percent changes in SPratio by at most 3%. These relatively small changes may have been due to random errors in measurement or may have represented actual environmental fluctuations as the baseline round had been measured 24 hours previously. The fact that these values remained relatively constant with the restoration of the altered branches, supported the assumption that SPratios are independent of changes in airflow.

Branch 11 was not deliberately altered, but did develop some settleing of wood chips at the hood face. The increased resistance resulted in a change of SPratio averaging 10%. This value also remained relatively constant with the restoration of the altered branches, adding further support to the independence of SPratios and changes in airflow.

For branch 5, after the obstruction was removed and the branch had been restored to its initial baseline configuration, the percent change in the SPratio unexpectedly increased by -17%. This may have been caused by an unstable orientation of the branch, which had been hooked at a 90 degree angle under a nearby grinding table. The hood entrance was open to the shop and any motion could have altered the curvature of the bends in the flexible duct and changed the duct's resistance to flow.

Table 13. Static Pressures for Study 3

Branch No.	SPH_1 "w.g.	$SPmid_1$ "w.g.	SPH_2 "w.g.	$SPmid_2$ "w.g.	SPH_3 "w.g.	$SPmid_3$ "w.g.
1	0.16	0.18	0.15	0.18	0.15	0.18
2	1.91	3.83	1.24	2.19	(1.90) 2.90*	4.13
3	1.26	4.14	1.44	4.72	1.44	4.72
4	2.88	3.35	3.22	3.87	3.22	3.87
5	2.44	3.38	1.32	1.99	2.64	4.38
6	4.01	4.18	4.96	4.83	4.96	4.83
8	2.47	4.33	2.44	4.39	2.44	4.39
9	2.37	4.74	2.61	5.17	2.61	5.17
10	1.70	4.46	0.02	0.07	1.72	4.37
11	1.83	3.41	1.99	3.36	1.97	3.35

Subscript "1" indicates round just before obstructions deliberately inserted
Subscript "2" indicates round just after obstructions deliberately inserted
Subscript "3" indicates round just after all obstructions removed
*A transcription error is suspected, since one would have expected static pressure to decrease when the damper was closed

Table 14. Static Pressure Ratios for Study 3

Branch No.	$SPH_1/SPmid_1$	SPH2/SPmid2	$SPH_3/SPmid_3$	%Change with inserted obstructions	%Change with obstructions removed	Inserted Obstructions
1	0.85	0.82	0.82	-3	-3	no
2	0.50	0.57	0.70	13	(-8) 41*	damper partially (20%) open between hood and mid, modest
3	0.30	0.31	0.31	0	0	no, wood dust at junction
4	0.86	0.83	0.83	-3	-3	no
5**	0.72	0.66	0.60	-8	-17	downstream of mid at damper, modest
6	0.96	1.03	1.03	7	7	no, wood dust in band saw
8	0.57	0.56	0.56	-2	-2	no
9	0.50	0.51	0.51	1	1	no
10	0.38	0.24	0.39	-38	3	(duct approximately 80% closed) between damper and mid,downstream of hood and mid, substantial
11	0.54	0.59	0.59	10	9	no, wood chips at hood screen

Subscript "1" indicates round just before obstructions deliberately inserted
Subscript "2" indicates round with obstructions deliberately inserted
Subscript "3" indicates round just after all obstructions removed
*Calculated value is higher than expected, believed to contain a transcription error
**Branch moved and bent 90 degrees

APPENDIX G: DATA COLLECTION FORM

MODEL SHOP (18:23 BLDG) - The Boeing Company

Data Collection Form 10-Point Traverse and Center-Line

Date: ____________

ROUND NO.:__________

P.I.: Ann Pinsky/Steven Guffey Ph.D.

Address: 20403 68th Ave.S.
Kent, WA 98032

DATA LOG

System ID						Measurement Location				VP Traverse (inches w.g.)										
ID	Type	ID ColUp	ID LatUp	Galv. Steel Dia (inches)	Flex Duct Dia (inches)	SPH	SP mid	SP vp	SP end	1	2	3	4	5	C.L.	6	7	8	9	10
1	BR	0	0	6	6															
1	BR	0	0	6	6															
2	BR	0	0	5	4															
2	BR	0	0	5	4															
21	Closed BR w/end reducer	0	0	5-4	4															
15	SUB	1	2	8	0															
15	SUB	1	2	8	0															
3	BR	0	0	5	5															
3	BR	0	0	5	5															
20	SUB	15	3	9	0															
20	SUB	15	3	9	0															
30	SUB	40	4	10	0															
30	SUB	40	4	10	0															
4	BR	0	0	5	5															
4	BR	0	0	5	5															
40	SUB	50	5	8	0															
40	SUB	50	5	8	0															
5	BR	0	0	5	4															
5	BR	0	0	5	4															
50	SUB	7	6	8	0															
50	SUB	7	6	8	0															
6	BR	0	0	5	0															
6	BR	0	0	5	0															
7	BR	0	0	5	0															
7	BR	0	0	5	0															
60	SUB	20	30	14	0															
60	SUB	20	30	14	0															
8	BR	0	0	5	5															
8	BR	0	0	5	5															

MODEL SHOP (18:23 BLDG) - The Boeing Company

Data Collection Form 10-Point Traverse and Center-Line

Date: ____________

ROUND NO.:__________

Address: 20403 68th Ave.S.
Kent, WA 98032

P.I.: Ann Pinsky/Steven Guffey Ph.D.

DATA LOG

System ID						Measurement Location				VP Traverse (inches w.g.)										
ID	Type	ID ColUp	ID LatUp	Galv. Steel Dia (inches)	Flex Duct Dia (inches)	SPH	SP mid	SP vp	SP end	1	2	3	4	5	C.L.	6	7	8	9	10
70	SUB	60	8	14	0															
80	SUB	11	90	10	0															
80	SUB	11	90	10	0															
11	BR	0	0	5	5															
11	BR	0	0	5	5															
90	SUB	9	10	8	0															
90	SUB	9	10	8	0															
9	BR	0	0	5	4															
9	BR	0	0	5	4															
10	BR	0	0	5	4															
10	BR	0	0	5	4															
100	MAIN	70	80	14	0															
100	MAIN	70	80	14	0															
110	Collector Inlet	100	0	14 to 10x24	0															
115	Collector	110	0	------	0															
120	Fan Inlet /prefan (reducer)	115	0	22-14	0															
125	FAN	120	0	------	0															
130	Fan Outlet	125	0	10-18	0															
140	STACK	130	0	18	0															
140	STACK	130	0	18	0															

APPENDIX H: EQUATIONS DERIVATIONS

VALUES OF X AND AIRFLOW DISTRIBUTION

$SP_a\text{-}Fen_aVP=SP_b\text{-}Fen_b$ (1)

<u>note 1</u>: $TP=VP+SP$
$SP=TP-VP$

$TP_a-VP_a-Fen_aVP_a=TP_b-VP_b-Fen_bVP_b$ (2)
$-VP(1+Fen_a-TP_a/VP_a)=-VP_b(1+Fen_b-TP_b/VP_b)$ (3)

<u>note 2</u>: $Xbranch=-TP/VP$

$-VP_a(1+Fen_a+X_a)=-VP_b(1+Fen_b+X_b)$ (4)
$VPa/VP_b=(1+Fen_b+X_b)/1+Fen_a+X_a)$

<u>note 3</u>: $Q=VA \leftrightarrow V=Q/A$
&
$VP=\rho(V/4005)^2$
$\leftrightarrow$ $VP=\rho(Q/4005A)^2$

$\rho_a(Q_a/4005A_a)^2/\rho_b(Q_b/4005A_b)^2=(1+Fen_b+X_b)/1+Fen_a+X_a$ (5)

$Q_a/Q_b = (A_a/A_b)(\rho_{b/}\rho_a)^{1/2}[(1+Fen_b+X_b)/1+Fen_a+X_a]^{1/2}$ (6)

STATIC PRESSURE RATIOS AND VALUES OF X

Since TP=SP+VP, it follows that:

$$SP_H/SP_J=(TP_H-VP_H)/TP_J-VP_J \qquad (1)$$

$$SP_H/SP_J=(TP_H/VP_J-VP_H/VP_J)/TP_J/VP_J-VP_J/VP_J \qquad (2)$$

Assuming VP_J is neglibibly different from VP_H:

$$SP_H/SP_J=(TP_H/VP_H-1)/TP_J/VP_J-1 \qquad (3)$$

Substituting $X_J=-TP_J/VP_J$ and $X_H=-TP_H/VP_H$

$$SP_H/SP_J=(X_H+1)/X_J+1 \qquad (4)$$

APPENDIX I: EQUIPMENT LIST

Alnor CompuFlow® ElectroManometers (model 8530D-I)

Precision Micro Barometer (Model PMB-1)

Bendix Psychron (Model No. 566)

Dwyer 1/8" and 3/8" Pitot tubes

Dwyer Air Velocity Meter (Model No. 400-10)

1/4" ID X 1/16" Wall Tygon® tubing

Toshiba Potege Model T3400 Laptop Computer

HEAVENT Ventilation Software (version 7.134)

HV_MEAS Spreadsheet Software (Version)

Data Desk (version 4.0) Statistical Analysis Software

Microsoft Office (version 6.0)

Traverse Device with Dwyer 1/8" Pitot Tube, 12" long

Traverse Device Slide Inserts: 4"-14"

Dwyer 1/8" Pitot Tube, 12" long

Dwyer 3/8" Pitot Tube, 18" long

Tygon® Tubing

Plastic Interlocking Couplers for Tygon® Tubing

Cordless Drill

Yashica Microtec Zoom 70 (35 mm) Camera

Industrial Technologies Incorporated Video Borescope, 16 mm Diameter Scope with Four-Way Articulation (Model No. MI II, Boeing Property No. 30270088 BD&SG)

10 & 12 Foot Ladders

Safety Glasses

3/4" plugs