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List of Terms and Abbreviations

AST – Access Sensor Technologies, LLC (awardee)
CAD – computer aided design
CSU – Colorado State University
EPA – Environmental Protection Agency (of Unites States of America)
FRM – Federal Reference Method
GPS – Global Position System
MEMS – micro electro mechanical systems
PID – proportional-integral-derivative
PM – particulate matter
$PM_{2.5}$ – particulate matter with aerodynamic diameters less than 2.5μm
SLPM – standard liters per minute (flow in liters per minute at STP atmospheric conditions)
STP – Standard Temperature and Pressure (atmospheric)
UPAS – Ultrasonic Personal Aerosol Sampler

Abstract

Exposure to particulate matter (PM) air pollution is the fifth leading cause of premature disease and death on the planet and the number one environmental risk factor for the global burden of disease (posing a greater danger than all other environmental risk factors *combined*) according to the World Health Organization.[1] Despite the growing need (and demand), the state-of-the-art for assessing personal exposure to PM is based on decades-old technology that is inefficient, burdensome, and expensive. For personal monitoring, active air sampling technology typically consists of a battery-powered diaphragm pump connected by tubing to a separate size-selective inlet (e.g., a cyclone or impactor) to measure inhalable, respirable, or $PM_{2.5}$ size fractions within the wearer's breathing zone. Such personal sampling equipment is expensive (typically >$1500 each), relatively heavy (>550g in total), noisy (emitting >50 dB from the pump along with substantial mechanical vibration felt by the subject), and bulky (in size and via tubing connections). The physical burden posed by these monitors (weight, bulk, noise, visual aesthetic) make them burdensome to wear. Importantly, the cost of these monitors also prevents air pollution exposure monitoring at scales relevant to epidemiologic research and occupational hazard surveillance. Further, diaphragm pumps involve a failure-prone and inefficient check valve, and the cumbersome tubing often pinches or disconnects if the wearer is physically active. There is a clear need for improved PM monitoring technologies both in the U.S. and abroad. In Phase I of this project we designed, developed, and tested a novel, lightweight, and inexpensive personal sampler based on ultrasonic piezoelectric pumping modules (a.k.a. 'micropump'). A Phase II proposal for continuation of this project was submitted in September of 2017. Three Phase II specific aims were proposed: (1) Integrate a novel, real-time PM sensor into the UPAS hardware/firmware; (2) Develop a suite of different plug-and-play size-selective inlets to make the UPAS more versatile and optimize the UPAS for weight, power, performance, and usability; (3) Validate performance of the prototype through laboratory and field testing.

Section 1:

Significant or Key Findings

Our Phase I project had four primary objectives: (1) develop a mechanical air pump subsystem, (2) develop a lower-cost, pump drive and flow measurement and control subsystem, (3) design and fabricate a wearable pump prototype, and (4) evaluate prototype performance through laboratory and field testing. We completed the four objectives through the work described below, with the final Phase I output being the development of a deployable, fully-functional Ultrasonic Personal Aerosol Sampler (UPAS) prototype which we continue to develop, and have proposed next-step development of in Phase-II.

Aim 1: Development of the mechanical air pump subsystem

Output: Development and refinement of a miniature lobe pump design to find an optimum balance between reduced cost and manufacturing precision, including performance evaluation across multiple operating conditions as well as initial durability testing.

Our major, initial finding was that an ultrasonic pumping module was superior in virtually every way to a lobe pumping subsystem – namely the former is smaller/flatter, lighter, quieter, simpler/less-complex and arguably even more robust. Thus, this new pumping subsystem had even greater benefits over the state of the art of the samplers. As such, we switched our efforts to focus on developing the ultrasonic pumping module.

Through following a classical iterative development process of ideation, computer-aided-design (CAD), prototyping, testing and review, we were able to quickly advance a novel air pumping subsystem to a very impressive level within the phase-I timeframe. The outcome from our final iteration was a pumping system that weighs ~8.5g, occupies 240mm^2 of printed circuit board area at a height of only 3.25mm (780mm^3 of volumetric space) and which could easily pump 2 SLPM of airflow through a typical 37mm diameter aerosol sampling filter (when highly loaded). The ultrasonic pumping module is between 2-3x more energy efficient (depending on flow parameters) vs. traditional diaphragm pumps, moves flow near-silently and without perceivable vibration, and features no observably-moving (sliding, rotating) components nor, importantly, the typically troublesome check-valve which traditional samplers have.

We have by now achieved substantial proof that the subsystem could be manufactured in a high-volume assembly line using full-automated processes – yielding massive cost savings over all prior art. In short, the pumping 'heart' of the UPAS is truly unique, giving impressive functional performance, packaging and cost advantages over prior art – and promising far greater benefits with additional development.

Aim 2: Development of a low-cost, electric motor drive and flow-control subsystem

Output: Development and integration of flow control techniques into a working prototype that delivers constant flow rate with changing vacuum pressure.

We conducted a rigorous development of the methods to drive the pumping subsystem, and to accurately measure and then control air flow rate. We were from the outset constrained to achieve these functions in a manner and embodiment that tightly integrated to the air pumping subsystem (and thus the printed circuit board (PCB) form-factor). We demonstrated that a micro electro mechanical systems (MEMS)-based anemometric flow sensing element integrated to the pumping module itself could achieve flow measurement directly, without needing to be connected via extraneous tubing. This integration is critical to be allowing high-volume manufacturing. Low-cost ambient air condition sensors were integrated into these flow structures, and used to calculate air density.

We investigated several types of pump drive circuit, and integrated one onto our PCB. A code-based PID flow control which fully accounted for filter loading and changes in atmospheric conditions was developed and tuned such that the UPAS was able to stay well within an industry-standard +/-4% of-setting flow control, remaining so even after months of field deployment time/cycles. In addition to these basic functions, the electronics and code also achieves high-resolution logging to onboard memory of all sensor outputs.

Aim 3: Design and fabricate a wearable pump prototype

Output: CAD modeling and fabrication of a product-level prototype with integration of the pump and control sub-systems from Aim 1 and 2 into a wearable housing with special attention to design for manufacturability and assembly.

An overall embodiment was developed, keeping a very close eye on with the overarching goal of the sampler offering revolutionary packaging, ergonomics, utility, and cost. Rigorous ideation>CAD>prototyping>testing and evaluation iterations were pursued continuously. We integrated the traditionally-separate sampling pump and a size-selective inlet with modular filter cartridge into a single, compact form factor small enough to wear in the subject's breathing zone. The UPAS prototype at the time of publishing this report has a size of 127 x 70 x 23 mm (main body), and a weight of 220g - roughly the footprint of a smartphone (and 2-3x thicker), and <1.5 times the weight. This sampler is packed full of additional sensors including GPS, and a sensor for a new real-time PM concentration proxy based on observing the pressure drop across the filter. All internal electronics except the mass flow sensor and battery itself are mounted to/against the custom circuit board, which is manufactured via industry-standard methods for low cost.

Aim 4: Evaluate prototype performance through laboratory and field testing
Output: A critical evaluation of the prototype pump performance with testing in the laboratory and a realistic field environment. Along with comparisons to commercially available pumps (i.e., the current competition) as a reference to benchmark the prototype pump performance.

The UPAS was evaluated thoroughly in both lab and field environments for the most critical function of PM filter sampling. Experienced practitioners following good practices rigorously compared the UPAS to industry 'gold' standards. In the lab the UPAS agreed within a 5% band to the EPA PM2.5 protocol on a particle size/count basis, separately showed an average PM mass-basis difference of 7% compared to an EPA Federal Reference Method (FRM) sampler, and compared favorably to a Harvard Impactor in the field. Such validations were good enough that outside groups of exposure scientists have decided to use the UPAS for their work, which is extremely encouraging for such an early stage.

Translation of Findings
The UPAS addresses every major criticism of today's modern air sampling: poor ease of use, manual data transcription, high up-front equipment costs, bulky burdensome equipment size, distracting noise/vibration levels, and annual maintenance expense that is 20% of the product cost. At approximately half the cost of existing time-integrated monitoring technology (and one fifth the cost of existing real-time monitoring technology), the UPAS can empower greater sample size, which, in turn, will enable faster, more certain, and more economical decision-making. This advantage will be a key selling point for potential customers. By reducing the weight and size, we also anticipate improved subject compliance, which improves data reliability.

Successful development of our product will provide environmental health professionals, industrial hygienists, and other risk assessors with a sensitive, in-situ technique to assess airborne hazards at reduced cost while setting the stage for production of a consumer level product in the future. Such technology represents a paradigm shift in the fields of environmental and occupational health by supplementing traditional lab analysis of air sampling filters with a real-time exposure tool that allows for immediate or same-day results that are later confirmed by accredited laboratories that analyze the resulting filter sample with established regulatory gravimetric analysis procedures.

Research Outcomes/Impact
The Ultrasonic Personal Air Sampler (UPAS) depicted in **Figure 1** was developed with our company's vision of making environmental diagnostic technology accessible to everyone. The UPAS is a one-piece/integrated, air sampler the size of a cell phone that monitors air quality and particulate matter in the air. It is small enough to be worn by workers to monitor occupational exposure and even children. While early in development (i.e. a 'beta'), our present UPAS prototype has seen strong initial sales, and is currently deployed in epidemiological studies in twelve countries. The UPAS is currently being used solely by academic researchers but, if funded, our proposed Phase II efforts will prepare the UPAS for widespread use in occupational settings. The Phase II proposal includes optimizing the pseudo-real-time PM concentration sensor (patent-pending), improving wireless functionality (mesh networking, alert/alarm notification, and cloud-based storage), and expanding its marketability with additional size-selective inlets that plug-and-play with existing hardware.

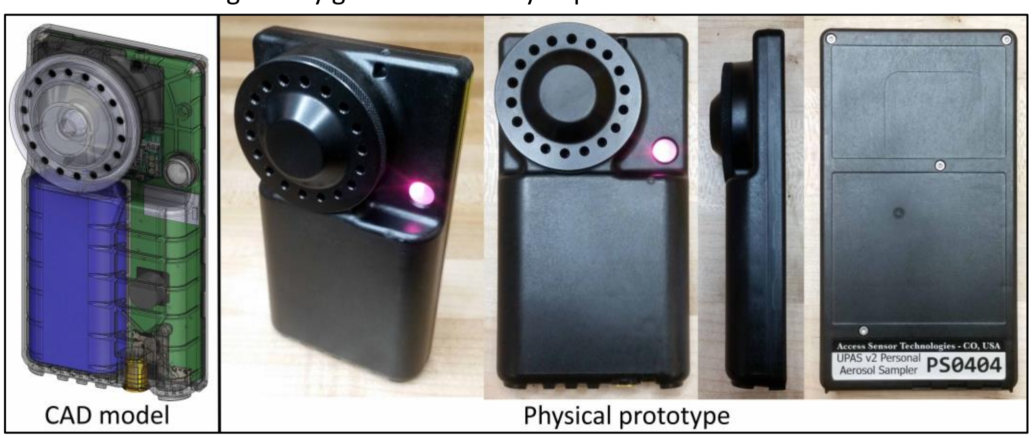


Figure 1. Output of Phase I; a fully-integrated (one-piece) personal sampler combines size-selective inlet, filter cartridge, silent pump, data logging, and next-generation pseudo-real-time PM concentration sensing, and is connectable to a mobile device via Bluetooth, and programmable through a smartphone application.

Section 2:

Scientific Report

Background: We have come to expect *simple* near *real-time* feedback throughout our lives from products and services such as the FitBit, Apple Watch, and the National Weather Service Emergency Alert System. These technologies have the potential to increase personal and public safety and health while broadcasting vital information in a frictionless manner. While the market for wearable technologies has grown enormously over the past decade, only a few wearable innovations have reached the occupational health sector where workers are continually exposed to environmental hazards on a daily basis (**Figure 2**). Access Sensor Technologies (AST) was founded on the belief that lower-cost wearable technologies can have a major impact on the health and well-being of people at risk for environmental and occupational exposure around the world. Exposure to particulate matter (PM) air pollution is currently the fifth leading cause of premature disease and death on the planet and the number one environmental risk factor for the global burden of disease (posing a greater danger than all other environmental risk factors *combined*).[1] Particulate air pollution in the workplace continues to pose substantial health risks from hazards such as mold, silica, metals, pathogens, organic aerosols, and dusts. Many professions such as welders, oil and gas workers, miners and environmental remediation professionals face additional exposure risks from mixtures of these aforementioned hazards. Unfortunately, these risks are often poorly quantified (or even unknown) at many workplaces due to the cost, complexity, and burden of available exposure assessment tools.

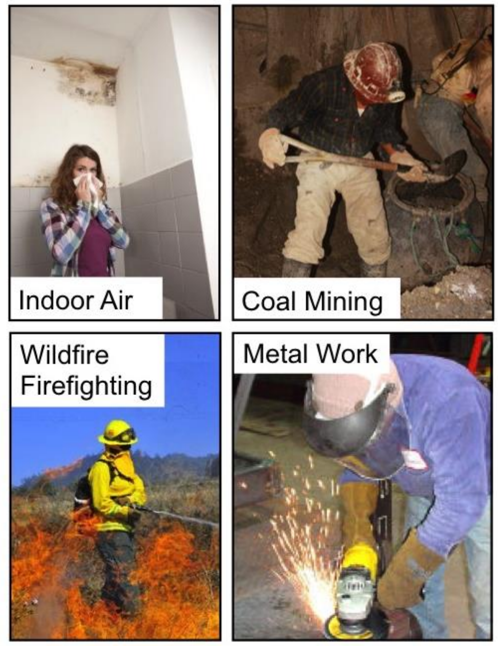


Figure 2. Particulate matter air pollution is a global problem. The AST product offers a lower-cost tool that enables widespread exposure assessment to create actionable change and improve health.

Access Sensor Technologies (AST) was founded on the belief that lower-cost wearable technologies can have a major impact on the health and well-being of people at risk for environmental and occupational exposure around the world. AST is developing a next-generation lower-cost air sampling tool, the Ultrasonic Personal Aerosol Sampler (or UPAS), to address the need for modernized airborne pollution exposure assessment. **Figure 3** shows a direct comparison between the existing UPAS prototype and current state-of-the-art measurement technology. By creating a disruptive lower-cost product for air sampling, we will enable a shift from infrequent exposure sampling of too few people to widely empowering professionals and citizens to understand their exposure.

Successful development of our product will provide environmental health professionals, industrial hygienists, and other risk assessors with a sensitive, in-situ technique to assess airborne hazards at reduced cost while setting the stage for production of a consumer level product in the future. Such technology represents a paradigm shift in the fields of environmental and occupational health by supplementing traditional lab analysis of air sampling filters with a real-time exposure tool that allows for immediate or same-day results that are later confirmed by accredited laboratories that analyze the resulting filter sample with established regulatory gravimetric analysis procedures.

The impact of a modern air sampler for personal exposure will ultimately produce better risk management in the workplace. This, in turn, will lower health care costs and extend worker productivity through improved health and reduced absenteeism. More quantitative risk assessment (and management) has the potential to catalyze structural and behavioral change that will have an enduring positive impact on workers and citizens (e.g. evidence-based policy changes in safety, emissions, tool and equipment design). Through the following Phase I specific aims, we have designed, developed, and tested a novel, lightweight, and inexpensive personal sampler to fulfill the need for a modern air sampling device for improved occupational monitoring.

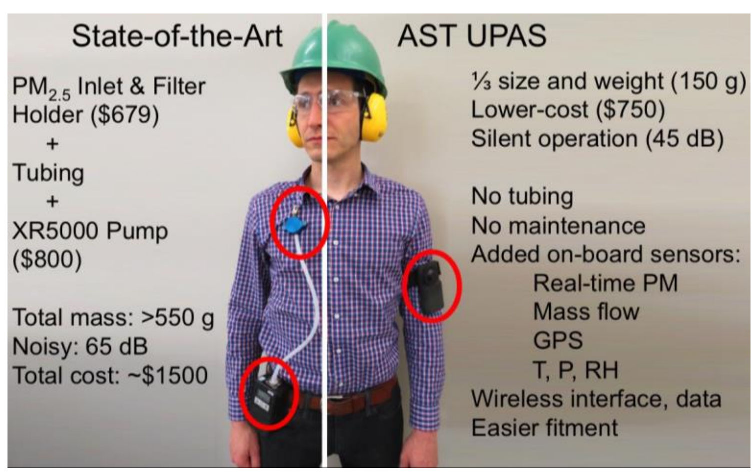


Figure 3. Old vs. new sampling. Left - The traditional sampling approach with a heavy pump, distracting tubing and separate filter with PM size selection. Right – UPAS prototype, a fully integrated air sampling solution.

Objectives 1 and 2 (100% completion):

Our Phase I Objective 1 focused on developing a pumping subsystem; Objective 2 focused on pump drive and flow measurement circuitry for active flow control. Our effort on the former began with a critical review of pumping technologies with potential to outperform diaphragm pumps (the current state-of-the-art). Performance evaluations were based on three primary categories: (1) system cost, (2) pump power/weight ratio, and (3) system simplicity/robustness. Secondary considerations included noise, vibration, and supply chain (potential for scalable manufacturing). We identified the Murata MZB1001T02 piezoelectric micropump (**Figure 4**), The Nidec-Copal TF029 centrifugal blowers/pump (**Figure 5**), and the existing Colorado State University (CSU) FP1 lobe pump prototype (**Figure 6**) as candidate pumping subsystems and conducted significant investigation and/or basic testing. Analysis of the centrifugal pump showed that while it had an impressive power density, it did not have favorable pressure/flow relationship and would yield lower energy efficiency and also control stability issues, especially at low flows. The existing CSU miniature lobe pump prototype had been developed based on published design guidelines. Further lab testing of the lob pump showed that elevated power consumption, larger size, and substantial complexity/engineering difficulty would be difficult to surmount.[2,3] Contrary to those concerns, piezoelectric pumping elements (referred to here as 'micropumps') are widely available due to their proliferation in the electronics industry (primarily for component cooling). After evaluating performance and pathways to commercialization, we chose the micropump over the miniature lobe pump for our Phase I efforts for several reasons. First, the micropump elements had the lowest cost ($8 ea., 3 required to meet flow/pressure requirements) and highest power/weight ratio (over an order of magnitude higher than lobe or diaphragm pumps). Second, the micropump is silent, lightweight, highly efficient and amenable to printed circuit board mounting (removing the need for internal tubing). *Those aspects allowed us to innovate (and patent) the most compact 1-2 SLPM air sampler developed to date.* A summary of the critical flow-normalized aspects of these three final pumping technologies we evaluated can be seen in **Table 1.**

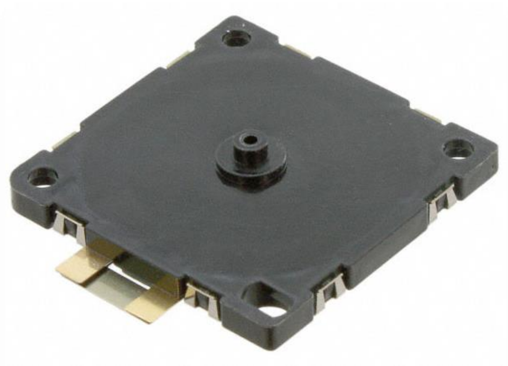


Figure 4. Oblique image of the outlet side of the Murata MZB1001T02 ultrasonic piezoelectric micropump element (three of which are employed in UPAS within proprietary, multifunctional manifold.)

Figure 5: Nidec-Copal TF029 centrifugal pump initially considered.

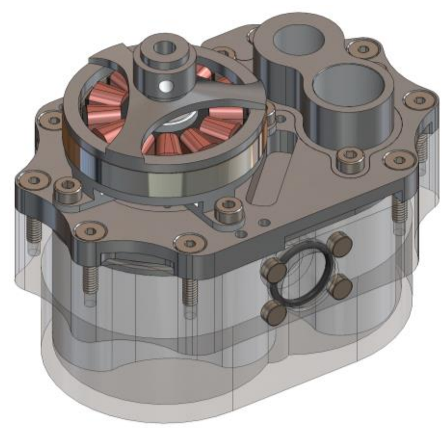


Figure 6: Translucent CAD model of CSU FP1 lobe pump prototype initially considered.

A single Murata MZB1001T02 piezoelectric micropump element (**Figure 4**) achieved a flow of 1.2 SLPM at max drive voltage, while passing air through a 37mm Pall Fiberfilm filter in an open-faced sampler. To serve the aerosol monitoring needs of the industrial hygiene sector, however, the device must flow up to 2 SLPM (through highly-loaded filters) to cover most NIOSH protocols. On the basis of the flow vs. pressure relationship for a number of micropump elements as seen in **Figure 7**, a manifold as seen in **Figure 8** was designed to house three piezopumps operated in parallel to achieve 2 SLPM at pneumatic loads relevant to filter sampling.

		Type of pump module	centrifugal	lobe	Piezopump
		(Identification)	Nidec TF029B	CSU FP2	AST UPAS assm.
Basic specifications	Height	(mm)	33	49	3.5
	Width 1	(mm)	41	57	48
	Width 2	(mm)	48	33	50
	Space (vol.)	(mm^3)	77000	41000	780
	Mass	(g)	55	65	8
Max. power/flow*	Max. Pressure~	(kPa)	2	12	4
	Max Flow	(SLPM)	7	11	3.6
	Power	(W)	14.9	17	2.2
	Efficiency	(SLPM/W)	0.47	0.65	1.64
	Sound	(dBA)	65	70	50
Sampling-relevant 2 ($L*min^{-1}$) flow*	Power	(W)	12	8	1.5
	Efficiency	(SLPM/W)	0.17	0.25	1.33
	Sound	(dBA)	57	65	45

**With clean 37mm MTL PT37 PTFE filter in AST UPAS cartridge, generating ~0.5kPa load*

Table 1: Comparison of basic performance metrics of mechanical pump subsystem candidates: Nidec TF029B centrifugal pump, CSU FP2 lobe pump, and the micropump based AST UPASv2 pumping manifold subsystems.

Next, we worked to develop an ultra-compact integration of a miniature mass sensor element that would allow for closed loop flow control. We selected several options from manufacturers Sensirion and Omron on the basis of size, cost, accuracy/precisions and ease of integration into our other chosen electronics. Both vendors sell small devices with accessible communication lines that can be read directly by a microcontroller or after an analog to digital signal conversion. The Omron D6F-P0010A1 sensor was selected based on ease of integration into a traditional bypass flow measurement layout on a custom manifold in a favorable form factor. To integrate this sensor into the UPAS, we directly mounted the bare sensor element to the top of our custom flow manifold/pump housing (**Figure 8**) to form a sensor-integrated flow duct. Development of this integrated pumping, sensing and flow control system that eliminates tubing and fits within <7 cm^3 of space was central to the pending US utility patent, and critical to achieving a truly disruptive wearable device. We also did initial experimentation with using a SDP31-500Pa sensor mounted directly to the PCB – moving to that sensor in the future will provide additional space, part cost and labor savings – *and yield a device where every single electronic component is mounted to the PCB which is mass manufactured at a low cost*.

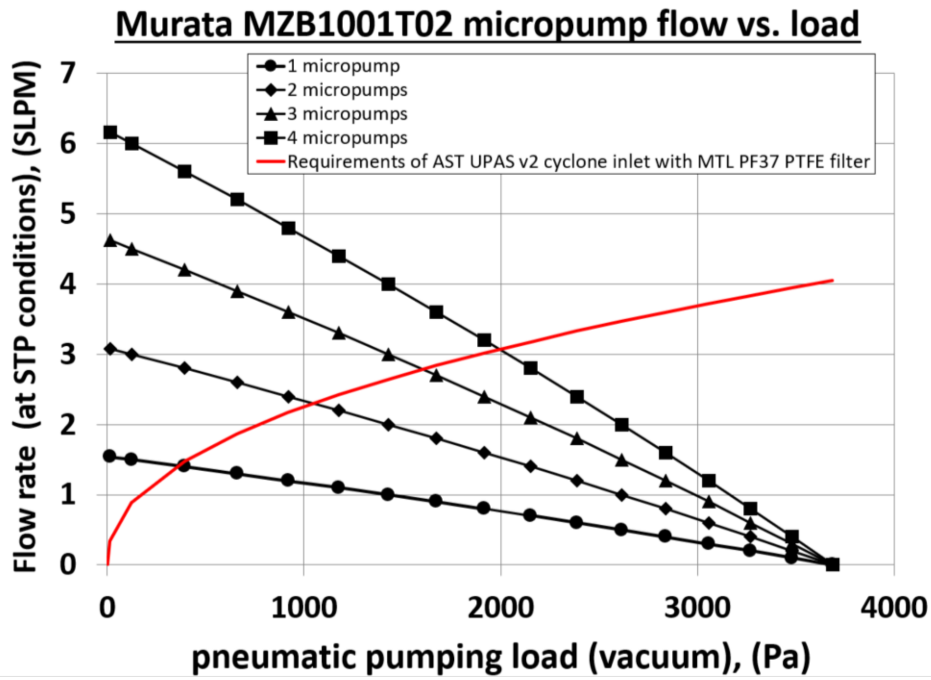


Figure 7. Piezoelectric micropump element flow rate vs. pneumatic load (pressure head) for 1-4 qty of micropump. Ideal operating range that yields good efficiency and control stability/controllability is highlighted in yellow. 3 qty micropumps were selected on this basis in light of application requirements.

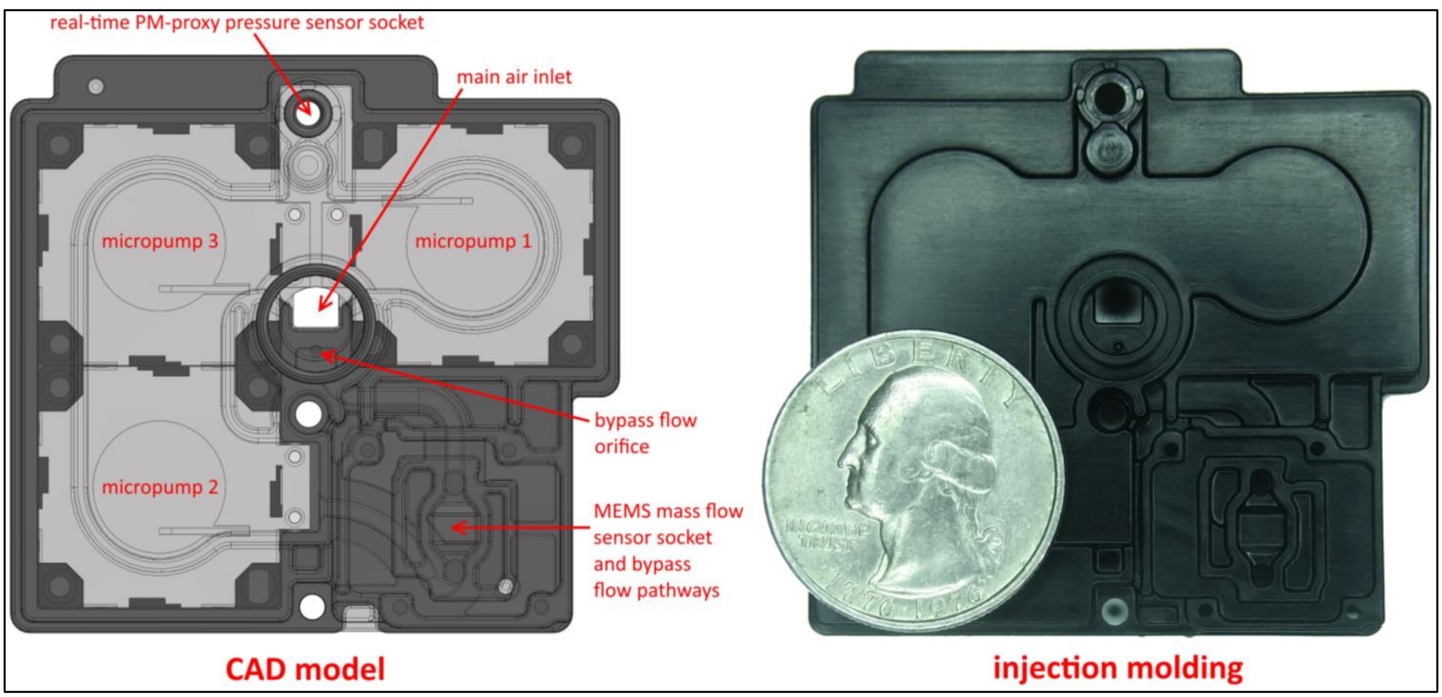
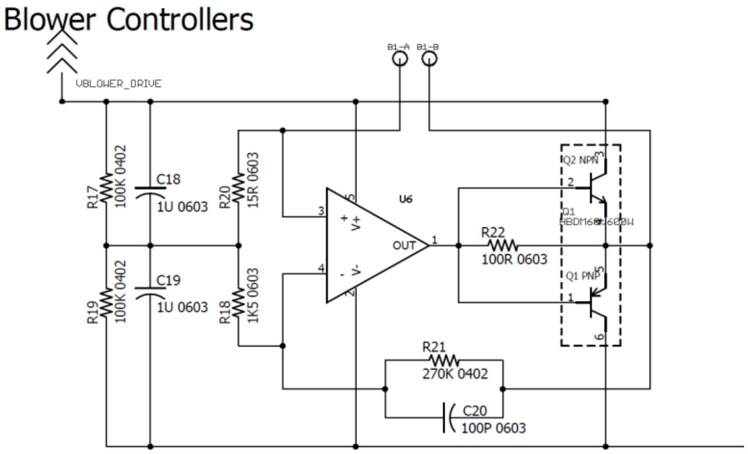


Figure 8. AST PCB-interfaced pumping module that integrates three micropump modules, MEMS mass flow sensor, real-time PM concentration proxy differential pressure sensor, and environmental sensors. Thickness in dimension normal to view is 3.5mm, weight 8g.



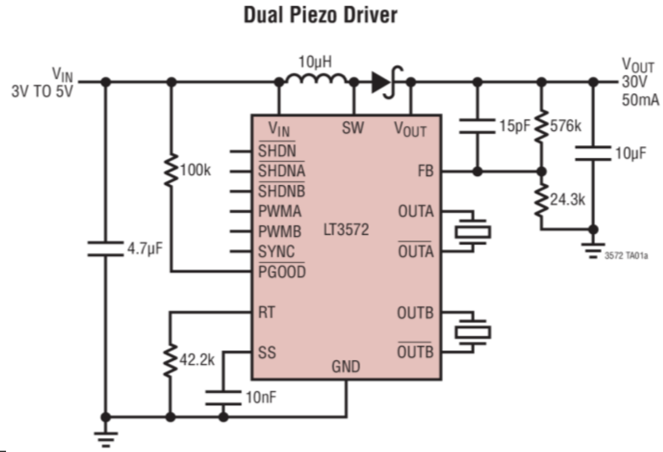


Figure 9: Circuit schematic for resonator-type piezo driver that was tested, and ultimately employed on the UPAS.

Figure 10: Circuit schematic for Linear Technology LT3572 piezo driver circuit which was tested, but not employed.

We evaluated two major branches of pump drive circuitry: (1) a traditional voltage booster plus a resonator-based circuit as seen in **Figure 9**, and (2) a single-chip, completely integrated driver circuit that includes both an internal charge booster and piezo driver (the LT3572, from Linear Technologies) shown in **Figure 10**. As seen in the test data provided in **Figure 11**, the LT3572 driver gives very similar, but slightly better performance than the resonator circuit. The LT3572 would require a much more sophisticated drive control scheme to be developed. We selected the resonator circuit option on that basis, as it was simpler to enact with fewer variables – and self-corrected for 'drift' in pump parameters (capacitance, response, etc.) due to temperature, load, aging, etc. The direct control variable in the circuit is the boost voltage, controlled through firmware via a digital potentiometer voltage divider. We will likely move to the LT3572 circuit in future work as the circuit is phenomenally small, simple and inexpensive. To do this we will need to develop much more complex controls on drive frequency, etc., in order to handle pump operation drift, etc. – all of which the simpler resonator circuit does not require.

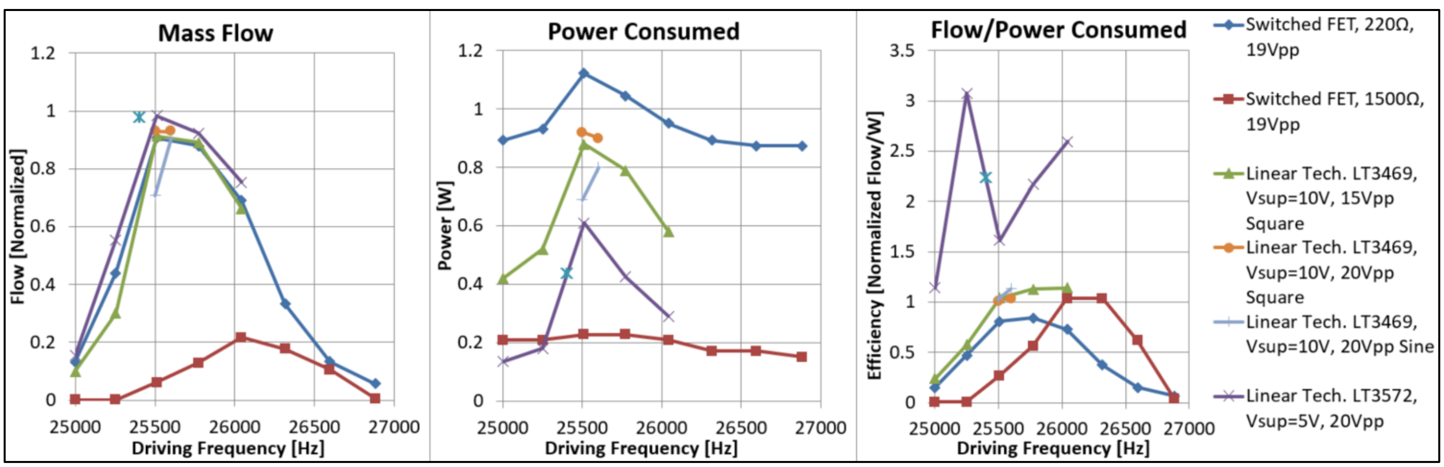


Figure 11: Schematic for resonator-type piezo driver that was tested, and ultimately employed on the UPAS.

Objective 3 (100% complete): Basic serial UPAS concept prototypes were originally developed at CSU under separate funding (R01OH010662, PI: Volckens). In conjunction with this Phase I project, AST licensed this fundamental UPAS technology from CSU, having elected to focus on the micropump pumping subsystem paradigm over diaphragm, centrifugal and lobe technologies (for reasons stated above). The original CSU prototypes shown in **Figures 12A-C** initially feature off-shelf proto-board electronics and later, a basic custom-printed circuit board with an integrated microcontroller (mbed^{TM}; ARM$^{®}$ Ltd. STM32) and housing and mechanical components formed via stereolithographic (SLA) and selective laser-sintering (SLS) 3D printing processes. A stand-alone Bluetooth Low-Energy^{TM} development module was included for app-based wireless communications and programming (iOS and Android).

The AST prototype is shown in **Figure 12D** and includes critical and novel upgrades and improvements over the initial, basic CSU technology: a manufacturable injection-molded sensor-integrated pumping manifold featuring a new real-time PM proxy sensor, a water and bug-resistant threaded cyclone inlet with exchangeable molded filter cartridge, an impact-resistant and highly-compact molded housing, an ultra-efficient power supply and charge controller, a high-resolution pump drive controller, a GPS receiver, accelerometer, many additional circuit enhancements, and wide-ranging functional improvement and industrialization of the controlling firmware. The novel, multi-hole inlet cap avoids flow blockage from a single inlet design (**Figure 13, 14**), offers significant rain and bug-ingress resistance, and allows the cyclone to be sunk further into the housing by integrating the cyclone outlet into the top of the filter cartridge. All pneumatic seals are formed via o-rings so that when the cap is screwed tight, the flow train of cyclone, filter cartridge, and pump inlet are all connected without leaks. The final prototype is compact, with total geometry of 127 x 70 x 23 mm (main body), and a weight of 220 g. *There are no samplers on the market remotely close to this specification – especially not integrating size-selective inlets, sampler, pump, and accompanying sensors.*

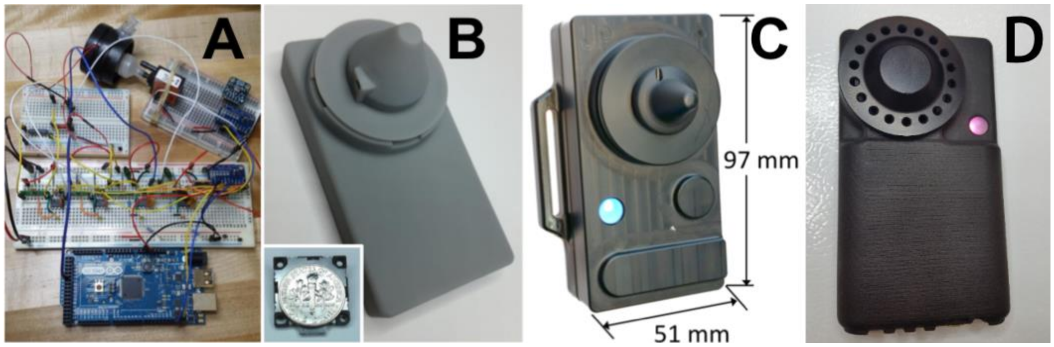


Figure 12. Full history of the development of the Ultrasonic Personal Sampling Pump (UPAS): (A) CSU Breadboard circuit and pump; (B) CSU rapid-prototype proof-of-concept device; (C) CSU initial machined prototype; (D) AST's final prototype featuring low-profile design (127 x 70 x 23 mm), threaded interchangeable $PM_{2.5}$ inlet, GPS module, and internal filter cartridge.

Figure 15 contrasts the compact 'tubing free' design of the UPAS to the Omni personal sampling pump (Mesa Labs) – a diaphragm pump that typifies the current state-of-the art for wearable, active air samplers. In the diaphragm pump design (right side of **Figure 15**), the individual flow system components (inlet, pressure taps for a mass flow sensor, pump, and noise-reducing baffles) are connected via tubing, which necessitates considerably expensive assembly labor, a large internal void volume and greater weight. Shown at the right of **Figure 15** is the UPAS (for details on the inner workings of the flow system see **Figure 19**). In the UPAS, every single electronic component associated with flow is mounted directly to the circuit board and sealed by an injection-molded manifold (mass flow sensor connects via top side of manifold). The flow manifold is bonded to the printed circuit board (PCB) with a laser-cut piece of adhesive foam to constrain pumped airflow over surface-mount sensors on the PCB without the need for tubing or other pneumatic connectors. This innovative (patent-pending) design affords a dramatic reduction in part count and device size.

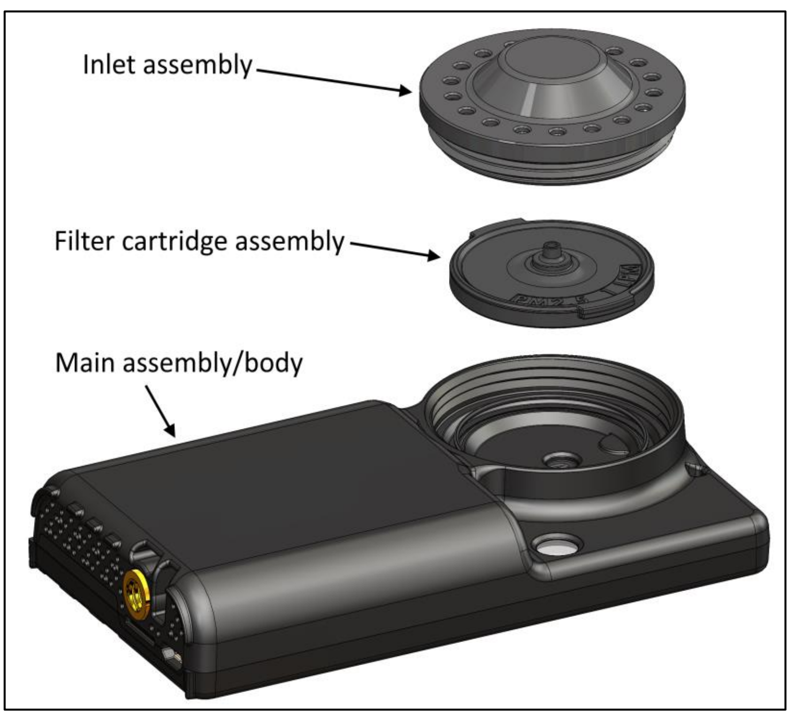


Figure 13. AST UPAS showing the main components which are separated to install/remove filter cartridges.

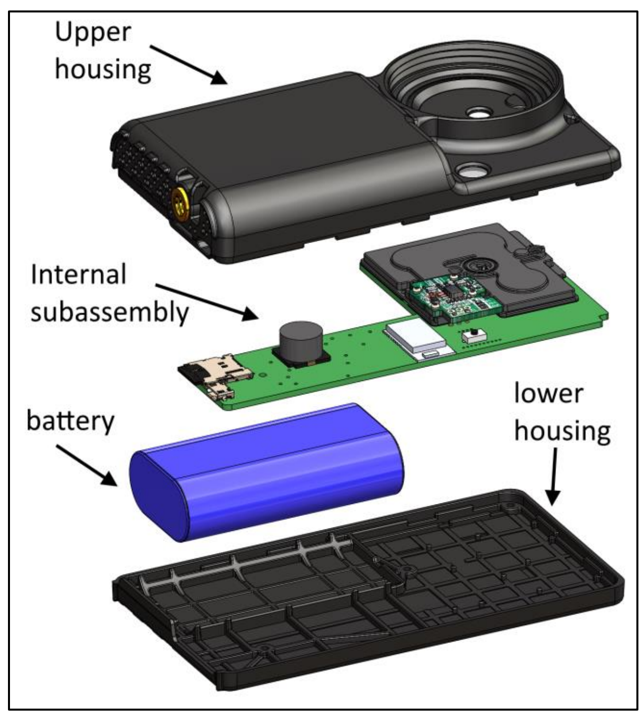


Figure 14. AST UPAS main internal components

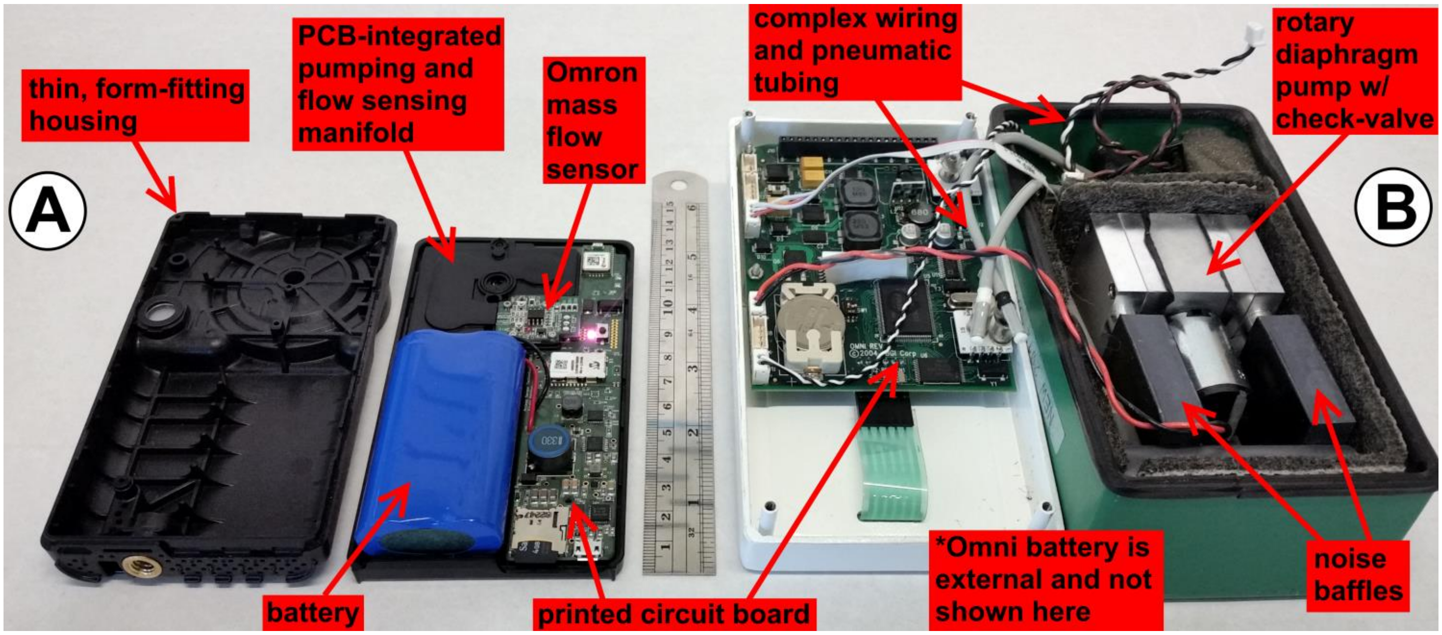


Figure 15. Internal components for AST UPAS prototype (LEFT, A) vs. Mesa Labs Omni personal sampling pump ($3,000 retail, RIGHT, B)

AST licensed the functional, internal geometric parameters of a miniature cyclone, designed by the Volckens' group at CSU, to provide an aerodynamic size cut of 2.5 microns ($PM_{2.5}$) for the sampler inlet. Kenny and Gussman[5] showed that for cyclones of the same shape, the relationship between d_{50}, the aerodynamic diameter of particles collected with 50% efficiency expressed in µm; D_c, the cyclone diameter in cm; and Q, the flow through the cyclone in SLPM, is

$$\ln(d_{50}) = a + b\ln(D_C) + (1-b)\ln(Q) \qquad (1)$$

where a and b are constants that depend on the shape of the cyclone. For cyclones they designate as "sharp cut," Kenny and Gussman[6,7] report that a = 1.447 ± 0.018 and b = 2.131 ± 0.017. These values were used with Equation (1) to determine the cyclone diameter that would operate at 2.0 SLPM and have a d_{50} of 2.5 µm.

Cyclones designed using this method were rapid-prototyped and tested to determine their efficiency as a function of particle size; from these curves revised values for constants *a* and *b* were determined and the iterative process continued until the measured and intended performance of each cyclone matched the $PM_{2.5}$ standard.

AST then worked to translate these fundamental cyclone geometric elements into an inlet system which: (1) allows the user to remove the inlet via thread-on inlet cap to get at a (new, AST-designed) exchangeable filter cartridge, (2) provides rain and bug ingress resistance via protective sheltering and a screen, (3) allows easy disassembly for routine

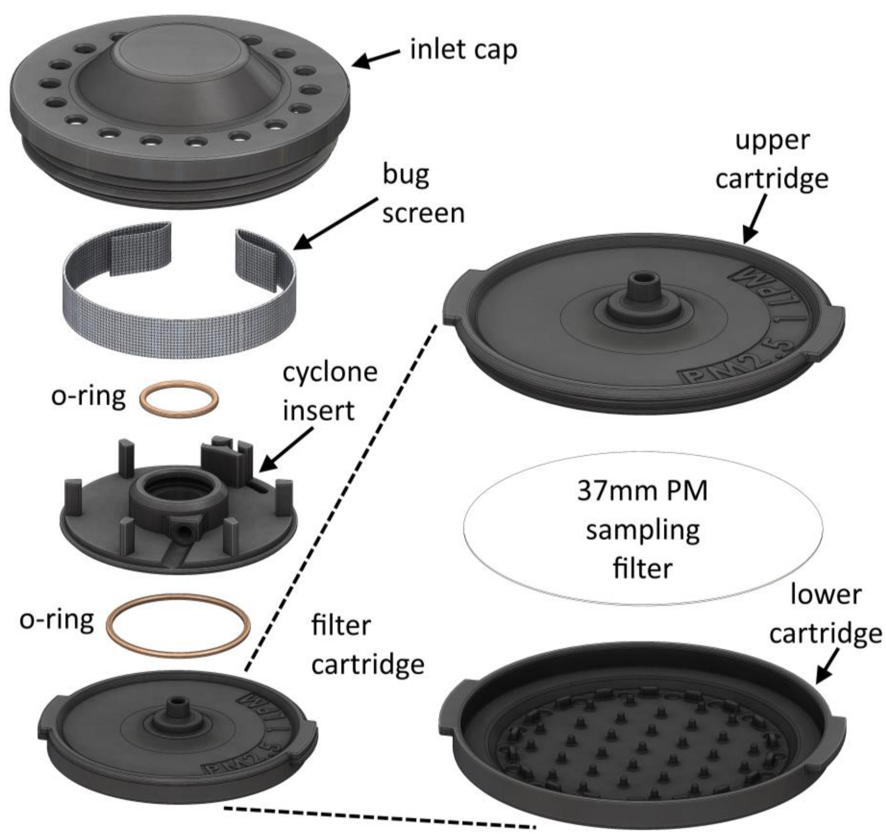


Figure 16. Exploded CAD view of size-selective inlet system of the AST UPAS, including breakout of the filter cartridge, showing details of filter support structures and drain holes.

cyclone cavity cleaning - all in a compact, low-height, lightweight and leakproof embodiment which is quite amenable to high-volume manufacturing methods at an acceptably low cost. As with the rest of our work, AST designed, fabricated and tested numerous prototype generations in order to achieve these functions and form-factor.

AST developed numerous designs of the aforementioned modular cartridge which allows the user to safely handle and swap sampling filters in the field without risk of contamination. Iterations of parts were fabricated using stereolithographic plastic and tested before cyclone inlet cap and insert were made via machining, and the upper and lower cartridge halves were made in a low-cost prototype plastic injection molding process. The CAD model of our final design and construction can be seen in **Figure 16**. These cartridge prototypes were extensively tested both in the laboratory and field to verify that proper support is provided to the filter, and that support-based effects on the collected PM (i.e. support 'blinding', etc.) were minimal and acceptable. *The cartridge we developed weighs only 3.3g – far less than any sort of filter-holding cartridge presently on the market.*

All of the subsystems described above were developed substantially on their own before we worked them into the tightly-integrated printed circuit board and housing designs through numerous iterations of the classical conceptualize->CAD model->prototype->test->review cycle. We relied heavily on our FormLabs stereolithographic 3D prototyping machine and outside rapid machining services for manifold and housing parts. Three generations of printed circuitboard were prototyped and tested. Greater than 200 iterations of firmware were generated and tested in order to get excellent flow control and smooth operation. *Many prototypes were assembled, tested and deployed by early-adopter partners in the United States, Canada, Ecuador, Peru, China, South Africa, Ethiopia and Uganda during our Phase I work.* ***Figure 17*** *shows some examples of the many prototypes built during our work.*

Figure 17. Examples of the many different iterations of prototypes of the UPAS sampler that AST built during our Phase I activities.

As the AST UPAS uses a MEMS anemometric mass flow sensor element (the Omron D6F-P0010A1) applied to our custom bypass manifold to measure the mass flow through the device, we needed to establish a means to calibrate the sampler. We developed a set of hardware and code for this purpose. A Bronkhorst F-101-DI primary mass flow sensor was coupled with a National Instruments FieldPoint modular distributed I/O unit to communicate with a custom LabView UI on a PC. A flow adapter and tubing connected the UPAS to the Bronkhorst flow primary. A special script and UPAS operating mode was devised and included in the firmware such that the user merely connects the UPAS to this system via micro USB cable, enters some parameters and settings in the LabView VI (i.e. user interface application), and initiates the process. The calibration system then essentially walks the UPAS from minimum to maximum pumping power by way of many power level step 'data points'. The UPAS is held at each power level until both the measured mass flow through the Bronkhorst F-101-DI system mass flow primary, and the signal from the Omron D6F-P0010A1 onboard the UPAS stabilizes – and then takes a mass flow reading from the former, and a resolved output voltage from the latter. This is done for all power levels between idle and maximum. A script then fits a 4^{th}-order polynomial to the relationship of UPAS Omron mass flow sensor signal voltage and calibrated mass flow. This polynomial is then programmed to the UPAS non-volatile EEPROM. The UPAS is then able to use that polynomial transfer function to convert voltage coming from its mass flow sensor into measured mass flow during active pumping/sampling. This process of calibrating the UPAS mass flow sensor is itself verified to usually achieve <1% of value error. A slight amount of additional error in UPAS volumetric flow rate is associated with error in temperature, pressure and relatively humidity measurement and which feeds through the density calculation. The success of our calibration system is not a small feat considering that most existing samplers use a pressure-drop basis means of measuring mass flow – which has less inherent challenges but requires an energy-wasting intentional pressure drop in order to work. Our method removes that loss. In numerous cases UPAS which have been deployed in real-world scenarios for several months were received back and evaluated to show no change in their operation from that after initial calibration. This suggests that the sensor signals are stable over time and use.

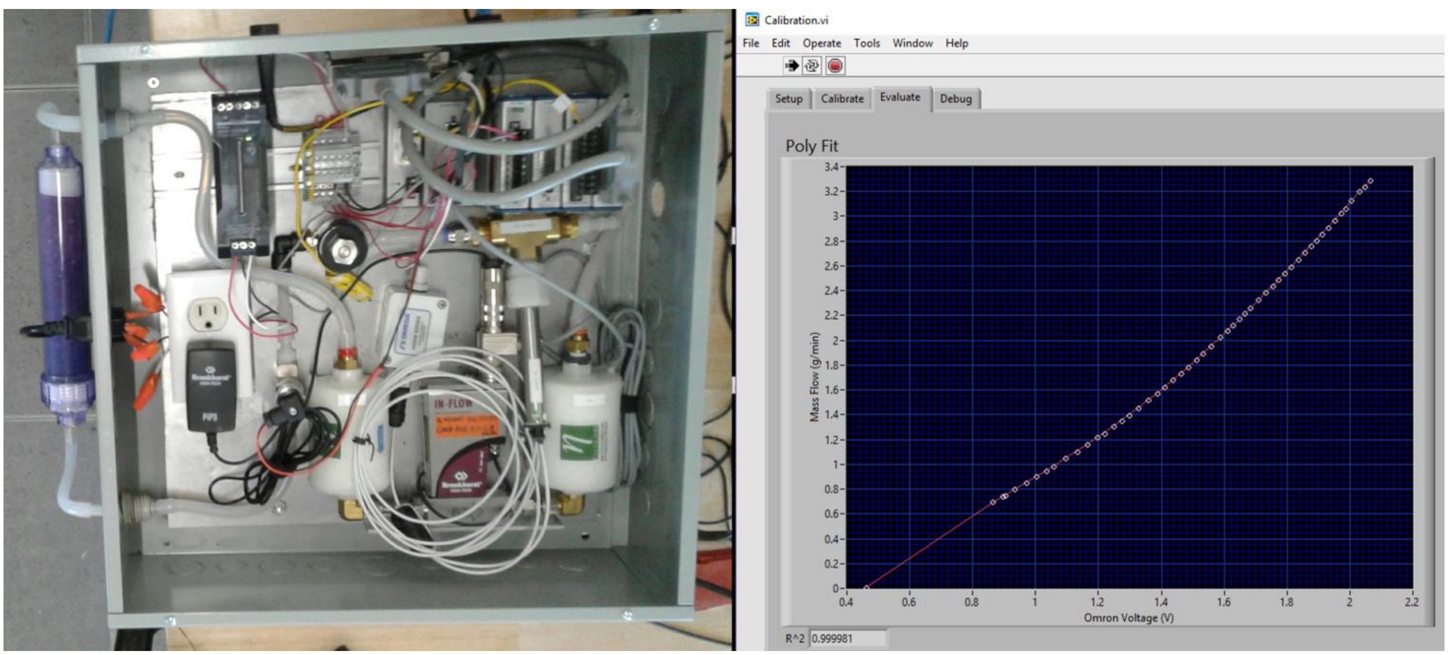


Figure 18: UPAS calibration station hardware (left view), and screenshot (right view) of application including the polynomial curve fit relating UPAS mass flow sensor output ('Omron Voltage (V)', X-axis) and calibrated mass flow rate (Y-axis) for an actual UPAS that was calibrated.

Description of device operation

To initiate operation, the user sequentially completes the following steps: power on the UPAS, open up the smartphone application (app) and use the app to connect the phone and UPAS via Bluetooth, complete sample identification fields (subject ID, filter cartridge ID, etc.), set the desired sampling duration, and initiate sampling. At this point the UPAS is mounted to the user within their breathing zone (arm band, shirt clip, lanyard, chest strap, or backpack clip) for the entire sampling duration. The microcontroller and firmware within the UPAS then maintains sample air flow at the desired volumetric flow rate as preset in the range of 0.1-3 SLPM (as appropriate for the size-selective inlet), accurate to within +/- 4% of setting. Logged data files can be transferred to the personal device via Bluetooth connectivity with the app, or simply through physical transfer via removal of the micro-SD card. The UPAS samples PM though a size-selective inlet (currently limited to $PM_{2.5}$) and collects the sample onto a standard 37 mm filter, which is located in a secure, portable filter cartridge. The sample air flow path is as follows: particulates of all sizes flow into the entrance of the inlet (flow pathway 1 in **Figure 19**) and move towards the cyclone within the inlet cap. The cyclone geometry (flow pathway 2 in **Figure 19)** is specifically tailored such that only $PM_{2.5}$ may penetrate down to the filter (flow pathway 3 in **Figure 19**). Downstream there are onboard sensors that measure sample air mass flow rate, temperature, pressure, and relative humidity. The unique measurement of differential filter pressure (flow pathway 3 in **Figure 19**) proposed here will allow for estimation of PM concentration deposited on the filter in real-time. The device also includes GPS and an accelerometer (to measure a person's activity level), both of which are practical but not traditionally incorporated onboard with personal samplers. We chose a filter diameter of 37 mm because it is a standard size sold by virtually all commercial vendors and because this size allows the user to perform multiple secondary analyses from a single filter (via a punch) while archiving the remainder. A micro-USB port provides charging for the internal lithium-ion battery and a means of updating device firmware. We developed a duty-cycle sampling regime that allows the battery endurance of the UPAS to be extended by enacting an on/off cycling of the pump on a 30 second cycle basis (i.e. at a 50% duty cycle, the UPAS pumps/samples for 15 seconds, and then sits idle for 15 seconds, repeatedly). Duty cycle sampling generally increases battery endurance by the inverse of the duty cycle fraction (e.g. in a scenario where the UPAS runs for 40hrs at 1 SLPM continuous on a fully charged battery, it's endurance is increased to nearly 80hrs when running at a 50% duty cycle). This is a very powerful tool for researchers needing to cover extended deployments on a single battery charge – or needing to reduce the collected sample mass for gravimetric or other purposes on the basis of the environment having extremely high PM concentrations.

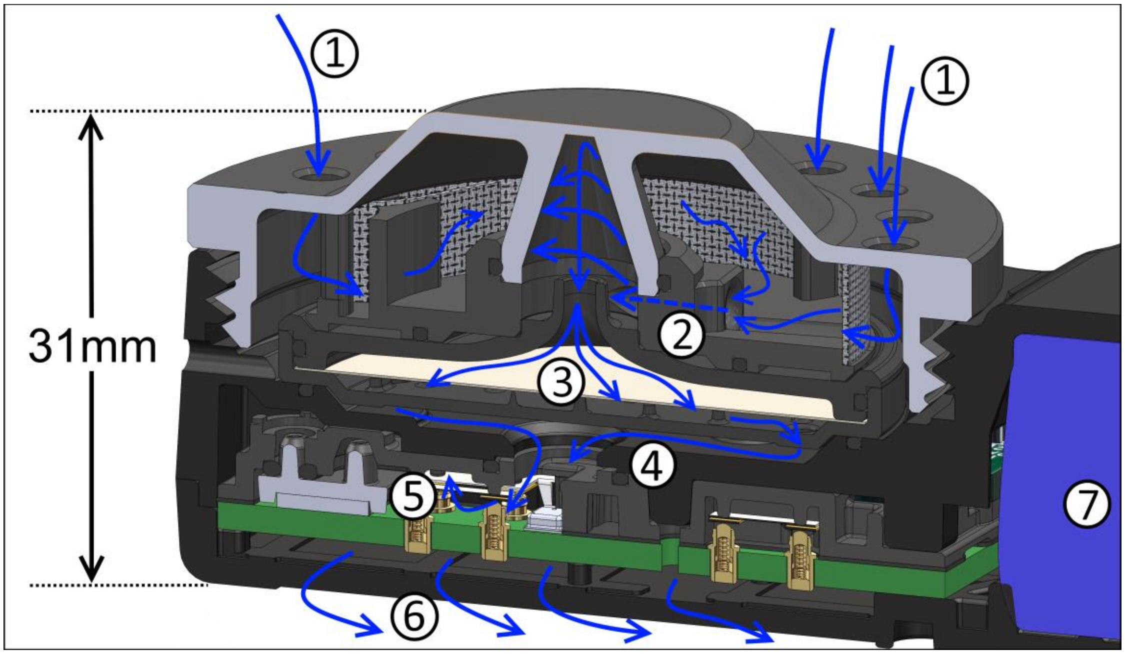


Figure 19. Illustration of flow pathways and progression of air flow (following numbers) within the UPAS size-selective inlet (cut-away section view)

Industry representatives and practitioners, researchers, public citizens have shown great interest in the UPAS system because of how easy it makes workplace sampling (mining, construction, manufacturing, and agriculture), large-scale sampling for epidemiologic studies, and individual sampling for the citizen scientist. Our Phase I work led us to the design of a device that was functional enough to be produced in pilot quantities. We have been actively selling small quantities of these UPAS alpha-prototypes to the academic research community (primarily for epidemiological research) since February 2017, with positive feedback and excellent results, indicating the market pull is present even without an active marketing program.

Objective 4 (100% completion): The fourth and final objective for the Phase I project was to evaluate the performance of the prototype relative to standard reference instruments.

The UPAS was rigorously tested for its ability to control sampled air volumetric flow rate using its combined system of integrated mass flow sensor, ambient air pressure/temperature/relative humidity sensors and subsequent control scheme. The UPAS has repeatedly proven it can reliably hold volumetric flow rate (i.e. $L*min^{-1}$) to well within our initial goal of +/-4% of reading (%OR) when evaluated against a primary flow standard (Alicat Whisper 5 SLPM, and Bronkhorst low-ΔP series meters, both having 0.5%OR accuracy). The UPAS can fully account for ambient air density changes which occur from rising or falling temperatures, changes in barometric condition, or changes in subject altitude above sea level. We tested the UPAS in an atmospheric chamber which could be pressurized or depressurized substantially – and found virtually no error associated with such changes. The UPAS prototypes have been employed by early adopters in altitudes up to 12,000ft above sea level and was found vs. mobile primaries (Alicat Whisper 5 SLPM) to hold volumetric flow rate the same as at sea level. The UPAS thus ranks with all prior-art and competing sampling pump technologies presently on the market – and better than many in terms of its ability to quickly adjust for changes in air density, the precision of its drive power control adjustment, etc.

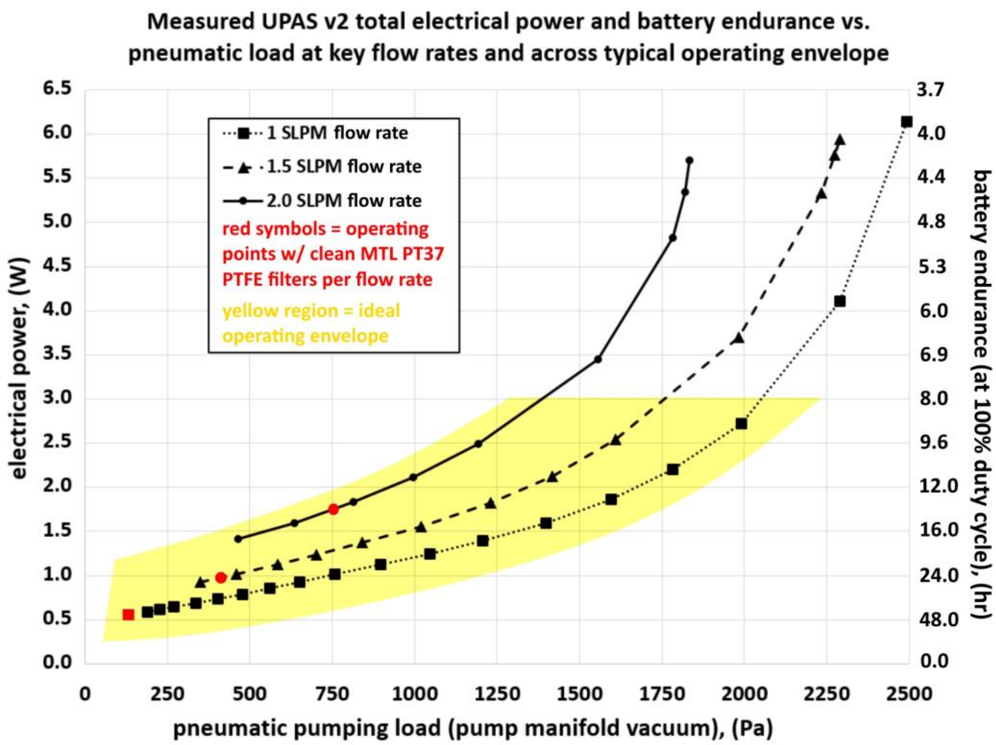


Figure 20. Pneumatic pumping load (associated with filter and inlet) vs. required total device electrical power and associated battery endurance for AST UPAS at 1.0, 1.5 and 2.0 SLPM flow rates. Red icons represent the operating points of typical new/clean 37mm filters at the respective flow rates and yellow region outlines the ideal operating envelope.

The UPAS was evaluated for its efficiency and resultant battery life – the latter being very critical for completing sampling deployments. The internal UPAS battery (lithium-ion; rechargeable via a micro-USB port on the side of the unit) lasted approximately 15 hr at 2.0 $L*min^{-1}$ and 42 hr at 1.0 SLPM (in Fort Collins, CO air density), respectively, when sampling air through a 37 mm Pallflex Fiberfilm filter and with all other sensors running. Pneumatic pumping load vs. total device electrical power (including microprocessor and sensor operation) and subsequent battery endurance (how long until battery 'dies') for the three flow rates of the UPAS is intended to run at is shown in **Figure 20** (adjusted to standard temperature and pressure (STP) conditions for these tests). The yellow shaded area on the figure represents the ideal operating envelope. While the UPAS can operate substantially outside of this envelope, it will do so at lower efficiency. The practical operating range of the device spans up to 2.5 kPa (~10 in-H_2O) of static pressure head at 1 SLPM, or, upwards of 3.5 SLPM through a typical sampling filter at full power. The UPAS is capable of drawing air against 2.5 and 1.8 kPa of backpressure at 1.0 and 2.0 SLPM flows, respectively[4]. This encompasses the requirements of all typical (market-available) sampling filters at up to 2 SLPM flow, while loaded with substantial amounts of sample PM. Shown also in **Figure 20** are three red points that correspond to the flow-pressure relationships for the UPAS running with a clean/new typical 37mm sampling filter installed in the full inlet system (i.e. an MTL PT37 PTFE membrane installed in the UPAS cartridge within 1.0, 1.5, and 2.0 SLPM $PM_{2.5}$ inlets). Those locations on the three flow rate curves represent the device operating points (pneumatic load, electrical power, and thus battery endurance).

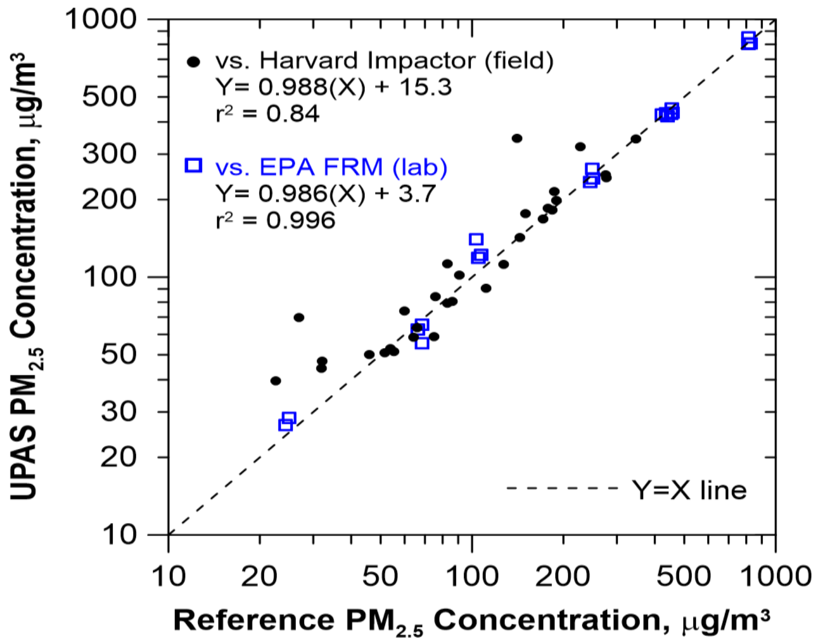


Figure 21. UPAS validation for $PM_{2.5}$ mass from lab (□) and field (•) campaigns.

At 20 cm (the approximate length from the ear to a hypothetical sampler mounted on a lapel within the breathing zone) the UPAS produced 45 dB of A-weighted noise. For comparison purposes, the PEM and XR5000 pump combination emitted 65 dB under similar conditions.

Chamber tests were conducted at Colorado State University to evaluate the performance of the UPAS relative to the EPA federal reference method (FRM). Results of these tests are shown in **Figure 21**. Chamber concentrations spanned a range from 25-800 μg/m^3 over these tests. The UPAS showed a strong correlation to the EPA FRM across the range of test concentrations. A simple linear regression between the UPAS and FRM gave a slope of 0.996 with an intercept of 3.7 μg/m^3. Among replicate samples (i.e., instruments co-located within the chamber), the coefficient of variation was 1.4% for the FRM and 5.1% for the UPAS. The average difference (in absolute terms) in measured $PM_{2.5}$ mass concentration was 7% between the UPAS and FRM. A Bland-Altman analysis showed no directional bias between the UPAS and FRM measurements as a function of chamber concentration (data not shown). Shown also in the figure (black circles) are stationary/site sampling co-location results (UPAS vs. Harvard Impactor sampler) collected in India for biomass combustion aerosol. The field comparison tests show good agreement when sampling under uncontrolled conditions.

At time of writing this final report, no less than 15 U.S., Canadian, European, Asian and South American research groups are using the UPAS v2 prototypes to gain useful personal exposure data in the field. Initial feedback on data yet-to-be-published continues to support the statement that the UPAS is working well as a drop-in for the cumbersome traditional sampling equipment it seeks to replace. One example we have been given permission to share, is the initial data of a study by the Dr. Maggie Clark research group at Colorado State University on personal exposure to indoor biomass cookstove emissions (The Honduras Cookstove Intervention study). **Figure 22** shows a scatterplot comparison of PM2.5 concentration levels found through simultaneous side-by-side personal (same human subject) gravimetric sampling with UPAS v2 vs. the commonly used BGI Triplex SCC1.062 sampler powered by a separate SKC AirCheck XR5000 sample pump (~750g total sampler + pump weight). The initial data from this study of n=44 samples showed good agreement between the two samplers, yielding a Pearson correlation coefficient of r=0.86 and Spearman coefficient of r=0.83. *Furthermore, anecdotal feedback from practitioners using the UPAS v2 prototype suggests that the device is not only working well, but allowing research that would otherwise be virtually impossible because of the constraints which traditional sampling apparatus put on cohort and study workers alike.*

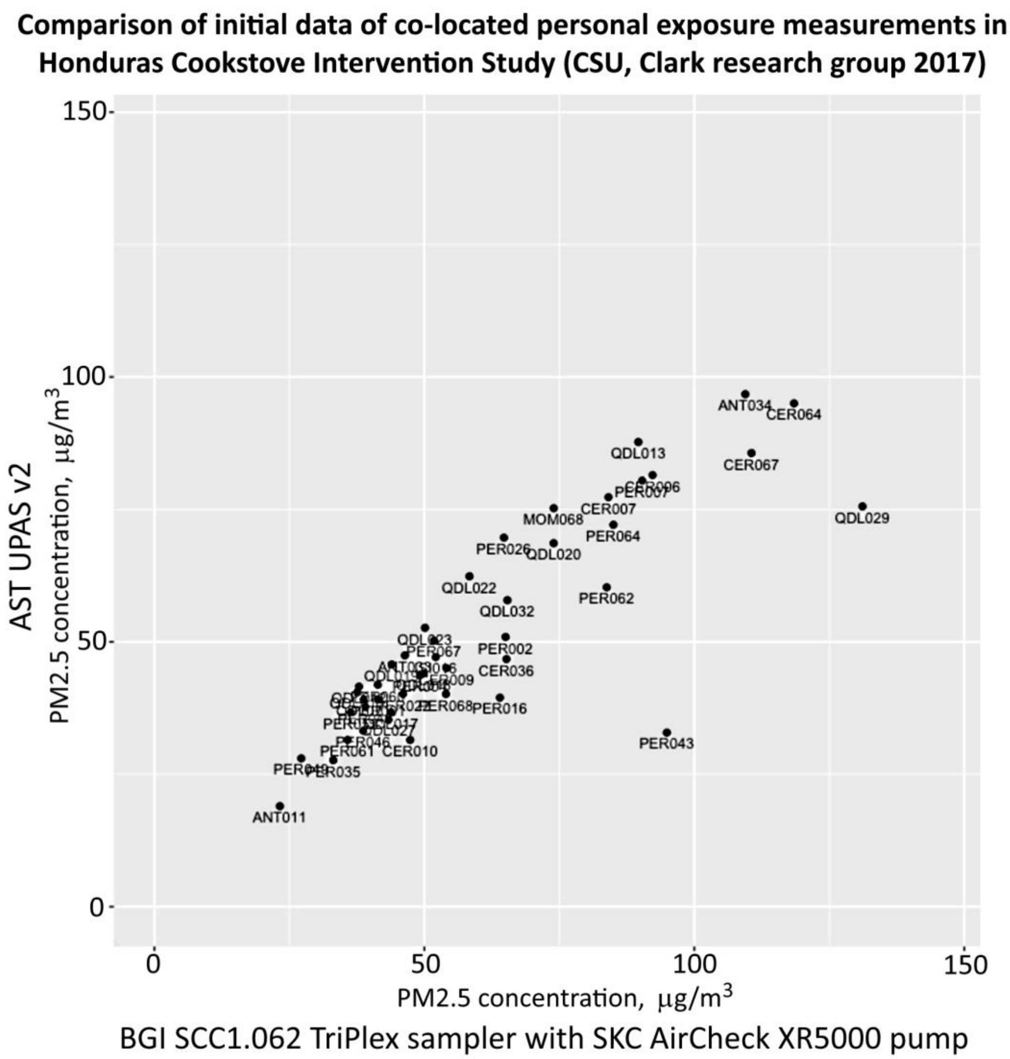


Figure 22. Comparison of initial data of n=44 samples of personal exposure measurement simultaneously co-sampled (same human subject) over 24 hours, 1:1 scale. (approval to include this unpublished data granted by Dr. Maggie Clark, CSU).

Publications:

1. Volckens, J., Quinn, C., Mehaffy, J., Henry, C.S., and D. Miller-Lionberg. (2017) "Development and Evaluation of an Ultrasonic Personal Aerosol Sampler (UPAS)." Indoor Air. 27(2): 409-416 doi: 10.1111/ina.12318
2. Miller-Lionberg D, Volckens J: (2017) Portable Air Sampling Device (pending). USPTO Utility Patent Application 15442657.

Cumulative Inclusion Enrollment Table

Not applicable.

Materials Available to Other Investigators:

The air sampling device, named UPAS, that resulted from this project is currently available for sale. All interested parties can inquire via our website for a quote or more information. The data contained in our publication on the technology is also available online.

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(4) Volckens, J.; Quinn, C.; Leith, D.; Mehaffy, J.; Henry, C. S.; Miller-Lionberg, D. Development and Evaluation of an Ultrasonic Personal Aerosol Sampler. Indoor Air **2017**, 27, 409–416.

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