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# An investigation of the performance of the 10-mm nylon cyclone

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## Introduction

Sampling and analytical methods for the determination of respirable silica developed in our laboratory employ a sampling device consisting of a 10-mm nylon cyclone and 37-mm cassette loaded with PVC-type filter and operated at 1.7 lpm.<sup>(1)</sup> Recently, both the X-ray diffraction and infrared spectroscopic methods for respirable silica were collaboratively tested.<sup>(2)</sup> In that test, both methods exhibited significant sampling errors, e.g., the sampling precision of the X-ray diffraction method was 17% at loadings of 50-200 µg/sample. The poor precision in the collaborative test contrasted with the much better precision obtained in two studies of similar sampling devices undertaken in this laboratory.<sup>(3,4)</sup>

In order to elucidate these inconsistencies, the respirable silica sampling device described above was subjected to a statistically rigorous determination of the sampling precision under controlled laboratory conditions. Nine sampling devices were challenged with a homogeneous concentration of a quartz-containing aerosol within an exposure chamber. An analysis of variance of the gravimetric results was performed to obtain the sampler precision.

In a subsequent study, five different leak locations were determined, and leaks in those positions were tested for their effect on sampling precision, using a generation system as in the precision evaluation. The results were subjected to a statistical analysis to determine which leaks were significant.

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The sampling device recommended by the National Institute for Occupational Safety and Health for the determination of respirable silica is a 10-mm nylon cyclone and 37-mm cassette loaded with a PVC-type filter and operated at 1.7 lpm. The device has been subjected to a statistically rigorous determination of the sampling precision under controlled laboratory conditions using a silica-rich mine dust in a laboratory-built generation system. The statistical design used in the investigation eliminated contributions to the precision estimate from run and position effects. The precision of the device over the deposition range 826-1800 µg/sample was found to be 2.18%. In a follow-up study of air leaks in the device, five possible locations of leaks were selected. A set of sampling devices was made with air leaks of varying magnitude in the selected locations. The devices were tested using a vacuum leak testing apparatus. They were then placed in a generation system and challenged with a uniform concentration of aerosol side by side with control (leakless) cyclones. The samples were analyzed gravimetrically and the results subjected to a statistical analysis to determine which leaks had a significant effect on the sampling performance. The experiments indicated that the devices were remarkably rugged, with only the most excessive leaks affecting the amount of dust collected. Finally, a number of simple tests were developed so that significant air leaks could be detected. **Carsey, T.P.; Shulman, S.A.; Lorberau, C.D.: An investigation of the performance of the 10-mm nylon cyclone. *Appl. Inc. Hyg.* 2:47-52; 1987.**

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## Experimental

### *Procedure for using Cyclones*

Several authors have recommended procedures for improving cyclone performance.<sup>(3,5-8)</sup> From these recommendations, a protocol was developed to ensure the optimum precision of operation of the sampling unit. The protocol contained the following items:

1. Cyclones were physically tight. In practice, components were exchanged until a reasonably tight fit was obtained, especially in the fitting of the vortex finder.
2. Air leaks were reduced by gluing

the vortex finder to the body of the cyclone with a water-soluble cement (Elmer's Glue) and by application of vacuum grease (Dow High Vacuum Silicon Lubricant) to each o-ring seal. Each cyclone was tested before and throughout the experiment for leaks using a leak-tester described below. Leaks did not develop during the course of the work.

3. The PVC-type filter was mounted with the matte face of the filter towards the inlet so that particles were deposited onto the matte surface.

**TABLE I**  
Summary of generation experiments

Run No.	Level	Time (min)	Concentration (mg/m <sup>3</sup> )	Load (μg)	Precision (%SR)
1	Low	200	2.4	826	3.5
2	Low	200	2.9	979	3.0
3	Low	200	2.8	958	2.1
4	Low	200	2.8	938	3.8
5	High	300	3.1	1584	2.9
6	High	300	3.5	1800	1.6
7	High	300	3.4	1733	1.4
8	High	300	2.7	1360	2.7

- Pump fluctuations were eliminated by pumping all sampler units through flow-limiting orifices from a central manifold. Orifices designed to provide a flow of 1.7 lpm were made in this laboratory from nylon or aluminum stock. Actual flows were  $1.78 \pm 0.03$  lpm and did not change substantially throughout the experiment.
- Gravimetric analysis on a six-place balance was employed to maximize the analytical precision. Load levels on the filters were high (826-1800 μg/sample) to reduce the contribution of any analytical imprecision.

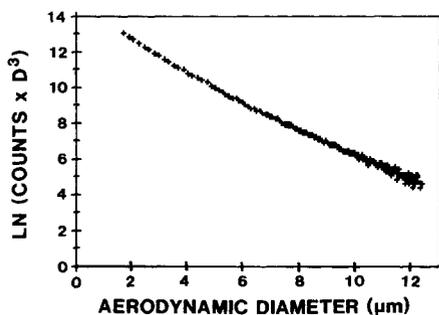


Figure 1—Particle size distribution of mine dust aerosol over the region 0.5 to 10 μm.

#### Generation of aerosol

Sampling took place in the Large Inorganic Sampling Assembly (LISA) aerosol generation system described elsewhere.<sup>(9)</sup> It has been used in the development and evaluation of analytical methods at our laboratory.<sup>(10)</sup> Generation runs were 2 to 5 hours long. Aerosol concentrations were 2.4-3.5 mg/m<sup>3</sup>. The details of the eight generation runs are given in Table I.

Particle size distributions of the mine dust aerosol were obtained with a Climet Model 208A optical particle size detector, over the particle size range pertinent to cyclone performance,

using apparatus previously described elsewhere.<sup>(9)</sup> Output from the Climet was directed into a multichannel analyzer (Tracor-Northern Model TN7200) and into an Apple-IIe microcomputer for data analysis and storage. The aerosol contained a sufficient amount of non-respirable size to adequately challenge the cyclone (Figure 1).

#### Mineral dust

An ore sample from a uranium-vanadium mine in Colorado was ground in a freezer-mill at liquid nitrogen temperature (77°K) for ten minutes and sieved to < 53 μm. The material contained approximately 90% α-quartz.

#### Sampler units

Nine sampler units were used, each consisting of a Dorr-Oliver 10-mm nylon cyclone in an MSA holder assembly (MSA part 456243), a two-piece 37-mm monitor cassette (Millipore part no. M000-037-AO), and a 37-mm diameter, 5-mm pore size PVC filter (MSA type FWSB). The nylon cyclones were chosen randomly from laboratory supplies.

#### Leak tester

A sampler leak testing device was built

to test for air leaks. The device, shown in Figure 2, drew a ~20" H<sub>2</sub>O (5 kPa) vacuum on the cyclone, the inlet port of which has been sealed with a removable sealing putty. A manometer measured the vacuum. The cyclone was assumed to be free of leaks if less than 1" H<sub>2</sub>O (0.25 kPa) vacuum loss occurred in 30 seconds.

#### Gravimetric analysis

Filters were preweighed twice and post-weighed twice following overnight equilibration in a temperature and humidity controlled weighing room (24°C, 44% RH). Weighing was performed on a Cahn Model 25 balance reading to 1 μg. Weighings were repeated until two weights within 5 μg were obtained; the average of the two was recorded. Two blank filters were included with each generation run to assure freedom from non-statistical errors in the gravimetric analysis. Each mass was corrected for deviations in the air flow from 1.7 lpm according to equation 1. These deviations amounted to ≤ 5%.

$$\text{Corrected Mass } (\mu\text{g}) = \frac{\text{Uncorrected Mass } (\mu\text{g}) \cdot 1.7 \text{ lpm}}{\text{Measured air flow (lpm)}} \quad (1)$$

#### Leak effects experiments

Following the determination of the sampling precision, a study of the effects of air leaks on cyclone performance was initiated. Four prominent leak locations were noted (Figure 3): 1) between the vortex finder and the cyclone body, 2) in the lower adapter o-ring, 3) in the upper adapter o-ring, and 4) in the cassette-to-frame seal. A fifth location, the lower body (dust trap) o-ring, was not considered, as the air from such a leak would be forced through a constrained, cir-

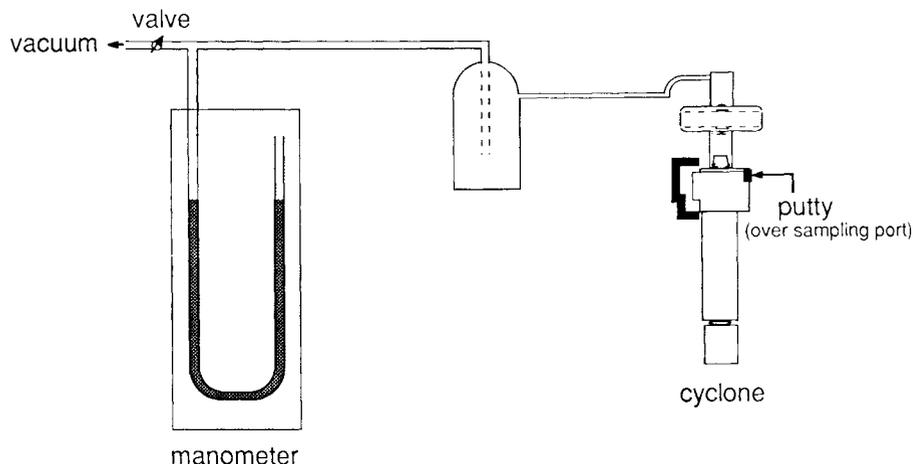


Figure 2—Leak testing apparatus for use with 10-mm nylon cyclone sampling devices.

cuitous path resulting in minimal air flow.

Nine sampling devices randomly chosen from laboratory supplies were used. Five cyclones were assigned as controls and four as leaky (test) cyclones, onto which leaks were imposed. All cyclones were complete and in physically sound condition. In particular, the lower vortex finders were clean and smooth, as were the walls of the cyclone in which the vortex finders were seated. For the five control cyclones, the vortex finders were glued to the cyclone with a water-soluble cement (Elmer's Glue). Tygon® tubing and o-rings were replaced if worn.

Each sampling device was tested before and throughout the experiment for air tightness leaks using the leak tester described above. The control devices lost less than 1" H<sub>2</sub>O (0.25kPa) vacuum in 30 seconds. The leaky cyclones had leaks in specific locations which lost a vacuum of 20" H<sub>2</sub>O (5 kPa) in two seconds or less. Unintentional leaks were not observed during the course of the work.

A group of four cyclones with specific leaks and five control cyclones were randomly placed in the LISA generation system and challenged with an aerosol similar to that used in the precision studies described above. The samples were analyzed gravimetrically.

### Statistical design

For the precision studies, an experimental design was sought which would separate the chamber effects from sampler effects. Among the designs considered were the Lattice Square<sup>(11)</sup> and the Youden Square<sup>(12)</sup> design. The Lattice Square design was chosen for several reasons.

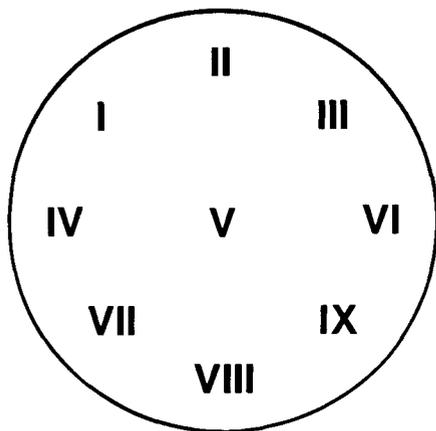


Figure 3—The 10-mm nylon cyclone showing the locations of air leaks examined in this work.

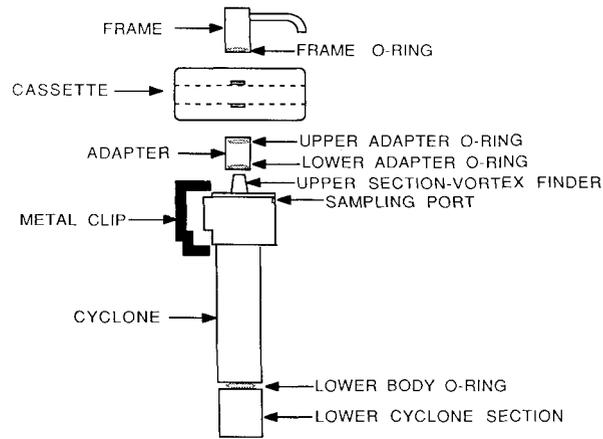


Figure 4—Sampling unit positions inside the LISA generation system.

In the Lattice Square design, the interior of the chamber is approximated by a 3 × 3 grid of rows and columns (Figure 4). After an initial run, the samplers were moved in a precise way to a different arrangement for second run determined by the Lattice Square statistics. As a result, the position effects and sampler effects were independent (not confounded). Also, [Position] × [Level] interactions were separable and could be estimated and removed if significant. However, this design was intended for the situation when interactions can be removed by transformation of the data.

Another feature of the design was that any concentration inhomogeneity in the chamber would be distributed over rows and columns. The data have been used to develop a statistical description of the chamber performance.<sup>(13)</sup> Lastly, each set of experiments (pair of runs) was statistically complete in itself and was easy to repeat if needed.

The experimental data were reduced using an analysis of variance (ANOVA) routine which permitted ready determination of Run, Position, and Sampler effects. The ANOVA analysis was performed using the general linear model (GLM) procedure on the Statistical Analysis System (SAS) series of statistical programs.<sup>(14)</sup> The dependent variable was the deposited mass (*M*) on each of the 68 samples (72 minus 4 outliers), corrected for variation in flow rate (equation 1). Samples were considered outliers if evidence for breakthrough was observed (material found on the back-up pad) or if the analytical results failed Grubb's test (at the 1% level). The SAS model assumed the following sources of variability:

Run[ <i>i</i> ]	Deviation due to the <i>i</i> <sup>th</sup> run ( <i>i</i> = 1 to 8).
Pos[ <i>j</i> ]	Deviation due to the <i>j</i> <sup>th</sup> position in the chamber ( <i>j</i> = 1 to 9), fixed by the geometry of the chamber. The lattice square model assumed a perfect 3 × 3 square; however, the circular geometry of the chamber required approximating this square somewhat. The positions were denoted by Roman numerals I-IX in Figure 3.
Sampler[ <i>k</i> ]	Deviation due to the <i>k</i> <sup>th</sup> cyclone sampler ( <i>k</i> = 1 to 9). This was the inter-sampler or between-sampler effect and had a variance of ( $\sigma_s$ ) <sup>2</sup> .
Intra[ <i>i,j,k</i> ]	The intra-sampler (within-sampler) variance for the <i>k</i> <sup>th</sup> sampler ( <i>k</i> = 1 to 9) in the <i>j</i> <sup>th</sup> position of the <i>i</i> <sup>th</sup> run. The variance was ( $\sigma_e$ ) <sup>2</sup> and was considered independent of position, run, and samples.

The ANOVA model resolved each datum into the following:

$$M[i,j,k] = \mu + \text{Run}[i] + \text{Pos}[j] + \text{Sampler}[k] + \text{Intra}[i,j,k] \quad (2)$$

where  $\mu$  was the overall mean.

### Results

Nine cyclones (denoted A through H) were prepared and placed in the LISA chamber positions. Four sets of experiments were performed at two different load levels. Each set contained two runs with different arrangements of cyclones. Position changes for subse-

quent sets were found by interchanges between row and column and permutations (within rows and columns) of the Lattice Square design arrangements.<sup>(11)</sup> Two samples were considered outliers because of leakage of material around the filter onto the backup pad, and two other samples had residuals which failed the Grubb's test (1% level). Both of the latter samples were from the same run of the generation system. One of these was about 200 mg/m<sup>3</sup>, whereas all eight other samples from the run were between 700 and 1000 mg/m<sup>3</sup>. No statistical test is needed to question such a value. The fourth measurement was determined to be an outlier when its residual was found to be an excess of 3.8 times the estimated residual standard deviation—including both components for within and between sampler variability. It is this result which fails the Grubbs test at the 1% significance level. When this fourth measurement is not excluded, the total relative standard deviation is about 3.2%, about 1% higher than the estimate derived below.

Following the gravimetric analysis of the filters, the ANOVA analysis was performed. That analysis determined the mean deposition of 1272.240 and other values shown below. Interactive terms were taken to be negligible, on the basis of a nonsignificant result (5% significance level) from the additivity test due to Tukey.<sup>(15)</sup> Of particular concern was any possible interaction between sampler measurement and run or position. Also, residual plots supported the

assumption of homogeneous variance of  $(\sigma_\epsilon)^2$ . A normal probability plot of the residuals did not contradict the assumption of normality.

The variances predicted by the model and the degrees of freedom (DOF) were obtained from the value of the expected mean square (EMS) term produced by the ANOVA calculation.

The total (overall) precision of the cyclone sampler unit,  $(\sigma_T)^2$ , should reflect both intra-sampler and inter-sampler variance. It has been defined here as the linear combination of these two variances, viz, equation 3 (designates an estimate).

$$(\hat{\sigma}_T)^2 = (\hat{\sigma}_S)^2 + (\hat{\sigma}_\epsilon)^2 \quad (3)$$

From the EMS terms,  $(\hat{\sigma}_\epsilon)^2 = 631.909$ . With a DOF of 44, the 95% confidence limits were found to be

$$433.084 \leq (\sigma_\epsilon)^2 \leq 1007.391$$

The inter-sampler variance,  $(\hat{\sigma}_S)^2$ , was obtained from the EMS terms:

$$\begin{aligned} (\hat{\sigma}_S)^2 &= [\text{MS}(\text{Sampler}) - \text{MS}(\text{Error})]/6.613 \quad (4) \\ &= A \cdot \text{MS}(\text{Sampler}) + B \cdot \text{MS}(\text{Error}) \\ &\quad \text{with } A = (1/6.613) \text{ and } B = -(1/6.613) \\ &= 133.781 \end{aligned}$$

A standard approximation was used to determine the DOF for  $(\hat{\sigma}_S)^2$ .<sup>(16)</sup> This approximation is intended for balanced data. The data studied here were almost balanced; consequently, the approximation was considered adequate. Using that equation,  $\text{DOF}(\text{Samp}) = 2.64$ . Using a formula from Searle,<sup>(16)</sup> the range at 95% confidence was then calculated.

$$40.596 \leq (\sigma_S)^2 \leq 2354.55$$

where  $\text{DOF} = 2.64$ . The range calculation may be unreliable, however, as the condition of significance,  $(\text{Pr} < 0.025)$ ,<sup>(17)</sup> was not met; here  $\text{Pr} > F = 0.0304$ .

Using equation 3, the total variance could then be obtained:

$$\begin{aligned} (\hat{\sigma}_T)^2 &= 631.909 + 133.781 \\ &= 765.690 \end{aligned}$$

and  $\text{DOF}$  for  $(\hat{\sigma}_T)^2$  was computed to be 44.72.<sup>(16)</sup> From the overall mean of 1272.240, the overall relative standard deviation ( $s_R$ ) of the 10-mm nylon cyclone was:

$$\begin{aligned} \hat{s}_R &= (\sqrt{765.690})/1272.240 \\ &= 0.0218, \text{ or } 2.18\% \end{aligned}$$

The estimated variance of  $\hat{s}_R$  was found to be the following:<sup>(18)</sup>

$$\begin{aligned} \text{Variance}(\hat{s}_R) &= (\hat{s}_R)^2 \cdot [1 + 2 \cdot (\hat{s}_R)^2]/(2 \cdot \text{DOF}) \\ &= 5.294 \times 10^{-6} \quad (5) \end{aligned}$$

giving an estimated band for  $s_R$  at 95% confidence of:

$$0.0172 \leq (s_R) \leq 0.0263 \quad (6)$$

Equations 5 and 6 assume normality of  $\hat{s}_R$ , which is approximately true for large enough degrees of freedom (here  $\text{DOF} > 40$ ), and small  $s_R$ .<sup>(18)</sup>

## Leak testing

The statistical test employed computed the probability that the mean deposition of the leaky samples was significantly different from the mean of the controls (at a 95% confidence limit). The details of the generation runs are described below and summarized in

TABLE II  
Summary of leak experiments

Run No.	Leak Type	No. of control samples/ No. of leaky samples <sup>a</sup>	Approximate aerosol concentration (mg/m <sup>3</sup> )	Average deposition of control sampler (μg)	% RSD of control	Average deposition of leaky sampler (μg)	% RSD of leaky sampler	Percent difference	Probability (Pr > t) <sup>b</sup>
1 <sup>c</sup>	unglued	7/1	1.96	1043	6.0	998	—	(4.3)	—
2	unglued	7/1	0.57	308	2.7	407	—	—	—
3	seam	3/5	0.50	234	3.0	223	3.8	4.7	0.1342
4	seam	4/3	4.91	3410	1.9	3388	1.0	0.7	0.6252
5	1.adapter	4/2	5.72	3134	1.0	4177	—	33.3	0.0001
6	1.adapter	3/3	4.93	2767	2.7	2814	2.4	1.7	0.4537
7	1.adapter	5/4	4.54	2544	1.2	2673	1.6	5.1	0.0012
8	u.adapter	5/4	7.24	4165	1.8	4246	2.8	1.94	0.2480
9	u.adapter	4/4	6.84	3833	0.1	3973	1.9	3.65	0.0099
10	1.adapter	4/5	6.05	3441	2.5	3817	6.5	10.93	0.0242
11	holder	4/3	6.31	3628	0.14	3623	0.9	3.6	0.9428

<sup>a</sup>Most runs lost samples due to cassette seal leakage or other problems. The number of remaining control and leaky samples is shown here.

<sup>b</sup>A significant difference (at the 95% confidence level) between the leaky and the control samples is indicated by a  $\text{Pr} > t$  value of 0.05 or lower.

<sup>c</sup>The sampling devices for Run 1 were not charge neutralized. Significant deposits of dust, attributed to electrostatics, were observed inside each cassette.

Table II. In many of the runs, some samples had to be discarded as outliers, usually because of leaking of air around the filter and consequent deposition of material on the back-up pad. The numbers of control and leaky samples used in the statistical calculations are given in Table II.

It should be noted that although there are relatively few samples (one to seven) in each group, the relative standard deviations for leaky sample groups and for control sample groups are quite low—in only two instances in excess of 4%. The power of the two sample t-tests with three samples in each group is such that a t-test done at significance level of 5% has about a 90% chance of identifying as significant a 16% difference between the means of the two groups—if the pooled relative standard deviation is about 4%. Thus, in general, for the comparisons described below (based on the figures given in Table II), differences in excess of 16% should be detected with high probability. Where the pooled relative standard deviation of the two groups being compared is less than 4%, smaller differences will be detected with high probability.

*Runs 1 and 2*—A noticeable amount of dust was observed on the inside of every cassette in Run 1. This was attributed to electrostatics, as no precautions had been taken to neutralize charges on the samplers.<sup>(19)</sup> The resulting precision values were quite poor. In Run 2 and subsequent runs, the charges on each filter, cassette, and cyclone were neutralized with <sup>210</sup>Po charge neutralizer strips (Nuclear Products Co.) and checked with a non-contacting electrostatic voltmeter (Trek model 300).

*Run 3: Leaky Vortex Finder Seam.* Leak was not significant (Pr = 0.1342).

*Run 4: Leaky Vortex Finder Seam.* Leak was not significant (Pr = 0.6252).

*Run 5: No Lower Adapter o-ring.* Leak was significant (Pr = 0.0001).

*Run 6: Leaky Lower Adapter o-ring.* Lower adapter o-rings modified until they just failed to hold the weight of cyclone with metal clip. Leak was not significant (Pr = 0.04537). Statistical significance of the run was compromised by the loss of three samples due to leaks around the filters.

*Run 7: Leaky Lower Adapter o-ring.*

Repeat of Run 6. Significant (Pr = 0.0012).

*Run 8: Leaky Upper Adapter o-ring.* Upper adapter o-rings modified until they failed to hold the weight of a cassette plus another adapter, but did hold the weight of the cassette alone. Not significant (Pr = 0.2480).

*Run 9: Very Leaky Upper Adapter o-ring.* Upper adapter o-rings modified until they would not hold the weight of a cassette. Significant (Pr = 0.0099).

*Run 10: Very Leaky Lower Adapter o-ring.* Lower adapter o-rings modified until they did not hold the weight of the adapter (when inverted) even momentarily. Significant (Pr = 0.0242). All four test filters had central depositions on the filter. These four were the only samples in the entire series of experiments which had central depositions. Additionally, these four had significantly higher deposition than the others.

*Run 11: Leaky Frame o-ring.* Frame o-ring modified until the frame would hold the weight of a cassette alone, but would fail to hold the weight of a cassette and adapter. Not significant (Pr = 0.9428). However, it is noted that a leak in this location would have a possible deleterious effect on the sampling pump.

## Discussion

The impetus of this study was the collaborative test of the silica methods discussed above,<sup>(2)</sup> in which an unacceptably poor sampling precision ( $s_R$ ) of 17% was obtained. In addition to that study, the precision of the particulate sampling using the 10-mm nylon

cyclone has been reported by other authors. These results, from reference 5 and elsewhere, are summarized in Table III. Considerable variation existed in the sampling devices, sampling strategy, and sampled environment so that a numerical comparison of those results is unwarranted. However, the reported precision values were not as good as those reported here. The two exceptions (Table III) are a study of the Coal Mine Personal Dust Sampler Unit (CMDPSU)<sup>(3)</sup> and a study of the penetration of the 10-mm nylon cyclone.<sup>(4)</sup> The former study obtained an intra-sampler error of 1.37% and an inter-sampler error of 1.62%. The latter obtained an intra-sampler error of 1.15% and an inter-sampler error of 0.19%. This study obtained an intra-sampler error of 1.98% and an inter-sampler error of 0.91%. Although differences exist as to the partitioning of the inter- and intra-sampler errors, there is agreement that the overall precision of the unit is about 2%. A limitation of these comparisons was the lack of replicates necessary to accurately determine small variances.

The leak experiments demonstrated that only major leaks in the adaptor collar had a statistically significant impact on the mass of material collected by the sampling device, assuming that the device was complete and structurally sound. The presence of leaks could best be determined with the vacuum apparatus (Figure 2). In lieu of that, simple gravity tests were devised so that adequate tightness of the sampling unit could be assured in the field without any test equipment. These tests were that 1) the sampling unit be complete; 2) the lower adapter o-ring can hold onto a cyclone including the metal clip (i.e., the cyclone is gripped sufficiently tightly by the o-ring in the adaptor that it

TABLE III  
Evaluation of precision of the 10-mm nylon cyclone: laboratory tests

Author	Degrees of freedom	Pooled % $s_R$	Comments	Reference*
Jacobsen (1971)	8	6.4	Bendix	20
Jacobson (1971)	7	11.1	MSA	20
BOM data (1972)	58	8.0	MSA	21
Almich & Carson (1974)	66	4.8	custom-made	22
Harris <i>et al</i> (1976)	37	8.0	MSA	23
Harris <i>et al</i> (1976)	37	11.8	Bendix	23
Gray and Tillery (1979)	154	7.1-4.6	custom-made	24
MSHA data (1981)	29	4.3	Bendix	25
Bowman <i>et al</i> (1982)	18	2.3	MSA	3
Baron (1983)	15	1.16	MSA	4
This report	45	2.18	MSA	

\*Results for references 20-25 are given as summarized in reference 5.

will not fall when held up against gravity by only the adaptor); 3) the upper adapter o-ring can similarly hold a cassette; and 4) the frame o-ring can hold a cassette. No precautions are necessary for the vortex-finder. With a sampling unit passing those tests, any remaining leaks should not have an important impact on the respirable dust obtained.

Additionally, it was found that a central deposition on the filter did not occur except with a significant leak, e.g., a central deposition was indicative of a fatally leaky sampling device. Lastly, the precision of sampling was considerably improved by the elimination of electrostatic charges on all parts of the sampling devices.

Sources of error in the use of the 10-mm nylon cyclone include intra-cyclone variance, inter-cyclone variance, pump performance, concentration inhomogeneity, and electrostatic effects. This paper has evaluated the first two sources and has determined a variance of around 2% RSD. The other sources of variance were intentionally reduced to negligible size or eliminated by experimental design. Thus, sampling precision is not limited by inherent high variability in the performance of the 10-mm nylon cyclone. For common field use of the cyclone, stratagems for reduction of the other sources of error must be followed (e.g., references 6, 19, 22, 26). To that end, the effect of air leaks has been qualitatively evaluated in this work and a regimen for reduction of those errors developed.

## Recommendation

These results indicate that the 10-mm nylon cyclone sampling unit is capable of adequate precision for routine size-selective sampling. In addition, we have demonstrated the ruggedness of the unit with respect to minor air leaks. Thus, to insure precision similar to that reported herein, it is recommended that the operator make a determination of sampler completeness and integrity and also check for audible leaks while the unit is being pumped. The gravity tests described in the paper should be employed if a higher level of leak testing is needed in the field.

## Acknowledgement

We wish to thank Tom Fischbach for assistance with statistics and Alexander Teass, Ph.D., for his helpful review of the manuscript.

## Disclaimer

Mention of commercial names or products does not constitute endorsement by the National Institute for Occupational Safety and Health.

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