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Force Health Protection Automated Exposure Assessment

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University of Utah

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for September 2016 to April 2018

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14. ABSTRACT
A laboratory evaluation of low-cost multi-sensors developed specific to this project (Utah Modified Dylos Sensor [UMDS]) was performed to assess the sensors' efficiency in sampling respirable and inhalable particulate matter at elevated concentrations, which are most common in occupational settings. Particle concentrations were measured in a low-speed wind tunnel with three UMDSs, co-located with an aerosol spectrometer (Grimm 1.109) and gravimetric respirable and inhalable samplers. In total, 10 tests consisting of 5 different concentrations and 2 different test aerosols, Arizona road dust and aluminum oxide, were conducted. The laboratory test indicates the UMDS can be used as a low-cost tool to estimate respirable and inhalable particulate matter concentrations found in many workplaces. A subsequent pilot project evaluated a networked array of UMDS in an Air Force maintenance depot occupational environment. The networked array required a customized informatics, hardware, and software suite to provide occupational exposure reporting potentially useful to Air Force bioenvironmental engineers charged with force health protection. The field evaluation confirmed the networked array is capable of providing real-time measurements of particulate matter and occupational noise in the immediate occupational environment in which they were operating when compared to reference instrumentation measuring exposures in the same environment. A final finding from the field evaluation indicated the networked array of UMDSs can electronically interact with a "proximity sensor" within the array. As such, a worker's location within the array can be estimated and an exposure estimate (particulate matter and/or noise) for the worker can be generated. A secure, web-based management and monitoring platform (graphical) was modified to provide a baseline example for which enhanced metrics, management, alert, and reporting mechanisms can be developed in the future. Additionally, all project data were encrypted and securely transmitted and housed in a secure database with common application programming interface that will readily facilitate future informatics requirements/developments including manipulating the data into virtually any database format required by the Air Force.

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1.0 SUMMARY

A laboratory evaluation of low-cost multi-sensors developed specific to this project (Aim 1) identified as Utah Modified Dylos Sensor (UMDS) was performed to assess the sensors' efficiency in sampling respirable and inhalable dust at elevated concentrations, which are most common in occupational settings. Dust concentrations were measured in a low-speed wind tunnel with 3 UMDSs, collocated with an aerosol spectrometer (Grimm 1.109) and gravimetric respirable and inhalable samplers. A total of 10 tests consisting of five (5) different concentrations and two (2) different test aerosols, Arizona road dust and aluminum oxide, were conducted.

For the Arizona road dust, total particle count was strongly related between the spectrometer and the UMDS with a coefficient of determination (R^2) between 0.86-0.92. Particle count concentrations measured with the UMDS were converted to mass and also were highly related with gravimetrically collected inhalable and respirable dust. The UMDS small bin (i.e., all particles) compared to the inhalable sampler yielded a R^2 of 0.86-0.92 and the large bin subtracted from the small bin (i.e., only the smallest particles) compared to the respirable sampler yielded an R^2 of 0.93 to 0.997. Tests with the aluminum oxide demonstrated a lower relationship across all comparisons. Further, assessment of intra-instrument variability was consistent for all instruments but inter-instrument variability indicated that each instrument requires its own calibration equation to yield accurate exposure estimates.

The laboratory test indicates the UMDS can be used as a low-cost tool to estimate respirable and inhalable concentrations found in many workplaces. A subsequent pilot project evaluated a networked array of UMDS in an Air Force maintenance depot occupational environment. The networked array required a customized informatics, hardware and software suite to provide occupational exposure reporting (Aim 2) potentially useful to United States Air Force Bio Environmental Engineers charged with force health protection. The field evaluation confirmed the networked array is capable of providing real-time measurements of particulate matter (aerosol—not defined) and occupational noise in the immediate occupational environment in which they were operating (Aim 3) when compared to reference instrumentation measuring exposures in the same environment.

A final finding from the field evaluation indicated the networked array of UMDS can electronically interact with a 'proximity sensor' within the array. As such, a worker's location within the array (workplace) can be estimated and an exposure estimate (particulate matter and/or noise) for the worker can be generated. A secure, web-based management and monitoring platform (graphical) was modified to provide a baseline example for which enhanced metrics, management, alert and reporting mechanisms can be developed in the future. Additionally, all project data were encrypted and securely transmitted and housed in a secure database with common application programming interface that will readily facilitate future informatics requirements/developments including manipulating the data into virtually any database format required by the United States Air Force (e.g. Defense Occupational & Environmental Health Readiness System – (Defense Occupational & Environmental Health Readiness System).

2.0 INTRODUCTION

Occupational aerosol exposure is a well-known risk factor for several respiratory and systemic diseases including chronic obstructive pulmonary disease, asthma, hypersensitivity pneumonitis, and lung cancer [1]. Occupational aerosol hazards exist in many industry sectors such as construction, manufacturing, agriculture, and mining [1-3]. In the US alone, costs related to direct medical expenses due to respiratory disease caused by occupational aerosol exposures are estimated to be $3.7 billion dollars annually [4].

In order to protect workers from exposure to excessive amounts of particulate matter, the United States Occupational Safety and Health Administration (OSHA) has set permissible exposure limits (PELs) that vary depending on the substance or material of exposure [5]. For particles without specific PELs or standards, known as particles not otherwise regulated, OSHA has set PELs at 15 mg/m^3 for total dust (i.e., particulates collected with a 37-mm closed faced cassette) and 5mg/m^3 for the respirable fraction (3.5 µm cut point) [6]. Particles not otherwise regulated include all inert or nuisance dusts not specifically listed in OSHA standard 29 Code of Federal Regulations 1910.1000 whether mineral, inorganic, or organic [6]. Technological advances and current research demonstrate many of OSHA's PELs inadequately protect worker health. Additionally, some non-government agencies have developed more stringent occupational exposure limits (OELs) as guidelines to assist in the control of health hazards [7]. For example, the American Conference of Governmental Industrial Hygienists (ACGIH) recommends that particles not otherwise specified should be kept at airborne concentrations below three (3) mg/m^3 for the respirable fraction (Four (4) µm cut point), which are particles that enter the deep lung, and 10 mg/m^3 for the inhalable fraction, which are particles that enter the nose or mouth and impact any part of the respiratory tract [8].

In order to demonstrate compliance, OSHA requires traditional filter-based sampling methods with an air pump and sampler, as this sampling method provides a direct means of quantifying a collected aerosol mass for a known volume of air [9].

Although these integrated sampling methods are considered the reference standard, they can only provide an overall assessment of exposure and do not take into account the complexity of work processes or other activities affecting levels of exposure [10]. Such sampling can also be labor intensive and only yield a few data points. Furthermore, once collected, samples need to be sent to a laboratory and results are not usually available for days or weeks [11].

An attractive alternative to filter based sampling is real-time detection systems, such as optical particle counters (OPCs). OPCs are real-time instruments capable of measuring airborne particle counts and/or mass concentrations and have the benefit of providing real-time analysis, thereby eliminating the need for laboratory analysis and its attendant delay in results. These instruments are commercially available and have successfully been used to measure dust concentrations in a variety of occupational settings [12]. OPCs work by illuminating particles, typically with a laser. The light scattered by the particles is then detected, and depending on the instrument, the particles are separated into different size bins. However, due to the high cost of these instruments, ranging from $7,000 to $15,000, it may not be feasible for all but the largest organizations and research institutions to utilize such instrumentation [13].

Recently, several manufacturers have introduced low-cost (<$450) particle counters. These low-cost OPCs, specifically the Dylos DC1700 and DC1100 Pro (Dylos Corporation, Riverside, CA), have proven effective at determining indoor and ambient air particulate concentrations, but little investigation of these sensors' efficiency with respect to occupational aerosols has been conducted [11, 13-16].

The Dylos is a commercially available laser based particle counter marketed for home and office use. The Dylos uses a small computer fan to draw air through a series of baffles and across a laser that are contained within the unit. A photodiode is positioned to capture the scattered light from many angles. The monitor tallies particle counts in two size bins: (1) a small bin that measures all particles 0.5 µm and greater and (2) a large bin that measures all particles 2.5 µm and greater [14].

In ambient and indoor sampling studies, the Dylos correlated well with mass concentrations measured by medium- and high-cost instruments [14-16]. Northcross et al. used a modified Dylos DC1100 Pro and tested it against a TSI DustTrak [14]. When exposed to ambient outdoor particles, they reported a coefficient of determination (R^2) of 0.80. Steinle et al. modified a Dylos DC 1700 and tested it against a tapered element oscillating microbalance, Thermo Scientific, Franklin, MA, USA) at two national monitoring network sites and found good agreement, with an R^2 of 0.9 at a rural background site and R^2 of 0.7 at an urban background site [15]. Semple et al. tested the DC1700 against an aerosol photometer (SidePak, TSI Inc., Shoreview, MN, USA) for indoor exposure to second-hand smoke concentrations, and reported a R^2 of 0.86 [16].

Recently, Jones et al. used an unmodified Dylos DC1100 as a low-cost alternative to evaluate respirable dust concentrations in a swine concentrated animal feeding operation during winter conditions [11]. The DC1100 was evaluated against an aerosol photometer, (pDR-1200, Thermo Scientific, Franklin, MA, USA) and gravimetric respirable air sampler with a cyclone. Jones et al. found a strong linear relationship between the small bin data for the DC1100 and the mass concentration with the pDR-1200 ($R^{2=}$0.85). This finding indicates that the two monitors responded similarly to respirable dust.

Sousan et al. performed a laboratory evaluation of several low-cost particle counters for multiple aerosols at higher concentrations, as is typical for occupational exposures [13]. In that study, the Dylos DC1700 was shown to have the lowest coefficient of variation of all instruments tested with 2.2–14% for the small bin and 5–15% for the large bin. The Dylos DC1700 showed a good linear fit with an R^2 value ranging from 0.91 for welding fume on the low end to 0.99 for 5% salt solution on the high end. Detection efficiency was also examined and found that the DC1700 detection efficiency was extremely low for sub 0.5 µm particles, which is consistent with the manufacture. However, it was found that the Dylos DC 1700 did misclassify some particles larger than 2.5 µm as small, which suggests that there is a gradual cut for the large bin.

While this growing body of research shows the Dylos to be a promising low-cost sensor for measuring particulate matter, there is less data on how the Dylos performs at the higher concentrations that are of concern in occupational settings. Specifically, there is little information on how the Dylos performs in estimating inhalable or respirable dust. There has also been little information on the inter-instrument variability of the Dylos. Thus, this laboratory study's three primary objectives will contribute important information to key areas. The first objective is to evaluate the performance of a modified Dylos known as the Utah Modified Dylos Sensor (UMDS) to measure aerosols at higher concentrations, which are common in the occupational setting. The second objective is to investigate whether modification of the Dylos 1100 Pro into the UMDS negatively affects the performance of the particle counter. Finally, the third objective is to investigate the inter-instrument variability of the UMDS sensor to determine if a network of UMDSs could effectively operate with the same calibration curve or if individual calibration curves would be needed for each sensor. The final objective is to integrate the noise dosimeter into the UMDS and update the informatics and network capabilities such than a field evaluation in an occupational environment (United States Air Force [USAF] maintenance depot) can be conducted.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

The research team located at the University of Utah (UOU) in Salt Lake City, UT conducted the preponderance of their sensor development, informatics upgrades and laboratory testing on the campus of the UOU. The pilot project field evaluation was conducted at Hill Air Force Base (AFB), UT.

3.1 Utah Modified Dylos Sensor (UMDS)

The Dylos DC1100 sensor was modified by researchers at the UOU Department of Electrical and Computer Engineering, and the new modified sensor was named the Air Force (AF) UMDS. To facilitate data logging, a compact Python-based LoPy 1.0 microcontroller (Pycom, Paris, France) was incorporated into the UMDS. Further, a new display and temperature/humidity sensor were installed. The UMDS was programmed to log and transmit the small (>0.5 µm) and large (>2.5 µm) particle bin count data, temperature, and humidity in 1-minute intervals.

The main features that set the UMDS apart are its ability to connect to a wireless gateway via a Wi-Fi standard and to automatically stream data to a database and informatics platform. This allows a health and safety professional with any internet-connected device access to real-time data. The Dylos 1100 Pro retails for $260.99, and the UMDS total cost, including the Dylos 1100 pro and all the aforementioned modifications, is approximately $500.

A weakness of using the Dylos DC1100 Pro sensor as the UMDS base is the sensor's inability to accurately measure high particle concentrations. Currently, concentrations that are above 65,536 particles per 0.01 cu ft. (231 particles/cm^3) exceed the sensor's 16-bit memory capability [16] causing the internal logging register to roll over to zero. Thus, the Dylos provides unreliable measurements when particulate concentrations are high. Additionally, the manufacturer has stated that the upper level of quantification is 106 particles/cm^3; above this limit, coincidence loss can occur.

3.2 Reference Instruments

During the laboratory tests described below, three (3) Dylos DC1700 and three (3) identical UMDS units were compared against two different existing air sampling methods: (1) a real-time aerosol spectrometer (Grimm Model 1.109, Grimm Aerosol Technik, Ainring, Germany) and (2) traditional gravimetric (i.e., integrated) particulate samplers measuring respirable and inhalable dust.

The Grimm Model 1.109 is a laser-based optical particle counter with the ability to sort particle counts into 31 discrete size bins. This allows the Grimm 1.109 to provide a detailed distribution of particle sizes from 0.25 µm to 32.0 µm in either count or mass concentration. The Grimm possesses an internal filter on which all particles are collected after the optical measurement. This feature allows for further analysis of the filter.

Respirable (4 µm cut point) sampling consisted of a SKC aluminum respirable dust cyclone (SKC Inc., Eighty-Four, PA, USA) connected to an SKC AirCheK XR5000 (SKC Inc., Eighty-Four, PA, USA) sampling pump operating at 2.5 L/min. The cyclone was fitted with a 37-mm glass fiber filter (5-µm pore size).

Inhalable sampling consisted of a novel high-flow rate disposable sampler for inhalable aerosol. The sampler is currently being used in studies and monitoring events by researchers in a variety of environments. The new sampler closely matches the low-velocity inhalability criterion for particles ranging from 9.5 to 60.1 µm and shows good agreement with the IOM sampler [17]. It runs at 10 L/min using a Leland Legacy pump (SKC Inc., Eighty-Four, PA, USA) and is fitted with a 37-mm glass fiber filter (5-µm pore size) bonded to an internal capsule for capturing wall deposits.

The sampling pumps were all calibrated using a Bios 510 Defender Drycal (Mesa Labs, Butler, NJ, USA). Gravimetric analysis of the filters was conducted using a Sartorius Cubis MSA225S-100-DI (Sartorius Stedim North America Inc., Bohemia, NY, USA) digital semi-microbalance.

During the field evaluation, a Grimm was used to provide comparison measures of aerosol. Similarly, 3M The Edge Dosimeters (Maplewood, MN, USA) were used for assessing the UMDS noise measurement capabilities. Finally, in identifying the locations of the sensors, distance measurements to fixed locations in the workplace were taken with a Bosch Blaze Laser Distance Measurer (Robert Bosch Gmbh, Stuttgart, Germany).

3.3 Laboratory Tests

Two different sets of Dylos sensors were evaluated during the laboratory evaluation. First, a set of three (3) unmodified DC1700 Dylos sensors were evaluated followed by three (3) UMDS sensors that had been modified as described previously. Each group of sensors had an identical injection series of tests conducted, as described below.

The laboratory evaluation was performed in an aerosol wind tunnel designed to operate at low-wind speeds (below 0.5 m/s), as such speeds are known to be typical of most occupational environments [18]. The wind tunnel was specially designed to deliver a uniform distribution of well-characterized aerosols [19]. The tunnel's dimensions were 1.22 m x 1.22 m x six (6) m with the sampling section having a length of approximately three (3) m. Airflow through the tunnel is generated by four fans oriented to pull air downstream of the sampling area. These fans are controlled by a frequency inverter, which allows for control of air velocity.

The air velocity was related to the static pressure drop across the upstream filters, measured by a TPI 623 digital manometer (Test Products International, Beaverton, OR). In this case, -0.060-inch WC corresponded to roughly 0.3 m/s (~59 fpm), which is the air velocity used for these tests. This velocity was chosen because it falls within range of those measured in indoor work environments [18]. Temperature and humidity were not controlled within the tunnel itself, but by the building's climate control system. Typical values for temperature ranged from 21-23 °C and 21-27% relative humidity.

In order to test the instrument in a uniform and consistent environment, test aerosol was injected into the wind tunnel using a Topas SAG 410 Aerosol Generator (TOPAS GMbH, Dresden, Germany). To control aerosol generation, the instrument uses a moving toothed belt with equal spaces between the teeth. These spaces ensure a reproducible and constant supply of powder is converted into aerosol. The particle concentration of the generated aerosol can be adjusted by changing the speed of the feeder belt, which is displayed as a percentage of maximum belt speed (0-100%). The aerosol generator was attached to a 2-axis moving spray wand designed to traverse the width and partial height of the anterior section of the tunnel in order to create an aerosol concentration that can be considered uniform when averaged over time.(19)

The series of injection tests consisted of testing two (2) aerosols at five (5) different concentrations for a total of 10 tests for all instruments. This gave us a total of 60 datasets; 30 datasets for the unmodified Dylos and 30 for the UMDS. As described above, particle concentration of the generated aerosol could be varied by adjusting the feeder belt speed, given as a percentage of maximum belt speed. The five lowest feeder belt speeds of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% were chosen in effort to produce aerosol concentrations below 231 particles/cm^3.

Each injection test was conducted for 60 minutes after an initial three (3)-minute stabilization period for the particle injection system. Of the two (2) separate test aerosols utilized during the injection tests, the first set consisted of monodisperse, fused alumina particles (Duralum, Washington Mills, Niagara, NY, USA), with a mass median aerodynamic diameter (MMDAD) of 4.9 µm (Geometric Standard Deviation (GSD) = 1.73). This aerosol was produced by the manufacturer by grounding down a 9.5 µm MMAD test aerosol. The second set of injection tests used ISO 12103-1, A1 Ultra Fine Test Dust (Powder Technology Inc., Arden Hills, MN), a poly-disperse Arizona road test dust (ARD) with mass median optical diameter of 2.6 µm as determine by the Grimm.

In order to simulate personal sampling, a stationary life-size half-torso mannequin was fitted with the three (3) respirable cyclones and three (3) inhalable gravimetric samplers and placed inside the sampling section of the wind tunnel during the injection tests. A Grimm Model 1.109 and the Dylos/UMDS were placed on the floor inside the wind tunnel's test chamber after being time synced and programed to sample in 1-minute intervals.

3.4 Data Analysis – Mass Concentration

Particle counts are useful for comparing one particle counter to another, but in order to compare them to traditional gravimetric sampling methods, count concentrations must be converted into mass per unit volume concentrations. For the Dylos DC1700, UMDS, and the Grimm Model 1.109, Microsoft Office (Microsoft, Seattle, WA, USA) was used to compute Eq. 1 and convert count concentration to a mass per unit volume concentration:

$$m(d_p) = \frac{\pi}{6} d_p^3 \rho_p n(d_p) \tag{1}$$

where, $n(d_p)$ is the concentration number, which is converted into mass concentration $m(d_p)$ as a function of median particle diameter (d_p) and particle density (ρ_p) [20].

Sixty data points were recorded from each device for every injection test for both the Dylos and UMDS; the recorded data included the small particle count, large particle count, date and time. The Grimm recorded 31 discrete size counts ranging from 0.25 µm to >32.0 µm along with date and time. Although the Grimm also generates mass per unit volume data, these data were not used in order to ensure consistent data conversion between all instruments.

All the data points generated by each device for each individual run were averaged for each size bin, thereby yielding a single data point for that bin. The Dylos and UMDS records count data per 0.01 cubic foot, so a conversion factor was applied to convert the Dylos and

UMDS data into the same units recorded by the Grimm (i.e., counts/L) before being applied to Eq. 1.

Mass concentrations from each of the five (5) injection tests for each of the two (2) test aerosols were compared in a series of scatter plots with regression lines of best fit and coefficients of determination (R^2) calculated for each device comparison. The regression equations are of particular importance for their potential use as a calibration equation, which, once applied to the Dylos or UMDS data, would bring the data into agreement with either the Grimm or gravimetric sampler results.

3.5 Data Analysis – UMDS Variability

To assess inter-instrument variability analysis of variance analysis (ANOVA) was performed on each belt rate for the three (3) UMDS sensors for ARD and aluminum oxide. This yielded a total of 10 sets of comparisons, five (5) for each test dust. Significance level was set at 0.05 and analysis was completed with Stata 14 (StataCorp LLC, College Station, TX, USA). Intra-instrument variability was assessed by comparing coefficient of variations for the three (3) UMDS sensors at for each belt rate using the average count concentration for each test. Similar analysis for the unmodified DC1700 was not performed, as testing for variability of the UDMS was the objective of the study.

3.6 Field Evaluation – Network Array

The low-cost real-time sensor network array consisted of an AF UMDS sensor (Figure 1). Each multi-sensor was comprised of several components: a Pycom LoPy 0700 FCC ID 2AJMTOLPY1R for wireless communications to an intermediate gateway device; a DC1100 PRO Dylos equipped with 94v-0 v2.1A expansion board to measure particulate matter.

Figure 1. AF UMDS deployed in the Hill AFB, UT Depot Bead Blast Building.

As the UMDS were equipped with a Pycom LoPy 0700. These Pycom chipsets allow wireless connectivity by the use of LoRa (<3 km), Wifi (<100 m), and BLE Micropython (<20 m) enabled micro controller with Espressif chipset. Although low-powered, these chipsets have the potential for wireless connectivity of several kilometers in distance.

Data packets containing frequent (0.125ms interval, in the case of noise), highly-detailed exposure measurements were calculated into 1-minute averages by the multi-sensors onboard processing unit. A Gateway device was constructed to serve as a collection point for all sensor data and subsequently securely transferred to a secure database (Figure 2). Although originally configured to connect to a secure local area network via LAN cable or secure Wi-Fi, the Gateway had to be reconfigured to utilize a 4G secure cellular data wireless device (Verizon Jetpack MiFi 7730L, Basking Ridge, NJ, USA) as utilizing the USAF Depot internet was not be permissible. The time-stamped 1-minute exposure values were transmitted by local area network to a gateway intermediate device equipped with cellular data transmission capabilities. The data packets were then transmitted to a UOU server for access. The entire data collection and transmission processes were secured by IEEE 801.22 WPA2 wireless security protocols and multibit encryption on the network side. Under the operational conditions, secure data transmission was nearly instantaneous for data reporting and visualization. With this technology, near real-time exposure monitoring data was made immediately available by the multi-sensor network. Additional computation and visual interfaces allowed data to be quickly and easily accessed and interpreted.

Figure 2. Gateway device initially located in Depot Bead Blast Bldg 220, observation room.

A field evaluation of the multi-sensors was comprised of comparisons against reference instruments. A single Grimm and five 3M Edge (noise) Dosimeters were rotated among the UMDS one at a time (Sensors 1-16). For the in-field calibration, the Grimm and noise dosimeter reference grade instruments were located within one foot of each UMDS. Comparison duration between the custom sensors and the reference instruments was approximately 1-hour in length.

The UMDS were located in fixed positions around two high-performance fighter aircraft undergoing upgrades and maintenance in an expansive aircraft hangar that had dozens of aircraft located inside. These UMDS were fixed to scaffolding, immediately adjacent to the aircraft both at the ground level working environment as well as the work level above the wings. UMDS were fixed to the scaffolding about adult human waist-to-head height above the standing surface to approximate a worker's breathing/hearing location when in a kneeling or standing on that surface (Figures 3 & 4). Additional UMDS were located in a separate building in which high performance fighter aircraft underwent extensive surface modifications. In this latter location, sensors were not located adjacent to the aircraft undergoing surface modification. Instead, they were limited by the confines of non-obtrusive structures located in the vicinity, where workers observed the highly controlled surface modification area as well as aircraft prep, and personal protective equipment don/doff areas. The sensor locations were also located based on the discreetness of power supply wires and taking into account the safest placement in regard to the hazard and the employee's job power requirements. The Grimm sampling rate was a one-minute average to match the sampling rate of the sensors.

Figure 3. USAF UMDS (right, black) and Grimm (left) affixed at approximately head height, ground level proximal to fighter aircraft (Hill AFB, UT Bldg 225).

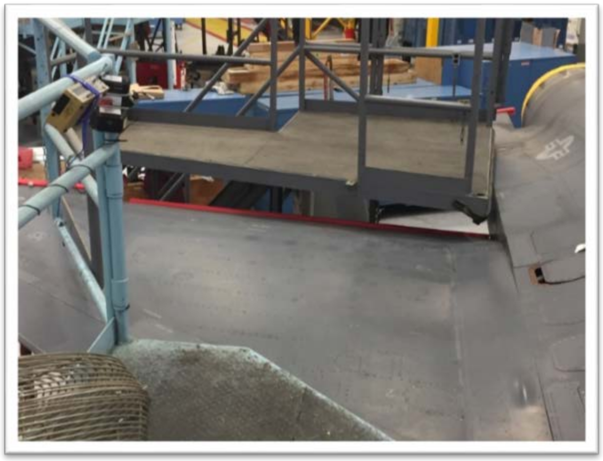

Figure 4. USAF UMDS (right, black) and Grimm (left) affixed at approximately waist height, wing level proximal to fighter aircraft (Hill AFB, UT Bldg 225).

4.0 RESULTS AND DISCUSSION SUMMARY

The laboratory and field evaluation demonstrated promising results. The low-cost sensors are capable of estimating noise loudness and particulate matter counts (or concentration) at levels that would represent potentially low exposure levels with respect to regulatory, recommended and voluntary health levels. They maintain an effective operational range at increasing exposure estimates to around the action level for noise regulation and below published exposure limits for inhalable and respirable dust. This means an operational networked array of low-cost sensors can provide an occupational health practitioner (e.g. Bioenvironmental Engineers-BEE) a useful tool for conducting surveillance monitoring in an effort to promote and protect the health of the workforce. Moreover, because the cost of the networked array of sensors are nominal in comparison to regulatory and reference instrumentation, devices can be left in place for long-term monitoring of a workplace permitting the health practitioner to identify work events, practices, operations and/changes in work procedures that result in excursions beyond what is anticipated. By capturing exposure estimates digitally, an informatics platform can be developed that could provide continuous monitoring similar to control limits, excursion alerts and automated reporting for quality control and continuous improvement management strategies.

4.1 Results – Laboratory

The Dylos DC1700 and the UMDS operated throughout the laboratory tests without any malfunctions.

4.1.1 Dylos DC1700 (unmodified). Figure 5 shows a scatterplot of 60-minute average concentrations for the Grimm total counts from bin 0.5 µm and greater compared to the DC1700 small bin (>0.5 µm) for the ARD. A strong linear relationship was observed with R^2 of 0.944, 0.978 and 0.960 for Grimm concentrations ranging from 58 counts/cc to 118 counts/cc. Using the mass median diameter of 2.6 µm—derived from the Grimm data for the ARD 60-minute average—the Grimm mass conversion is compared to the DC1700 mass conversion in Figure 6. A strong linear relationship was observed, with R^2 of 0.864, 0.919, and 0.996. Further comparison of the DC1700 60-minute average mass conversion compared to the gravimetric average (n=3) inhalable samplers is shown in Figure 7. A moderate to strong linear relationship was observed with R^2 of 0.769, 0.874, and 0.950. The DC1700 60-minute average mass conversion compared to the gravimetric average (n=3) respirable samplers is shown in Figure 8. A moderate linear relationship was observed for 2 of the 3 instruments (R^2 of 0.726, 0.686, and 0.177).

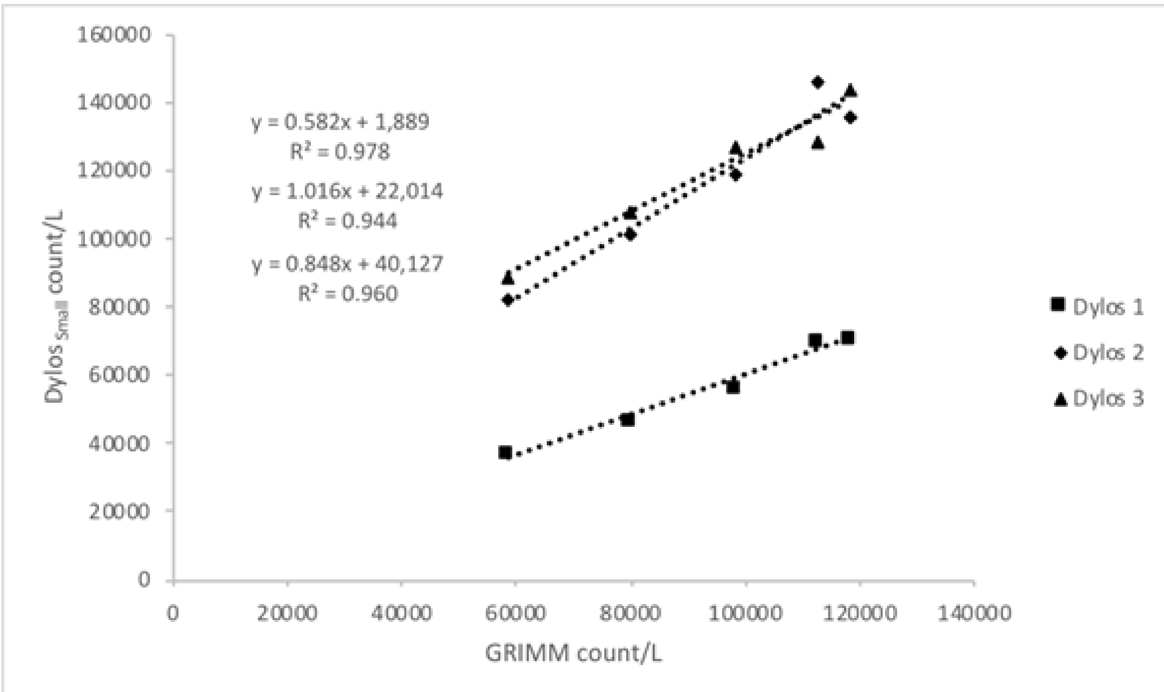

Figure 5. Comparison of the Grimm total count of bins 0.5 and greater compared to Dylos small bin for ARD.

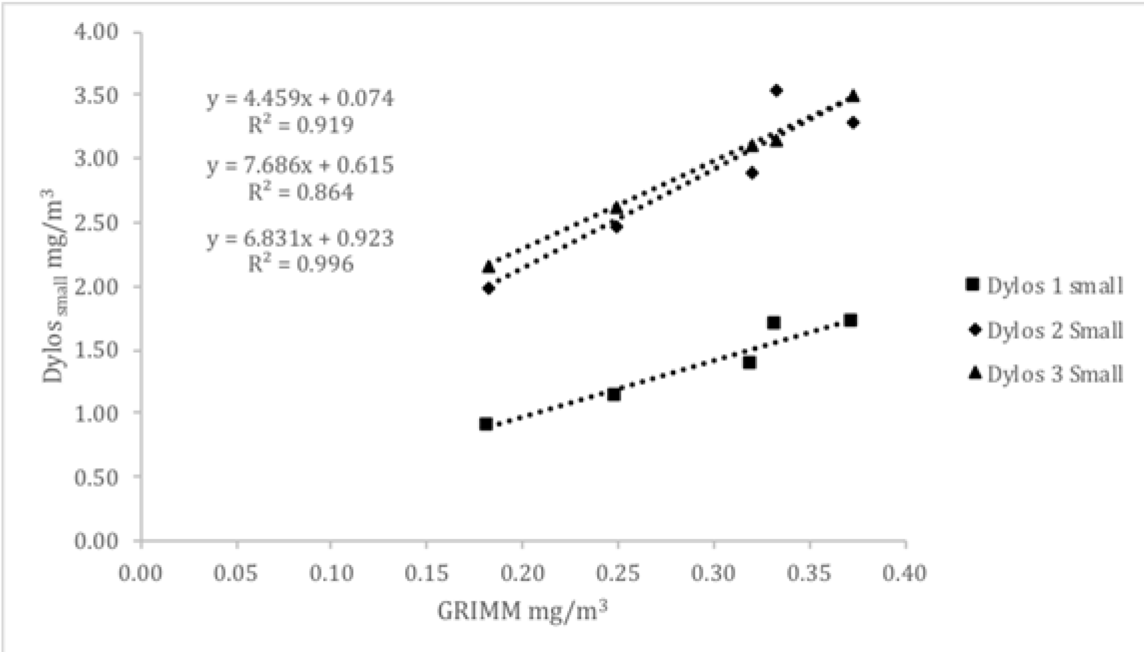

Figure 6. Comparison of the Grimm mass conversion to the Dylos small bin mass conversion for ARD.

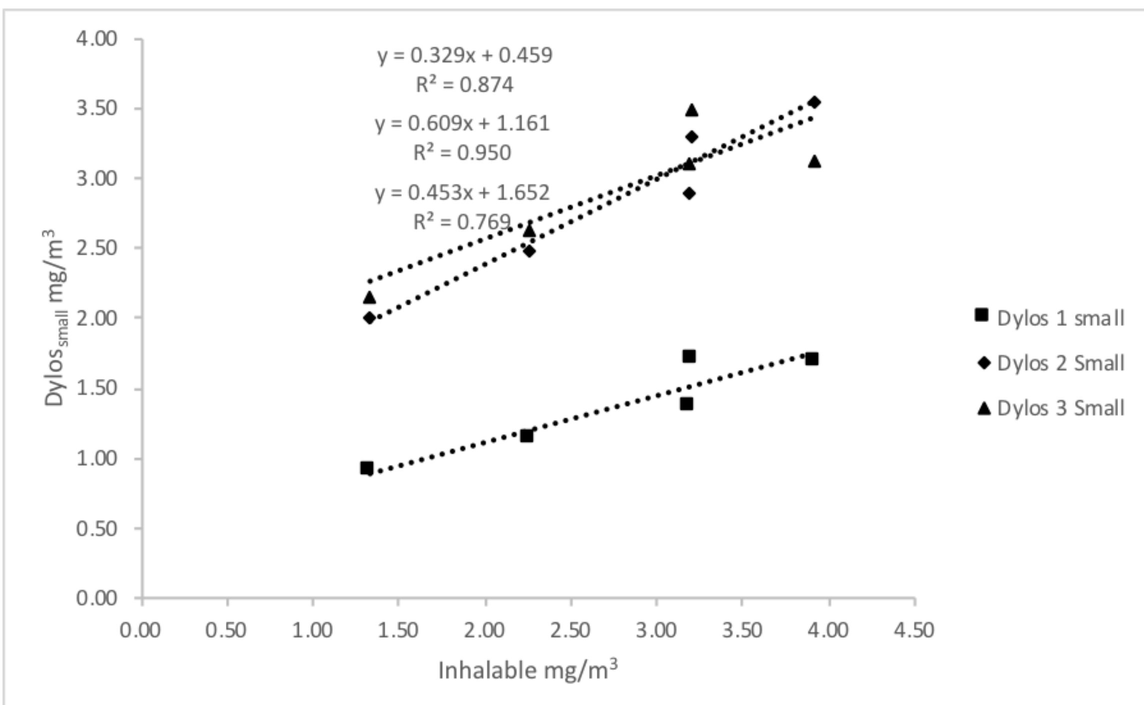

Figure 7. Comparison of the average gravimetric inhalable concentration to the Dylos small bin mass conversion for ARD.

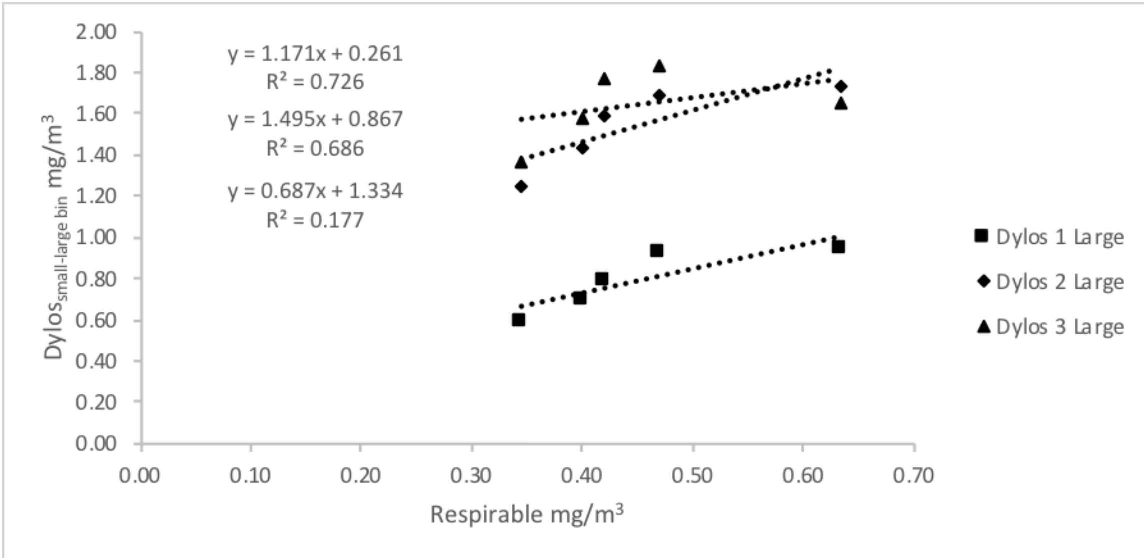

Figure 8. Comparison of the average gravimetric respirable concentration to the Dylos (small minus large bin) mass conversion for ARD.

For the aluminum oxide test dust, there was a weaker relationship observed compared to the ARD. The 60-minute average total counts for the Grimm 0.5 µm bin and above compared to the DC1700 small bin 60-minute average is shown in Figure 9. A poor-to-moderate linear relationship was observed with R^2 of 0.184, 0.458, and 0.640 for Grimm concentrations ranging from 86 counts/cm^3 to 178 counts/cm^3. Using the same mass median diameter of 2.6 µm as was used in the mass conversion concentration for comparison of the (unmodified) Dylos and Grimm; Figure 10 shows a comparison of the Grimm mass conversion and the DC1700 mass conversation for aluminum oxide. A poor linear relationship was observed with R^2 of 0.254, 0.026, and 0.312. Further comparison of the DC1700 60-minute average mass conversion compared to the gravimetric average (n=3) inhalable samplers is shown in Figure 11. A poor linear relationship was observed (R^2 of 0.04, 0.073, and 0.121) with similar results observed for the respirable sampler (Figure 12; R^2 of 0.008, 0.345, and 0.357).

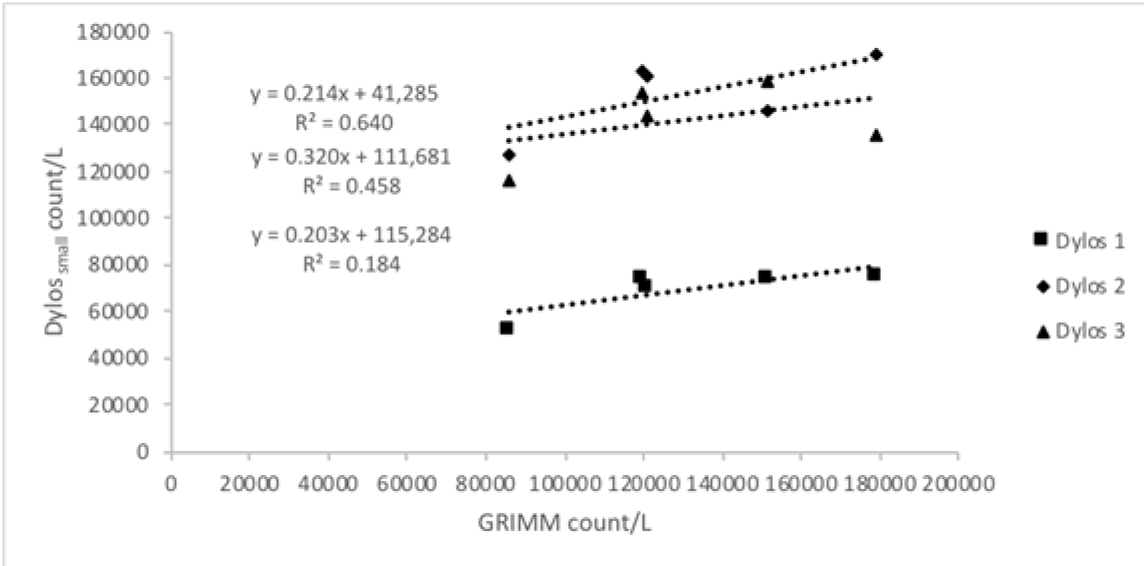

Figure 9. Comparison of the Grimm total count of bins 0.5 and greater compared to the Dylos small bin for aluminum oxide.

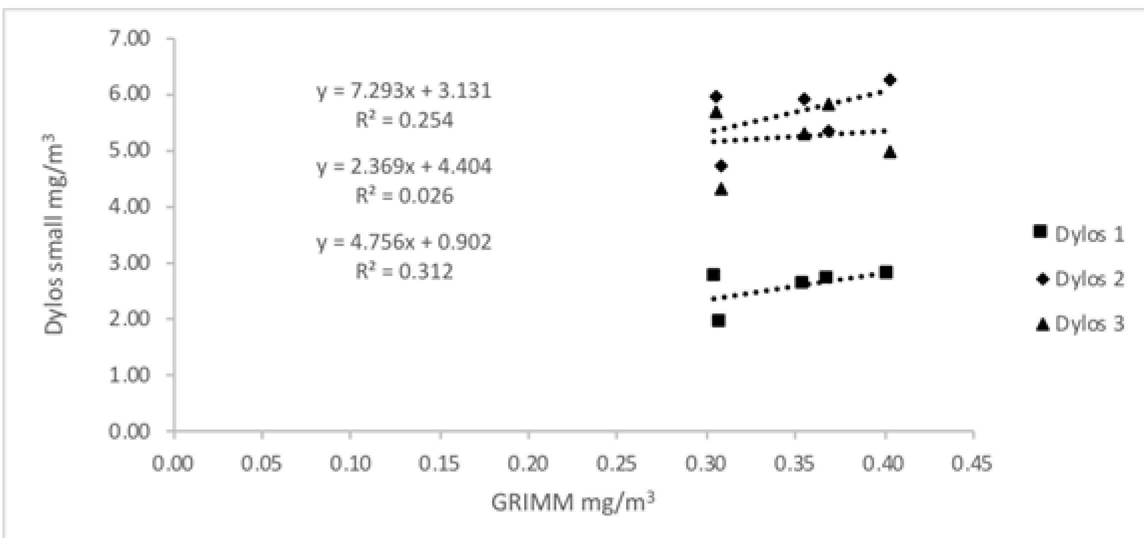

Figure 10. Comparison of the Grimm mass conversion to the Dylos small bin mass conversion for aluminum oxide.

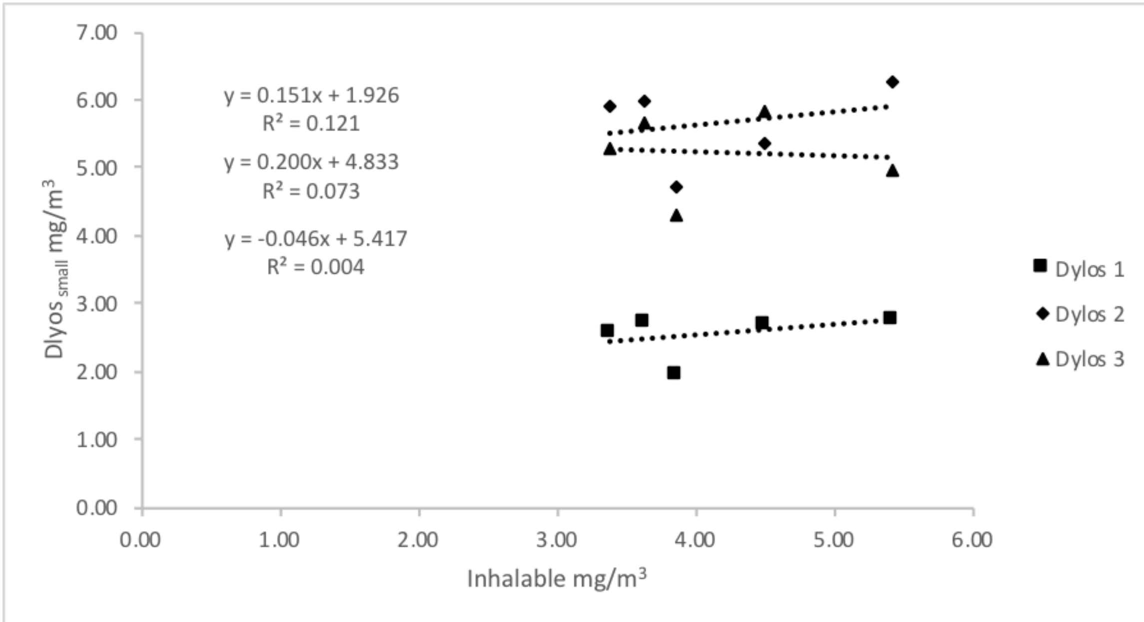

Figure 11. Comparison of the average gravimetric inhalable concentration to the Dylos small bin mass conversion for aluminum oxide.

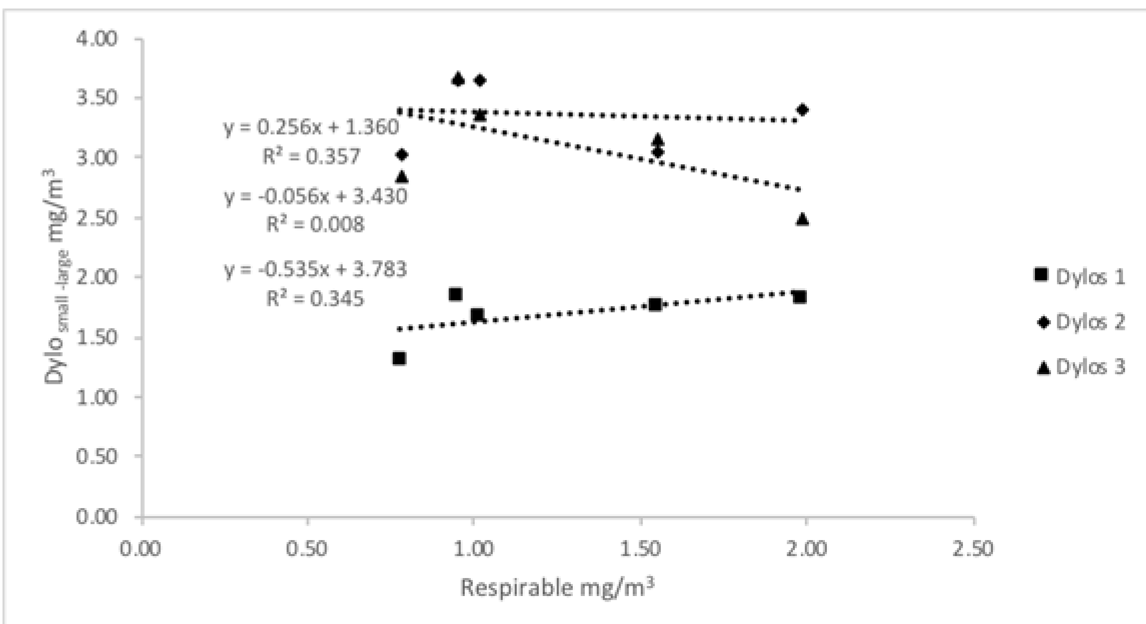

Figure 12. Comparison of the average gravimetric respirable concentration to the Dylos (small minus large bin) mass conversion for aluminum oxide.

4.1.2 Utah Modified Dylos Sensor (UMDS). Similar results for the UMDS compared to the Dylos were observed for both the ARD and the aluminum oxide. A scatterplot of the Grimm total counts from bin 0.5 µm and greater compared to the UMDS small bin for the ARD 60-minute average concentration is shown in Figure 13. A strong linear relationship was observed with R^2 of 0.858, 0.873, and 0.922. The Grimm mass conversion compared to the UMDS mass conversation in Figure 14 shows a moderate linear relationship (R^2 of 0.571, 0.579, and 0.678). Further comparison of the UMDS 60-minute average mass conversion compared to the gravimetric average (n=3) inhalable samplers, shown in Figure 15, demonstrates a strong linear relationship (R^2 of 0.855, 0.897, and 0.925). The UMDS 60-minute average mass conversion compared to the gravimetric average (n=3) respirable samplers is shown in Figure 16; a strong linear relationship was again observed with R^2 of 0.928, 0.963, and 0.997.

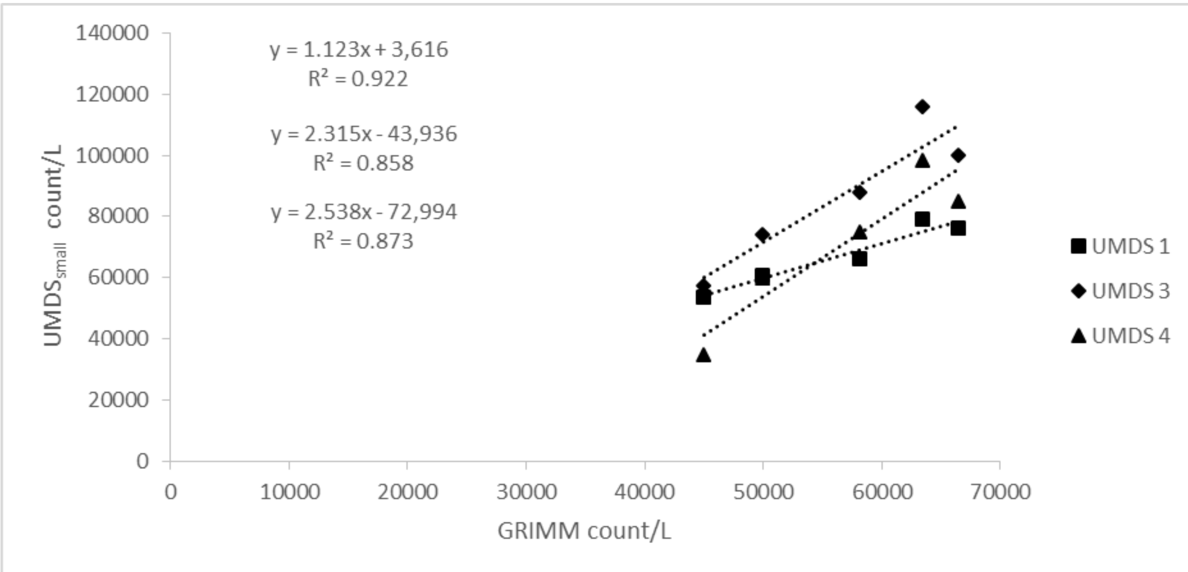

Figure 13. Comparison of the Grimm total count of bins 0.5 and greater compared to the UMDS small bin for ARD.

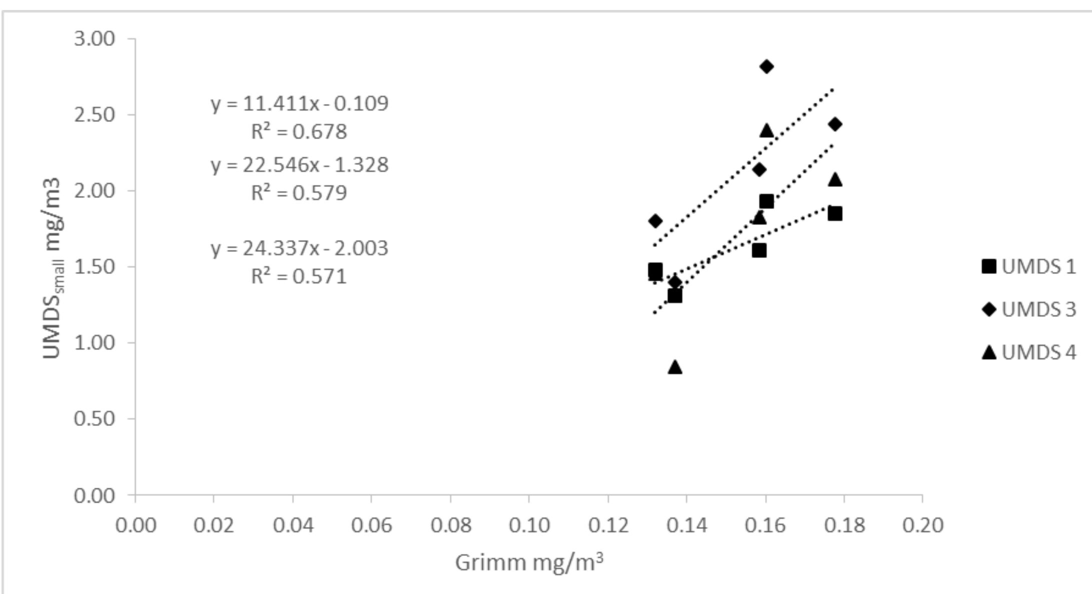

Figure 14. Comparison of the Grimm mass conversion to the UMDS small bin mass conversion for ARD.

For the aluminum oxide, the results were consistent with the Dylos DC1700 and a decrease in relationship was seen across all tests. The total counts from the Grimm 0.5 µm bin and above compared to the UMDS small bin demonstrated a poor to moderate linear relationship with R^2 of 0.220, 0.689, and 0.796 (Figure 17). The Grimm mass conversion compared to the UMDS mass conversation (Figure 18) shows a moderate to poor linear relationship (R^2 of 0.577, 0.464, and 0.102). Further comparison of the UMDS 60-minute average mass conversion compared to the gravimetric average (n=3) inhalable samplers is shown in Figure 19 and demonstrates a poor to moderate linear relationship, with R^2 of 0.089, 0.601, and 0.801. Similar results were observed for the respirable samplers as well (Figure 20) with R^2 of 0.011, 0.260, and 0.648.

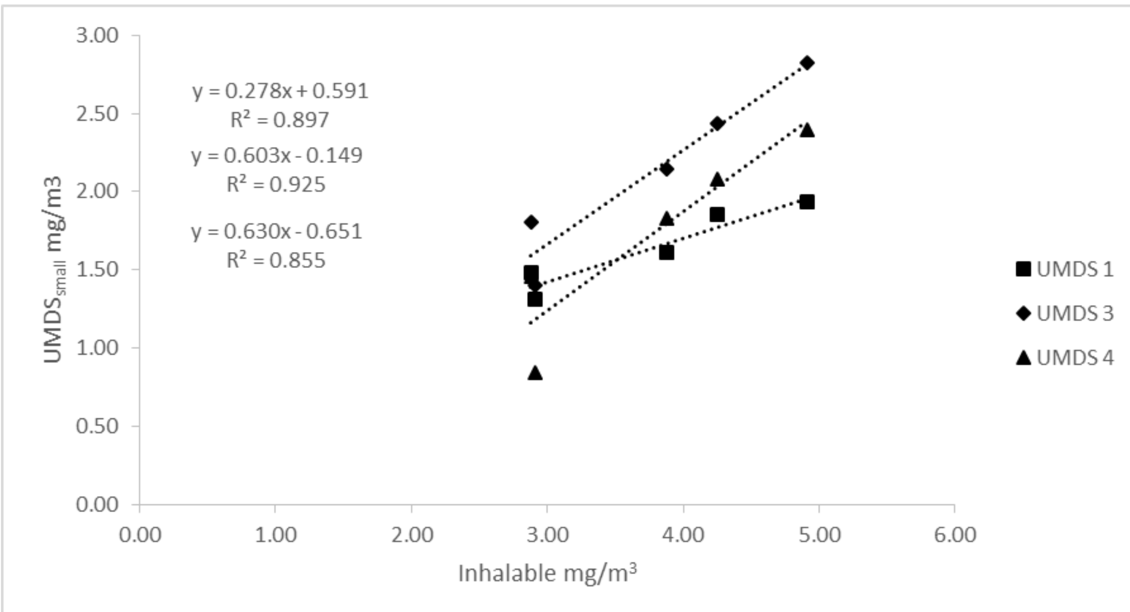

Figure 15. Comparison of the average gravimetric inhalable concentration to the UMDS small bin mass conversion for ARD.

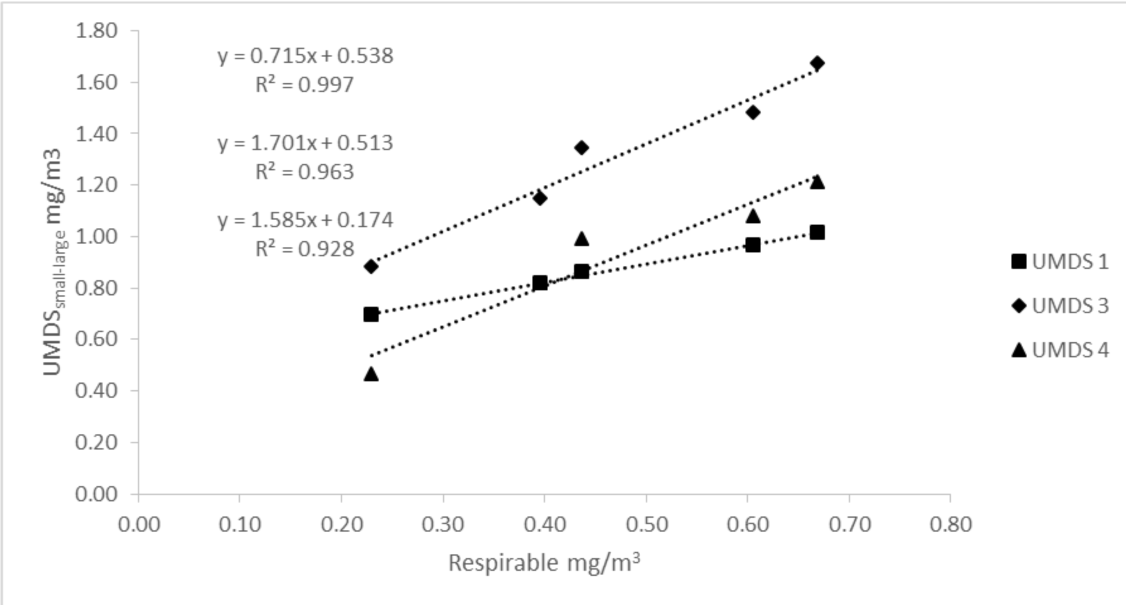

Figure 16. Comparison of the average gravimetric respirable concentration to the UMDS (small minus large bin) mass conversion for ARD.

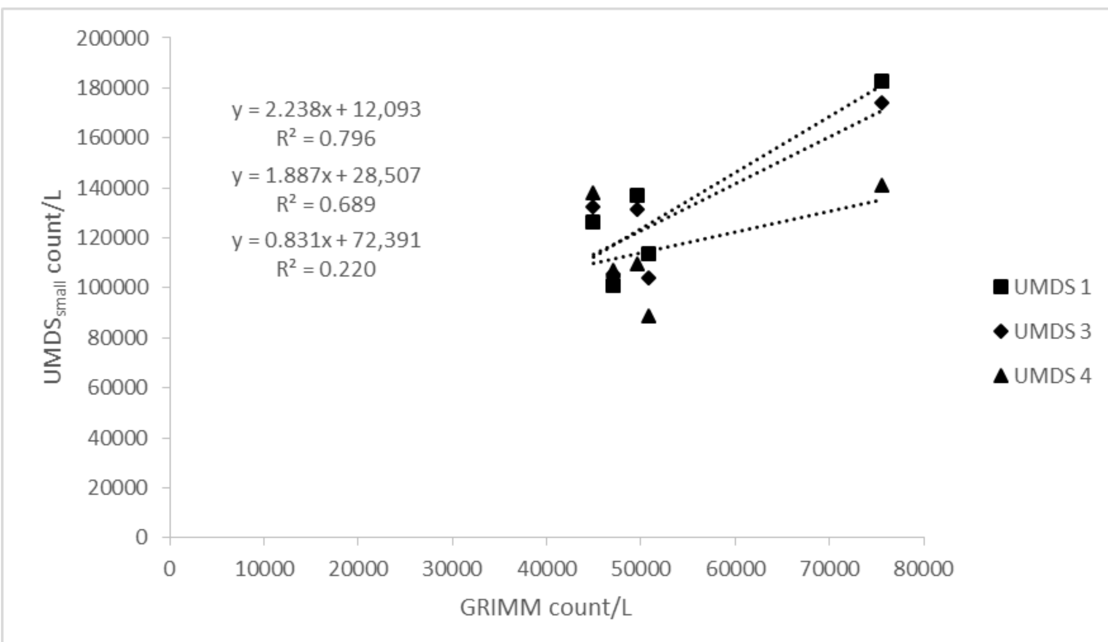

Figure 17. Comparison of the Grimm total count of bins 0.5 and greater compared to the UMDS small bin for aluminum oxide.

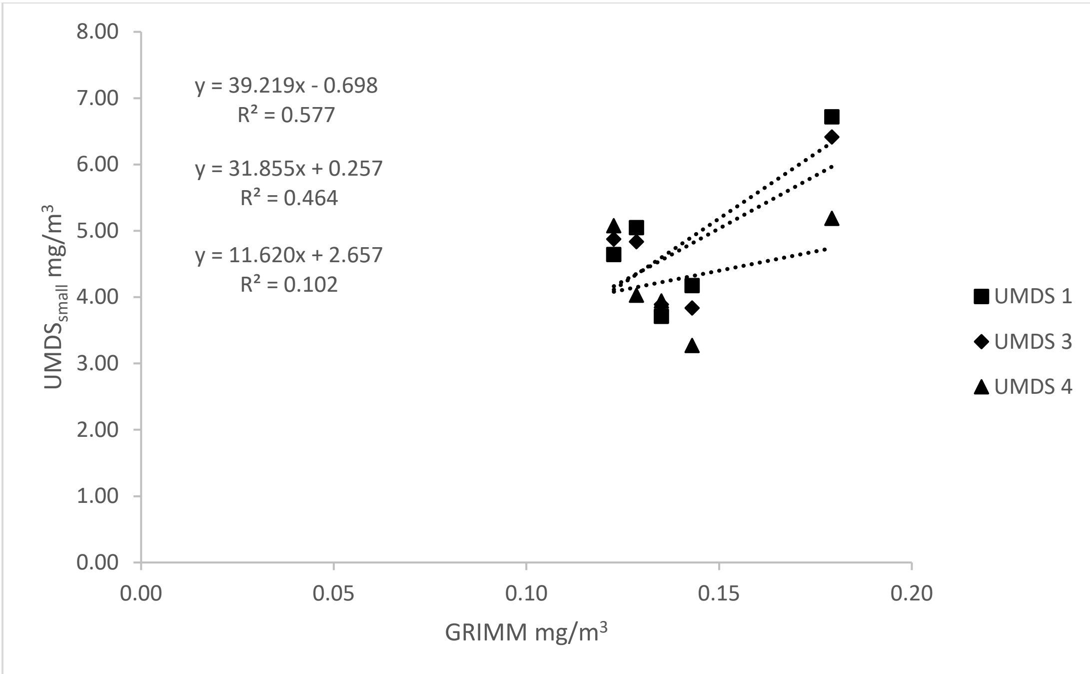

Figure 18. Comparison of the Grimm mass conversion to the UMDS small bin mass conversion for aluminum oxide.

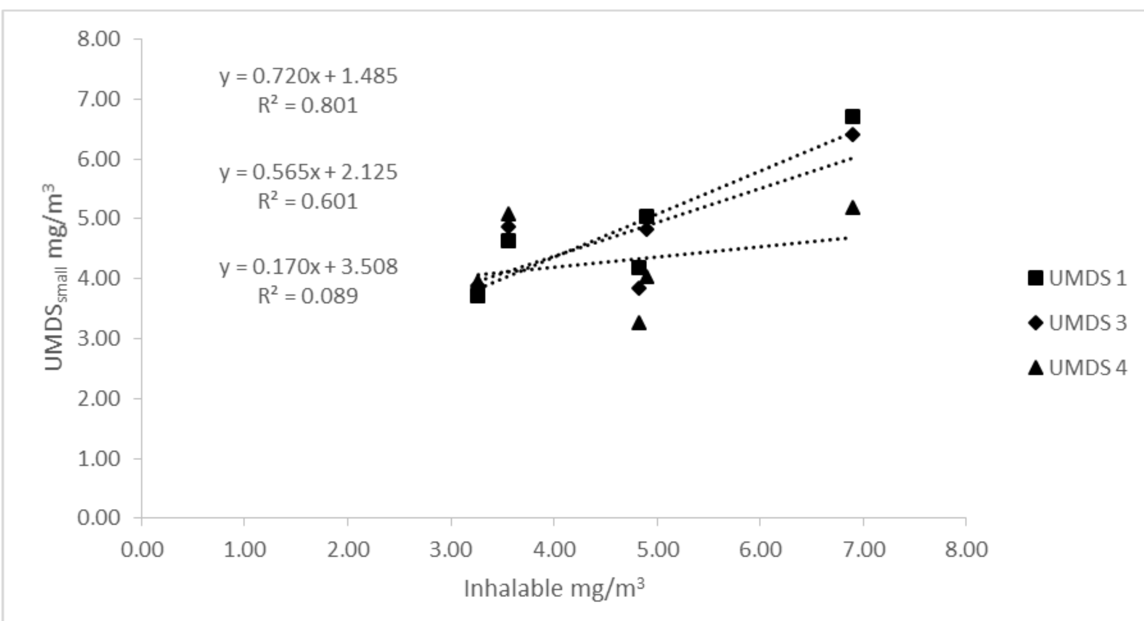

Figure 19. Comparison of the average gravimetric inhalable concentration to the UMDS small bin mass conversion for aluminum oxide.

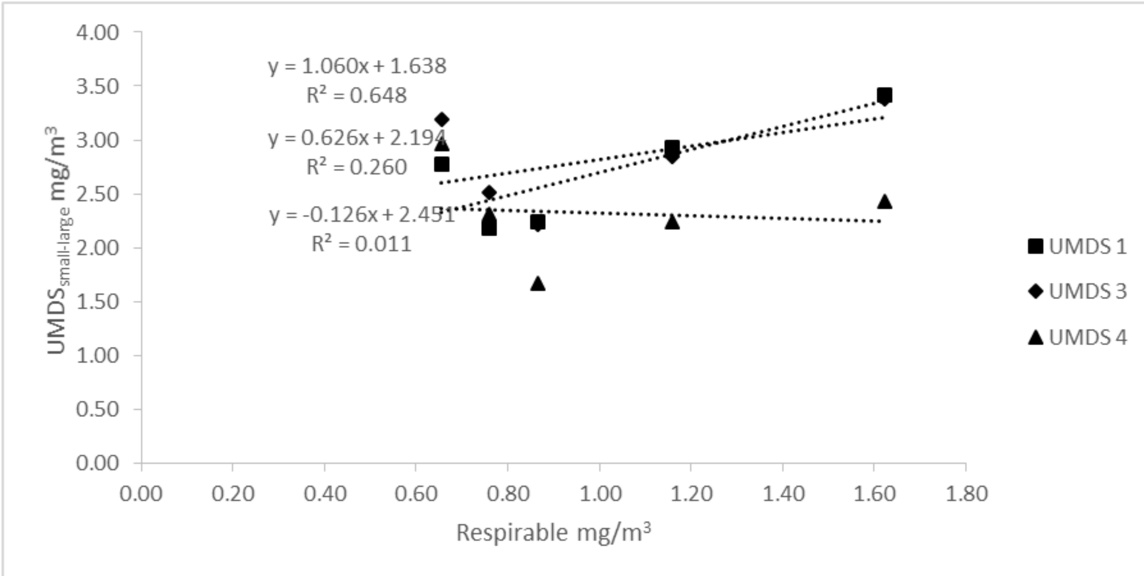

Figure 20. Comparison of the average gravimetric respirable concentration to the UMDS (small minus large bin) mass conversion for aluminum oxide.

ANOVA analysis was performed for each belt rate for the 3 UMDS sensors for ARD and aluminum oxide. For all ARD concentrations, there was a significant difference in mean concentrations (p-value <0.0001). Table 1 summarizes the mean, coefficient of variation and the ANOVA analysis. Similar results were seen for the aluminum oxide (Table 2) with a significant difference in mean concentrations for belt rates 0.2%, 0.3%, and 0.5%.

Table 1. Comparison of UMDS Raw Count Means, Coefficient of Variation (CV), and ANOVA Results for ARD

	UMDS 1		UMDS 2		UMDS 3		ANOVA
Belt Speed (%)	Mean (count/L)	CV	Mean (count/L)	CV	Mean (count/L)	CV	P Value
0.1	53698	0.24	57489	0.21	34640	0.34	<0.0001
0.2	60807	0.19	73940	0.12	59942	0.22	<0.0001
0.3	66016	0.21	88032	0.14	75025	0.21	<0.0001
0.4	75997	0.18	99956	0.11	85156	0.18	<0.0001
0.5	79213	0.18	115785	0.09	98373	0.17	<0.0001

Table 2. Comparison of UMDS Raw Count Means, Coefficient of Variation (CV), and ANOVA Results for Aluminum Oxide

	UMDS 1		UMDS 2		UMDS 3		ANOVA
Belt Speed (%)	Mean (count/L)	CV	Mean (count/L)	CV	Mean (count/L)	CV	P Value
0.1	100835	0.29	105734	0.21	107092	0.24	0.373
0.2	126141	0.11	132434	0.11	137973	0.13	0.0003
0.3	137093	0.16	131367	0.16	109497	0.23	<0.0001
0.4	113435	0.66	104179	0.65	88945	0.69	0.142
0.5	182479	0.10	174230	0.17	140955	0.21	<0.0001

4.2 Discussion – Laboratory

For ARD, the UMDS responded similarly to the more expensive Grimm Aerosol Spectrometer (~$25,000) when comparing the total counts from the 0.5 µm bin and above to the small bin of the UMDS. This is a promising finding considering that the UMDS currently costs roughly 50 times less than the Grimm does. When comparing the Grimm and UMDS converted to mass, a decrease in relationship was observed, with R^2 values ranging from 0.57-0.68. One explanation for the decrease in relationship is the Grimm's higher resolution for classifying particles into 32 discrete bins compared to the UMDS's 2 bins. For the Grimm, mass was calculated for each bin size and then totaled, whereas for the UMDS, mass could only be calculated from 1 bin using one particle size (i.e., 2.6 µm).

The count concentration data measured by the UMDS can be converted to mass, and this conversion allows comparisons between the UMDS data and more traditional filter-based sampling methods of inhalable and respirable dust concentrations. When the UMDS was compared to the gravimetric respirable dust samples, the UMDS accounted for 93 to 99.7% of the variability of the mass collected with the respirable sampler. For that comparison, only the UMDS data from the small bin minus the large bin (approximately 0.5-2.5 µm) were used. This convention of comparison was chosen because this size range is assumed most similar to the respirable size range than either the large or the small bin on its own. This finding is of particular interest because the only other study that has compared the Dylos to the respirable fraction found only a moderate relationship with R^2 of 0.62-0.63 when sampled in a concentrated animal feeding operation [11].

Additionally, the UDMS accounted for 85-92% of the variability of mass collected with the inhalable sampler when compared to the small bin (i.e., all particles). Gravimetrically-measured inhalable aerosol concentrations ranged from 2.9 mg/m^3 to 4.9 mg/m^3. No other studies providing a direct comparison of the Dylos to the inhalable fraction were found in the literature. These results imply that the Dylos could be utilized to estimate inhalable dust as high as 4.9mg/m^3, approximately one-half the ACGIH Threshold Limit Value (TLV). Given the favorable agreement between the UMDS and respirable and inhalable concentrations, indications are that the UMDS could be a useful tool in estimating mass concentrations in the work place.

Count concentrations measured with the UMDS compared to the Grimm for the aluminum oxide did not show as strong of a relationship as with the ARD. Two of the UMDSs responded with a moderate relationship with R^2 of 0.68 and 0.80 while the third UMDS responded with a poor relationship (R^2 of 0.22). Figure 17 demonstrates that the instruments had a significant decrease in linearity above 106 particles/cm^3. A possible explanation for the decrease in coefficient of determination and linearity was that the count concentration for the aluminum oxide was much higher than that of the ARD. In the series of tests performed with the aluminum oxide, the count concentration, as measured by the UMDS, was 101 particles/cm^3 up to as high as 182 particles/cm^3. This series of tests was therefore above the upper limit of quantification of 106 particles/cm^3, as specified by the manufacturer, but was still below the roll over concentration of 236 particles/cm^3.

The Dylos manufacturer has stated the instruments become unreliable above the specified upper limit of quantification. While there was a moderate relationship for two of the UMDSs, it can be reasonably assumed that these measurements may not be reliable or reproducible at higher concentrations. Additionally, data from the Grimm indicated there were a significant amount of aluminum oxide test particles in the <0.50 µm range. Even though it has been observed that the Dylos has low sampling efficiency for sub-micron particles, it could be that these very fine particles caused coincidence and were misclassified, resulting in an inaccurate count [13].

The UMDS variability was also investigated for the ARD and aluminum oxide series of tests. The intra-instrument variability was similar for all instruments, but was slightly more variable than seen by Sousan et al [13]. Additionally, results from the ANOVA comparisons for ARD indicate that the mean count concentrations were showing significantly different concentrations between the instruments. This was true at all five (5) belt rates. Due to the variability in the mean concentrations for each UMDS at the same belt rate, it would be recommended that individual calibration curves be applied to each sensor to accurately estimate mass concentrations.

Due to the implication that each instrument will need its own calibration curve to estimate mass exposure accurately, several aspects should be studied further. There has been no published investigation into the required frequency of calibration for these low-cost sensors. Due to that lack of current information, future studies should focus on the possible length and frequency with which these instruments will need to be calibrated. While relatively inexpensive calibration standards exist for gas monitoring instruments, access to a more expensive reference instrument would probably be needed to calibrate an instrument like the UMDS. Ideally, at least a three (3)-point calibration at varying concentrations would be performed initially in a wind tunnel or similar set-up.

Performing individual calibrations in a wind tunnel would be the ideal method of calibration to get the most accurate estimations. It would add a significant cost to a low-cost instrument. Depending on the specific use of the instrument, an increased level of variability or decrease in accuracy may be acceptable to the user. With this scenario, a single calibration curve applied to all instruments may be acceptable. A field calibration with a reference instrument may also prove to be sufficient, which could significantly decrease the cost of calibration. Instruments such as a TSI DustTrak or Thermo pDR-1200 are readily available to rent from a variety of vendors and could be used to calibrate the UMDS in the work place. Field calibration was not performed in this study, but will be investigated further in future research. Despite these limitations, the UMDS remains a viable tool for estimating occupational exposures.

The UMDS is not intended to be a reference instrument and personal gravimetric sampling is still essential for assessing worker exposure. However, low-cost instruments like the UMDS can be a useful tool for the occupational health practitioner. An occupational health professional can utilize a tool like the UMDS or a network of UMDSs as a broad survey tool.

Having a real-time, inexpensive, way to estimate inhalable or respirable dust concentrations could allow quick estimate of employee exposure. If results are a magnitude less than the OEL, further sampling may not be indicated. On the other hand, if results are above a user defined set point, such as 10% or more of an OEL, personal filter-based sampling could be indicated.

Further, real-time dust estimations would allow safety and health professional to respond quickly to changing environments. For example, being able to accurately determine if concentrations have increased by a pre-determined amount could swiftly identify work processes that are malfunctioning and/or if controls such as personal protective equipment need to be implemented immediately. Such a device could also help quickly determine if engineering controls, such as local ventilation, are working properly. Further, the UMDS demonstrated that it could estimate inhalable dust concentrations up to approximately 50% of the ACGIH TLV when tested with ARD and up to approximately 25% of the respirable dust TLV. This is a suggested practical range of operation, as many practitioners try to maintain employee exposures at 10% or below occupational exposure limits [5].

Additionally, the UMDS is a network-enabled sensor that allows the real-time observation of data. This enables the health practitioner to access the data from anywhere there is internet connectivity. An associated mobile phone application, cell phone text interface, and graphical web based dashboard has also been developed for the UMDS. The associated informatics platform will allow users to set alarm points that will notify the user when concentrations approach a defined set point, such as 10% of the TLV. This connectivity would allow a greater understanding of employees' exposure levels in real-time and allow a safety and health professional to implement controls rapidly if conditions change.

4.3 Field Evaluation Results and Discussion

An initial 'kick-off' meeting was held with our partners, the Force Health Protection office at Hill AFB, UT in April 2017. Attending were representatives from the UOU (Project Investigators), project sponsors from USAF School of Aerospace Medicine (USAFSAM), and Hill AFB leadership. There was general agreement on the aims of the field evaluation, support for the activity from all parties in attendance and approvals were identified that would be needed in order to actually conduct the project. Despite judicious efforts on all involved, final approvals for the field evaluation were not gained until late October 2017 and access to the facility was not scheduled until November 2017. UMDS network deployment and initial testing occurred in November and early December. Formal field evaluation activities began in December of 2017 and the array was uninstalled in 2018.

Walkthroughs of facilities staffed by the maintenance group was conducted to observe work spaces and activities; discuss which areas were priorities and/or amenable to the aerosol and noise monitoring we proposed (no office/management areas for instance); reprioritize based on which areas we could get security/escorted access; and then those areas were evaluated for cellular network data connectivity as the array would be dependent on this secure data transmission via the Gateway. The networked sensor array was deployed above two aircraft in building 225 and also in an observational area, plane prep areas, and personal protective equipment don/doff areas in building 220. A public release schematic of both buildings is provided in Figures 21 and 22 and these were further marked with exact UMDS locations by study staff.

Initial Gateway deployment in the observation room of Hill AFB building 220 proved problematic as the bulk of the network UMDS were located in building 225 and continual connectivity to all of those sensors all of the time was not constant. This was likely due to the reliance of LoPy network connectivity, which has very good data transmission over long distances but lacks high throughput. Because most sensors required this data transmission methodology, near real-time data transmission was not always observed. Subsequently, the Gateway was relocated to building 225 allowing the array's local, secure Wi-Fi and Bluetooth networks to take on the majority of the UMDS data transfer needs leaving the LoPy network to service the few units in building 220. This was an important finding as future deployments will need to consider the bandwidth needs of sensors and locate the Gateway to optimally maximize data transmission and/or utilize multiple Gateways in the deployment to appropriately service the UMDS network data transmission needs.

During the field evaluation, reference noise and particle measurement instruments (3M and Grimm respectively) were collocated with each UMDS to confirm measurement equivalence (Figures 3 & 4). The field validation of particle measurements resulted in R^2 between 0.93 to 0.99 for the respirable dust and 0.78-0.96 for inhalable dust when compared to appropriate mass conversions against the reference instrument. The UMDS noise monitor demonstrated good precision with measurements within 2% dbA against the reference instrument. It is important to note, the activity level of personnel and machinery in and around the test array was often limited. The field validation reference measurements were always within the operational range for particulate and noise measurements of the UMDS, and often within a small range and low level of particulate concentrations and noise. UMDS exposure measurements estimates were securely, wirelessly transmitted to the secure, open-source SQL compatible database. A sample export of sensor data from the database is shown in Figure 23. In preparation for the field evaluation, a secure (2-factor authentication login) web graphical interface was devised to show sensor data in real-time. This interface can also graph output over various time parameters. An example of this graphical interface is shown in Figures 24 and 25 for a single UMDS. Approved users may toggle between views for single and multiple UMDS and the interface can be customized to meet the oversight, management and reporting needs of various end-users.

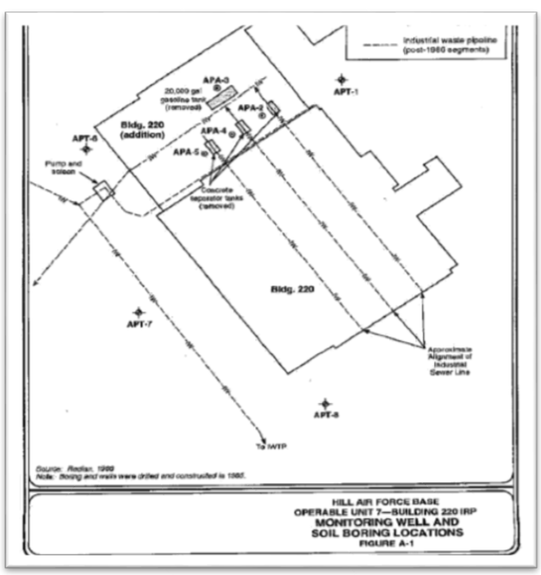

Figure 21. Hill AFB, UT Bead Blast Building, Building 220.

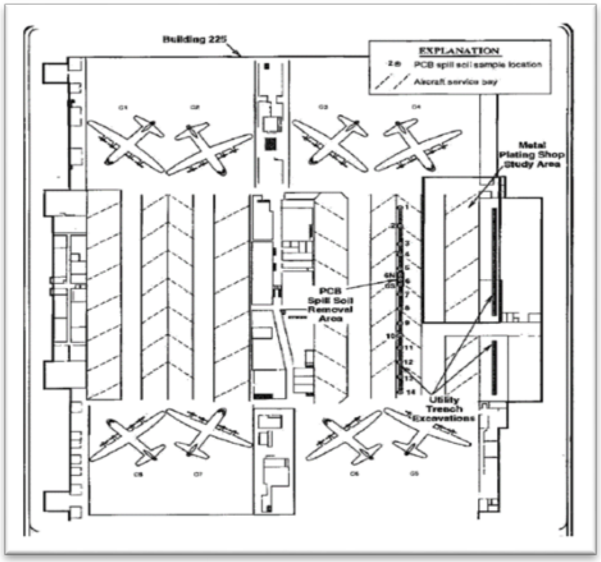

Figure 22. Hill AFB, UT Maintenance Building, Bldg 225 (scale removed from both images).

sensor16

device_id	sequence	sensing_time	tick_diff	small	large	temperature	humidity	noise	c1	c2	c3
16	1	64	0	1550	33	17	33	69	0	0	0
16	2	125	0	1483	26	17	33	108	0	0	0
16	3	166	0	1523	29	17	33	115	0	0	0
16	4	227	0	1509	29	17	33	93	0	0	0
16	5	288	0	1506	34	17	33	102	0	0	0
16	6	349	0	1463	25	17	33	109	0	0	0
16	7	410	0	1519	27	17	33	93	0	0	0
16	8	471	0	1470	30	17	33	91	0	0	0
16	9	532	0	1437	27	17	33	113	0	0	0
16	10	594	0	1423	33	17	33	123	0	0	0
16	11	655	0	1426	29	17	33	99	0	0	0

Figure 23. Example-SQL database export of UMDS.

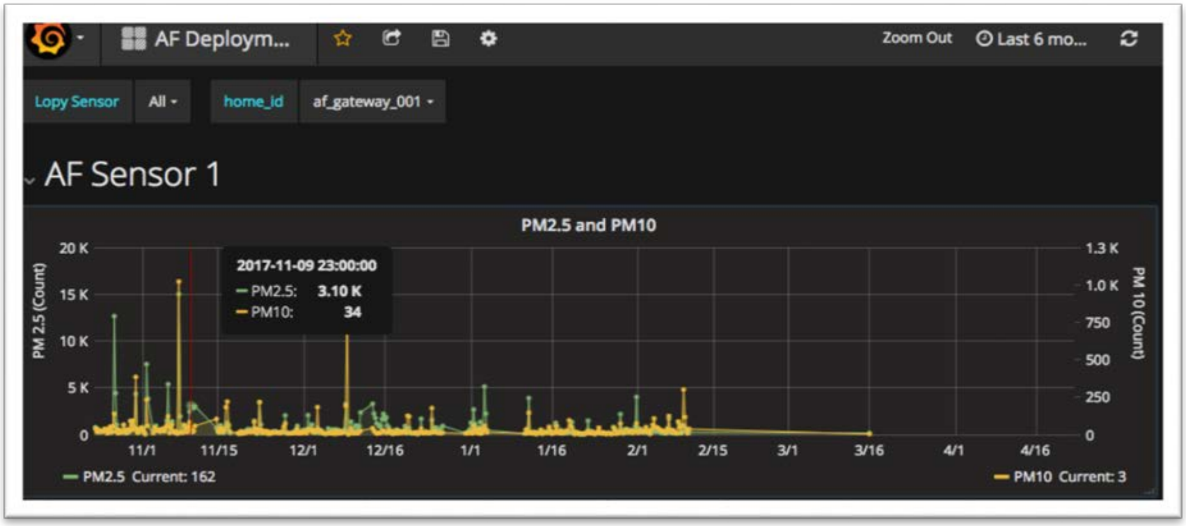

Figure 24. Graphical User interface Screenshot #1.

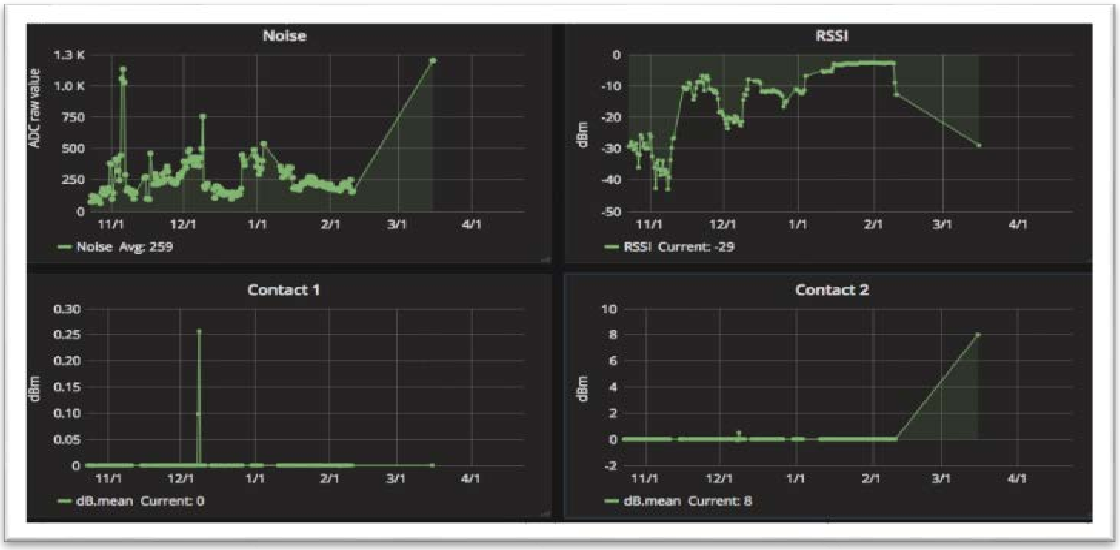

Figure 25. Graphical User interface Screenshot #2.

A specific application of the network array of sensors was done in conjunction with a proximity sensor—a small, pocket size device that operated via battery power and communicated with the sensor network. By 'calibrating' the proximity sensor within the array (various 'fixed' locations were corroborated using signal strength to individual UMDS and measured distance to same UMDS), we were able to estimate the location of the proximity sensor when carried by a worker. As a result, we demonstrated with some success the ability to temporal-spatially locate a worker within the array. This has potentially significant benefits that warrants further investigation (see Future Study section). In this field evaluation, during a 1-hour period, two workers conducted riveting and metal grinding activities during plane up-fitting while simultaneously wearing a noise dosimeter (for actual noise exposure estimation) and having the proximity sensor in their pockets (Figure 26).

Figure 26. Workers metal grinding while wearing proximity sensors (in pocket) and wearing personal noise dosimeter.

The vast amount of exposure data transmitted by this relatively small sensor array has implications for BEE staff. It is easy to be overwhelmed with data and it will be important to consider when and where alerts may be useful, as well as visualization of data streams (control charts, isopleth hazard maps of exposures for instance). Moreover, the proximity sensors integrated within a network array of sensors show great promise. By understanding the location of a worker within an array of sensors, personal exposures can be estimated based on their movement within that array (moving about in the isoplethic hazard map). Personal exposure sampling is resource intensive for the BEE and often burdensome to the worker. It may impact a worker's productivity and quality as sampling trains and equipment impact how they perform their duties. As a result, personal exposure sampling is often done infrequently. Further development of the proximity sensing technology operating within a networked array of low-cost sensors is warranted as it has the opportunity to provide the most useful estimates of exposures—that is, those of an individual worker as they go about their occupational activities unencumbered by typical personal exposure monitoring equipment. Understanding where a worker is at all times via the proximity sensing technology also posed a concern for our partners from Hill AFB organized labor (union leadership). As this was a geographically limited sensor array with a defined (and limited) proximity evaluation, this concern was quickly dismissed but it does pose a concern for a greater array of sensors that could indeed indicate location of workers at all times. The benefits to knowing worker location at all time, and thus estimating worker exposures (and safety implications) must be weighed against the concerns of organized labor and individual workers and management knowing their location at all times.

5.0 LIMITATIONS, STRENGTHS, AND FUTURE WORK

5.1 Limitations

There were limitations to this study. First, the ability to measure mass with the UMDS and Dylos is dependent on the size distribution and density of the aerosol. Depending on the work atmosphere (e.g., the type of processes and materials being used), some assumptions can be made about particle size and density, but ideally a size characterization and determination of the particle density would be made with a research grade instrument, such as the Grimm. It is likely that the UMDS would function similarly to other particle counters if concentrations did not greatly exceed the manufacturer's stated upper level of quantification of 106 particles/cm^3. Figure 17 also demonstrates that the instruments have a significant decrease in linearity above 100 particles /cm^3. Further, the UMDS uses a computer fan to pull air through the housing, thus, there is no way to precisely measure and/or change the actual airflow through the instrument. At best, concentrations are good estimates when using analytical calibration equations for aerosols.

Unlike reference instruments, there are no published calibrations schedules, cleaning schedules or manufacturer maintenance schedules for the components of the UMDS. Ultimately, the ability to accurately count particle concentrations could diminish as the UMDS becomes loaded with particulates, electronic particle counting hardware (light emitting diode and/or digital sensor) degrades or becomes contaminated, or the fan performance declines or there are changes in airflow. Measurement drift during long-term operation should be investigated (Future work paragraph 5.3)

Building 220 and especially building 225 are extremely large industrial facilities and they are some distance apart. Based on preliminary testing off-site (not Hill AFB) we had some expectation that a single Gateway and multiple UMDS sensor array would perform (near real-time wireless data transmission) adequately. We desired to test the wireless transmission capabilities of the UMDS to the Gateway and initially found the configuration with the Gateway in building 220 (with the fewest UMDS) to be problematic. Moving the Gateway to building 225 greatly helped the successful data transmission but subsequent data analysis showed intermittent failures to transmit data in near real-time from all UMDS at all times. As the sensors get an accurate time-stamp from connection to the Gateway and therefore secure internet, non-connected sensors lose an accurate timestamp—instead defaulting to an unreliable random timestamp unrelated to the actual (web derived) time. This anomaly was not discovered until post processing data and should be addressed in future renditions of hardware/software.

5.2 Strengths

To the investigators knowledge, this effort represents the first-of-its-kind investigation of a low-cost, real-time networked sensor array aimed at accurately estimating aerosol and noise exposure in a data-secure environment. Laboratory and field evaluation were conducted in a scientifically sound manner (UOU investigators were recently notified of pending publication of the laboratory evaluation in the Journal of Occupational and Environmental Hygiene). The work product represents the activities of a multidisciplinary team comprised of experts trained in industrial hygiene, environmental science, informatics, embedded systems, computer and software engineering, computer science and statistics. The field evaluation benefitted from the input and collaboration of uniformed and civilian personnel at Hill AFB. Overall project management and strategy benefitted from active participation and collaboration of USAFSAM, the KBRwyle Quick Reaction USAFSAM Assessments, Studies, Analysis, Evaluation, and Research Task Order project leadership team, and research team in Utah.

5.3 Future Work

Based on the outcomes of this project, sponsors and investigators may consider future studies that build on the success and address some of the limitations uncovered. General topics for consideration may include:

- As the UMDS components have no published calibration, cleaning and/or manufacturer maintenance, an investigation into sensor drift and potential cleaning procedures may be undertaken to address the long-term operational measurement efficacy of this type of device.

- Post-processing of the field evaluation data revealed ‘gaps’ in the time-stamped database. Further investigation showed that lack of UMDS-to-Gateway connectivity resulted in incorrect time-stamps being coded with environmental exposure measurement data during the lack of connectivity. Software and/or hardware upgrades to maintain an accurate time-stamp and thus a complete database record should be addressed (battery backup etc.).

- The proximity-sensing feature was a small component of this study but showed promise. Maintenance workers observed in this study find themselves in awkward positions periodically to do their work. Force health protection workers investigating potential exposures often utilize personal exposure monitoring equipment that is large and sometimes cumbersome for a worker to wear while performing their work duties. A small proximity sensor in conjunction with a network array of low-cost ambient sensors may be able to accurately estimate a worker’s exposures without actually conducting personal monitoring. A workers existing security badge (radio frequency identification-RFID) may be sufficient to know their location with appropriately up-fitted UMDS, eliminating a special proximity sensor.

- The UMDS was designed as a platform to integrate virtually any digital exposure measurement device. Future sensor integration could be driven by force health protection exposure measurement priorities—chemical specific detectors are a prime candidate for integration for health protection in industrial environments.

- As technology advances, size, weight and power requirements of environmental sensors and related hardware continues to be more diminutive and often with declining costs. UMDS with a large number of sensors are a possibility and becoming battery operated and even wearable are possibilities.

- Even the rather limited network array of sensors as demonstrated herein captured and transmitted multiple data variables every minute of every hour of every day—although for a limited time period, it is readily foreseeable that informatics requirements need more attention. Especially for the modeling, machine learning, continuous improvement and other ‘big data’ demands and benefits that may be realized.

6.0 CONCLUSIONS

Particle count concentrations of ARD measured with the UMDS were strongly related with a reference particle counter costing significantly more than the low-cost sensor when tested in a low-speed wind tunnel. Mass concentrations estimated with the UMDS were also strongly related with both respirable and inhalable dust measured gravimetrically. These data suggest that the UMDS is comparable to industry when concentrations stay below 50% of the inhalable TLV and 25% percent of the respirable TLV. However, it is recommended that a research grade instrument be used to establish a baseline for count-to-mass conversion for different industries. Further, individual calibration curves need to be applied to each instrument. The field evaluation confirmed the networked array is capable of providing real-time measurements of particulate matter and occupational noise in the immediate occupational environment in which they were operating, thereby providing a valuable exposure surveillance tool for the BEE teams charged with promoting and protecting the health of the workforce.

7.0 REFERENCES

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LIST OF ABBREVIATIONS AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AF	Air Force
AFB	Air Force Base
ANOVA	analysis of variance
ARD	Arizona road-test dirt
BEE	bioenvironmental engineers
CV	coefficient of variation
HAFB	Hill Air Force Base
LoPy	low power Python-based communications protocol
OEL	occupational exposure limit
OPC	optical particle counter
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
$\mathbf{R^2}$	coefficient of determination
TLV	threshold limit value
UMDS	Utah Modified Dylos Sensor
UOU	University of Utah
USAF	United States Air Force