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Hard Metal Exposures. Part 1: Observed Performance of Three Local Exhaust Ventilation Systems

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Not every ventilation system performs as intended; much can be learned when they do not. The purpose of this study was to compare observed initial performance to expected levels for three saw-reconditioning shop ventilation systems and to characterize the changes in performance of the systems over a one-year period. These three local exhaust ventilation systems were intended to control worker exposures to cobalt, cadmium, and chromium during wet grinding, dry grinding, and welding/brazing activities. Prior to installation the authors provided some design guidance based on *Industrial Ventilation, a Manual of Recommended Practice.*[(7)] However, the authors had limited influence on the actual installation and operation and no line authority for the systems. In apparent efforts to cut costs and to respond to other perceived needs, the installed systems deviated from the specifications used in pressure calculations in many important aspects, including adding branch ducts, use of flexible ducts, the choice of fans, and the construction of some hoods. After installation of the three systems, ventilation measurements were taken to determine if the systems met design specifications, and worker exposures were measured to determine effectiveness. The results of the latter will be published as a companion article.

The deviations from design and maintenance failures may have adversely affected performance. From the beginning to the end of the study period the distribution of air flow never matched the design specifications for the systems. The observed air flows measured within the first month of installation did not match the predicted design air flows for any of the systems, probably because of the differences between the design and the installed system. Over the first year of operation, hood air flow variability was high due to inadequate cleaning of the sticky process materials which rapidly accumulated in the branch ducts. Poor distribution of air flows among branch ducts frequently produced individual hood air flows that were far below specified design levels even when the total air flow through that system was more than adequate.

To experienced practitioners, it is not suprising that deviations from design recommendations and poor maintenance would be associated with poor system performance. Although commonplace, such experiences have not been documented in peer-reviewed publications to date. This publication is a first step in providing that documentation.

Keywords Intervention Research, Ventilation, Stellite, Tungsten Carbide, Metal Exposures, Cadmium, Cobalt, Hard Metal

Concern about hard metal exposure in Washington State has increased recently with reported cases of hard metal lung disease and elevated worker exposures in tool manufacturing and re-sharpening shops.[(1−3)] Attempts to reduce worker exposures by substituting less toxic materials or modifying the work process have proven insufficient in controlling cobalt exposure. For that reason the Field Research and Consultation Group (FRCG), an applied research and service group associated with the University of Washington's Department of Environmental Health, recruited a hard metal tool re-sharpening shop with documented overexposures to cobalt, chromium, and cadmium and evaluated worker exposures prospectively after three new ventilation systems were installed.

In the authors' experience, employers may maintain their systems poorly and they rarely systematically monitor their systems' effectiveness. Ventilation systems often are installed and then ignored until complaints or obvious problems force attention. This neglect may be due to insufficient knowledge and motivation. The latter may be related to the lack of ventilation monitoring and reporting requirements in all but a few Occupational Safety and Health Administration (OSHA) exposure standards. In addition, there are no published surveys or other studies that highlight the effects and costs of such neglect.

Given the relatively long history of industrial exhaust ventilation and its importance to worker protection, one could reasonably expect that the published literature would be replete with studies of the effectiveness of ventilation systems in a variety of industries. It is not. There are many publications that report changes to exposure levels after installing or greatly improving a ventilation system.[4–6] These publications can only confirm the widespread experience of practitioners that it is possible to control most exposures with sufficiently well-designed and maintained ventilation systems. What is lacking are studies of (1) conditions where system fail to perform as desired and the frequency of those occurrences, (2) the observed accuracy of current design procedures, (3) the typical changes to system performance that may occur over time, and (4) the effects of changes in air flow on the effectiveness of working hoods. Indeed, despite diligent searches, the authors were unable to find any published studies that examine field data relevant to any of these four issues for any industry.

Knowledge of the potential for failure and the actuality of failure is a powerful spur to innovation in engineering and management. Knowledge of the specific conditions associated with failure could suggest where changes to design procedure or practice are needed. Lack of that information may be retarding innovation in ventilation design engineering and failing to spur industry to monitor and maintain their systems. As a start in filling that void, this article documents the performance of three working ventilation systems from soon after installation until roughly one year later. Ideally, the authors would have documented the performances of systems installed and operated according to consensus practices. Unfortunately, the authors had little influence on the actual installation and operation of the systems. Perhaps as a result, this article instead documents the results obtained for three poorly maintained systems whose actual layout deviated somewhat from the original design.

The parameters of interest to this portion of the study are total air flow, the distribution of air flows among hoods, and the resistance to flow of entire branch ducts. The observed values are compared to expected values for all but resistances to flows. For the latter, percentage changes over time are explored. Deviations of initial resistances from expected values will be reported in a subsequent publication.

The effects of the changes in air flow levels on worker exposures are discussed in part II as a second publication.

METHODS

This hard metal tool re-sharpening shop has been in business for 15 years. The company has 16 production employees, 12 of whom conduct hard metal grinding activities. There were two eight-hour shifts but only two employees worked during the second shift. The company agreed to install three new ventilation systems to replace the single system then in place, and to work with FRCG to evaluate ventilation effectiveness. As will be discussed, many design, installation, and maintenance recommendations were not followed. Most of the hood designs remained the same throughout the study with the exceptions of three new hoods designed by the authors and then installed by the company after a few months of operation.

Plant Layout

The participating plant consisted of two general work room areas, referred to as the Bandsaw and Roundsaw rooms. The Bandsaw room (BS) covered approximately 3700 square feet. The primary operations in this room included dry grinding on stellite and steel band saws and welding/annealing on stellite-tipped band saws. Band saws were composed of mild steel with either steel or stellite teeth. There were seven band saw machines on the north wall. Along the east wall, there were two stellite side dressers and a stellite welder/annealing machine. The Roundsaw room covered approximately 2200 square feet. Many different sizes of circular saws (e.g., trim, rip, shingle), chipper knives, planer knives, and router bits were sharpened and repaired in this area by six employees. The saws consisted of a steel body with carbide or stellite tips. This open bay room was divided into four general stations: wet grinding (manual and automatic), dry grinding, tool grinding, and brazing of round saws and small machine parts. Two separate ventilation systems were needed for this area, referred to as the Roundsaw-Dry system (RSD) and Roundsaw-Wet system (RSW). The Roundsaw-Dry system was established for brazing, dry grinding, and welding activities. The Roundsaw-Wet system was for wet grinding and tool grinding activities.

Ventilation Design

An existing exhaust ventilation system had been connected to a few machines prior to the study. It had consisted of a combined exhaust fan and cyclone dust collector unit and a rather nondescript exhaust duct system built with polyvinyl chloride piping. The investigators did not see that system until it was no longer operational. There were no identification plates on the collector unit indicating the manufacturer or the capacity of the unit. The direct drive fan motor name plate indicated a 10HP, 3450 rpm motor. The exhaust duct system attempted to serve both the Bandsaw and Roundsaw areas, which included wet and dry grinding operations. No air flow measurements had ever been taken on the system, but the duct velocities apparently were inadequate to carry the dust because some were blocked completely by settled material. In general, the duct system was in significant disrepair and did not have the capacity to provide the required exhaust ventilation for control of the contaminants generated by the wet and dry grinding operations. Over exposures to constituents in the dusts resulted in citations by the state of Washington's OSHA program.

Three new systems were designed by a local ventilation design engineer according to the methods described in the 22nd edition of *Industrial Ventilation, A Manual of Recommended Practice*.[7] The designer developed the system design based on the following:

1. Each of the three areas were to have separate exhaust systems.
2. The design engineer selected hood airflows based upon his experience and recommendations in *Industrial Ventilation*.[7]
3. No dampers were to be installed. Proper distribution of air flow was to be controlled by initial selection of duct sizes. This recommendation was followed.
4. Short lengths of steel flexible ducts were to be used to connect some ducts to hoods.
5. Cleanouts were to be installed at elbows and for every 10 feet of duct length. This was not done.
6. The designer specified designs for the minority of hoods that were not integral parts of existing machines. As will be discussed, the actual installed hoods often were different from those recommended.
7. For the Bandsaw ventilation system (see Figure 1), design air flow rates (Q_T) at the grinders were based on criteria from *Industrial Ventilation*,[7] the physical size of the incorporated exhaust hood of the grinding machine, and the size and speed of the grinding wheels.[7] The design transport velocity was 4000 fpm. The estimated total required air flow was 3000 cfm and the fan pressure was 7.5 inches water gauge. The system included a dry dust collection system that utilized the existing fan/collector unit. A bag type after-filter was added to the unit to capture the fine dust particles that pass through the cyclone collector.
8. For Roundsaw-Dry ventilation system (see Figure 2), the estimated total required exhaust flow rate of 3200 cfm with a total static pressure of 7.75 inches water gauge at the collector inlet. A Torit Model 30FB Cyclone with an after-filter section and fan was installed to provide the air flows and pressures. The design transport velocity was 4200 fpm. The system required a dry dust unit similar to the existing collector with an after-filter for dry grinding.
9. The Roundsaw-Wet ventilation system (see Figure 3) design transport velocity was 3500 fpm. The estimated total required exhaust flow rate was 3500 cfm with a static pressure of 6.0 inches water gauge at the collector inlet. The wet collector for the system was a Torit Dryflo Model D2 Mist Collector. Because wet grinding operations generally produce a fine airborne mist, enclosures around the grinders were recommended (and actually installed).

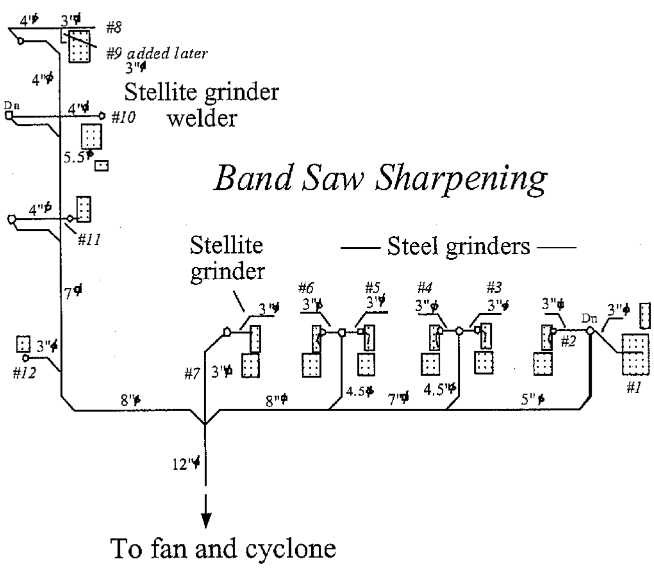

FIGURE 1
Layout of the Bandsaw system.

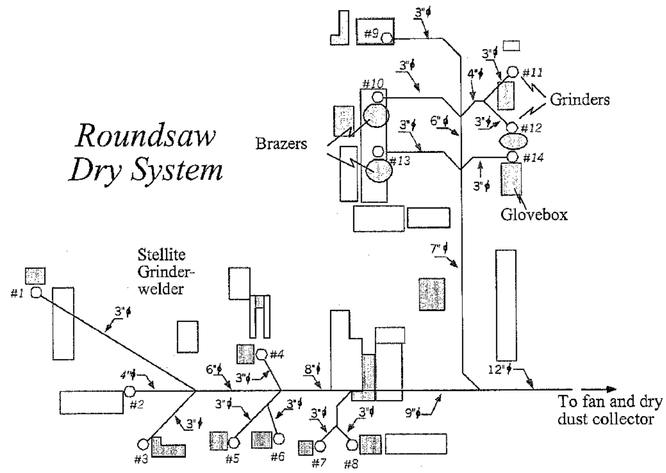

FIGURE 2
Layout of the Roundsaw-Dry system.

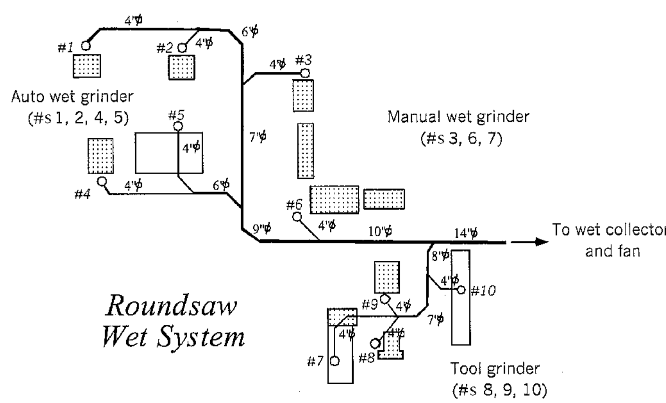

FIGURE 3
Layout of the Roundsaw-Wet system.

Actual Installed Systems

As will be discussed, the actual installed system differed substantially from the designers' recommendations. An industrial ventilation vendor installed the three separate systems, including developing the hood designs (typically plain duct capturing hoods) for cases where the hood was not integral to the ventilation machine. Due to differences between the layout assumed in computations and the actual layout, duct lengths for branches often were much shorter than those used in design computations. The systems were installed with the assistance and input from company management, with special attention to production needs and traffic flow. Those requirements apparently led to the deviations from the original design.

Ducts were constructed from 22-gauge, spiral galvanized steel manufactured in 10-foot lengths. The ducts were joined by crimping one end, sliding it 2 to 4 inches into the next duct, and fixing it with sealant and sheet metal screws. Elbows in the 4-inch and 5-inch ducts were stamped with 1.5 diameters radii, while elbows in larger ducts were 5-gore, each with a radius of two duct diameters. The junction fittings were standard SMACNA types with the lateral entering at a 45-degree angle into a tapered body with a maximum 15-degree taper.

In most cases, the duct work was simply connected to the existing hood on the grinding machines. Many hoods were connected by 2 to 10 feet of smooth-bore flexible duct to the galvanized duct. The flexible duct was either steel or fabric-over-wire construction and was installed with no kinking or excess length.

Bandsaw System Installation (see Figure 1)

To reduce costs for the Bandsaw system, company management chose to use one of their old fans for this system, despite the designer's concerns about its capacity. It was not possible to identify the model or manufacturer of that fan. Eight of the grinders already had incorporated exhaust hoods. A branch duct was connected to each of them. Branches 1 to 7 had three feet of flexible duct that were connected to a steel fitting to form a flanged duct capturing hood roughly nine inches from grinding wheels. The other three grinding machines had no enclosing hood, using a distant capturing hood (a plain duct opening) instead. After a few months of operation, the enclosures recommended by investigators were installed as Hoods #8 and #9, which involved breaking a single branch duct into two new branch ducts, one for each hood. The management also installed a partial enclosure for Hood #10.

Access to the top of the Bandsaw grinder had to be free for rotating the band saws on to and off of the grinding machines. For that reason ductwork from the band saw hoods ran from the hoods to the floor level before climbing vertically to connecting ducts roughly 10 feet overhead.

The authors suggested partially enclosing the grinding wheel area in band saw hoods. Judicious placement of the duct take-off would have sharply reduced pickup of the sticky materials thrown by the grinding wheels. However, the plant personnel did not do that, citing concerns about physical and visual access. Another possible solution, placing a "drop-off box" as far upstream as possible, was infeasible. The available locations most upstream were downstream of the settling areas in each case. The same was generally true for branches on the other systems, as well.

Roundsaw-Dry System Installation (see Figure 2)

Eight of the grinding machines had exhaust hoods incorporated into the machines. Six operations required a length of flexible metal exhaust duct and a tapered exhaust hood. The grinders had integral hoods which were then connected to branch ducts. The other hoods were branch duct openings acting as simple, unflanged ("plain-duct") capturing hoods.

Roundsaw-Wet System Installation (see Figure 3)

Only one of the wet grinders had a factory-built exhaust hood incorporated in the grinding machine. Branches 7 to 9 included roughly 10 feet of flexible duct. The wet grinding machines required enclosures to contain the fine spray of coolant generated by grinding. The design engineer recommended enclosing the back, sides, top, and as much of the front as possible for all wet grinding machines. He also recommended using a light-weight clear plastic strip curtain at machine openings where access was required. Those recommendations were not implemented. Instead, a plain duct opening was placed near the source to act as a simple, unflanged capturing hood.

Summary

There were many deviations between the design envisioned by the ventilation practitioner and the actual installation, including some hood designs, more extensive use of flexible ducts, lengths and pathways of some branch ducts, and two branches added to one system (Bandsaw). All of those changes would affect relative resistances to flows, so one could reasonably expect widespread differences between expected and observed distributions of air flows.[8]

Ventilation Measurements

Ventilation measurements of each system were made after installation of the systems and were repeated monthly for one year, concurrently with monthly personal exposure sampling. Velocity pressures were taken using Dwyer stainless steel Pitot tubes (model 167, 1/8 inch diameter, 6-inch maximum insertion depth, 1.5-inch lead tube, Michigan City, IN). Ten equal area insertion depths for a 3-inch diameter were etched on two Pitot tubes. The appropriate insertion depths for a 4-inch diameter were etched on two other Pitot tubes. All velocity pressure measurements were taken with the appropriate diameter etched Pitot tube, which was held by hand. To determine air flows, either one or two perpendicular 10-point velocity traverses were taken at the most suitable available location for each duct. For air flow measurements, the Pitot tubes were connected by 0.25″ I.D. plastic tubing to an Alnor CompuFlow ElectroManometer (Model 8530D-I) whose calibration was verified several times against a Dwyer Hook Gauge (model). Prior to measurements on a given day the Alnor manometer was connected to an RS232

Datalogging module (Serial #1194, Alnor Instruments) which, in turn, connected to the 9-pin serial port on a portable computer. The data-logging module converted the signal from the digital manometer from analog to digital so the data could be entered directly into a Hewlett-Packard 100LX Palmtop pocket-sized computer.

Velocity pressures were logged electronically from the digital manometer to the computer-using specially written software (HV_Meas).[9] As measurements were taken on a given duct, the person taking the measurement also input descriptive information, such as temperatures and comments regarding each hood condition. HV_Meas instantly calculated air flows for all branches and submains and compared values to previous measurements, allowing real-time feedback about possible measurement errors. A borescope (Olympus) 3/4 inches in diameter and 20 inches in length was also used to examine the condition of the duct work and hood interiors. Wet and dry bulb temperatures were recorded during each sampling day from values taken using a battery-powered psychrometer (Cole-Parmer Psychro-Dyne).

Analyses of Observed Versus Expected Air Flows

The ventilation system was designed to deliver specific "design" or "target" air flows (Q_T) to each hood through its particular branch duct. The degree of success in attaining those air flows can be evaluated by comparing the observed air flow (Q_{obs}) to the value of Q_T for each hood or the "branch" duct connected to it. In this case the ratio, %DesignAirFlow, was computed as:

$$\%\text{DesignAirFlow} = \frac{Q_{\text{obs}}}{Q_T} \times 100\% \qquad [1]$$

where Q_{obs} = observed air flow for a given hood, Q_T = design air flow for a given hood. A hood or duct receiving exactly its target air flow would have a computed value of %DesignAirFlow equal to 100 percent. Note that all branch duct air flows (and thus the hood air flows) were all computed as the values that would exist at standard density, thus removing the effects of different densities for different air flows.

If all values of %DesignAirFlow were about the same but not equal to 100 percent, it could be because the total air flow delivered by the fan was too high or too low. The total air flow through a system is the air flow at the fan inlet, but if leakage into the ducts is not substantial, it can be approximated with little error as the sum of the hood air flows (Q_{Total}):

$$Q_{\text{Total}} = \sum_{i=1}^{n} Q_i \qquad [2]$$

where i = index, n = number of hoods in system, Q_i = design or observed air flow through hood i, Q_{Total} = design or observed total air flow. Note that for this study Q_{Total} was not computed for months in which one or more branch air flows were suspect or missing. A value was considered suspect if more than three traverse values were missing or if the velocity profile appeared to indicate plugging of the Pitot tube or if there were other obvious problems. For example, a convex instead of parabolic profile would be rejected as indicating plugging of the Pitot tube or failure to attach the static pressure "leg" of the Pitot tube.

If the air flows through the branch ducts were not equal to design values, it may not have been due entirely to incorrect air flows. The total air flow may not have been divided among the branches in the desired proportions (i.e., poor distribution) so that the share of air flows received by individual hoods was not the design proportion of total air flow. The share of the total air flow can be computed as the fraction or percentage of total system air flow each hood or branch duct receives or is expected to receive. For each hood, i, that can be expressed as:

$$\%\text{AirFlowShare}_i = \frac{Q_i}{Q_{\text{Total}}} \times 100\% \qquad [3]$$

where $\%\text{AirFlowShare}_i$ = percentage of total air flow through a given branch duct. Ideally, the observed values of %AirFlowShare would exactly equal the values computed from design specifications for each and every branch duct. For the non-ideal distributions the percentage deviation between design and observed share of total air flows for a given branch duct or hood can be computed as:

$$\%\text{ShareDev}_i = \frac{(\text{observed } \%\text{AirFlowShare}_i - \text{expected } \%\text{AirFlowShare}_i)}{\text{expected } \%\text{AirFlowShare}_i} \times 100\% \qquad [4]$$

where %ShareDev = relative deviation from expected share of total system air flow. For a system whose total air flows were distributed among the branch ducts in the exact proportions intended, every value of %ShareDev would equal zero. Note that because the sum of the shares must equal the total, the mean value of %ShareDev must equal zero. Thus, if one duct receives more than its share of the total air flow, the air flow through one or more of the other ducts must be less than their intended shares. The quality of the distribution for the whole system can be characterized by the maximum absolute values of %ShareDev and by the standard deviation of the %ShareDev values. Increasingly large values of the standard deviation indicate increasingly poor compliance with the intended air flow distribution.

As has been demonstrated elsewhere[8] the distribution of air flows in a system is determined entirely by the relative air flow densities, cross-sectional areas, and resistances to flows for the ducts terminating in junction fittings. If relative densities and duct cross-sections remain constant, changes in air flow distribution can only be because of a changes in resistance to flow in one or more ducts. For that reason, it is useful to evaluate changes to the resistance to flows. For this study, the "equivalent resistance" (X_{br}) for each branch duct was computed from[8]

$$X_{br} = -\frac{SP_{end} + VP}{VP} \quad [5]$$

where SP_{end} = static pressure measured a few duct diameters upstream of the junction fitting, VP = mean velocity pressure in the duct. A duct that shows a sharp increase in X_{br} from one monitoring date to another probably has become partially obstructed or has experienced some other alteration that increases resistance. Hence, comparing values of X_{br} over time is a quantitative indication of failure to remove settled material that tends to accumulate in ducts. A sharply lower value could indicate the removal of an obstruction or the presence of a leak.

RESULTS

Observed Air Flows in the Initial Month

The observed air flows measured within the first month of installation did not match the predicted design air flows for any of the systems (Table I) in either absolute amounts or relative amounts distributed to hoods.

In the Bandsaw system, the total air flow was little more than half of the design total, validating the concerns about the adequacy of the existing fan for the task. The distribution of the air flow also was very poor, with initial air flows ranging from 17 to 74 percent of design levels. Individual deviations from desired distribution (%ShareDev) ranged from −65 to 54 percent. The coefficient of variability of the deviations from ideal distribution (i.e., %ShareDev) was 37 percent. The very poor distribution is partly attributable to adding two branches (ID = 9 and ID = 12) during installation of the system that were not part of the original design calculations and to use of flexible ducts that also were not included in the design computations. Because these changes were made during installation, it was not possible to observe performance without them.

The Roundsaw Wet system had a total air flow 20 percent above the design total. As a result, only Hoods 3 and 7 had observed air flows below design air flows while all other hood air flows exceeded specified levels. This system also had the best distribution with a %ShareDev standard deviation of 26 percent. Nevertheless, the deviations from desired distribution was only somewhat better than the other two systems, ranging from −55 to 45 percent.

The total air flow for the Roundsaw Dry system initially was 100 percent of design levels. The air flow was very poorly distributed, as shown by %Design Air Flow values ranging from 9 to 206 percent and a %ShareDev standard deviation of 45 percent. The deviations from desired distribution ranged from −72 to 107 percent. For example, grinding hoods 13 and 14 received only 10 and 15 percent of their design air flows, respectively.

TABLE I
Ratio of observed to design branch air flows for initial month

System	Mean	Coef.Var[A]	Min	Max
Bandsaw	0.57	0.33	0.30	0.98
Roundsaw Dry	0.99	0.53	0.09	2.06
Roundsaw Wet	1.19	0.42	0.14	1.72

[A]Mean divided by standard deviation.

Hood Air Flows over the Course of the Study

As discussed in following sections for each of the three systems, air flow levels were extremely variable for all systems, and the total air flows were very low for Bandsaw. Total air flows for all three systems declined over the course of the study (see Figure 4). As explained in an earlier section, not all months are represented in Figure 4 because total air flows were computed only for the months where all branch air flows were measured without indication of error.

The buildup of sticky material was a widespread problem. In general, the worst cases in each of the three systems were associated with grinding, which tended to fill ducts quickly with compacted clumps of grinding materials (see Figure 5). The grinding wheels contained a binder that when abraded released a sticky resin that bound the metal dust into increasingly large hardened clumps. These clumps easily blocked the duct work, almost always within 10 diameters of duct length near elbows and at the hood entrances. No settling was observed beyond the most upstream vertical duct in branches or in submains or mains. The investigators themselves sometimes cleaned out the branch ducts; otherwise, the incidence of plugging in ducts may have been greater. Because the investigator cleaning was done after measurements were taken on a given day, the beneficial effects of that cleaning were lost in the re-accumulation of materials during the following month. At six months it was clear that cleaning

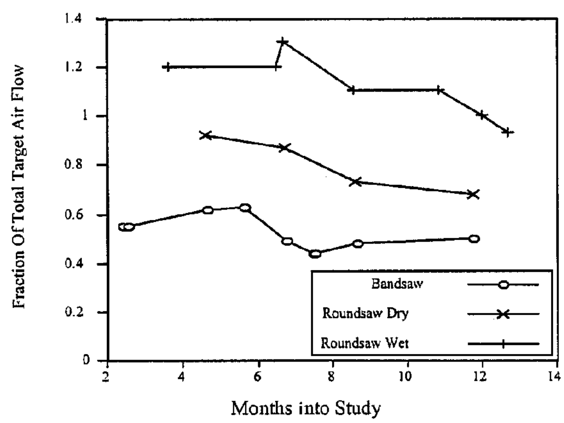

FIGURE 4
Total air flow for all systems based on first 10 hoods.

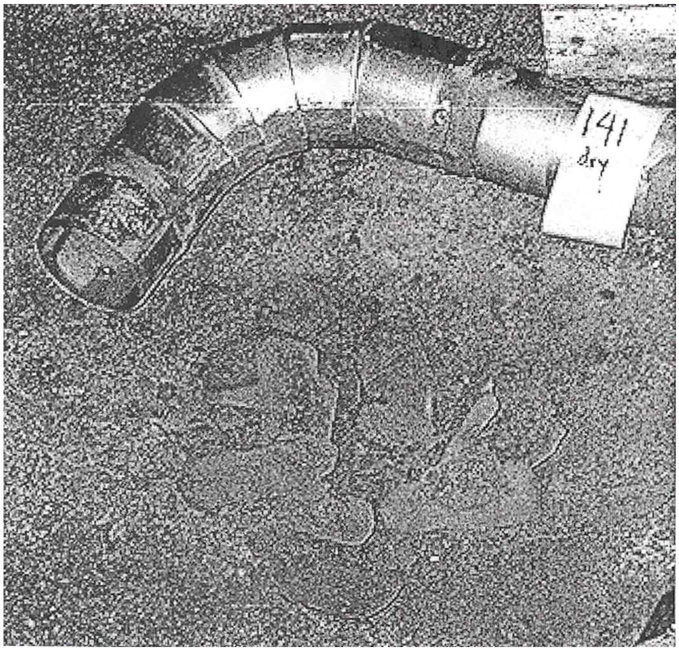

FIGURE 5
Settled material partially plugging duct number 12 in Roundsaw Dry.

should be done on a weekly basis. The authors counseled the management and demonstrated cleaning to the employees. In succeeding months substantial accumulations still were evident by even casual external inspection.

Most likely as a result of chronic plugging problems, the distribution of air flows (i.e., fraction of total air flow intended for a given branch duct) never matched the design specifications or previous month's distributions for any system. Individual hoods received from 3 to 210 percent of their intended shares of total air flows (see Table II) with coefficients of variability ranging from 32 to 55 percent for the three systems. As a result, even for systems with sufficient total air flow many hoods were receiving less than design air flows when checked during any given month.

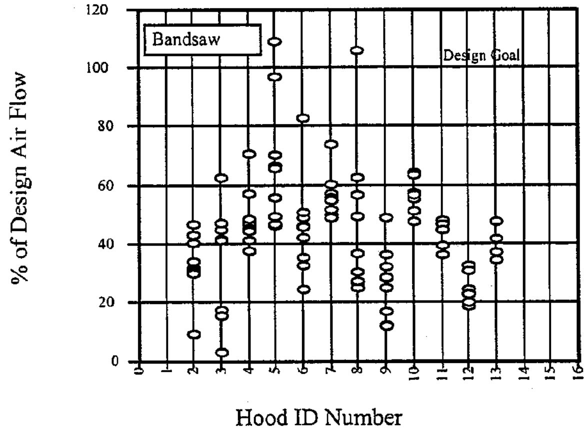

FIGURE 6
Air flow statistics for Bandsaw ventilation system by hood.

The specific results for each system are discussed in the following sections.

Bandsaw

The stellite grinder/welder used hoods 8, 9, and 10 and the steel grinder used hoods 3 and 4. Remaining hoods were used by other employees (1, 2, 5–7) or not used at all (11–13). Although airflows were low and poorly distributed even immediately after installation (Table I), distribution later was exacerbated by chronic partial plugging. The products of grinding the steel bands tended to compact into clumps just inside and downstream of the plain duct openings used as hoods (see similar materials shown in Figure 5). Removing these materials required removing sheet metal screws and pulling the ducts apart and banging them forcefully, a time-consuming and tiresome task.

The actual air flows through individual hoods were between 20 and 109 percent of design values (Figure 6). The highest air flows for a given hood corresponded to cases where its duct was not plugged but other ducts were. The band saw hoods almost never reached design air flows, in part because the overall air flow levels at the fan were very low. As shown in Figure 4, the total air flow to the system dropped from a high of about 60 percent

TABLE II
Variability of the ratio of observed to design air flows over the study

System	Count	Mean	Minimum	Maximum	Coefficient of variabilty Total[A]	Total, normalized[B]	Within, normalized[C]
Bandsaw	98	0.53	0.03	2.10	0.55	0.50	0.36
Roundsaw dry	112	0.79	0.09	2.06	0.46	0.44	0.24
Roundsaw wet	94	1.14	0.14	2.10	0.32	0.30	0.12

[A]Includes variability between and within hood air flows.
[B]Air flow ratio normalized for total air flow (equivalent to observed share of air flow).
[C]Includes only variability within hoods, not between hood air flows.

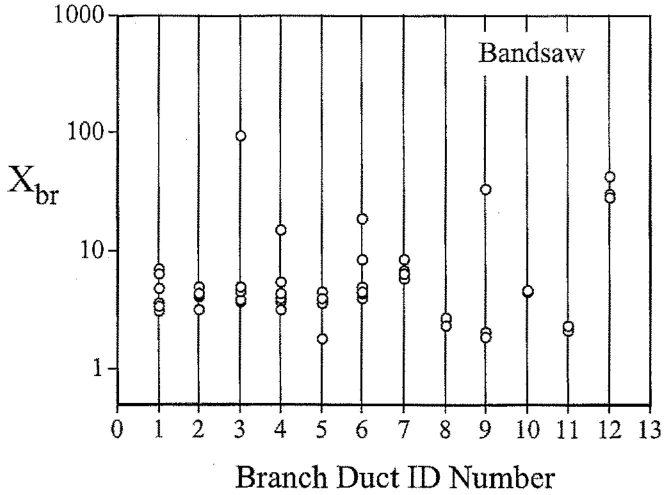

FIGURE 7
Bandsaw branch resistances (X_{br}) to flow over time.

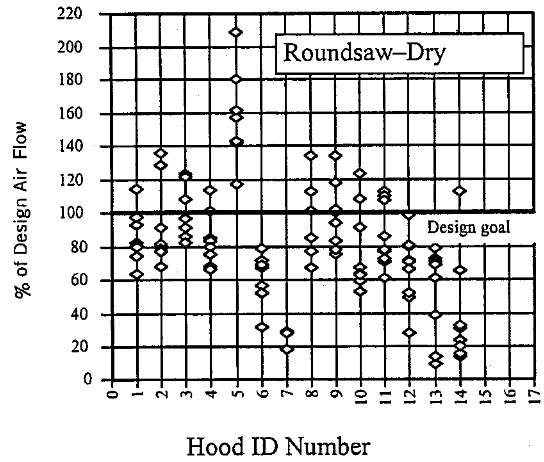

FIGURE 8
Air flow statistics of Roundsaw-Dry ventilation system by hood.

of desired total air flow level when more energetically cleaned at six months to about 40 percent at seven months. However, the changes in total air flows produced less than 10 percent of the variability in hood air flows (see Table II). The variability in air flows across the system includes the variances due to changing total air flow, the fact that some hoods received a higher proportion of their intended values on average, and changes in air flows within the same hood. The latter represents shifts in air flows from one hood to another as their relative resistances were altered by clumps of settled materials either accumulating or being removed from one month to the next. The coefficient of variability for flows within the same hood was 36 percent out of a total of 50 percent from all causes.

As shown in Figure 7, the resistance to flow for most branch ducts (X_{br}) varied greatly for several of the ducts. The branch ducts that ventilated grinding (ducts 1 to 7) were nearly always coated or partially plugged. The extreme values of X_{br} for a given branch indicate times of substantial blockage. The other values were associated with the varying degrees of moderate coating and blockage, which were difficult to rank order by degree due to the lengthy times between viewings and often poor visual access. Ducts 3, 4, 6, and 9 showed large excursions in resistances, indicative of severe plugging. The changes in values for duct 1 may have been due to varying degrees of kinking for the 15-foot-long flexible duct connected to it, in addition to the effects of varying degrees of plugging. Ducts 8 to 11 were never coated or clogged. Changes to their X_{br} values were attributable in each case to modifications to the ducts or hood that affected resistance to flow. Duct 12 had a highly obstructed hood entry for every round of measurements.

Roundsaw-Dry

This system included the hoods brazers (ducts 10 and 13), grinders with integral hoods (ducts 11 and 12), and Roundsaw stellite welder/grinder area hoods (hoods 1–8).

The air flows through hood 5 were consistently much higher than intended, but all other hoods' air flows were below design levels for at least half of the months sampled (see Figure 8). The hood air flows were highly variable, but less than 10 percent of the variance was explained by the declining total air flows (see Table II). The coefficient of variation was 24 percent for changes in hood air flows due to shifts in relative distribution as some branch ducts were partially plugged or cleaned to differing degrees than others.

Hoods 6, 7, and 12 were grinders with integral hoods having very narrow duct inlets that easily clogged and were difficult to access for cleaning. Their chronic heavy plugging (see Figure 5) produced the high X_{br} values shown in Figures 9a and 9b. As shown in Figure 9c, all three appeared to benefit from a thoroughly cleaning just after the tenth month. The brazing hoods (ducts 10 and 13) were lightly coated with brazing residues but had little buildup. The bimodal distribution of X_{br} values for duct 10 (see Figure 9a) was due to a change in hood design. The initial high values for duct 13 (see Figure 9c) dropped to a much lower, nearly constant value when a rag inside the duct was discovered and removed.

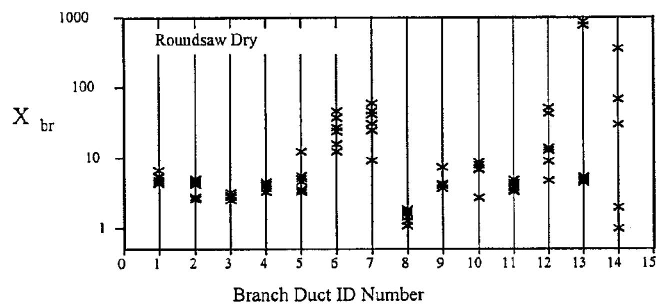

FIGURE 9a
Roundsaw Dry branch resistances for each branch duct.

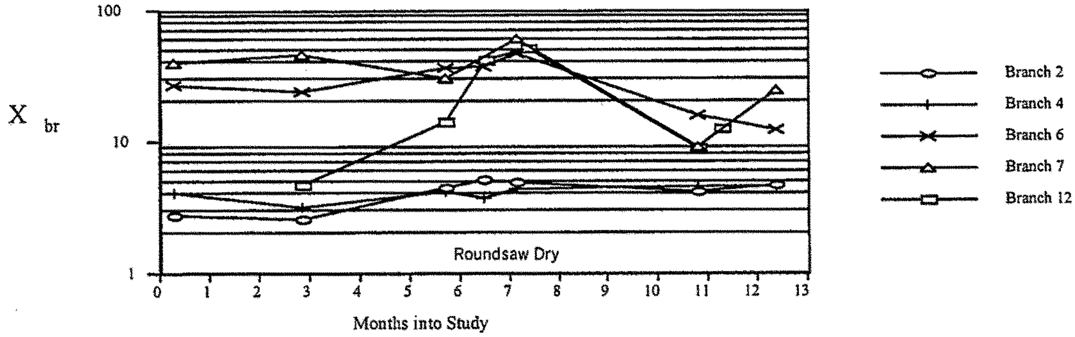

FIGURE 9b
X_{br} for branches 2, 4, 6, 7, and 12.

Hoods 8 and 14 were rarely used glove boxes. The variations in their X_{br} values were attributable to leaving doors latched or open and to other changes, not accumulations of settled materials.

Roundsaw-Wet

The workers using this system included the wet carbide grinders and tool grinders. Hoods 3, 6, and 7 were used by the manual carbide grinder. Hoods 1, 2, 4, and 5 were used by the automatic carbide grinder, and hoods 8, 9, and 10 were used by the tool grinders.

The Roundsaw-Wet ventilation system exceeded design air flows more often than the other two systems (Figure 4). Only hoods 3 and 7 were consistently below design goals throughout the study period (see Figure 10). However, the hood air flows were generally declining throughout the study period (see Figure 4). Indeed, all but hoods 1 and 2 were below target levels at the end of the study (not shown). That decline was due to increasing blinding of the fabric filter due to the moisture and oil drawn into the ducts. As can be seen in Figure 10, the hood air flows were highly variable. As with the other two systems, normalizing for declining total air flows reduced the coefficient of variability by about 10 percent. However, the variations due to air flow shifting from one hood to another ("Within" in Table II) was much lower than the values for the other two system, suggesting that this system either had less plugging or less variable plugging.

Although some ducts experienced sharp changes in resistance to flows (see Figure 11), the changes to resistance were much more modest for this system than for the other two, indicating

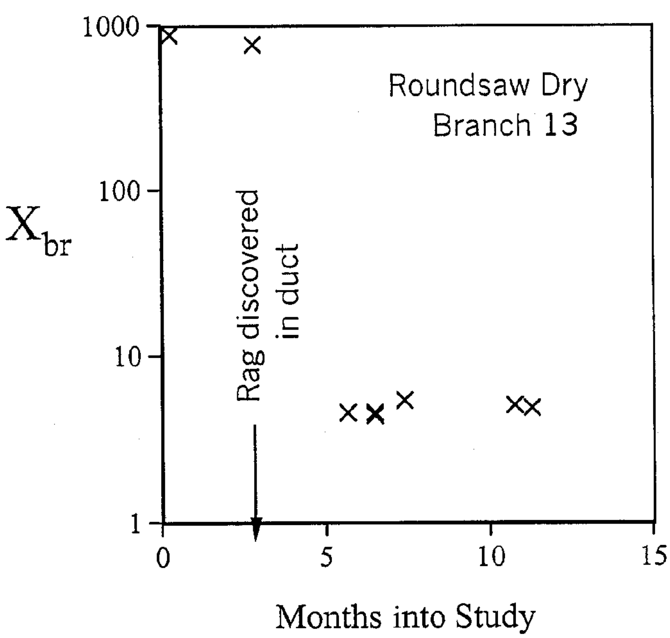

FIGURE 9c
X_{br} for branch 13.

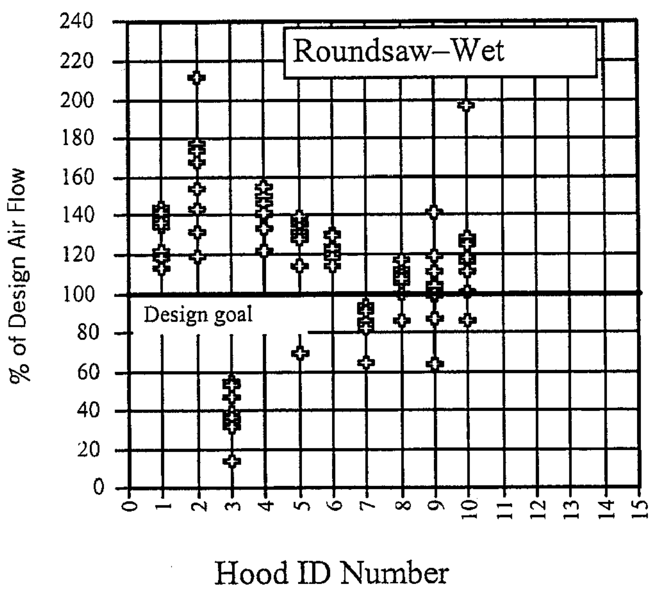

FIGURE 10
Air flow statistics of Roundsaw-Wet ventilation system by hood.

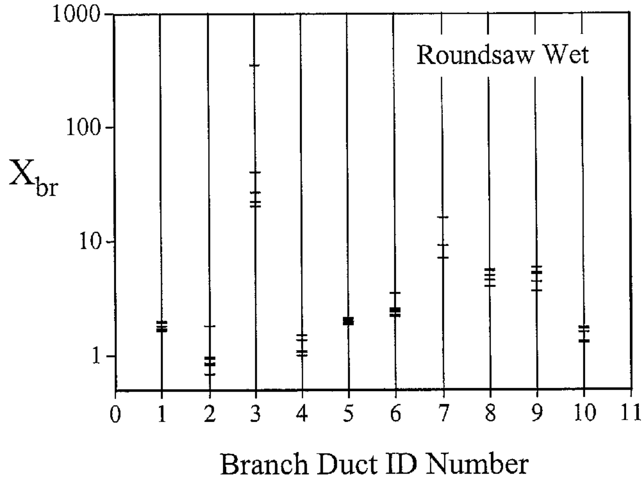

FIGURE 11
Roundsaw Wet branch resistances to flow over time.

less widespread settling and plugging than in Bandsaw and Roundsaw Dry. Borescope evaluations indicated that very little clogging occurred in the duct work in the system. The exception was duct 6, a manual wet grinder similar to the grinders in the other two systems and affected by similar problems.

DISCUSSION

The air flows for all three new ventilation systems failed to meet design goals due to low overall system air flows (Bandsaw) and to poor distribution (all three systems). Total air flow for the Bandsaw system was insufficient throughout the study, but the other two systems had sufficient or nearly sufficient air flows initially. The air flows for most hoods were highest shortly after the systems were first installed and declined thereafter due to increasing pressures across air-cleaning devices (Roundsaw Wet) or to increasing problems with settled materials (Bandsaw and Roundsaw Dry). Cleaning the ducts restored air flows substantially but not completely. Most of the cleaning was done by the investigators.

Interestingly, although settled material greatly exacerbated maldistribution of air flows, the air flows were poorly distributed from the beginning, probably because of numerous substantial differences between design and actual construction. The initial poor distribution could not be easily corrected because flow dampers were not installed. Although dampers are usually avoided when sticky materials are in the ducts, in this case the materials settled far upstream of suitable damper locations.

These systems provide object lessons of the things that can and do go wrong in industrial exhaust ventilation from the time of design and installation and throughout the working lifetime of systems. It is likely that experienced ventilation practitioners would be surprised only at the speed of the deterioration, which is attributable to the stickiness of the particulates generated in both the dry and wet processes. There was insufficient space to install “drop-out” boxes immediately upstream of the points where plugging began. Alternate hood designs (e.g., enclosures) and other steps that could have greatly reduced pickup of sticky materials were either infeasible or were rejected by management as interfering with the work.

In this case, at least one fan (Bandsaw) was a poor choice dictated by first cost considerations. During installation, two branches were added to the Bandsaw system without reconsidering duct diameter choices or the choice of the fan. For the Roundsaw-Wet system, lack of effective maintenance on the air-cleaning devices contributed to declining air flows throughout the 12 months of the study.

With insufficient air flows, one would expect the reduced duct velocities to allow accelerated settling of sticky materials. Although settling was a severe, chronic problem, it only occurred in the first few feet of the branch ducts and never in the submains and mains. It is possible that moderately higher velocities would have only carried the materials a somewhat greater distance into the branch ducts before they stuck to the sheet metal.

The effects of insufficient cleaning and maintenance on these systems was clear and dramatic. Settled materials built up to levels that reduced air flows in some hoods by 90 percent within a single month. Use of sheet metal screws produced problems for two reasons: (1) the screw points caught and held rags inadvertently sucked into hoods, leading to drastic reductions in air flow, and (2) the time and difficulty in removing and reinserting the sheet metal screws discouraged cleaning.

CONCLUSIONS

The three systems in this plant all failed to deliver the intended air flows to hoods. The air flows were very low in one system due to use of a existing fan that was too small for the task. Air flows in all three systems declined over the course of the study due to poor maintenance of ducts carrying sticky particulates. Air flow distributions for all three systems were substantially different from intended proportions from the beginning until the end of the study. Initially, the cause was probably the substantial deviations from design conditions, a problem that could have been averted with close consultation and cooperation among the designer, installer, and plant management. The initial distribution problems were exacerbated during the course of the study by the chronic buildup of settled materials in the branch ducts, which also contributed to reductions in total air flows over the course of the study. The distributions were so poor that even if total air flows had always been adequate, many hoods on a given month would have received less than half of their intended air flow levels.

Much more frequent cleaning of settled materials would have been necessary to avoid the shifts in air flow due to obstructions. Plant management was unable to effect a program of frequent cleaning despite the very visible evidence of problems, in part because the ducts were difficult to disassemble and rejoin for cleaning. Without the interventions by the investigators, it is possible that many of the ducts may have remained plugged indefinitely. Despite monthly reminders and demonstrations of the effects of plugging made by the investigators, the contribution of management and workers to maintaining the system was inadequate.

Among other things, this experience represents a failure of risk management. Whether risks were clearly communicated in this instance or not, it is clear to the authors that such failures of implementation are not necessarily due to inadequate communications. Consultants and advisors generally are present at the behest of management and with rare exceptions can influence management decisions only by persuasion. As noted by Lundgren and McMakin,[10] effective risk communication requires more than individually effective communicators. The clearest of messages may be rejected if the recommendation is not consistent with the perceived self-interest of the audience. The management of small companies have many pressing demands which can conflict with demands related to maintenance of ventilation systems and the protection of workers. For the great majority of operations, there are no enforcable governmental regulations prescribing performance of ventilation systems. Under those conditions, a well intentioned, well-informed, and intelligent manager could rationally choose to put minimal effort into maintaining a ventilation system. If exposures are below the permited levels, further investment in ventilation is not required. Indeed, one could argue that governmental regulation of health and safety are necessary to force improvements in health and safety conditions in the vast majority of operations, not just in those managed by an inadequately informed minority. For those reasons, it is possible that only regulatory requirements by OSHA would provide sufficient inducement to shift more time and energy to ventilation system maintenance.

Recommendations

The conclusions from this study support what experienced practitioners already believe:

1. Where feasible, hoods should be designed to avoid transferring sticky or other hard to convey materials to the duct systems.
2. Ventilation professionals and vendors should develop less expensive means to quickly disassemble ducts where plugging can be expected and should strongly encourage clients to specify them for systems where means of avoiding pickup of sticky materials are infeasible.
3. Ventilation designers and installers should work closely to insure that the final design computations and duct sizes are based on the system that will actually be installed.
4. For systems protecting worker health, OSHA should require that managements specify minimum air flow levels for hoods and document monitoring to demonstrate that those levels are met or exceeded.
5. Recommendations to management should include a realistic monitoring and maintenance plans, but where possible, it is prudent to employ designs that minimize the need for diligent maintenance efforts, especially for small and medium-size operations.
6. Owners of systems should follow design and maintenance recommendations (perhaps this publication could be a useful cautionary tale to those making that point).

The first phase of this study, as described in this article, was to test the ventilation systems for one year beginning soon after the date of installation. The second part of the study (a separate submission) describes the observed worker exposures over time and how they relate to the ventilation parameters described here.

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