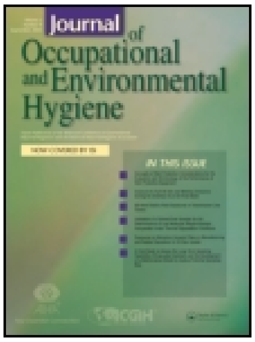

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Characterization of a Hooded Human Exposure Apparatus for Inhalation of Gases and Aerosols

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A human exposure apparatus was designed to administer a gas and/or aerosol directly to the subject's face. This apparatus utilized a hood associated with a powered air-purifying respirator. The design criteria included the need to maximize subject comfort, maintain consistent atmospheres of a gas or dust within the hood, and the accurate use of direct-reading instruments to monitor exposure levels. An 83-L drum was used to pre-mix the gas or aerosol with the main dilution air prior to entering the hood worn by the subject. A clear plastic oxygen tent, ventilated with room exhaust air, was used to contain contaminants exiting the hood. Bypass valves were added to allow for a startup period during which contaminant concentration levels were allowed to stabilize prior to exposing the human subject. Results from characterization studies demonstrated that the system adequately contained contaminants within the oxygen tent, provided adequate mixing of contaminant and dilution air, produced stable contaminant concentrations over time, and was responsive to sudden changes in contaminant generation rate.

Keywords aerosol delivery, direct-reading instruments, gas delivery, human exposure apparatus

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Understanding the health effects associated with breathing hazardous airborne substances by workers in occupational settings can be aided by human exposure studies. These studies can lead to a determination of direct cause-and-effect relationships while removing many of the confounding variables resulting from field studies. The ideal experimental setting permits the delivery of a contaminant in a concentration and route similar to those found in the workplace. Methods available for simulating workplace exposures involve the use of room-sized chambers, facemasks, and hoods.

A large chamber (20–60 m^3) minimizes constraints on breathing and maximizes subject comfort. Several subjects may be exposed simultaneously in these chambers and subjects are free to exercise if desired. These chambers have been used to administer both gases(1–5) and aerosols(6,7) to human subjects. However, these chambers are expensive to build and operate and require a large amount of source material to reach a desired concentration. The long residence time typically inherent to these large chambers may complicate studies involving reactive gases and increases the time required to reach a steady-state concentration. Forces and phenomena that alter aerosol concentrations such as sedimentation, agglomeration, and wall-losses are also more significant in large volumes.(8) An increase in the spatial distribution of contaminant concentration can also occur with larger chambers.(9) To avoid some of these problems, smaller chambers (5–12 m^3) have been designed to administer aerosols to humans.(10–13)

Exposure studies have also been conducted by direct injection into a facemask worn by a subject. A small-volume exposure apparatus was designed that relies on the use of a half-facemask attached to a 27-L cylinder within which the contaminant is generated.(14–15) This device has been used for the exposure of both aerosols(14) and gases.(16) A half-facemask was also used for 4-hr human exposures to ozone during which rapid fluctuations in concentration were induced.(17) Although these systems reduce the difficulties associated with fumigating large volumes, a facemask may be uncomfortable to wear and can constrict normal breathing.

A third type of human exposure apparatus involves the use of a hood over the subject's head into which the gas or aerosol is injected. This apparatus minimizes both constraints on normal breathing and the volume of air containing the exposure agent. Bowes et al.(18) developed a "head dome" consisting of a 37-L polycarbonate plastic cylinder with solid top and flexible neck seal that was suspended by counterweights over the subject's head. An aerosol or gas was injected towards the subject's face at 250 L/min and exited through a vent in the top to minimize leakage into the laboratory. Because of the rigid nature of the plastic cylinder, this device was also used to monitor ventilation rate with a pneumotachograph. Likewise, a hood with a clear face shield originally developed as part of a powered air-purifying respirator (PAPR) has been used to introduce an aerosol of powdered latex at 14 L/min directly to the face of a human subject.[(19)] In both systems, the contaminant was injected directly into the airstream entering the head covering, although a diffuser was added to the head dome to aid in mixing.

Our initial objectives were to develop an exposure apparatus that would minimize constraints on normal breathing, maximize subject comfort, and not be cost-prohibitive. We determined that a hooded exposure apparatus best fit those criteria. The system was therefore designed to meet those criteria as well as to inhibit leakage of the contaminant into the surrounding room, and facilitate the use of both active sampling and direct-reading instruments for measuring and recording contaminant concentrations. Unlike other hooded exposure systems we also designed the apparatus to enable a startup/conditioning period, and added a mixing vessel to maximize both the homogeneity of an aerosol in the airstream as well as the stability of the resulting concentration over time.

APPARATUS DESCRIPTION

A bathroom exhaust fan was used to move air through an 83-L steel drum (Figure 1). The fan pulled air directly from the room housing the exposure apparatus. This room was provided with air conditioned by high-efficiency filters and carbon adsorption trays. A larger blower may be required if attached directly to filters of this sort if the room air is not properly filtered. Flexible tubing with a diameter of 7.6 cm connects the fan to a home dryer exhaust vent mounted on the drum lid. This vent, designed to be attached through the wall of a home, has an angled shield on one end and tube connection on the other end. The angled shield was placed under the lid to deflect the incoming air toward one side of the drum interior. The inlet for contaminants was placed adjacent to this attachment in order to adequately mix contaminants with incoming air within the drum.

Air exiting the drum was directed via 3 cm diameter flexible tubing to a Tyvek hood with plastic face shield (RACAL Air-Mate, 3M Inc., St. Paul, Minn.) that allowed the contaminant-laden air to flow down across the face and out holes in the chin covering (Figure 2). An orifice meter, placed in-line after the blower, was calibrated to relate the velocity pressure measured with a Magnehelic pressure gauge to flow rate through the apparatus. Flow rate was controlled by changing the voltage to the blower with a variable voltage controller. However, the maximum voltage (120 V) was needed to produce the desired flow rate of 170 L/min, which was maintained throughout all trials associated with testing the apparatus. A flow rate of 170 L/min is required for loose-fitting PAPRs of this type to ensure that outside contaminants do not enter the hood even under conditions that induce heavy breathing.[(20)] In this case, however, that flow rate was maintained to ensure that the subject did not breathe in surrounding room air, to minimize re-breathing exhaled air, and to provide a sufficient supply of air moving across the face to prevent overheating the face area.

To avoid contaminating the exposure room with a gas or aerosol exiting the hood, the subject sat within a clear plastic oxygen tent with a side port connected directly to the room exhaust via 7.6 cm diameter flexible tubing. Polyvinyl chloride piping (2.5 cm) and associated connectors were used to construct the tent frame. As shown in Figure 1, direct connection to the room exhaust created a flow rate, Q_4, out of the tent that was greater than the flow of air exiting the hood, Q_3. Additional air (Q_5) from the room supply was provided through the gap between the floor and the slightly-raised oxygen tent

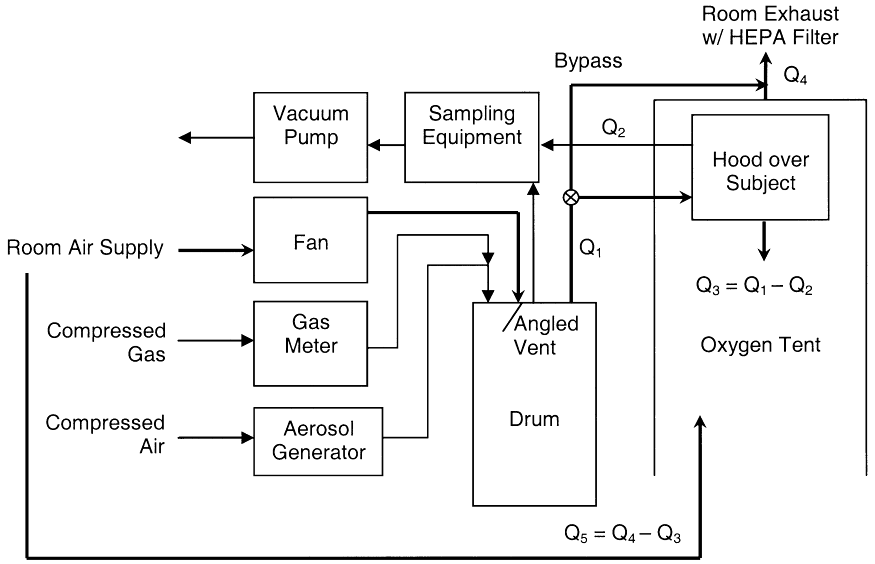

FIGURE 1. Human exposure apparatus schematic diagram

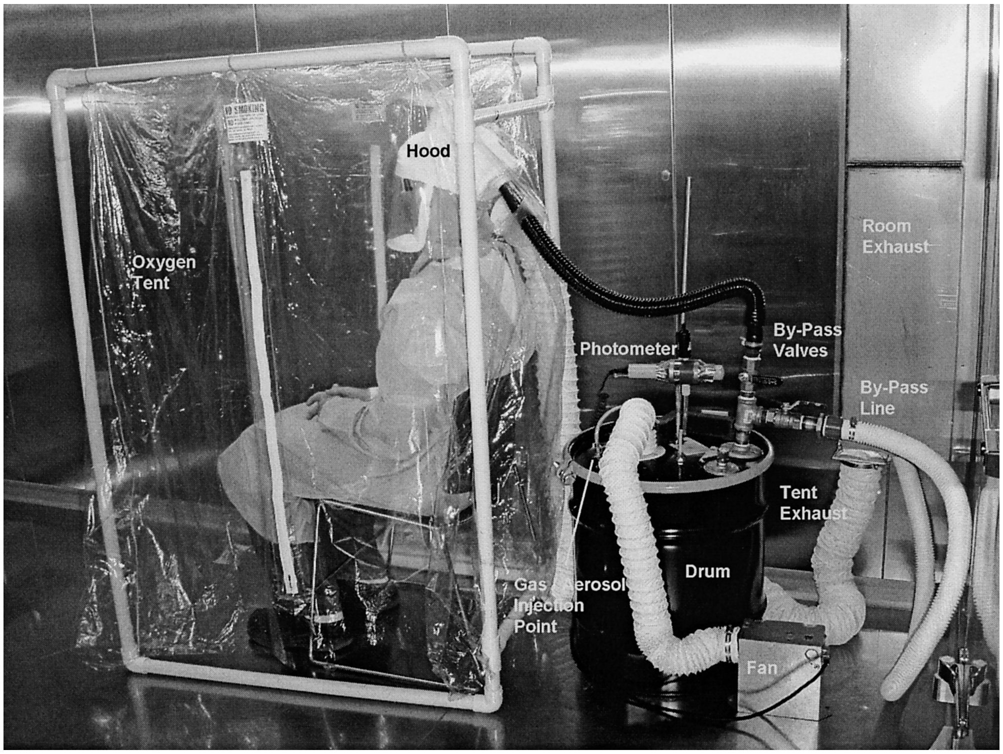

FIGURE 2. Exposure apparatus with subject wearing PAPR hood and sitting in an oxygen tent

sidewalls. The exhaust flow rate, Q_4, was verified with the use of a vane anemometer to ensure that it exceeded the hood exhaust rate, Q_3.

A flow-bypass line was added to shunt air exiting the drum directly to the room exhaust. As shown in Figure 2 an exhaust vent, 0.5 m above the floor, was located in each of the corners of the room used to house the apparatus. When using the exposure apparatus one vent was used to connect to the oxygen tent while the other three were closed to ensure a high flow rate through the tent. Two ball valves were added to direct flow to either the subject or to the exhaust line. This feature provided the time needed to allow contaminant concentrations within the drum to reach an equilibrium level after initiating the generating devices, as well as the time needed to fit the subject with the hood and install sampling devices, before directing the flow to the subject. In practice the hood was placed over the subject's head just before directing flow to the hood. Furthermore, the subject donned a surgical hood to prevent dust from being captured in his/her hair.

APPARATUS EVALUATION

Comfort

The apparatus was initially tested for comfort by one of the authors. The hood was worn for an hour while a grain-dust aerosol was generated. A dust mask was worn to avoid breathing the dust. This constricted normal breathing but allowed the investigator to evaluate whether the dust-laden air blowing over the eyes and face was irritating. The high flow rate through the hood kept the face area cool and comfortable. Likewise, no eye irritation was evident. However, airtight goggles were made available to subjects if they desired (Figure 2).

The apparatus has also been used during the initial part of a study involving six human subjects exposed to a grain-dust aerosol and ammonia gas (unreported). Each exposure trial lasted for 30 min and each subject underwent 6 trials while being exposed to 2 levels of either the gas or the dust, or a combination of both. Subjects wore a nose-clip to ensure mouth breathing. During this investigation no complaints were made by any subject related to apparatus discomfort.

Expense

All parts associated with the apparatus were available at a local hardware store or through mail-order supply companies. The cost for all parts totaled $250.00—an expense that satisfied our desire to minimize construction cost.

Leakage

During two aerosol exposure trials three filter cassettes were placed at various locations adjacent to the exterior of the oxygen tent. None of the cassettes contained a measurable amount of dust indicating that the dust emitted through the hood and into the oxygen tent did not migrate into the adjoining room volume. As operated in the setting used to house the apparatus the flow out of the hood was approximately 170 L/min, but approximately 5600 L/min was pulled from the oxygen tent and into the room exhaust. Therefore, a strong negative pressure developed in the tent that prohibited airflow out of the tent except via the exhaust tubing.

Sampling

During human exposure trials involving this apparatus gas and aerosol sampling was performed at two locations: the hood and the drum. The hood volume was large enough to allow the addition of a filter cassette just to the left and below the mouth to determine the aerosol concentration within the hood. A sample line could also be inserted into the hood to draw air into a gas analyzer, particle counter, or aerosol photometer. Measurements made directly from the drum were primarily used to indicate whether a stable concentration level had been reached.

Gas analysis was performed with an infrared spectrometer (MIRAN SapphIRe, Thermo Environmental Instruments, Franklin, Mass.). We assumed that, once calibrated, the gas analyzer accurately monitored gas contaminant levels during an exposure period. In addition to the use of a filter cassette to determine the aerosol mass concentration, an aerosol photometer and particle counter were used to provide direct measurements of mass and particle concentrations, respectively. The aerosol photometer (HAM, PPM Inc., Nashville, Tenn.) detects light scattered from the particles and determines mass concentration based on an assumed dust density.(21) To accurately detect aerosol concentrations the photometer was pre-calibrated to determine a correction factor relating actual concentrations to measurements provided by the photometer. We found a relatively good correlation (Pearson Correlation Coefficient, $r = 0.80$) between dust concentrations measured with filters placed within the hood relative to the average of the associated photometer readings over the same sample time. In addition to determining the particle count size distribution the particle counter used during the human exposure study (Series 1.100, GRIMM Instrumentation Inc., Douglasville, Ga.) was also used to indicate mass concentration knowing the dust density and assuming each particle is a sphere. As when using the photometer, a good correlation was found ($r = 0.81$) when comparing filter measurements to an estimate of mass concentration based on an evaluation of the count of all particles greater than 5 μm.

Startup/Conditioning

At the beginning of each human exposure trial the gas and/or aerosol concentration was monitored with a direct-reading instrument attached to, and drawing air from, the drum. During this startup period the ball valves shown in Figure 2 were set to prevent flow to the hood and allow flow directly to the room exhaust. Direct measurements were monitored during the startup period until concentrations remained stable for at least 5 min, after which the valves were turned to direct air to the subject. The entire startup period typically lasted 15 min (10 min to stabilize plus 5 min at steady-state). Allowing concentrations to build to a steady level before exposing a subject was particularly beneficial during the short trials (30 min) conducted during the human exposure study to ensure that the dose received was uniform over the entire time period.

Mixing and Stability

The drum/inlet apparatus was designed to ensure that a contaminant was completely mixed prior to entering the hood. Mixing can be enhanced by promoting turbulent conditions with high-velocity air. If completely mixed the concentration of a contaminant added to the drum will decay exponentially after the supply has been turned off. Analysis of the resulting “tracer” curve can therefore be used to evaluate the degree of mixing.(22) To demonstrate mixing within the drum, sulfur hexafluoride gas was injected into the tank, allowed to stabilize, and then suddenly turned off. The infrared spectrometer recorded the resulting gas concentrations every 10 sec. As shown in Figure 3, the gas tracer curve after shutoff closely approximates an exponential decay curve, indicating good mixing within the drum. A numerical analysis of this curve indicated that the average residence time of the drum is 0.5 min.

Because of the high turbulence induced by high-velocity air in tubing with “rough” inner wall surfaces,(23) the use of ribbed, flexible tubing between the drum and hood also ensured that aerosol remained completely mixed prior to entering the hood. For example, a Reynolds number of 96,000 was computed given the tubing diameter and flow rate. A Reynolds number of that magnitude is indicative of fully-turbulent flow for rough-walled pipes.(23) However, ribbed tubing of this type also contributes to aerosol losses between the drum and hood, and therefore requires thorough washing or replacement after the apparatus is used to produce an aerosol. Although difficult to estimate given the complex geometry of the hood, it is also presumed that high turbulence is maintained within the hood. Therefore, sampling devices and lines placed anywhere within the hood should provide an accurate assessment of the concentration of the contaminant delivered to the subject.

As shown in Figure 3, gas concentrations in the drum quickly elevated and stabilized after turning on the gas supply.

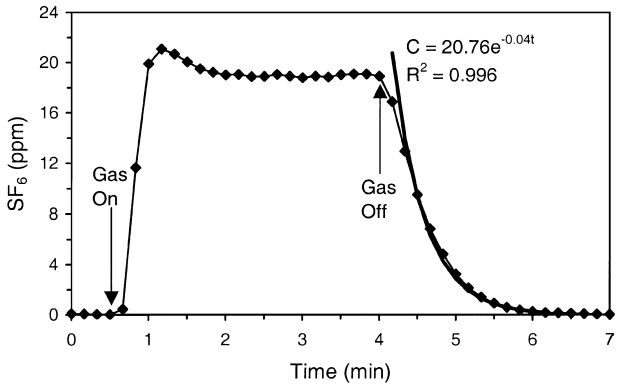

FIGURE 3. Drum tracer gas decay curve and best-fit exponential decay curve

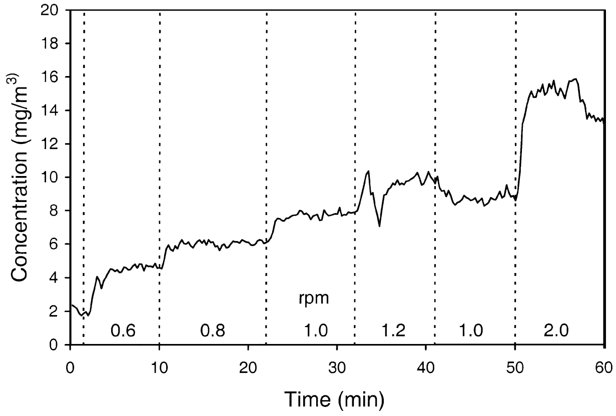

FIGURE 4. Aerosol concentrations relative to changes in generator mass output rate, and associated linear relationship between output rate and concentration level

This "responsiveness" of the apparatus to desired changes in contaminant concentration is also demonstrated in Figure 4. The results shown in Figure 4 were obtained by recording the concentration of the grain-dust aerosol produced with the use of a Wright dust feed (BGI Inc., Waltham, Mass.). The generation rate of this instrument was suddenly changed at varying time intervals by changing the rotation speed of a cylindrical scraper past the dust packed within a cylinder. The results demonstrate that a relatively stable concentration was achieved within 2 min of a change and that the resulting concentrations were linear in relation to generator output rate.

As an indication of contaminant stability direct-reading instruments were used to record both gas and aerosol concentrations during the human exposure trials. A plot of typical recordings for a specific trial is given in Figure 5. Some fluctuations are evident in the readings over time. However, concentrations remained near a mean level with a coefficient of variation for all aerosol and gas trials (n = 24 each) of 13.3 and 5.1%, respectively. The stability of aerosol concentrations over time (especially) will be largely dependent on the uniformity of the generation rate provided by the particular aerosol generator used with this apparatus.

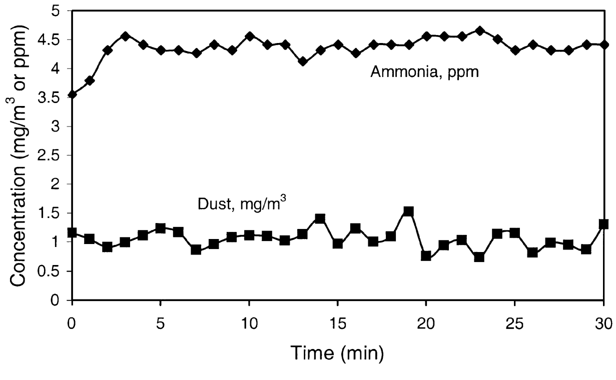

FIGURE 5. Examples of real-time measurements of ammonia and grain dust over a 30-min exposure period

CONCLUSION

A hooded human exposure system was designed and tested. This system proved to be comfortable and inexpensive. The high ventilation rate through the hood supplied a cool flow of air over the subject's face, provided the turbulence needed to properly mix contaminants within the main airstream, and created a quick response in concentration with a change in contaminant production rate. A pre-mixing volume and flow bypass valves proved to be beneficial additions to exposure systems of this type.

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