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**Original Article**

# Recommended flow rate of the aluminum cyclone for improved exposure assessment

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## Abstract

Samples of the respirable fraction of airborne particles to which workers are exposed are an important component of many health protection programs, especially in those workplaces where there is a risk of health problems from exposure to respirable crystalline silica. The most common technique for size-selection of the respirable dust fraction is to use a miniature cyclone preselector, many of which are based on the "Higgens-Dewell" (HD) design. A variant of the HD cyclone, commonly referred to as the "aluminum (or aluminium) cyclone," was developed in Scandinavia. Early work showed that a flow rate of 2.2 l min$^{-1}$ would be appropriate to meet the size-separation convention standardized under the International Organization for Standardization (ISO), while a later, non-peer-reviewed study suggested 2.5 l min$^{-1}$ and this flow rate is currently recommended by the manufacturers. The International Sampler Comparison Group is working on revising the European Standard EN13205 on sampler performance testing for consideration as an ISO standard. In this work, 5 aluminum cyclone units were tested at 2.5 l min$^{-1}$ and the cyclones were further tested at 2.3 and 2.2 l min$^{-1}$ to determine the optimal flow rate. While the flow rate of 2.3 l min$^{-1}$ had the lowest overall mean bias, a flow rate of 2.2 l min$^{-1}$ gave bias <±10% over the whole area of size distributions of interest. This supports earlier findings and suggests that 2.2 l min$^{-1}$ is the most accurate flow rate for sampling with the aluminum cyclone. However, 2.3 l min$^{-1}$ also meets the specification of EN13205 in that the area of bias >±10% is minimal. The consequence of continuing to use the aluminum cyclone at 2.5 l min$^{-1}$ is an underestimate of respirable particles when compared with the ISO convention.

**Keywords:** aluminum cyclone; cyclone calibration; respirable size-selective sampler.

**What's Important About This Paper?**

The current recommended air sampling flow rate of the aluminum cyclone likely underestimates respirable dust concentrations compared with the international standard respirable convention. The present study recommends sampling flow rates of the aluminum cyclone for improved respirable size-selective sampling.

## Introduction

Sampling of aerosols to which workers are exposed is an important component of assessing exposure, which can lead to the implementation of controls, including respiratory protection. For many airborne particle exposures, the primary health outcomes occur in the lungs (eg silicosis; chronic obstructive pulmonary disease) (NIOSH 1995, 2002). In such cases, sampling only the smaller particles that can reach deeper into the lung is more physiologically relevant than sampling all particles existing in the ambient atmosphere. Respirable aerosol sampling has been conducted since this issue was first recognized in the 20th century.

The most common technique for size-selection for the respirable fraction of ambient aerosol is to use a miniature cyclone preselector. There is a wide range of cyclones available. The Higgins-Dewell (HD) cyclone (Higgins and Dewell 1967) was based on a design from the British Cast Iron Research Association and

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was intended to meet the size-selection convention developed in the 1950s by the British Medical Research Council (BMRC), which has a curve of probability of particle penetration into the alveolar region of the lungs based on a range of particle sizes with a 50% probability ($d_{50}$) of penetration of 5 µm aerodynamic diameter. The design of the HD cyclone was then used in the Safety in Mines Personal Equipment for Dust Sampling (SIMPEDS) equipment, a device including the cyclone and pump incorporated with a miner's cap-lamp, developed by the UK Safety in Mines Research Establishment (Harris and Maguire 1968).

A variant of the HD cyclone was developed in Scandinavia and is popularly known as the "aluminum (or aluminium) cyclone." The design was based on the original HD concept, with a flow rate of 1.9 l min$^{-1}$ to meet the BMRC convention. Although its exact origin is obscure, it is believed to have originated in Denmark. Interestingly, the cyclone originally included a cowl in operation; however, it was later avoided to use because it interfered with flow rate measurements and adjustments. The cyclone became popular in Sweden and its subsequent history was documented by Lidén (1993), who noted changes in construction over time. The simplicity of design has made it popular, and 2 companies (SKC, Inc., Eighty Four, PA, USA, and Environmental Express, Ocala, FL, USA) offer supposedly similar products. The cyclone is made from 2 aluminum parts, a vortex tube and a vortex finder (with an O-ring for a press-fit connection to a cassette) with a slot inlet machined into the side of the vortex tube and a grit pot on the bottom. It is available with cassette fittings to both 25- and 37-mm "universal" plastic cassettes.

As noted by Lidén (1993), the quality of the manufacture of the aluminum cyclone was improved, and its dimensions changed twice to better match the dimensions of the SIMPEDS cyclone, such that the third iteration in 1990 became an almost exact copy. However, Lidén (1993) found all versions of the aluminum cyclone to oversample coarse aerosols with respect to the SIMPEDS cyclone when compared with the BMRC convention.

By this time, the BMRC convention was being reconciled with a different convention in use in the United States, and a new convention, ratified in an ISO Standard (ISO 7708, 1995) was based on particle distribution with a $d_{50}$ of 4.25 µm. Lidén (1993) estimated that the flow rate of 2.2 l min$^{-1}$ would allow the aluminum cyclone to best match the ISO respirable convention. Tsai and Shih (1995) confirmed this flow rate as the best match to the respirable convention using monodisperse fluorescent particles. Görner et al. (2001) tested the performance in a wind tunnel and also confirmed that a flow rate of 2.2 l min$^{-1}$ was a better match to the ISO convention. Lee et al. (2011) further confirmed this flow rate, which was then used in additional study (Lee et al. 2014). In the meantime, Harper et al. (1998) had examined the separation efficiency and concluded that 2.5 l min$^{-1}$ was the best match to the ISO respirable convention, and this has been the flow rate recommended since by manufacturers. This work was referenced when the aluminum cyclone was included in a revision of the NIOSH Manual of Analytical Methods method 0600 (NIOSH 1998) and 7500 (NIOSH, 2003), and the flow rate of 2.5 l min$^{-1}$ was adopted. More recent studies have shown that the samples collected with the aluminum cyclone had a lower respirable dust concentration than ones collected with other HD cyclones (Luecke 2003; Stacey et al. 2013). It is now known that most cyclones, including the aluminum cyclone, need to be used with conductive cassettes to minimize internal wall losses of the sample (Dobson et al. 2013; Soo et al. 2014; Caroll 2020). Soo et al. (2014) found in all cases, the collection on the walls could be minimized to within acceptable levels (Ashley and Harper 2013) through substituting conductive polypropylene cassettes. This recommendation is now included in appropriate standards from the American Society of Testing and Materials (ASTM International) Standard Guide D8358 (ASTM International 2021). The Harper et al. (1988) study did not employ conductive cassettes, nor did it use a direct connection to the cyclone outlet to avoid particle loss during testing the performance of size-selective samplers.

Testing of aerosol samplers has been standardized in EN13205 (CEN 2014), but literature reviews (Hanlon et al. 2021, 2023) suggest that its application has been variable, and this may be due to issues in the procedures. The aluminum cyclone has been included in a recent ongoing study through the Nickel Institute and the International Sampler Comparison Group (which is supported by the Nickel Institute) to characterize the between-laboratory ($n = 3$) variation of a protocol based on EN13205 for testing sampler performance. In all 3 participating laboratories, the aluminum cyclone was operated at a flow rate of 2.5 l min$^{-1}$, and in all 3, the $d_{50}$ was found to be smaller than expected. A smaller $d_{50}$ implies a lower concentration result, therefore underestimating workers' exposures when used in the field. The objective of the present study is to evaluate size-selective sampling performance of the aluminum cyclone with the currently recommended operating flow rate and to find optimal flow rate(s) for minimized sampling bias compared with the ISO respirable convention. This work was conducted at the NIOSH Pittsburgh Mining Research Division laboratory that participated in the intercomparison study.

## Materials and methods

### Penetration efficiency testing

Experimental setup of penetration efficiency testing is shown in Fig. 1. Two different sizes of poly dispersed

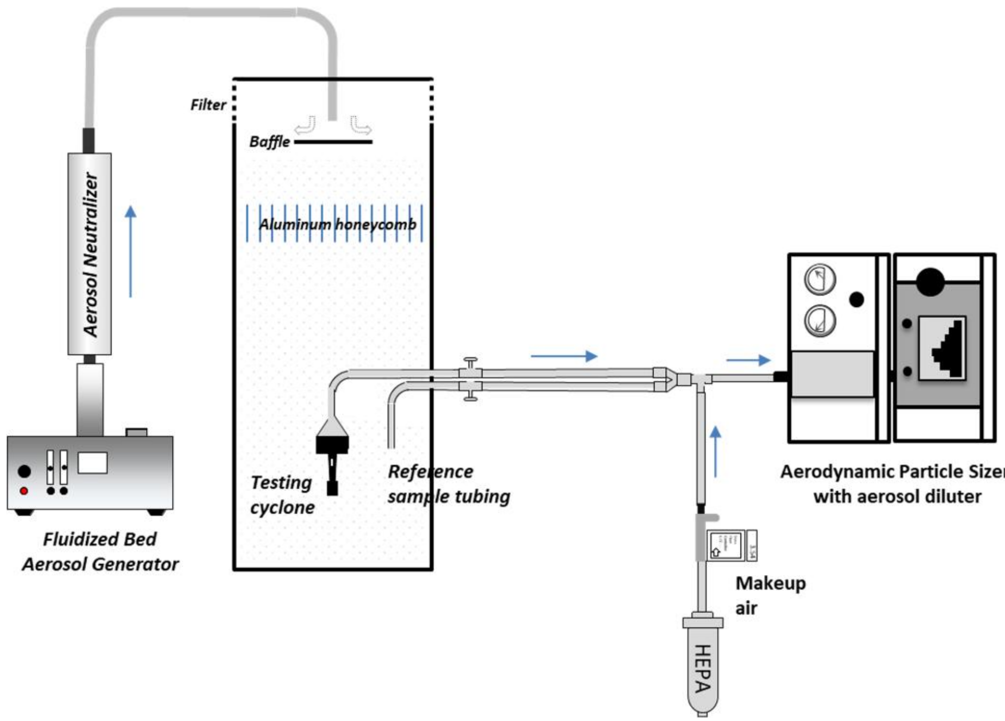


**Fig. 1.** Penetration efficiency test setup for aluminum cyclone.

glass sphere particles (geometric $d_{50}$≈4 and 10 μm, Cospheric, Santa Barbara, CA, USA) were mixed and generated with a fluidized aerosol generator (Model 3077A; TSI Inc., Shoreview, MN, USA). The airborne particles were introduced into a calm air chamber through a Kr-85 aerosol neutralizer (Model 3012A; TSI Inc.) and a baffle hung down from the top plate allowing the airflow to enter the chamber in a radial direction. Aluminum honeycomb was located between the baffle and sampling section to reduce turbulence in the air. The calm air chamber has been utilized in previous studies to evaluate the performance of size-selective samplers (Feather and Chen 2003; Lee et al. 2016, 2017, 2018). An Aerodynamic Particle Sizer (APS, Model 3321, TSI Inc.) with an aerosol diluter (Model 3302A, 100:1 dilution capillary; TSI Inc.) was used to measure particle size distributions of the aerosols. To minimize particle loss from the tubing, the APS and aerosol dilutor were positioned horizontally. The cyclones were connected to a conical shape adaptor to minimize particle loss in the tubing system. The airflows at the inlet of the cyclone and reference tubing, whether 2.2, 2.3, or 2.5 l min$^{-1}$ were adjusted to the APS sampling flow (5 l min$^{-1}$) with HEPA filtered make-up air. The flow rate before and after sampling was measured with a flow meter (Gilibrator; Sensidyne, Tampa, FL, USA). A total of 30 particle size distribution datapoints were measured in each experiment; particle size distribution from the reference tubing was measured for 20 s followed by measurement from the cyclone for 20 s and the process was repeated 15 times. Particle number concentration of each size bin from the cyclone was divided by that from the reference tubing and an average of the 15 ratios was determined. Five different aluminum cyclones (3 from SKC, Inc. and 2 from Environmental Express, Zefon) were tested with 3 repetitions at each testing flow rate.

Particle size distributions were measured with the same measurement procedure (30 measurements with 3 repetitions) for both the reference and the cyclone tubing without cyclone attachment prior to testing cyclones. Although the average ratios of aerosol concentration up to 6 μm mass median aerodynamic diameter (MMAD) from the 2 sets of tubing were near unity, the ratios of the particle > 6 μm MMAD were not close to the unity due to large variations in large particle concentrations. Air leakage was checked with a cassette leak tester (Omega Specialty Instruments, now Air Sampling Devices, Waltham, MA, USA) when a cyclone was attached in the tubing.

## Penetration efficiency comparison to the respirable convention

The penetration efficiencies of the aluminum cyclones were compared with the ISO respirable convention by calculating the bias. The estimated biases were calculated by using equations from (1) to (3)

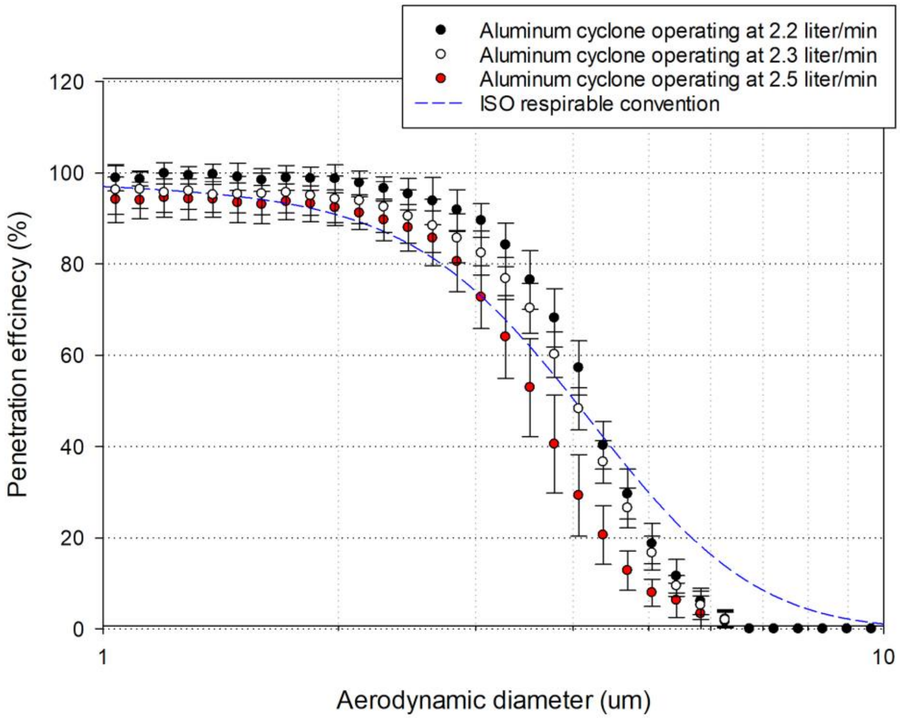


**Fig. 2.** Averaged penetration efficiencies of 5 aluminum cyclone at flow rates of 2.2, 2.3, and 2.5 l min$^{-1}$ and the ISO respirable convention.

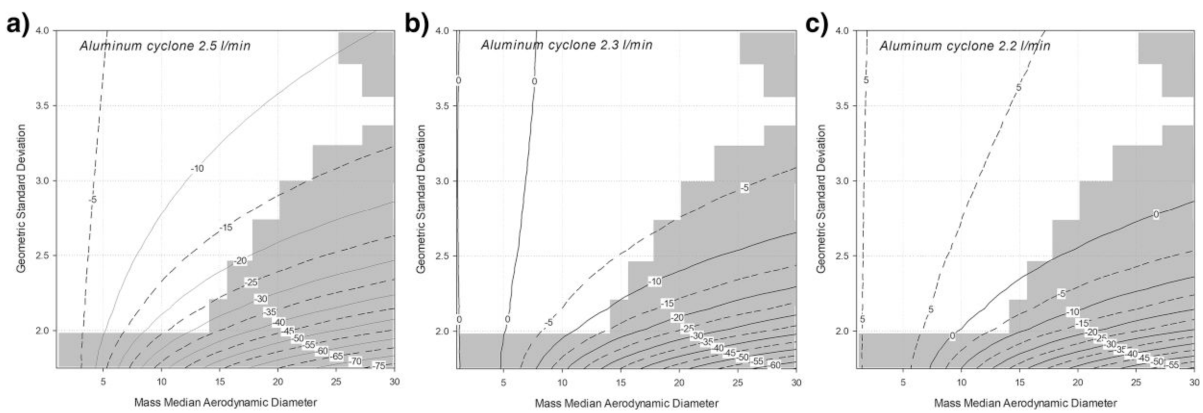


**Fig. 3.** Bias maps of averaged aluminum cyclone ($n = 5$) performance at flow rates of 2.5 (a), 2.3 (b), and 2.2 (c) l min$^{-1}$ compared with the ISO respirable convention. Shaded area represents extreme particle size distributions, which are not included when assessing performance.

(Bartley et al. 1994; Kenny and Bartley 1995; Aitken et al. 1999). Lognormal particle size distribution was assumed, and the calculation ranges of MMAD and geometric standard deviation (GSD) were 1 to 30 μm and 1.5 to 3.5, respectively. The bias of the sampler (Δ) is defined as

$$\Delta = \frac{\bar{C} - C_{std}}{C_{std}} \quad (1)$$

$$\bar{C} = \int_0^\infty \bar{E}(D)\, A(D)\, dD \quad (2)$$

where $\bar{C}$ is the mean measured concentration, $\bar{E}(D)$ is the mean sampling efficiency of the sampler, and $A\,(D)$ is the log-normal distribution.

$$C_{std} = \int_0^\infty \bar{F}(D) A(D)\, dD \quad (3)$$

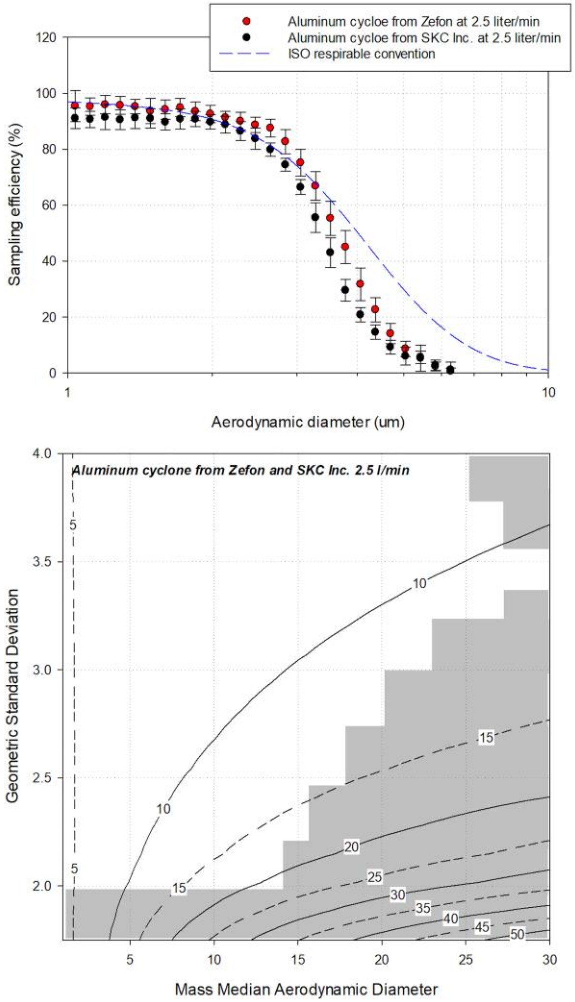


**Fig. 4.** Comparison of penetration efficiency with bias map for different cyclone models at 2.5 l min$^{-1}$ (average of 2 aluminum cyclones from Zefon and 2 cyclones from SKC Inc.).

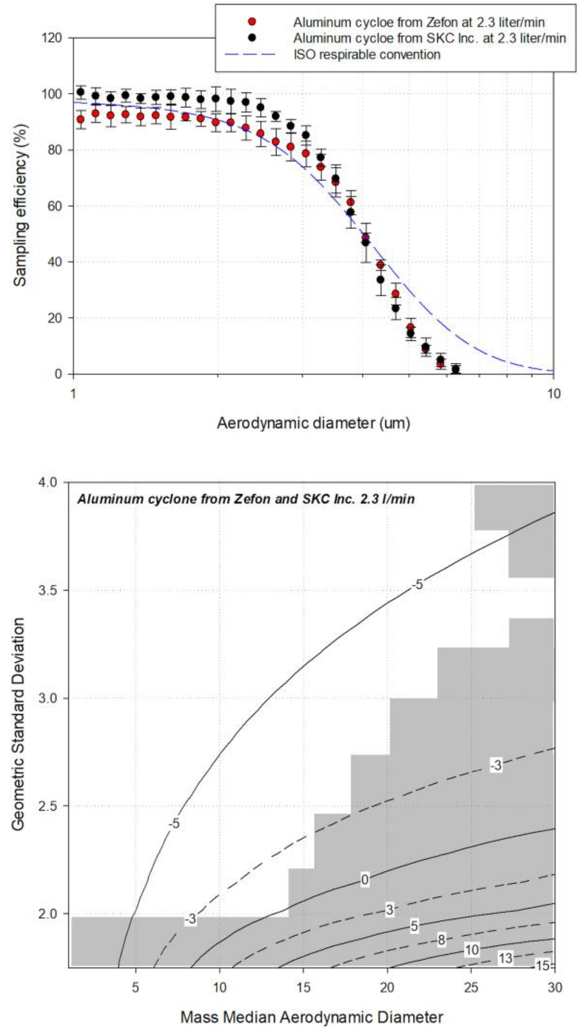


**Fig. 5.** Comparison of penetration efficiency with bias map for different cyclone models at 2.3 l min$^{-1}$ (average of 2 aluminum cyclones from Zefon and 2 cyclones from SKC Inc.).

where $C_{std}$ is the ideal concentration and $\overline{F}(D)$is the sampling efficiency of an ideal sampler, perfectly following the desired sampling convention.

## Results and conclusions

Averaged penetration efficiencies of the 5 aluminum cyclones at the flow rates of 2.2, 2.3, and 2.5 l min$^{-1}$ along with the ISO respirable convention are shown in Fig. 2. Each data point and error bars represent the average and standard deviation of the 5 units. The measured average cutoff diameters ($d_{50}$s) for the aluminum cyclones were $4.2 \pm 0.1$ µm at 2.2 l min$^{-1}$, $4.1 \pm 0.2$ µm at 2.3 l min$^{-1}$, and $3.7 \pm 0.2$ µm at 2.5 l min$^{-1}$. The $d_{50}$s were estimated from curves fitted (using sigmoid, 3 parameters curve fit) to the measured penetration efficiencies of the aluminum cyclones.

Bias maps of averaged aluminum cyclone performance at flow rates of 2.5, 2.3, and 2.2 l min$^{-1}$ compared with ISO respirable convention are shown in Fig. 3a to c, respectively. The bias at the flow rate of 2.2 l min$^{-1}$ did not exceed ±10% for any particle size distribution of interest (unshaded area in Fig. 3c) and this is therefore the most appropriate flow rate to be used to meet the ISO convention. The bias at the flow rate of 2.3 l min$^{-1}$ included some areas exceeding −10% (negative bias indicates an underestimation of mass concentration compared with the respirable convention curve). However, the area is small and <10% of the area of interest and thus would remain acceptable according to EN13205. With bias exceeding −10% over about half the area of interest the probability of underestimating exposure using this cyclone at 2.5 l min$^{-1}$ is

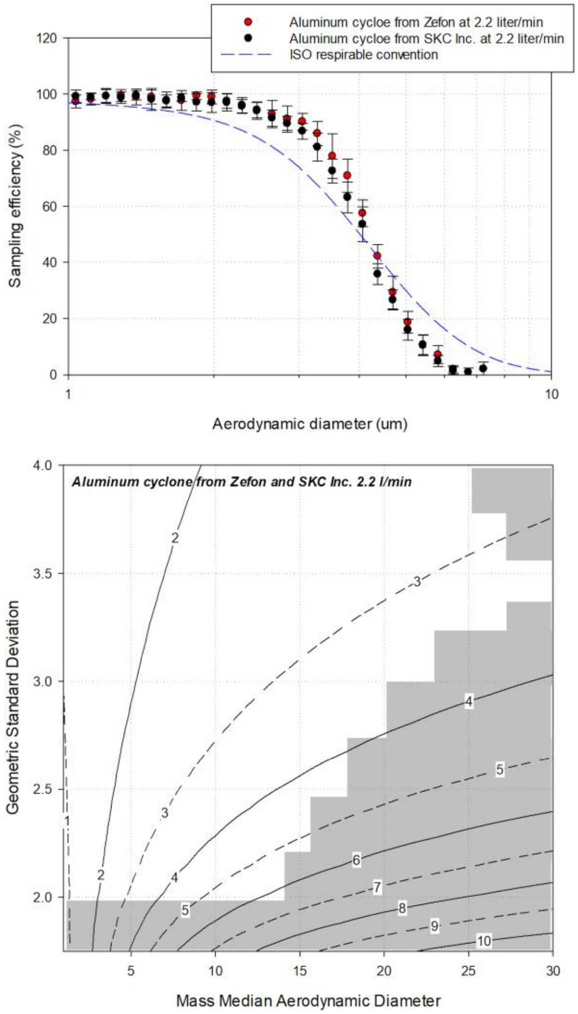


**Fig. 6.** Comparison of penetration efficiency with bias map for different cyclone models at 2.2 l min$^{-1}$ (average of 2 aluminum cyclones from Zefon and 2 cyclones from SKC Inc.).

unacceptably high. Based on findings of the $d_{50}$s and calculated bias between tested flow rates, the flow rate of 2.2 l min$^{-1}$ should be selected, but 2.3 l min$^{-1}$ may be allowed.

Average penetration efficiencies of 2 Zefon and 2 SKC Inc. aluminum cyclones at the flow rate of 2.5, 2.3, and 2.2 l min$^{-1}$ are shown in Fig. 4, Fig. 5, and Fig. 6, respectively. Biases between the penetration efficiency of the 2 cyclones from Zefon and SKC Inc. were calculated and shown in Figs. 4–6. The largest biases were found between the Zefon and SKC aluminum cyclones at the flow rate of 2.5 l min$^{-1}$ (up to 20%). However, small differences were found at flow rates of 2.3 (up to −7%) and 2.2 (up to 6%) l min$^{-1}$, indicating the differences are attributable to random error from testing conditions rather than systemic error.

Based on the results from the present study, the aluminum cyclone at a flow rate of 2.2 l min$^{-1}$, as recommended by Lidén (1993), is a better match with the ISO respirable convention, consistent with the studies of Tsai and Shih (1995), Görner et al. (2001), Lee et al. (2011), and Luecke (2003). A flow rate of 2.3 l min$^{-1}$ also meets the requirements for sampling in accordance with this convention. Operation at 2.5 l min$^{-1}$ would not be recommended due to underestimation of respirable dust concentrations.

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## Conflict of interest

The authors declare no conflict of interest relating to the material presented in this Article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

## Data availability

Data are available on request to T.L.

## Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company name or product does not constitute endorsement by NIOSH/CDC. Dr. Harper was at one time employed by both SKC Inc. and Environmental Express (Zefon), but currently has no relationship with either company. Dr. Harper is a consultant to the International Sampler Comparison Group. More information can be found on their website (https://www.ecu.edu.au/schools/medical-and-health-sciences/our-research/school-research-areas/real-time-monitoring-research/overview).

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