Preliminary Development of a Real-Time Respirator Seal Integrity Monitor With Low-Cost Particle Sensor

Yan Liu, Jonathan Corey, Michael V. Yermakov, Bingbing Wu, and Sergey A. Grinshpun

***Abstract*—In many industrial environments, properly fit and functioning respirators are required to reduce individual's exposure to particulate matter. Respirator fits are evaluated prior to use by the Occupational Health and Safety (OSHA) fit testing protocol. However, this testing cannot ensure that the seal is maintained during actual use. The OSHA fit testing equipment and laboratory grade aerosol monitors are both too expensive and bulky to be deployed in workplace environments. In this effort, a low cost portable device, the respirator seal integrity monitor (ReSIM) was developed to monitor the aerosol particle concentrations inside a wearer's respirator mask, alerting the wearer when seal breaches allow aerosol particles to enter the mask. Multiple low-cost particle sensors were tested, with the Shinyei PPD60PV-T2 sensor being selected. The PPD60PV-T2 sensor can detect particles of 0.5 μm and above. These large particles cannot penetrate a properly fit respirator in quantity; thus, their detection points to a compromised seal. ReSIM utilizes an air pump to consistently draw in-mask air into the sensor without allowing external air to be pulled into the mask. ReSIM aggregates all particle detection events over 30-s intervals and determines the percentage of time during, which particles are detected, identifying spikes in particle detection corresponding to seal failures. The newly-developed ReSIM system was tested with polystyrene latex spheres, salt, and combustion aerosols under different flow conditions including cyclic breathing at 30 and 85 L/min. Results obtained while testing under cyclic breathing conditions showed 96.9% accuracy in identifying intervals with leaks versus intervals without leaks.**

***Index Terms*—Fit test, particle sensor, real-time, respirator.**

I. Introduction

Many industrial environments create significant levels of hazardous particulate matter. To control the workers' inhalation exposure, they wear personal respiratory protective devices. Respirators require a seal against the wearer's face to ensure that the air entering the facepiece passes through the respirator filter(s). However, numerous laboratory evaluations of the performance of particulate respirators have found that leakage around the face seal is often the primary pathway for the particle penetration into facepiece respirators [1]–[6].

In Occupational Safety and Health Standards, part 1910.134 App D from Occupational Safety and Health Administration (OSHA) states that respirators are required when "effective engineering controls are not feasible, or while they are being instituted." It is also declared that respirators must be certified by the National Institute for Occupational Safety and Health [7]. The integrity of the face seal, which is vital to a proper respirator's operation, is evaluated prior to use utilizing one or both of the OSHA qualitative or quantitative fit tests (depending on industry standards). However, neither of these tests can ensure that the facepiece seal is properly maintained during actual use, when an inward leakage may occur due to a facepiece slippage or a different type of respiratory protective device failure.

This paper describes the preliminary development and evaluation effort, in which a new low-cost tool is integrated into a respirator allowing for rapid detection of respirator seal failures. The respirator seal integrity monitor (ReSIM) is designed to monitor the concentration of aerosol particles within an elastomeric respirator and alert the wearer when leaks are detected. ReSIM represents an innovative approach that addresses the need to continuously monitor the integrity of the respirator seal while the wearer is working.

II. Main Concept

The main idea of ReSIM is to capitalize on previously published findings that the protection factor of existing elastomeric respirators significantly increases as the particle size increases from $\sim$0.3 μm [8], [9]. Supermicrometer particles (>1 μm) essentially do not penetrate into a properly functioning half-mask or full-mask elastomeric respirator as long as an adequate fit is assured [2]. On the other hand, even a minor leak can open a path for these relatively large particles to enter the respirator cavity in a measurable quantity, which can be detected inside the respirator with a sensor. Some existing low-cost sensors can be integrated with a conventional LED to indicate loss of seal integrity and promptly alert the wearer of seal failure.

Several low-cost dust/particle sensors are currently available on the market. Their feasibility as particle detectors has been addressed in earlier studies, e.g., [10]. Portable particle sensors developed and utilized for different application scenarios have been compared to reference stationary instruments, e.g.,

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the DustTrak DRX 8533 Aerosol Monitor (TSI, Inc.) [11]. However, the application of sensors for monitoring airborne particles inside a respirator is unique application and requires specific operational capabilities and design characteristics as discussed below.

III. ReSIM Design and Sensor Selection

The ReSIM device consists of a data collection core, sensor, and supporting electronics. Currently two different data collection cores are used in the ReSIM device, a Raspberry Pi 3B [12] for prototyping work and an Arduino clone based on the ATmega 32u4 chip [13] with a microSD card breakout board for embedded use. Three dust sensors were evaluated to serve as the primary ReSIM sensor. These included the Sharp GP2Y1010AU0F (Sharp) [14], Shinyei PPD42NS (PPD42) [15], and Shinyei PPD60PV-T2 (PPD60) [16]. Supporting electronics include batteries, a dc motor mated to an air pump, switching power regulator, and a 10 bar LED array to indicate concentration of particles detected inside the respirator. The three candidate sensors detect and report detected particles in different ways, including reporting over different time intervals. The Sharp sensor, the Shinyei sensors, and the optical aerosol spectrometer (OAS, Model 1.108, Grimm Technologies) [17] used as a reference instrument, report at 10 ms intervals, aggregate pulses over 30 s (both Shinyei sensors) and average over 1 min intervals, respectively. To standardize measurements, ReSIM aggregates all particle detection events over 30-s time intervals and determines the percentage of the time interval during, which particles were detected. The Grimm OAS operated with special software can report at intervals as short as 6 s.

The Sharp sensor actively collects particle concentration data for 40-μs out of a 320-μs activation process. In this effort, stable readings at 2-ms activation intervals were achieved. This introduced two operational problems. The first stems from the sensor output voltage being polled every 2 ms with data recorded every 100 ms. The process of writing to the micro SD card is variable and relatively slow, with the more frequent write operations required by the Sharp sensor (300 writes for the Sharp for each write operation by the Shinyei sensors) causing timing drift and delayed responses. While this issue could be addressed through code optimization and balancing operational tradeoffs between polling and recording intervals, the second issue was considered fatal. With the Sharp sensor only reporting an output voltage based on particles detected during a 40-μs interval every 2 ms, the Sharp sensor was only actively detecting particles 2% of the time. At higher or more stable concentrations, this would not be a problem. However, when attempting to detect small number of particles in conditions that change on a second by second basis, the Sharp sensor is simply unsuited to the task. The Shinyei sensors (both PPD60 and PPD42) use light scattering methods similar to the Sharp sensor, but do so on a continuous basis. The Shinyei sensors can detect particles down to 1.0 μm (PPD42) or 0.5 μm (PPD60). The PPD42 and PPD60 can both report particle concentrations in terms of analog voltage or as low voltage pulses generated when particles are detected. For the PPD60 and PPD42, the sum of low pulse time during an interval divided by the interval length yields the percent time detecting particles, which can be related to particle concentration. Note that while pulses may represent individual particle detections, they may also represent closely spaced particles detected as a single particle, so pulse duration is not a direct measurement of particle size.

The operating temperature range for both Shinyei sensors is 0 to 45 °C. For the Sharp sensor, the operating temperature is −10 to 65 °C. The operating humidity for both Shinyei sensors is <95%. All three sensors require noncondensing conditions due to the sensors' use of optical scattering for particle detection. Condensation in the sensors will cloud lenses, resulting in degraded detection of light scattered by particles in the detection volume. Condensation in the sample line can also degrade ReSIM performance. Liquid in the sample line may capture particles between the respirator and sensor package. To address this problem in subsequent human subject testing, the authors used a moisture trap in the sample line.

Three challenge aerosols representing different mean particle sizes and distributions were selected to test the sensors. The first challenge aerosol is Polystyrene Latex (PSL) microspheres with 1-μm PSL spheres suspended in water aerosolized by a Collision nebulizer. The second was combustion aerosol generated via burning wood matches and paper. The third was NaCl aerosol generated by a Collison nebulizer. All testing was performed in a climate controlled building at atmospheric pressure, ambient temperature of 22 °C, and relative humidity <60%.

The challenge aerosols have different properties that make each one relevant to the ReSIM sensor selection. The 1-μm PSL particles were selected as a challenge aerosol because properly functioning elastomeric respirators and filters will admit effectively zero particles of that size, meaning that any significant detection of particles inside the respirator must be due to a leak. Combustion aerosols are represented primarily by very small particles that are generally below the designed sensitivity ranges of the candidate sensors and exhibit much higher penetration into elastomeric respirators than larger PSL particles. Involvement of combustion particles in the sensor testing allowed the research team to confirm that the sensors would not generate false alarms when small particles below the sensor detection thresholds penetrated. Finally, salt particles are of intermediate size with some particles larger than the stated sensor detection thresholds and the majority of particles below the stated sensor detection thresholds. Salt particles have an added benefit of enabling comparison with human subject testing.

Preliminary testing occurred with sensors placed inside a Level II Biosafety cabinet, which is equipped with high-efficiency particulate air (HEPA) filtration to generate clean air. Data were collected while the Collision nebulizer was turned ON and OFF, alternating with the Biosafety cabinet's HEPA filters. The test pattern involved setting the nebulizer 3 in away from the sensors for several minutes to achieve steady-state concentrations. This was followed by activating the HEPA filters and then testing whether a 3-s long blast from the nebulizer would be detected. After activating the HEPA filters again, the nebulizer was moved back to 6 in

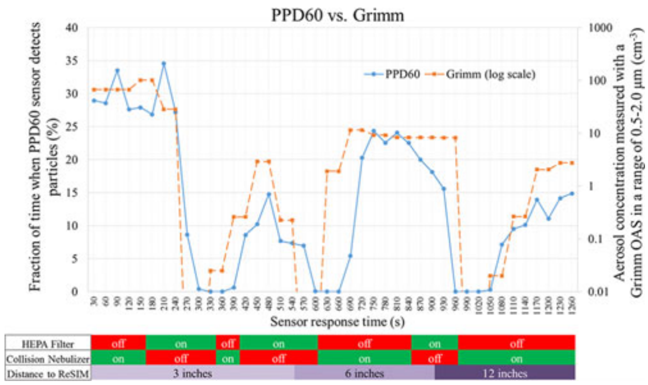

Fig. 1. PPD60 sensor versus Grimm OAS data with test process.

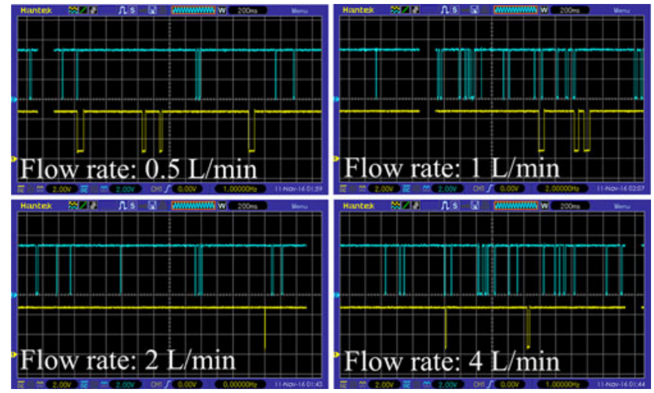

Fig. 2. PPD60 sensor versus PPD42 sensor oscilloscope results.

away from the sensors and activated long enough to achieve steady-state concentration. Finally, the nebulizer was moved back to 12 in away from the sensors and activated again. Each time the nebulizer was moved back, the aerosol concentration dropped by about an order of magnitude from approximately 100 particles/cm^3 to near 1 particle/cm^3. Fig. 1 shows data obtained from testing with PSL as the challenge aerosol. The operational positions of the HEPA filter and nebulizer and distance to sensors are specified at the bottom of the figure.

Fig. 1 shows the comparison between the PPD60 sensor reading (solid blue line) and the Grimm data (dashed orange line). The PPD60 data are presented as the percentage of time reporting low voltage pulses. Note that the PPD60 has a minimum value of 0% on time, so even small responses, such as those at 390 s and 1050 s may be reflective of the low Grimm OAS particle count within a size range of 1.0–2.0 μm.

The initial ReSIM sensor requirements focused solely on the detection of particles larger than $\sim$1 μm on the theory that any significant detection of such particles indicated a leak. Following initial testing, other operating parameters such as sensitivity to forced airflow via pumps as opposed to the convective airflow the sensors were originally designed for, were examined. This concern stems from the need to actively aspirate air from the respirator facepiece while preventing inhalation from drawing air back into the respirator through the sampling port.

This led to another sensor selection issue. Most dc air pumps cannot be reliably and stably controlled at very low flow rates and the Shinyei sensors were initially designed for convective air flow based on heat generated by small resistors in the sensor housing. To determine the extent of a problem this change in flow rate may cause, the two Shinyei sensors were tested at various pump driven flow rates. The PPD42 sensitivity was observed to decrease when the flow rate exceeded 0.5 L/min and decrease rapidly past 1.0 L/min. while the PPD60 is relatively insensitive to air flow rates from 0.5 to 2 L/min with sensitivity dropping off past 4 L/min (see Fig. 2).

Fig. 2 presents oscilloscope data comparing the PPD60 (blue) and the PPD42 (yellow) response at different flow rates. The two sensors were connected to the same sample line. The PSL particles used as a challenge aerosol were monitored by a Grimm OAS on a separate sample line, which reported densities in a range of 3 to 6 cm^{-3}. Fig. 2 shows that at a flow rate of 0.5 L/min, the PPD60 and PPD42 generated comparable results. When the flow rate increased to 1 L/min, the PPD42 started to miss more particles, generating a lower percent time detecting particles. As flow rates increased above 2 L/min, the PPD42 stopped detecting particles with any consistency and when it did detect them, the detection time was much lower. The PPD60 was able to consistently detect particles above 4 L/min, but the detection times began decreasing rapidly at higher flow rates. The region from 0.5 to 2 L/min produced consistent detections and length of detections for the PPD60. Based on the preliminary testing, the PPD60 sensor was chosen for integration into ReSIM.

The selection of a sampling flow rate for ReSIM involved a balance between competing factors. If the flow rate were set too low, it could reduce sensitivity and speed of reaction to leaks. Sensitivity to intermittent leaks would decrease by reducing the sampled air volume from the leak, which, in turn, reduces the number of potentially detectable particles. Speed of reaction would be reduced by having proportionally lower air flow rates for the same size tube connecting to the respirator facepiece. Too high of a flow rate could reduce sensitivity by moving particle through the sensor too fast to be reliably detected. Also, setting the sampling flow rate too high could introduce discomfort to the wearer by competing with the wearer for air. For the PPD60 sensor, the optimum balance between responsiveness, sensitivity, and flow rate was found to be 1 to 1.5 L/min.

IV. Sensor Calibration

The use of air pumps to create air flow instead of resistors to generate convective airflow invalidates the calibration performed by Shinyei at the factory. To rebuild the relationship between percent time detecting particles and particle concentrations the research team executed a calibration of the PPD60 with a flow rate of 1 L/min as seen in Fig. 3.

Fig. 3 shows that ReSIM can accurately detect particles down to 0.5 particles/cm^3 and up to about 400 cm^{-3}. Note that the PPD60 does detect particles below 0.5 cm^{-3}, but the difficulty lies in producing a stable test environment at such low particle concentrations. Additionally, as particle concentration decreases below that point, reliable particle detection becomes increasingly challenging with random affects introducing significant variability between samples and instruments.

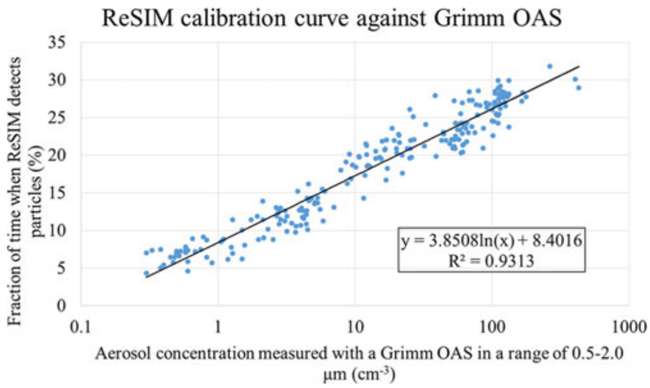

Fig. 3. ReSIM response to NaCl particle concentrations as measured by Grimm OAS.

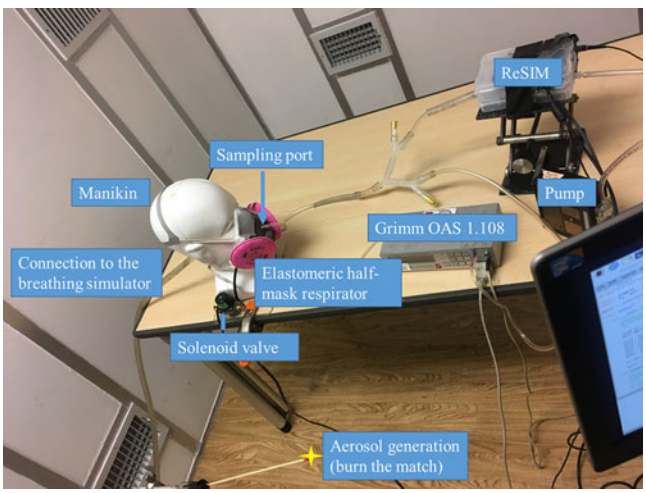

Fig. 4. Elastomeric half mask respirator leak detection testing.

The ability to accurately measure particle concentrations from <1 cm^{-3} to >100 cm^{-3} indicates that the PPD60 offers sufficient useful range to identify very clean air inside a properly fit and intact respirator through direct exposure to high particle concentrations. Importantly, the relationship is well fit by a formula with a high correlation coefficient (R^2) offering reassurance in the accuracy of estimating particle concentration based on PPD60 outputs. Note that the logarithmic relationship between PPD60 percent time detecting particles and the Grimm OAS measured concentration is actually beneficial to the intended operation of ReSIM because changes in particle concentrations at low initial concentrations are exaggerated. This makes detecting small leaks easier than they would be if the response were linear.

V. Leak Detection and Result Analysis

Given that ReSIM's design purpose is to monitor the integrity of the respirator seal in real time, the last stage of design is to test ReSIM's ability to detect leaks in a timely fashion. The experimental setup, as seen in Fig. 4, utilizes a manikin head with an elastomeric respirator sealed to the manikin's face with a breathing tube through the manikin head. The breathing tube is connected to a breathing simulator capable of replicating human breathing patterns. A solenoid valve connected to a 5-mm diameter tube can be opened to the outside environment to simulate a leak. Both the ReSIM and Grimm OAS draw air from a common sampling port. The Grimm OAS was used solely as a reference with leak detection relying on the readings from ReSIM. For leak detection with combustion aerosol, the experimental setup was placed in a large chamber (volume = 24.3 m^3) with HEPA filtration capabilities as seen in Fig. 4, while for the NaCl aerosol, the manikin and solenoid valve were placed in a small chamber (volume = 1 m^3) to make it easier to achieve elevated NaCl particle concentrations.

The elastomeric half-mask respirator shown in Fig. 4 is equipped with two P-100 filters with a collection efficiency of at least 99.97% for particles of 0.3-μm diameter (assumed to be the most penetrating particle size). It was assumed that the leak controlled by the solenoid valve is the only leakage.

The duration of induced leaks was controlled. Time intervals of 5 s and 10 s were chosen for testing. Leaks longer than 10 s were trivially easy to identify as well as posing contamination risks for the reference instruments when very high outside particle concentrations were used. Meanwhile, leaks shorter than the breathing cycle at approximately 4 s could be masked by the cleaning effect of the wearer's lungs, reproduced by a HEPA filter partway down the breathing simulator's hose.

The leak detection tests were conducted at two (sinusoidal) cyclic flows with the mean inspiratory flow (MIF) rates of 30 and 85 L/min. The 30 L/min cyclic flow was achieved with a breathing frequency of 15 cycles/min (2-s inhalation and 2-s exhalation); with a peak inspiratory flow (PIF) of 47.1 L/min. The 85 L/min cyclic flow was achieved with a breathing frequency of 25 cycles/min resulting in a PIF = 133.5 L/min. The current leak detection algorithm design is based on three components, a rolling average of the last five intervals ignoring intervals identified as being leaks, a threshold multiple to be identified as a leak, which decreases as the rolling average increases to reflect the logarithmic nature of the percent time detecting particles to particle concentration relationship, and a minimum threshold to be considered sufficiently severe to qualify as a leak. This formulation is designed to address variations in outside aerosol concentration, which are detectable as changes in background readings inside the facepiece as well as reporting meaningful leaks when changes in particle concentration result in larger changes in sensor response at low concentrations compared to high concentrations.

The threshold formula is

$$t = \max\left\{r_{\text{avg}} * \max\left\{\left(2 * \ln\left(35 - r_{\text{avg}}\right) - c\right), 1.25\right\}, 4\%\right\}. \tag{1}$$

Here t is the leak detection threshold in percent; r_{avg} is the rolling average percent time detecting particles for the last five intervals not identified as having a leak; and c is a constant that is specific to a challenge aerosol (5.6 for combustion particles).

Under this formulation, a leak must generate particle detections for at least 4% of the current 30-s interval as an absolute minimum to be considered a leak. Similarly, the minimum increase in concentration required to be detected as a leak is

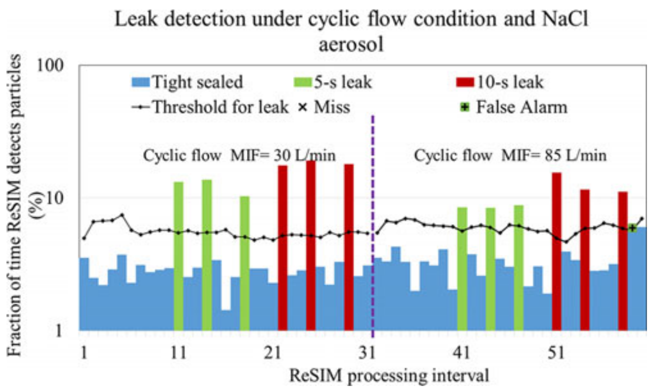

Fig. 5. Leak detection under cyclic flow at MIF = 30 and 85 L/min tested with NaCl.

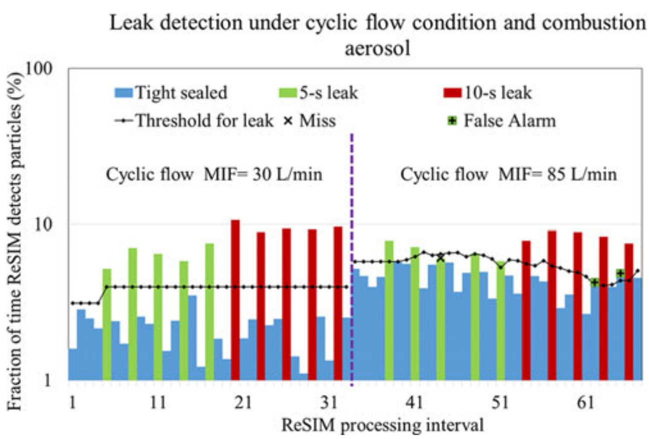

Fig. 6. Leak detection under cyclic flow conditions at MIF = 30 and 85 L/min tested with combustion aerosol.

1.25 times the rolling average. For a combustion aerosol, if the current interval's r_{avg} is 4.2%, then the threshold for leak detection would be 5.27%. This formulation is used to set the minimum at a constant level and then transition to a scaled difference in reported concentrations. Note that as background levels increase, the absolute level of concentration required to be counted as a leak increases compared to lower background levels because of the logarithmic relationship between sensor reading and particle concentrations.

Figs. 5 and 6 present the results of ReSIM's leak detection algorithm and the leak detection thresholds under different leak conditions and cyclic flow regimes. In the two figures, blue bars represent time intervals during which the seal integrity was maintained; green bars correspond to 5-s long leak openings; and red bars correspond to 10-s leak openings. The current threshold for detecting a leak is indicated by the black line. Intervals with leaks that were not correctly detected are indicated by black crosses, while false alarms are indicated by green boxes with plus signs. The current ReSIM algorithm achieves satisfactory results with 96.9% accuracy over a total of 127 intervals with one missed leak and three false alarms. All three false alarms occurred in high background particle concentration environments. Note that the dashed purple line represents a discontinuity as the breathing rate is changed from 30 L/min to 85 L/min.

When testing with NaCl particles, as seen in Fig. 5, the difference between sealed and leak intervals is quite clear. A single false alarm occurs when the background level increases significantly at the end of the test series under 85 L/min cyclic flow. In the next interval (the last bar) the threshold adjusts and a second false detection is avoided. Combustion aerosol poses a more difficult challenge, as seen in Fig. 6. At the 30 L/min cyclic flow rate, there is no significant issue, sealed and leaking intervals are quite distinct. However, at 85 L/min cyclic flow, the background particle concentration increases dramatically with a corresponding decrease in the difference between intervals with leaks and intervals where the seal was maintained. This decreased difference makes it more difficult to differentiate leak and nonleak intervals, leading to one missed leak and two false positive errors. Despite the errors, the current ReSIM prototype achieved a 96.9% accuracy rate discerning leak versus nonleak intervals.

Other lessons learned during this pilot testing include the impact of exhalation valves on seal integrity. While testing at a constant flow rate of 30 L/min., detected background concentrations were consistently lower than those observed with cyclic flow, particularly at the higher cyclic breathing and flow rate. Closer examination indicates that the exhalation valve is a probable point of seal degradation contributing to higher background particle concentration levels.

VI. Conclusion and Future Work

The real-time ReSIM was developed, and the prototype was built. Through an extensive review and testing of available sensors the PPD60 sensor was chosen for integration into ReSIM. The selection was based on its balance of sensitivity, particle size detection range, and relative insensitivity to increased air flow rates. Subsequently, the sensor was calibrated with NaCl aerosol. The results showed that the ReSIM could be reliably calibrated to report particle concentrations across a broad range of particle concentrations. During leak detection testing, ReSIM performed well in detecting leaks, at both 5- and 10-s durations. Based on this pilot study, it was concluded that ReSIM can accurately detect respirator leaks in real time.

Development and optimization of ReSIM hardware and algorithms is ongoing with particular focus on improving the identification of changes in background concentrations. Human subject testing will follow. The human subject testing phase of the study will focus on firefighters using elastomeric half-masks.

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References

[1] Y. Liu, M. Yermakov, J. Corey, B. Wu, and S. Grinshpun, "Development of a real-time respirator seal integrity monitor with low-cost particle sensor," in *Proc. 2017 IEEE Ind. Appl. Soc. Annu. Meeting*, Cincinnati, OH, USA, 2017, pp. 1–5, doi: 10.1109/IAS.2017.8101841.

[2] S. Rengasamy and B. Eimer, "Nanoparticle penetration through filter media and leakage through face seal interface of N95 filtering facepiece respirators," *Ann. Occup. Hygiene*, vol. 56, pp. 568–580, 2012.

[3] X. He, M. Yermakov, T. Reponen, R. T. McKay, K. James, and S. A.Grinshpun, "Manikin-based performance evaluation of elastomeric respirators against combustion particles," *J. Occup. Environ. Hygiene*, vol. 10, pp. 203–212, 2013.

[4] S. A. Grinshpun, H. Haruta, R. M. Eninger, T. Reponen, and R. T. McKay, "Performance of an N95 filtering facepiece particulate respirator and a surgical mask during human breathing: Two pathways for particle penetration," *J. Occup. Environ. Hygiene*, vol. 6, pp. 593–603, 2009.

[5] C. Coffey, Z. Zhuang, D. Campbell, and W. Myers, "Quantitative fit-testing of N95 respirators: Part II—Results, effect of filter penetration, fit-test, and pass/fail criteria on respirator performance," *J. Int. Soc. Respiratory Protection*, vol. 16, pp. 25–36, 1998.

[6] Z. Zhuang, C. Coffey, W. Myers, J. Yang, and D. Campbell, "Quantitative fit-testing of N95 respirators: Part I-method development," *J. Int. Soc. Respiratory Protection*, vol. 16, pp. 11–24, 1998.

[7] OSHA, "Occupational safety and health standards, part 1910.134 App D," Mar. 29, 2017. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table = standards&p_id = 12716

[8] W. C. Hinds, *Aerosol Technology: Properties, Behaviour, and Measurements of Airborne Particles*, 2nd ed. Hoboken, NJ, USA: Wiley, 1999.

[9] G. A. Stevens and E. S. Moyer, ""Worst Case" aerosol testing parameters: I. sodium chloride and dioctyl phthalate aerosol filter efficiency as a function of particle size and flow rate," *Amer. Ind. Hygiene Assoc. J.*, vol. 50, pp. 257–264, 1989.

[10] M. Budde, M. Busse, and M. Beigl, "Investigating the use of commodity dust sensors for the embedded measurement of particulate matter," in *Proc. 2012 9th Int. Conf. Netw. Sens. Syst.*, 2012, pp. 1–4.

[11] TSI, "DUSTTRAK DRX AEROSOL MONITOR 8533," May 26, 2015. [Online]. Available: http://www.tsi.com/dusttrak-drx-aerosol-monitor-8533/. Accessed on: Mar. 29, 2017.

[12] Raspberry Pi, "RASPBERRY PI 3 MODEL B." [Online]. Avaliable: https://www.raspberrypi.org/products/raspberry-pi-3-model-b/. Accessed on: Mar. 29, 2017.

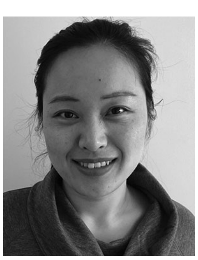
[13] Atmel, "8-bit Microcontroller with 16/32 K bytes of ISP Flash and USB Controller Datasheet." Jul. 2015. [Online]. Available: http://www.atmel.com/Images/Atmel-7766-8-bit-AVR-ATmega16U4-32U4_Datasheet.pdf. Accessed on: Mar. 29, 2017.

[14] Sparkfun, "Optical Dust Sensor - GP2Y1010AU0F," Jul. 1, 2017. [Online]. Available: https://www.sparkfun.com/products/9689. Accessed on: Mar. 29, 2017.

[15] Shinyei Technology, "Specification sheet of PPD42NS." Mar. 2010. [Online]. Available: http://wiki.timelab.org/images/f/f9/PPD42NS.pdf. Accessed on: Mar. 30, 2018.

[16] Shinyei Technology, "Product specifications, PPD60PV-T2." [Online]. Available: http://52ebad10ee97eea25d5e-d7d40819259e7d3022d9ad53e3694148.r84.cf3.rackcdn.com/UK_SHN_PPD60PV-T2_DS.pdf. Accessed on: Mar. 30, 2018.

[17] Grimm, "Aerosol Spectrometer 11-A," Aug. 21, 2017. [Online]. Available: http://wiki.grimm-aerosol.de/index.php?title = IAQ-11-A. Accessed on: Mar. 29, 2017.



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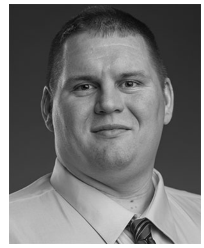

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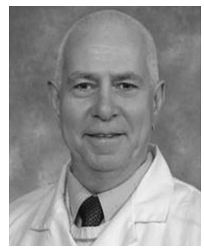

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