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To cite this article: David Leith, Christian L'Orange, John Mehaffy & John Volckens (2020) Design and performance of UPAS inlets for respirable and thoracic mass sampling, Journal of Occupational and Environmental Hygiene, 17:6, 274-282, DOI: [10.1080/15459624.2020.1741595](https://doi.org/10.1080/15459624.2020.1741595)

To link to this article: <https://doi.org/10.1080/15459624.2020.1741595>



Published online: 13 Apr 2020.



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## Design and performance of UPAS inlets for respirable and thoracic mass sampling

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### ABSTRACT

The Ultrasonic Personal Aerosol Sampler (UPAS) is a small, lightweight, and quiet sampler that collects airborne particulate matter on a filter for gravimetric or compositional analysis. The objective of this work was to develop UPAS inlets with collection efficiencies that match criteria for respirable or thoracic mass sampling. The two-stage inlet for respirable mass described here utilizes an impaction stage and a cyclone, whereas the one-stage inlet for thoracic mass sampling utilizes a circular slot impactor. Inlet designs are based on particle collection theory used in conjunction with an optimization algorithm to predict initial inlet dimensions; these predictions were the starting points for experiments that finalized dimensions and operating conditions. Both the respirable mass inlet and the thoracic mass inlet described here are interchangeable with the UPAS, and both have efficiencies that match well with their respective standards. With either inlet, the collected sample should be within  $\pm 5\%$  of what the standard specifies for aerosols with reasonably broad size distributions.

### KEYWORDS

Dust; exposure assessment; particle; personal sampler; respirable criterion; thoracic criterion

### Introduction

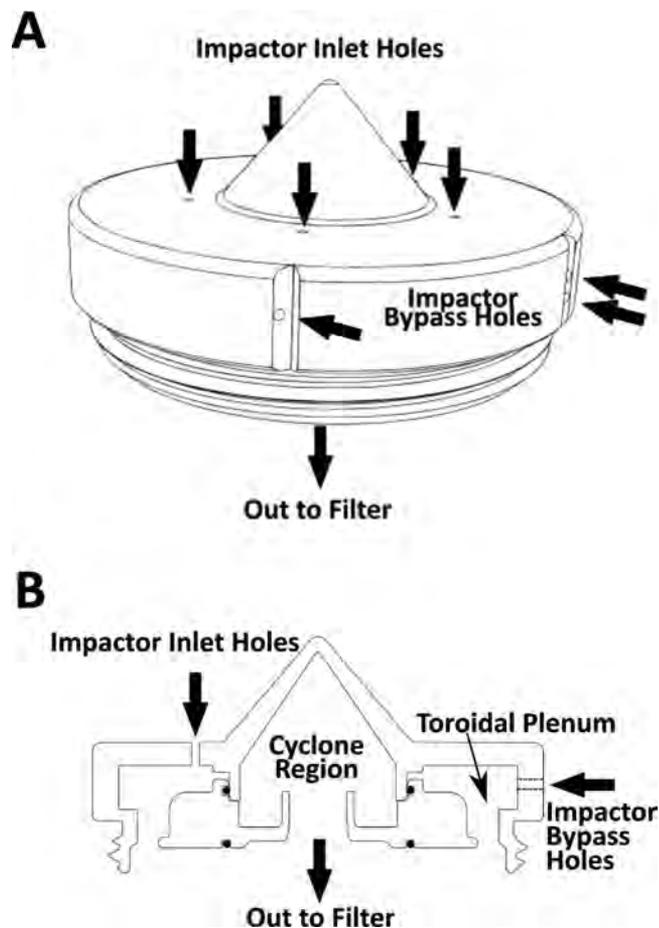
Respirable and thoracic mass sampling have been used for many years to assess personal exposure to particulate pollutants that deposit in the alveolar and thoracic regions of the lung (Lippmann 2001). Both methods fractionate particles by aerodynamic size, so that the sampled aerosol is representative of what penetrates to the relevant regions of the respiratory tract (i.e., to mimic aerosol intake). Standards have been set that describe the relationship between aerodynamic particle diameter and sampler collection efficiency for both respirable and thoracic mass sampling (International Standards Organization 1995), and an important design objective is to match a sampler's performance with its standard. Many samplers have been described and evaluated in the literature, some of which are commercially available and routinely used to assess occupational exposures (Lippmann 2001; Volkwein et al. 2011).

A respirable or thoracic mass sampler should meet several design objectives. In addition to performance that matches its standard, personal samplers should be small, quiet, lightweight, reliable, easy to use, and inexpensive. Battery capacity should allow operation for a suitable period. Achieving these objectives

requires compromises, yet substantial progress has been made over the decades in meeting the performance objectives for these samplers.

Recently, the Ultrasonic Personal Aerosol Sampler (UPAS; Access Sensor Technologies, Fort Collins, CO) was developed to address these compromises (Volckens et al. 2017). About the size and weight of a cell phone, the UPAS utilizes a silent piezoelectric pump and monitors temperature, pressure, humidity, light, and GPS location. A mass flow controller regulates flow, and operation is programable. At 2 L/min, battery life is about 16 hr. Sample air flows into the UPAS through a size-selective inlet, then to a filter. The original UPAS inlet utilizes a cyclone for PM<sub>2.5</sub> (airborne particulate matter less than 2.5  $\mu\text{m}$  in aerodynamic diameter) sampling and gives excellent agreement with federal equivalent method samplers for PM<sub>2.5</sub> over a range of concentrations (Volckens et al. 2017).

Although PM<sub>2.5</sub> and PM<sub>10</sub> sampling (airborne particulate matter less than 2.5 and 10  $\mu\text{m}$  in aerodynamic diameter) are appropriate to characterize exposures to environmental aerosols, respirable and thoracic mass sampling are appropriate to assess occupational exposures. Because the standard for PM<sub>10</sub>



**Figure 1.** (A) UPAS respirable mass inlet. Shown in (B) is a section view detailing one impactor inlet hole and one of the impactor bypass holes leading to the toroidal plenum. Not shown is the tangential cyclone inlet that connects the plenum to the cyclone interior.

sampling is very similar to that for thoracic sampling (Lippmann 2001), the same sampler might reasonably be used for both.

A sampler for respirable mass should collect the fraction of incoming particles that *does not* penetrate to the deep regions of the lung. Thus,  $E_{RF}$ , the intended collection efficiency for this sampler, is  $E_{RF} = 1 - RF$ , where RF is the fraction of incoming particles that *does* penetrate to these regions. Similarly, for a thoracic mass sampler,  $E_{TF} = 1 - TF$ . RF and TF depend on aerodynamic particle diameter,  $d$ , and are given by Hinds (1999) so that

$$E_{RF} = 1 - 0.5(1 + \exp(-0.06d)) \times (1 - \exp(-\exp(2.54 - 0.681d))) \quad (1)$$

$$E_{TF} = 1 - 0.5(1 + \exp(-0.06d)) \times (1 - \exp(-\exp(2.55 - 0.249d))). \quad (2)$$

The objectives of the present work were to develop sampler inlets that: (1) would fit and be compatible with the small size and weight of the UPAS for

respirable mass and for thoracic mass sampling; and (2) would have efficiencies close to their standards as given by Equations (1) and (2).

## Methods

### Design of respirable mass inlet

Equation (1) shows that a respirable mass sampler should have collection efficiency that gradually increases with particle diameter, reaches a value of 0.5 at  $4 \mu\text{m}$ , and unity at about  $10 \mu\text{m}$ . Cyclones such as the one for  $\text{PM}_{2.5}$  sampling in the UPAS, and those used in many respirable mass samplers, tend to have collection efficiency curves with slopes that are too steep; that is, they collect too few small particles and too many large particles (Görner et al. 2001). For aerosols with a broad size distribution these errors may compensate from a mass perspective, but sample composition could still be unrepresentative if composition changes with particle size.

**Table 1.** Inlet design parameters.

Parameter	Range Examined	Final Value
<b>Respirable Mass Sampling Inlet</b>		
Number of impactor holes	1 – 8	5
Number of bypass holes	1 – 4	3
Hole diameter	1 mm	1 mm
Air flow	1.0 – 2.5 L/min	2.1 L/min
Cyclone design	See text	See text
<b>Thoracic Sampling Inlet</b>		
Slot length	30 mm	30 mm
Slot width	0 – 1.3 mm	See text

Collection by an impactor and cyclone in series has been studied previously (Liu 2018); however, in the present case, a respirable mass inlet was designed that utilizes an impaction stage and a cyclone in series arranged so that only part of the sample flow passes through the impaction stage but all passes through the cyclone. The impaction stage flattens the slope of the performance curve by collecting small particles that the cyclone misses. Allowing some incoming flow to bypass the impaction stage keeps the sampler from collecting too many large particles. Designing a sampler with this configuration, and whose performance matches the respirable mass standard, requires balancing many parameters that affect impactor and cyclone efficiency.

Figure 1, a drawing of the UPAS inlet for respirable mass sampling, depicts how sample air flows through the impaction stage and cyclone. Some sample air enters the impaction stage through holes on the top of the inlet (Figure 1A). From the impaction stage, this air enters a toroidal plenum (Figure 1B). Other sample air bypasses the impaction stage and enters the plenum directly, through holes on the side of the inlet. Air jets from these bypass holes must travel about 30 jet diameters before they reach a plenum surface, minimizing impaction. The combined sample flow leaves the plenum by way of a tangential cyclone inlet (not shown in the figure), then goes through the cyclone and out to a filter.

Table 1 lists the impactor and cyclone design parameters evaluated to develop this inlet. All inlet holes have the same diameter and length so that flow through each will be approximately equal. The proportion of sampled air that flows through the impaction stage is then approximated by the number of impactor inlet holes divided by the total number of impactor and bypass holes. Hole diameter was fixed at 1.0 mm for practical reasons. Smaller holes would be more difficult to keep clean, whereas larger holes would reduce impactor efficiency and could allow coarse grit to enter the sampler. The cyclone was the largest that would fit onto the UPAS body that has the same shape as the cyclone used for the PM<sub>2.5</sub> inlet (Kenny and Gussman 1997; Kenny et al. 2000; Volckens et al. 2017). Larger cyclone size at

the same flow reduces efficiency (Kenny and Gussman 1997), and lower efficiency for larger particles was a design goal.

Impactor and cyclone efficiency,  $E$ , were both modeled to produce S-shaped curves (Rader and Marple 1985) using Equation (3):

$$E = \frac{1}{1 + \left(\frac{d_{50}}{d}\right)^\beta}, \quad (3)$$

where  $d$  is particle aerodynamic diameter,  $d_{50}$  is aerodynamic diameter collected with 50% efficiency, and  $\beta$  is a slope parameter. Values for  $d_{50}$  and  $\beta$  were determined from experimental measurements as described below. The dependence of  $d_{50}$  values on flow was taken from equations in the literature (Kenny and Gussman 1997; Hinds 1999; Kenny et al. 2000).

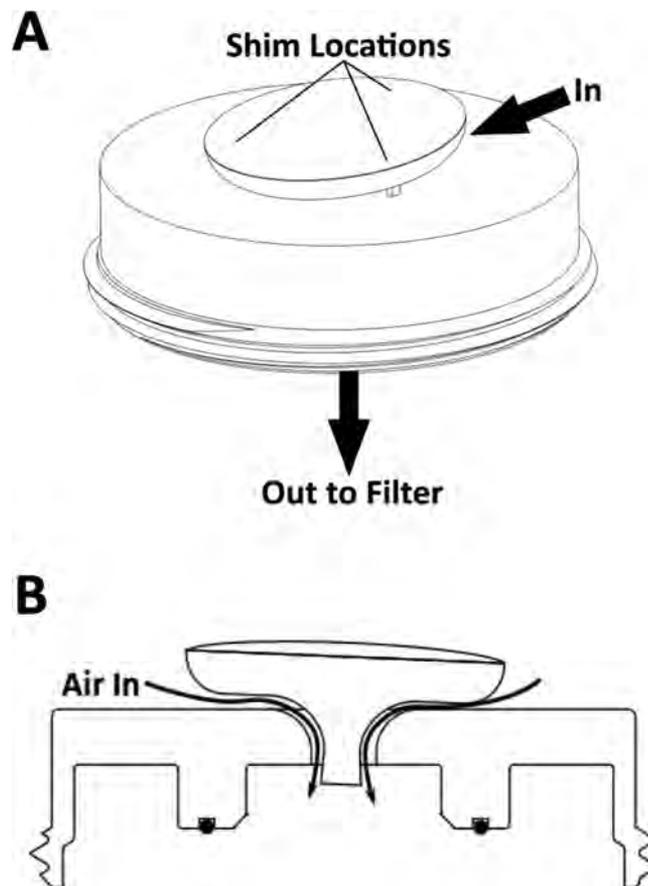
The efficiency of the inlet, considering the combined effects of all design parameters, was modeled in R version 3.6.1 (The Statistical Computing Software Project, R Core Team, Vienna, Austria). A “solver” function was used to estimate optimal values for all design parameters simultaneously, by iteratively minimizing the RMS (root mean square) difference between modeled efficiency and the respirable mass standard for particle sizes of concern here.

Because the modeling involved some non-ideal assumptions, the optimal solver results were used only as a starting point for the design. Final values were established through experiments with an inlet that had eight impactor inlet holes and four impactor bypass holes. The number and location of holes used in a test could be varied by blocking some holes with tape, allowing the evaluation of inlets with various configurations.

### Design of thoracic mass inlet

Sampling for thoracic mass requires a fractional collection efficiency of 0.5 for particles about 10  $\mu\text{m}$  in diameter that approaches unity for particles twice that size. Because small cyclones that would fit on the UPAS have efficiencies too high to meet this standard, a simple slot with a 90-degree bend, like the half-width of a slot impactor, was investigated. The slot was made circular to reduce sensitivity to inlet orientation. For a given flow the critical dimensions are slot length and width; simple theory suggests that bend radius does not affect efficiency (Hinds 1999).

Figure 2 is a drawing that shows gas flow into and from the thoracic inlet, which resembles a simple valve and valve seat. The extent to which the valve is open determines slot width and is fixed by three shims around the valve periphery.



**Figure 2.** (A) UPAS thoracic mass inlet and (B) section view of the thoracic mass inlet.

Collection efficiency for particles collected in a slot can be modeled by analogy to collection in an impactor jet half-width (Hinds 1999) as

$$E = \frac{d^2 v}{18 \eta W}, \quad (4)$$

where  $v$  is gas velocity in the slot,  $\eta$  is gas viscosity, and  $W$  is slot width.

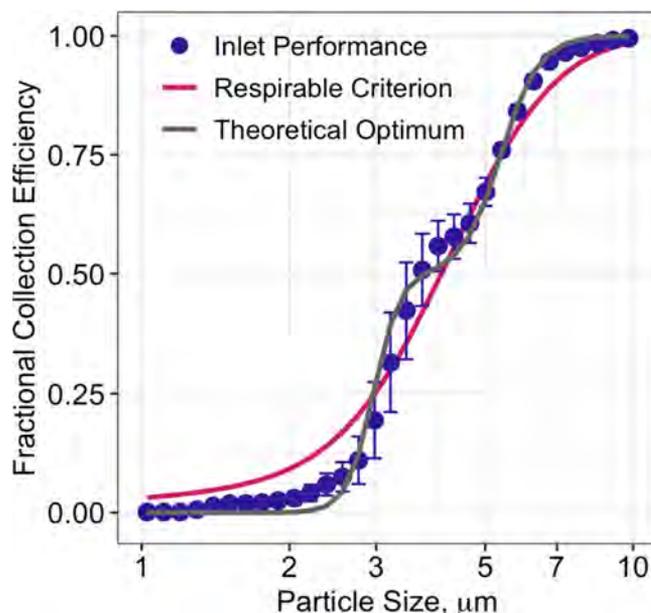
The largest circular slot that fits onto a UPAS is 30 mm in circumference. As with the respirable mass inlet, relevant design parameters were used with solver to determine the slot width that minimizes the RMS differences between modeled efficiency and the thoracic standard curve; see Equation (2). The solver results were again used only as a starting point for experiments to determine inlet performance. The height for each of the three shims that holds the valve open could be varied independently to investigate the effect of slot width on performance.

### Efficiency measurement

For each inlet, collection efficiency as a function of particle diameter was measured using experimental methods described previously (Volckens et al. 2017) and is

summarized here. Polydisperse droplets of compressor oil with density  $0.867 \text{ g/cm}^3$  (Ace Hardware Corp., Oak Brook, IL) were generated in a  $0.76 \text{ m}^3$  chamber that contained the inlet to be tested. Oil mist droplets were easy to generate in the right sizes and concentrations. An aerodynamic particle sizer, APS model 3321 (TSI Inc., Shoreview, MN) used with the Stokes correction option in its software, measured particle concentration. Sample flow into the APS is nominally  $5.0 \text{ L/min}$ , and the difference between APS flow and sample flow was provided by filtered bypass air, where the bypass flow was adjusted to account for the reduction in APS flow caused by upstream pressure drop.

Four independent tests were conducted with each inlet. In each test, seven 2-min concentrations were measured alternately, first after passing through the inlet and then without the inlet. From each measurement pair the ratio of particles counted with and without the inlet determined fractional penetration through the inlet,  $P$ , and fractional collection efficiency,  $E = 1.0 - P$ , as a function of aerodynamic particle diameter. Results from each test were taken as the averages from these seven measurements, and overall performance for the inlet was determined by the averages from the four independent tests.



**Figure 3.** Measurements of fractional collection efficiency against aerodynamic diameter for the UPAS respirable mass inlet at 2.1 L/min. Error bars represent one standard deviation. Also shown are the respirable mass standard and predicted performance for the optimal inlet determined using a solver algorithm.

### APS calibration

Because accurate measurements of aerodynamic diameter were critical, particle diameters reported using the APS were corrected in two ways.

First, aerosols of six polystyrene latex (PSL) spheres between 1.12 and 9.59  $\mu\text{m}$  in aerodynamic diameter (Thermo Scientific, Fremont, CA) with density of 1.05 or 1.06  $\text{g}/\text{cm}^3$  were generated in the chamber. For each sphere size, true aerodynamic diameter was calculated from its diameter, density, and slip correction factor. From APS measurements for PSL spheres of each size, a best-fit, normal distribution was identified using a least-squares procedure for the relationship between particle counts and APS particle size. True aerodynamic diameter was taken as the mode of this distribution.

Second, several studies have shown that liquid droplets distort due to shear when they pass through the APS, with the result that the APS-measured size for the distorted droplets is smaller than their size as undistorted spheres (Griffiths et al. 1986; Baron et al. 2008). The reduction in measured size  $\Delta$ , in  $\mu\text{m}$ , is related (Baron et al. 2008) to liquid viscosity and surface tension through

$$\Delta = 0.0002723 \frac{d^2}{\eta^{0.6486} \sigma^{0.3864}}, \quad (5)$$

where measured aerodynamic diameter  $d$  is in  $\mu\text{m}$ , viscosity  $\eta$  (0.231 here) is in Pa-s, and surface tension  $\sigma$  (0.020 here) is in N/m.

## Results

### APS calibration

Linear regression established the relationship between true aerodynamic diameters of the PSL test particles and the modes for normal distributions of these particles from APS measurements. The resultant equation, undoubtedly specific to the APS instrument used here, had an  $r^2$  of 0.9996. For our instrument, reported APS diameters underestimated true aerodynamic diameters by about 4% for particles larger than 1  $\mu\text{m}$ , a small percentage under many circumstances but important here.

The size correction due to droplet distortion increases with droplet diameter as shown in Equation (5). This correction was under 2% for droplets smaller than 5  $\mu\text{m}$ , but about 5% for 15  $\mu\text{m}$  droplets.

Both adjustments to droplet diameter cause the true aerodynamic diameter of a spherical droplet to be larger than the aerodynamic diameter measured by the APS. Adjustments from both mechanisms combined were, for example, 6.5%, 8.8%, and 10.5% for droplets the APS measured as 5, 10, and 15  $\mu\text{m}$ , respectively.

### Respirable mass inlet

The solver approach determined that the optimal number of impactor holes, bypass holes, and flow should be 4, 4, and 2.4 L/min, respectively. Tests with the prototype respirable mass inlet were conducted

with combinations of impactor holes, bypass holes, and flows centered on these values. For each, performance was quantified by calculating the RMS difference between measured efficiency and the respirable mass standard for all droplet diameters measured with the APS. The inlet configuration with the smallest RMS difference had five impactor holes and three bypass holes, and operated at 2.1 L/min. This inlet configuration was also evaluated at 2.0 L/min to determine performance at the intended, design flow. Two respirable mass inlets with this configuration were tested and four replicate tests were run with each at 2.1 L/min. Results presented here show the combined data from these eight tests.

In Figure 3, measured collection efficiency is plotted against the true aerodynamic diameter from these tests. Also shown in the figure is the respirable mass standard and the “optimal” relationship predicted from the solver analysis. For particles of all sizes, the average efficiency difference between the two prototypes was 0.029, whereas the average standard deviation for these efficiency measurements was smaller, 0.007. Thus, the size of the measurement error bars in this figure reflects performance differences between the two prototypes more than performance differences in replicate tests with the same prototype. The two prototypes had slightly different dimensions due to imprecision in 3-D printing and due to imprecision in inlet hole dimensions as the holes were drilled and reamed by hand. Although these dimension differences were small, they may account for most of the measurement imprecision shown in the figure.

Both the efficiency measurements and the optimal efficiency curve from solver show a multi-sigmoidal relationship with aerodynamic diameter that goes both below and above the standard. The efficiency increase for 3  $\mu\text{m}$  particles is due to collection in the impaction stage, which has a theoretical cut diameter close to 3  $\mu\text{m}$ . Efficiency for larger particles increases more slowly than would occur with the impactor alone because inlet air that enters through the bypass holes bypasses the impaction stage. For the largest particles, the cyclone determines efficiency.

Table 2 shows RMS differences between the respirable mass standard and the measured and the optimal inlet efficiencies. The RMS difference for measured performance, 0.045, is actually less than the value predicted as optimal, 0.058, as the tested inlet performed better than its model would suggest. At 2.0 L/min, collection efficiency decreased slightly for particles of all sizes, causing an increase in the RMS difference to 0.059.

**Table 2.** RMS difference between measured efficiency and its standard for sampler as measured and for optimal sampler design (see text).

Inlet	Measured	Optimal Sampler
Respirable mass		
at 2.1 L/min	0.045	0.058
at 2.0 L/min	0.059	
Thoracic mass		
at 2.0 L/min	0.056	0.053
PM <sub>10</sub> mass		
at 2.0 L/min	0.048	0.026

A sampler whose performance fails to conform to its standard can produce biased results. To assess bias, the difference between mass collected by the inlet and mass collected according to the standard was calculated for a matrix of log-normal dusts with mass median diameters from 0.5–10  $\mu\text{m}$  and geometric standard deviations from 1.5–3. These results were calculated using the measured sampler efficiencies shown in Figure 3.

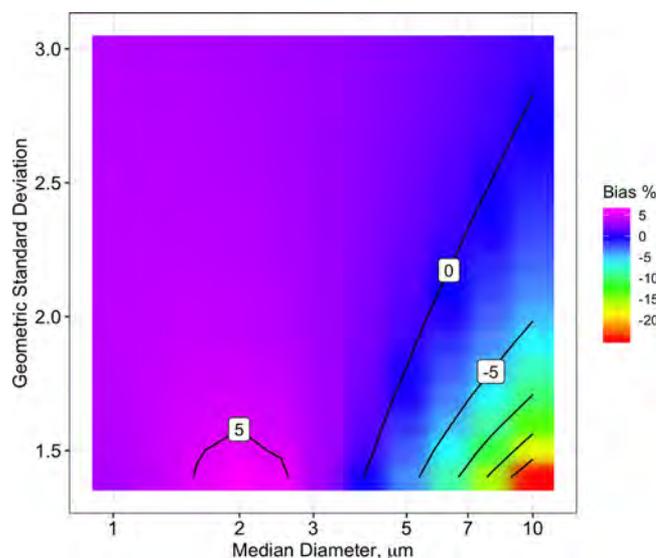
Results of the bias analysis are shown in Figure 4. For dusts with mass median diameters smaller than about 6  $\mu\text{m}$  the error in using this inlet is under 5%. For relatively monodisperse dusts of larger particles the error is greater; however, such dusts are uncommon in many work environments.

### Thoracic mass inlet

The solver approach predicted that the optimal slot width for the thoracic mass inlet would be about 1.1 mm. This value became the starting point for experiments to measure inlet performance in which shims of the same height were used at all three shim locations. Tests were conducted in the same way as with the respirable mass inlet for a range of uniform shim heights.

As expected, collection efficiency increased for particles of all sizes as slot width decreased. Inlet efficiency was measured to be about 50% for particles 10  $\mu\text{m}$  in diameter with a slot width of 1.0 mm, in conformance with the standard and close to the optimal slot width predicted by the solver; however, the slope of the efficiency curve was steeper than predicted and steeper than the standard specifies.

To increase efficiency for small particles and reduce efficiency for large particles, further tests were conducted with shims of different heights at the three shim locations. This arrangement should provide lower efficiency for sample air that enters the inlet where the slot is wider, and higher efficiency for air that enters where the slot is narrower. Again, sampler performance was evaluated by calculating the RMS difference between measured efficiency and the



**Figure 4.** Bias plot for sampling with the UPAS respirable mass inlet at 2.1 L/min.

thoracic mass standard for particle sizes the APS measured. The lowest RMS difference, and optimal sampler performance, was achieved for slot widths of 0, 0.76, and 1.14 mm at the three shim locations. These different shim heights cause the tilted appearance to the valve, as shown in [Figure 2](#).

Shown in [Figure 5](#) is the measured efficiency for the thoracic inlet against true aerodynamic diameter, along with the thoracic standard from [Equation \(2\)](#) and performance predicted by the model with the optimal, uniform slot width of 1.1 mm. Measured efficiency for the thoracic inlet is lower than the standard for particles smaller than about 12  $\mu\text{m}$ , but higher than the standard for larger particles. Shown in [Table 2](#) are the RMS differences between efficiency measurements and the standard for both the thoracic inlet, 0.056, and for the optimal sampler, 0.053. Although measured performance was not quite as good as the predicted optimal, it was close.

Bias for measurements using the UPAS thoracic mass inlet was evaluated using the same procedure used to assess bias with the respirable mass inlet, except that the upper range of particle sizes evaluated was increased to 19  $\mu\text{m}$ . The results of this analysis are shown in [Figure 6](#). Bias with this inlet is generally within a value of  $\pm 5\%$  but increases to between 10 and 20% for dusts with median diameters between about 13 and 20  $\mu\text{m}$  in diameter and that have geometric standard deviations under 2.0.

## Discussion

Differences between aerodynamic diameters reported by the APS and true aerodynamic diameters

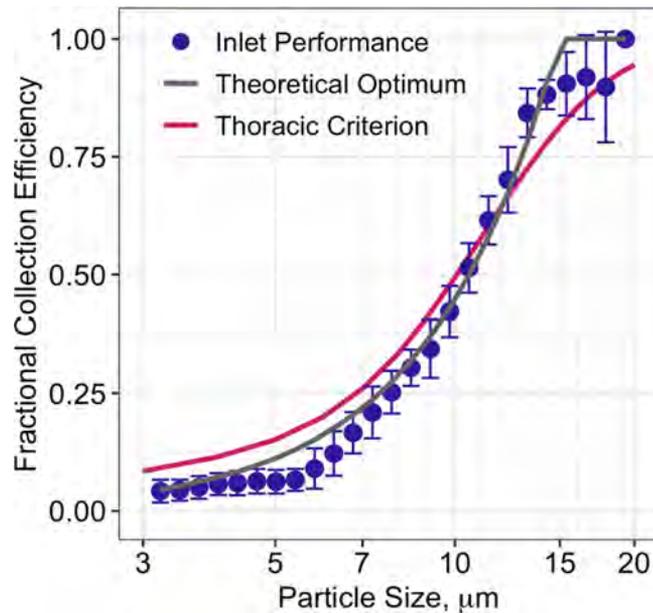
established by PSL measurements and corrections for drop deformation were generally small, although they increased with particle size. Often, these differences would not be important but here they were large enough to be of concern and needed to be considered.

Overall, the respirable mass inlet described here met the stated design objectives. The respirable inlet size and shape allow it to fit onto the UPAS as a direct replacement for the  $\text{PM}_{2.5}$  inlet originally developed (Volckens et al. 2017). The performance of the respirable mass inlet was found to be consistent with the standard for respirable mass sampling, and bias analysis suggests that errors due to non-ideal sampler performance should be under 5% for most dusts found in occupational environments.

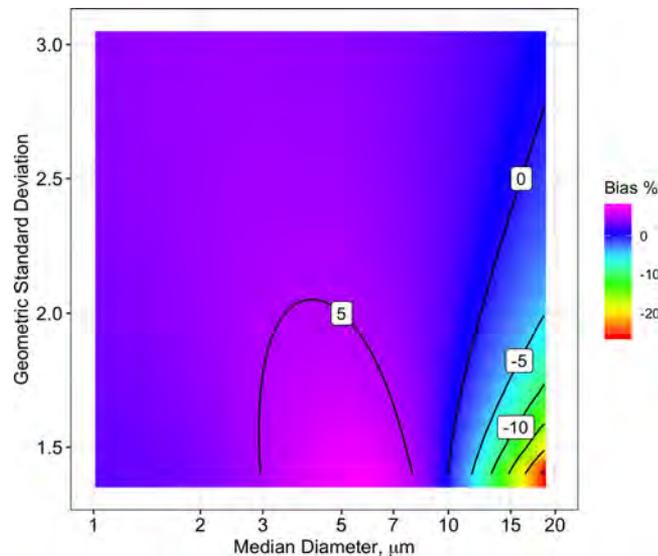
Similarly, the thoracic mass inlet described here generally met its design objectives as well. Like the respirable mass inlet, the thoracic inlet fits onto the UPAS as a direct replacement for the  $\text{PM}_{2.5}$  inlet. Bias analysis suggests that sampling errors for thoracic sampling with this inlet will generally be under 5%.

The standard for thoracic sampling in the workplace used to develop the thoracic inlet described here is very similar to the standard for  $\text{PM}_{10}$  sampling (Lippmann 2001) used to assess exposure outside the workplace. [Table 2](#) also lists the RMS difference between thoracic sampler collection and the  $\text{PM}_{10}$  standard. This value is 0.048, lower than the value for compliance with the thoracic standard, implying that this inlet approaches the  $\text{PM}_{10}$  standard even better than the thoracic standard for which it was designed.

The laboratory work described here has some limitations. All efficiency measurements reported here were obtained using nonvolatile oil droplets as the test



**Figure 5.** Measurements of fractional collection efficiency against aerodynamic diameter for the UPAS thoracic mass inlet at 2.0 L/min. Error bars represent one standard deviation. Also shown are the thoracic standard and predicted performance for the optimal thoracic inlet determined using a solver algorithm.



**Figure 6.** Bias plot for sampling with the UPAS thoracic mass inlet at 2.0 L/min.

aerosol. When these droplets hit a collection surface they will stick and not become re-entrained. Solid particles may bounce and be re-entrained when they hit a surface unless the surface is coated with an oil or grease that can absorb their impact energy (Marple and Olson 2011). Solid particles may bounce from a coated surface as well, if that surface is loaded with previously collected dust (Marple and Olson 2011). Further work can be undertaken to determine the extent of this potential problem; however, we note that cyclone separators should have a larger holding capacity relative to impactors for collected particles.

This problem is common to other samplers that collect particles by inertial mechanisms and has often been successfully addressed. Field studies of the UPAS equipped with these inlets can be done to compare their performance with that of other samplers and sampling methods.

## Conclusions

Sampler inlets described here fit onto the UPAS, a small, lightweight, and silent sampler used to assess personal exposure. These inlets allow sampling to

assess exposure to respirable or thoracic mass and should be accurate to within about 5% for most dusts and mists in the workplace.

Field work can be done to determine inlet performance with solid particles and dusts, and to compare inlet performance with other samplers for respirable and thoracic mass.

## Funding

Funding for this work was provided by the National Institute for Occupational Safety and Health, Centers for Disease Control, under grants R01OH010662 and R43OH010635.

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