Syracuse University

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Final Scientific/Technical Report

Micro-Environmental Control System

Contract Number 03330

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Program Director:	Dr. Marina Sofos
Principal Investigator:	Dr. Edward A. Bogucz
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Public Executive Summary

This project developed an innovative micro-environmental control system (µX) that enables office buildings to reduce energy used for heating and cooling by 15% or more. The µX is a compact, quiet, and ergonomic device that is designed to be installed under an office workstation; it is designed to maintain occupant comfort when room thermostat setpoints are incremented by 4°F or more (warmer in the summer and cooler in the winter) to save energy. When ambient room temperatures are outside of the usual comfort range, the µX maintains occupant comfort by delivering personalized cooling or heating locally to each office worker.

The µX provides personalized cooling using a micro vapor compression system that includes a new high-performance micro-scroll compressor and a novel thermal storage unit. The vapor compression system operates at night to freeze a phase-change material (PCM). During the workday, the cooling stored in the PCM is released as a cool breeze of air to make occupants more comfortable. The micro-scroll compressor was developed specifically for this application; it is smaller than any of its type, minimizing the amount of power needed. In heating mode, the µX maintains occupant comfort using a foot heating mat with an infrared reflective box.

The µX R&D project was conducted by Syracuse University in collaboration with United Technologies Research Center, Air Innovations, Bush Technical, and Cornell University. Over the course of the initial three-year project, the team developed and evaluated four versions of the unit, advancing the concept to Technology Readiness Level 6. The capabilities of individual proof-of-concept prototypes were verified in tests that were conducted with: 1) units in psychrometric chambers, 2) an instrumented manikin in a laboratory, and 3) human subjects in laboratories that simulate office environments. The tests verified that the µX prototypes met or exceeded all performance targets required to enable office buildings to reduce energy used for heating and cooling by 15% or more by maintaining occupant comfort when thermostat setpoints are incremented by 4°F or more.

Acknowledgements

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Accomplishments and Objectives

This award allowed Syracuse University to collaborate with United Technologies Research Center, Air Innovations, Bush Technical, and Cornell University to develop and demonstrate an innovative Micro Environmental Control System (µX). The original project was organized into nine Tasks that included a total of 41 milestones. At the successful conclusion of all milestones in the original Tasks, a tenth Task was authorized. Task 10 added four milestones associated with conducting a field trial of a pre-commercial version of the unit deployed in two buildings. Disruptions caused by the COVID-19 global pandemic prevented the field trial from being completed during the original performance period, and this testing will now be conducted post award.

At the beginning of the project, tasks and milestones were laid out in Attachment 3, Technical Milestones and Deliverables. Actual performance against the stated milestones is summarized in Table 1, below.

TABLE 1. KEY MILESTONES AND DELIVERABLES

Tasks	Milestones and Deliverables
Task 1. µX Analysis & Optimization 1.1 Define Requirements 1.2 Develop model of PCM melting & freezing 1.3 Develop model of µVCS with PCM/evaporator 1.4 Develop CFD model to evaluate air terminal device 1.5 Combine models into an integrated µX model 1.6 Exercise models to simulate & optimize µX design	**M1.1 PCM simulation model completed –** *A simulation model of the phase-change-material (PCM) module that predicts the time-dependent rates of melting & freezing as a function of geometry, air flow, refrigerant flow and temperatures.* Actual performance (completed 7/23/15): Reduced-order (RO) one-dimensional (1-D), Quasi two-dimensional (2-D) and 2-D simulation models were developed to predict the time-dependent rates of melting and freezing as a function of PCM/Evaporator geometry, air flow, refrigerant flow, and temperatures. These fast-executing RO models are intended for repetitive and iterative design analysis and optimization. The RO models of the PCM/Evaporator were enhanced through the use of the COMSOL Multiphysics® finite-element computer code to include the three important PCM melting effects: 1) 2-D conduction in the PCM; 2) natural convection in the melt; and 3) conjugate heat conduction through the evaporator's aluminum tubes, which act as surface enhancement (fins) in the melt. The incorporation of natural convection and conjugate conduction improves the cooling rate (increases it and makes it flatter). **M1.2 Workstation/Air Terminal Device (ATD) simulation model completed –** *A simulation model of a workstation with a computer-simulated person (CSP) and an ATD delivering a specified volume of air at a specified temperature to predict changes of the CSP's heat loss as a function of room conditions and those of the air issuing from the ATD.* Actual performance (completed 7/30/15): A computational fluid dynamics (CFD) model with a CSP and an ATD show that more than 25 W can be removed from the CSP when compared to the solution obtained with the ATD turned off. In the model, the ATD

	(a rectangular slot) is mounted immediately under the desktop, delivering 20 cubic feet/minute (cfm) of conditioned air at 71.2°F. The air velocity exiting the ATD is 1 m/s, directing air toward the torso of the CSP. Trade-offs of airflow vs. conditioned air temperature (at 50 W of cooling) were performed, as well as studies of the effect of CSP location within the 0.61 m range of movement from the ATD. **M1.3 Integrated µVCS simulation model completed** – *A simulation model of the integrated µVCS that predicts its steady-state & transient capacity & coefficient of performance (COP) under a range of operating conditions and PCM freezing & melting times.* Actual performance (completed 12/18/15): A 2-D finite element transient model of the PCM/Evaporator written in COMSOL has been integrated with a Dymola model of the rest of the vapor compression system. MatLab is used to call the two sub-models and manage their interface conditions and system refrigerant charge balance. **M1.4 Specifications of µX-1 breadboard proof-of-concept (POC) developed –** *Specifications of the optimal design parameters of a µX-1 breadboard based on specified available commercial, off-the-shelf (COTS) components and trade-off studies.* Actual performance (completed 9/18/15): Design specifications of the µX-1 POC Breadboard system were developed based on the results of the simulation models. Specifications for all key breadboard components were delivered to team member Air Innovations, which is responsible for designing, fabricating, and testing the Breadboard system.
Task 2. µX Breadboard Development & Evaluation 2.1 Develop µX-1 breadboard component specifications 2.2 Design µX-1 breadboard µVCS & PCM module 2.3 Procure/manufacture/ assemble µX-1 breadboard components 2.4 Test µX-1 system and evaluate risks 2.5 Analyze results and refine T1.0 models	**M2.1 Breadboard µVCS performance verified –** *A breadboard µVCS designed to deliver ≥60 W of cooling & a COP ≥ 4.5 at a 65F±1°F PCM freezing temperature and a 79°F ambient sink temperature.* Actual performance (completed 4/29/16): All M2.1 performance metrics were met or exceeded except the COP which fell short by less than 10% (4.2 instead of 4.5). This is to be expected because, with R123zd(E), the COTS Aspen compressor, which is designed to operate with the much denser R134a, was operated at only 1/8th of its rated power and because of pressure drop and heat gain in the breadboard lines and fittings that are not part of µX proper. When adjustments are made to account for these factors, we are confident that the 4.5 COP target will be exceeded. **M2.2 µX-1 POC breadboard performance verified –***A µX-1 breadboard designed to remove ≥50 W of heat from 20 cfm±10% of air to cool it from 79°F to 71F±1°F over >8h period.* Actual performance (completed 4/29/16): The performance metrics in this milestone were met or exceeded. In fact, these

	metrics were met even after >9h of melting. The results also highlighted the importance of freezing the PCM at or below 16°C. **M2.3 µX model recalibrated –** *A re-calibrated µX physics-based model that predicts capacity, COP and PCM freezing & melting time within ±5%.* Actual performance (completed 4/29/16): The freezing model results compared favorably with the experimental results obtained during Breadboard (BB) testing. Important results from the transient freezing model are predictions of: a) the refrigerant quality out of the evaporator as a function of time, b) instantaneous capacity, c) PCM frozen profiles as a function of time and location, and d) migration of refrigerant charge from the receiver to the evaporator and accumulator. The melting model predicted the melting rate accurately over a span of 8+ hours once the frozen PCM temperature and latent heat capacity were adjusted to match the experimental conditions and the detailed PCM manufacturer's data.
Task 3. µX-2 Demonstration Prototype Development/Design 3.1 Use T1.0 model to size & define µX-2 components 3.2 Design micro-compressor 3.3 Design PCM module with embedded evaporator 3.4 Design prototype µVCS 3.5 Produce specs & drawings of µX-2 components 3.6 Design desk-mounted air terminal device (ATD) 3.7 Develop/specify instrumentation & control package	**M3.1 Micro compressor design completed –** *A micro scroll compressor designed to deliver ≥60W of cooling with a COP of ≥5.7 at 61.7F SET (4F SH) & 100F SCT (10F SC), at a combined drive-motor-pump efficiency ≥45%.* Actual performance (completed 5/31/16): Compressor design was completed. A machine shop with the requisite precision machining and metrology capabilities was competitively selected for fabrication of the precision-machined components. Finished scroll parts were measured using a high-precision coordinate measuring machine (CMM) and uncoated parts were delivered for initial inspection and assembly. Three different configurations of electric motors were procured and assembly of the first complete micro scroll compressor was started. **M3.2 µX-2 design completed -** *Cooling Mode: A µX-2 prototype µVCS designed to deliver ≥60W of cooling to freeze PCM at ≤65F in <9h with a µVCS COP ≥5.4, while rejecting heat to a room at 79F; PCM module designed to remove ≥50W of heat from 20cfm±10% of room air to cool it from 79F to 71F±1F over >9h. Heating Mode: A µX-2 prototype heat delivery device (HDD) designed to deliver ≥60W of heating to a room at 66F.* Actual performance (completed 7/31/16): Design of µX-2A was completed employing previously developed and validated design tools, and the same PCM/Evaporator and condenser designs used in the Breadboard to ensure that the milestone performance metrics will be met. **M3.3 Drawings & specs of components completed -** *A set of drawings and specifications of all the major µX-2/µVCS prototype system components or parts thereof, including dimensions, tolerances, materials, sizes and minimum performance criteria*

	such as output, efficiency, etc, as well as overall system volume and weight (target <1ft^3 and <35lb). Actual performance (completed 7/31/16): Detailed drawings of sheet metal were released for procurement, and all components were specified and identified. Prototype A will be bigger and heavier than the target because of its fabrication method. Production intent design will be smaller and lighter.
Task 4. µX-2 Components Procurement/Manufacture 4.1 Develop BOM for prototype compressor & system 4.2 Select component vendors & parts manufacturers 4.3 Procure µX-2 components 4.4 Inspect and assemble components into systems	**M4.1 BOM and specs of components completed -** *A BOM plus supporting CAD drawings and specifications of all system components in sufficient detail for procurement and/or fabrication.* Actual performance (completed 7/31/16): All parts drawings for sheet metal were created, and all other µX-2 components were specified and were being procured. **M4.2 µX-2 components & subassemblies accepted -** *µX-2 parts, components & subassemblies that meet design specifications within allowable tolerances.* Actual performance (completed 10/31/16): Two µX-2A prototype units were assembled and delivered. These units include the “alpha” micro-scroll compressor, which was successfully tested and found to exceed performance targets (Milestone M5.1). One unit was delivered to team member UTRC and the other to SU’s Center of Excellence in Environmental and Energy Systems (SyracuseCoE).
Task 5. µX-2 Components & System Evaluation 5.1 Test & verify performance of µX-2 compressor 5.2 Test & verify performance of µX-2 PCM module 5.3 Test & verify performance of µX-2 prototype 5.4 Modify components and retest, if necessary 5.5 Validate T1.0 models and refine accordingly	**M5.1 Micro scroll compressor “alpha” performance verified -** *A micro scroll compressor “alpha” that delivers ≥60 W of cooling with a COP of ≥5.0 at 62.5F SET (2F SH) & 100F SCT (10F SC).* Actual performance (completed 7/31/16): Micro scroll compressor alpha was tested under steady state conditions at 3000 rpm speed and near the reference pressure ratio. Results were adjusted slightly to match the milestone reference conditions of 62.5°F SET/2°F SH and 100.0°F SCT/10°F SC. A capacity of 63-67W was confirmed at a COP of 5.3-5.6. **M5.2 Micro scroll compressor “beta” performance verified** – *A micro scroll compressor “beta” that delivers ≥60W of cooling with a COP ≥5.7 at 62.5F SET (2F SH) & 100F SCT (10F SC) in 3 test samples.* Actual performance (completed 7/31/17): Five (5) beta micro scroll compressors were tested on the calorimeter. All exceeded the target cooling capacity and COP. **M5.3 µX-2A prototype performance demonstrated -** *A µX-2A prototype µVCS that delivers ≥60W of cooling to freeze PCM at ≤65F in <9h with a µVCS COP ≥5.0, while rejecting heat to a room at 79F; PCM module designed to remove ≥50W of heat from 20cfm±10% of room air to cool it from 79F to 71F±1F over >8h. Heating Mode: A µX-2A prototype heat delivery device (HDD) designed to deliver ≥60W of heating to a room at 66F.*

	Actual performance (completed 3/15/17): Capacity during freezing exceeded the 60W target and a COP between 4.9 and 5.0 was achieved for 8 hours. The COP dropped to about 4.7 at 9 hours as a result of a gradual decrease in the evaporator pressure. This is slightly less than the 5.0 target. The COP shortfall is attributed to possible leakage of air into the refrigerant and oil-hold-up in the capillaries. The ≥50W air cooling capacity target was achieved during 8 hours of PCM melting by ramping the airflow from 16 to 24cfm. A 60-W heating mat was included in the µX-2A prototype. **M5.4 Analyze results and redesign components** – *Analyze the results of M5.3 and, if necessary, redesign and re-optimize the system components to improve performance to µX-2B levels.* Actual performance (completed 4/30/17): Results of micro scroll compressor "α" testing and µX-2A prototype testing were extensively analyzed and compared with analytical model predictions. Lessons learned from these tests were utilized to refine analytical simulation tools and to improve the design of both micro scroll compressor "β" and µX-2B prototype. The µX-2B prototype was designed based on the lessons learned and the improved simulation tools. The µX-2B prototype design is shorter and is expected to achieve higher performance than the µX-2A prototype. **M5.5 µX-2B prototype performance verified –** *Cooling Mode: A µX-2B prototype µVCS designed to deliver ≥60W of cooling to freeze PCM at ≤65F in <9h with a µVCS COP ≥5.4, while rejecting heat to a room at 79F; PCM module designed to remove ≥50W of heat from 20cfm±10% of room air to cool it from 79F to 71F±1F over >9h. Heating Mode: A µX-2B prototype heat delivery device (HDD) designed to deliver ≥60W of heating to a room at 66F.* Actual performance (completed 12/15/17): In cooling mode, the µX-2B prototype meets or exceeds targets for freezing and removed ≥50W of heat from 20cfm±20% of room air to cool it from 79F over >9h. **M5.6 Six µX-2B units assembled and packaged –** *Six fully assembled and packaged µX-2B demonstration prototype units that meet T3.0 design specifications.* Actual performance (completed 10/31/17): The project team assembled and packaged six units. One unit was used at UTRC for testing. Four units were used at Cornell for human subject testing.
Task 6. µX-2 Testing in Simulated Office Environment 6.1 Design experiment and install instrumentation/ DAQ 6.2 Install and evaluate selected ATDs and HDDs in BEESL	**M6.1 Specifications of µX/ATD/HDD completed –** *Specifications (configurations, dimensions, and mounting locations) of a µX-2B-compatible ATD/HDD capable of increasing manikin's heat loss by ≥23W in a 79F room and decreasing it by ≥18W in a 66F room.* Actual performance (completed 7/31/17): Tests were completed with the thermal manikin to compare the performance of the 3 ATD diffusers and the 2 HDDs. Results show that all diffuser

6.3 Test integrated µX/ATD/HDD and analyze results	configurations are capable of achieving or exceeding the target 23W of extra heat removal from the thermal manikin within the specified range of movement (0.61m). The essential parts of the HDD are a foot heating mat with an infrared (IR) reflective box. An additional infrared bulb was tested. The results show that the combination of using the heating mat with the reflective box can reduce manikin heat loss by ≥18W (actual amount was 19.4W with the 60W heat mat and reflective box). **M6.2 µX/ATD/HDD performance verified with manikin –** *A µX-2B/ATD/HDD demonstration prototype that increases manikin's heat loss by ≥23W in a 79F room or decreases it by ≥18W in a 66F room.* Actual performance (completed 1/31/18): Manikin testing was performed with air flows, temperature corresponding to the measured minimum cooling output (50W) of µX-2B. Tests were performed at both 79°F and 83°F room temperatures and verified the ability of µX to remove an extra ≥23W from the manikin at both room temperatures.
Task 7. Investigation of µX Environmental Ergonomics 7.1 Prepare laboratory testing environment 7.2 Carry out human-subject experiments 7.3 Perform statistical analysis to assess thermal comfort	**M7.1 Human subject test (HST) plan** – *Prior to initiation of any Human Subject Research, defined in Attachment 1 to this Award, the team must provide the ARPA-E Contracting Officer with the required Federal Wide Assurance and Institutional Review Board (IRB) certification indicating that the intended HST has been reviewed and approved by the appropriate IRB.* Actual performance (completed 4/20/17): HST test plan was approved by Cornell University's IRB. Cornell's IRB approval was submitted to ARPA-E. **M7.2 Beneficial effect of µX on thermal comfort verified –** *Statistical analysis of the human-subject testing of 32 males & 32 females, including comparative results of thermal sensation & thermal comfort vote and the statistical significance of the results with & without the µX.* Actual performance (completed 6/30/18): Human subject testing was completed with a final count of 43 test subjects for the cooling tests and 31 test subjects for the heating tests. HST in the heating mode in a 66°F room indicated that the µX foot warmer shifts thermal sensation from cool to slightly cool, i.e., an improvement in thermal comfort. Results of cooling HST at Cornell were inconclusive owing to the fact that the mean vote in a 79°F room without µX was "Neutral" on the ASHRAE thermal sensation scale; as expected, use of µX shifted vote to "Slightly Cool". Additional human subject testing was completed at Syracuse University with 32 test subjects in two scenarios. Sixteen subjects were asked to perform "step-walking" in a room at 79°F to elevate the metabolic rate to a level that is more typical of an office worker with mild physical activity (e.g., writing, typing), rather

	than just sitting and reading. Subjects reported to be "Slightly Warm" on the ASHRAE thermal sensation scale without the use of µX. Use of µX shifted the vote to "Slightly Cool." Sixteen additional subjects were subjected to a room at 83°F without step walking. Subjects reported to be "Slightly Warm" on the ASHRAE thermal sensation scale without the use of µX; use of µX shifted the vote to "Neutral."
Task 8. T2M and Techno-Economic Assessment (TEA) 8.1 Refine T2M Plan 8.2 Identify potential markets, sales channels and associated barriers to µX entry 8.3 Compute energy cost savings in 7 US cites & estimate allowable µX cost 8.4 Develop µX cost models for low & high volume 8.5 Rank opportunities and focus T2M initiatives 8.6 Technology development engagements 8.7 Estimate PBP, NPV & IRR for low and high volume	**M8.1 Commitments to T2M milestones secured –** *Specific partner obligations defined and T2M milestones accepted by partners.* Actual performance (completed 6/15/15): Team members participating in the T2M milestones reviewed the T2M milestones and indicated their commitments to completion of the T2M milestones by virtue of signing the contract documents and intellectual property management plan (IPMP). **M8.2 IP management plan developed & signed by all partners –** *Team partners agree to, and sign on the IP Plan.* Actual performance (completed 6/15/15): All parties engaged in the project signed the IPMP as well as a Master Intellectual Property Agreement (MIPA). As part of the IPMP, UTRC and Air Innovations agreed on terms defining rights of first refusal to exclusive IP licenses in the field of use during the project period and for a limited period after the project completion to pooled IP for the purposes of commercialization of the technology. **M8.3 TEA framework developed –** *A framework for TEA developed and accepted by ARPA-E.* Actual performance (completed 8/30/15): The T2M plan was reviewed with the full team and ARPA-E management with positive feedback on the plan from management. **M8.4 Factors affecting market entry identified –** *Economic factors including cost of energy, incentives, competing incentives, and policy factors that could affect µX deployment identified and catalogued in 7 representative cities and/or regions. Competing technologies/products for local thermal environmental control and/or peak electric load shedding/demand shifting identified.* Actual performance (completed 10/31/15): The cost of energy compilation was completed for the seven target cities defined in Task 8, plus two additional target cities. In addition, the cost of electricity was cataloged for 100+ cities. Research on technical, product, and policy factors that may affect market entry was completed with a review of HVAC & building system incentives, voluntary load reduction programs, and custom incentive plans, products in the market, and energy trends. **M8.5 Commercialization partners identified –** *Survey and assessment of potential licensees capable of commercializing the technology at low-and high-volume, including manufacturers and distribution channels completed.*

	Actual performance (completed 1/29/16): Project partners Air Innovations and UTRC agreed to terms defining threshold for exclusive licenses to Project IP for low-volume and high-volume manufacturing. Both companies bring multiple distribution channels, extensive experience, and strong relationships with suppliers and subcontractors necessary for both low- and high-volume commercialization. Project partners will investigate alternate compressors for low-volume commercialization and strategies for fabricating the PCM/Evaporator heat exchanger at low volumes. **M8.6 Model-based cost savings and allowable cost estimated –** *Energy savings based on T1.0 performance model estimated. Allowable product costs based on the energy cost savings, demand charges, time of day billing, incentive data, expected lifetimes and assumed rates of return calculated.* Actual performance (completed 1/29/16): The whole-building performance simulation model, EnergyPlus (E+), was applied to estimate the potential energy savings and cost reduction due to the use of the µX in office buildings. The analysis was conducted for the E+ reference medium-sized office building. Initial estimates were calculated for 7 cities representing different climate zones in U.S.: Miami (1A), Houston (2A), Phoenix (2B), San Francisco (3C), Washington D.C./Baltimore (4A), New York City (5A), and Denver (5B). Allowable installed costs were calculated for each target city. **M8.7 Revised energy cost savings and allowable cost estimated –** *Energy savings based on T1.0 performance model estimated. Allowable installed cost per unit based on the energy cost savings, demand charges, time of day billing, incentive data, expected lifetimes and assumed rates of return calculated.* Actual performance (completed 4/29/16): Refined whole-building energy performance simulations were completed for 7 cities representing different climate zones in U.S.: Miami (1A), Houston (2A), Phoenix (2B), San Francisco (3C), Washington D.C./Baltimore (4A), New York City (5A), and Denver (5B). The refinements include the use of gas reheat instead of electric reheat and using a more realistic operational schedule for summer and winter. Allowable installed costs were calculated for each target city based on the refined energy performance simulation results. **M8.8 Initial low-volume unit cost model developed –** *Preliminary unit cost for low volume offering based on µX-1 breadboard design estimated.* Actual performance (completed 4/29/16): A fabrication cost model was developed based on experience with similar low-volume products made by Air Innovations, vendor quotes, and other engineering estimates. The total fabrication costs for low volume

	(a few thousand units per year) are $500-650, but this estimate will be refined further after completion of the µX-2A design. **M8.9 Initial high-volume unit cost model developed -** *µX BOM & cost model completed based on T4.2, including cost uncertainty estimates.* Actual performance (completed 10/31/16): The low-volume (<5000/year) cost model was developed based on the BoM. The high-volume unit cost model was developed starting with a similar product (small vapor-compression refrigerator) as a benchmark. µX high-volume (5,000,000/year) costs were estimated based on differential costs of subcomponents added or deleted from the benchmark. The phase change material (PCM) represents the largest added cost compared to the benchmark. Typical mark-up multipliers were added to the manufacturing costs to arrive at consumer cost. A learning curve extending from low to high cumulative volume was developed and used to estimate costs at intermediate volumes (50,000 and 500,000 units/year). **M8.10 Refined µX cost models for low & high volume –** *Costing methodology and projected µX unit cost at annual volumes of 5,000, 50,000, 500,000 and 5,000,000 completed.* Actual performance (completed 10/31/17): We anticipate no change in the high-volume unit cost. Low-volume cost has been estimated based on a bill of material generated for an early introduction design by Air Innovations. The estimated low volume manufacturing cost for a volume of 5,000 units/year is $1,584 compared with $520 in our previous estimate. The increase is driven by the higher cost of components procured in small quantities from US vendors, and the more sophisticated control module required for the targeted early adopter market. Costs at intermediate volumes are estimated from extending a learning curve between the low and high-volume estimates as was completed for M8.9. **M8.11 Partners & applications refined and prioritized -** *Priority commercialization candidate companies and applications selected to focus market interview efforts.* Actual performance (completed 10/31/16): Project partner Air Innovations (AI) is pursuing additional desk manufacturers to expand their desk-mounted personal cooling and heating product sales. AI currently sells desktop ventilation and heating systems to mission-critical command-center customers and is investigating opportunities to expand their sales with the µX technology. Electric demand savings and comfort optimization applications have been researched for potential first-market sales. We are currently working with NYSERDA on extending the applications of µX to demand reduction in New York City (NYC), and we are developing a derivative of µX (µX-DR) with a separate award from

	NYSERDA that is dedicated for that purpose. HVAC system prevalence data has been researched to assess the benefits to specific segments within the NYC market. **M8.12 Entry market interviews completed** - *Market hypotheses will be tested on a cluster of our partners, partner networks, and ARPA-E connections to test assumptions regarding entry markets. One or more business canvas models defined to support licensing strategies.* Actual performance (completed 1/31/17): Air Innovations has conducted interviews with partners, including a technical desk manufacturer, a standard desk manufacturer, and a large design/architecture firm. All interviews were positive and fruitful. The technical desk market is a target for entry market. The interviews confirmed this assumption. Interviews are continuing to build on information gathered. Marketing documents were developed to support outreach to entry markets. Preliminary marketing documents were developed to support outreach to entry markets. **M8.13 Licensing proposal & pitch slide deck developed and presented to commercialization candidates** – *A licensing proposal, along with a pitch slide deck developed and presented to potential high-priority commercialization companies presented in workshops and special visits.* Actual performance (completed 4/30/17): In our IP management plan (IPMP), AI and UTRC/UTC agreed to terms defining production thresholds for exclusive licenses to Project IP for low-volume and high-volume manufacturing. Because of the provisions of the IPMP, which gives AI and UTRC/UTC the right of first refusal, we will not pursue other licensing options or develop a pitch-deck to market µX beyond AI's current marketing efforts. **M8.14 Refined energy cost savings in 7 cities estimated –** *Annual energy cost savings estimates for selected 7 cities (including demand shaving incentives, if any) refined based on results of T5.0 testing.* Actual performance (completed 7/31/17): Energy cost savings were calculated for the DOE reference medium-sized office building (post-1980 construction) for the same 7 cities previously analyzed with DOE reference medium-sized office buildings of new construction complying with ASHRAE Standard 90.1-2004. These results were coupled with our previously reported estimate of the unit installed cost at high-volume production ($165/unit at millions of units/year) to compute the internal rate or return (IRR) for various µX service lives. For a 15-year service life, the IRR ranged from a low of 10.6% in Houston to a high of 24.8% in Phoenix.

	M8.15 Economic benefits of µX in 7 cities estimated – *Results from assessment of energy savings & economic benefits (Payback, IRR, NPV) in 7 cities, and sensitivity to initial & operating cost uncertainty assessed, and results submitted to ARPA-E for approval.* Actual performance (completed 1/31/18): Monte Carlo simulations were completed to estimate the sensitivity of the economic assessment results to uncertainties in energy cost escalation rates (-0.2% to +0.6% uncertainty for electricity; +0.8% to +1.8% for gas relative to basic city-specific escalation rate), µX life expectancy (10-15 years) and high-volume unit cost (-15% to +20%). Results were submitted to, and approved by, ARPA-E.
Task 9. Project management and reporting 9.1 Execute mgmt. plan & track progress/milestones 9.2 Coordinate stage-gate process 9.3 Prepare and submit reports 9.4 Organize project reviews	**M9.1 Report of human subject testing expected results –** *Submit to ARPA-E for approval a report describing the expected results of the human subject testing to be performed in Task 7, and the impact of these expected results on future technical efforts.* Actual performance (completed 9/15/15): A report was submitted to ARPA-E outlining the expected results of human subject testing to be performed in Task 7. We anticipate that the use of µX will significantly improve occupant thermal sensation and comfort in the simulated office environment that, in order to save energy, has been made somewhat uncomfortable by widening thermostat set-point range by 4±°F. **M9.2 Technical and financial reports submitted –** *Quarterly technical performance and financial reports submitted on time.* Actual performance (completed 4/30/18): All required technical and financial reports were submitted. **M9.3 Annual intellectual property report and changes to IP –** *Annual intellectual property report and changes to IP management plan.* Actual performance (completed 4/30/18): All annual reports were submitted. **M9.4 Final technical report submitted –** *Draft final technical report documenting project findings, and invention/patent report submitted for approval by ARPA-E Program Director.* Actual performance (completed 4/15/22): This report and a companion report on inventions and patents fulfill the requirements for this milestone.
Task 10. µX Field Study 10.1 Recruit building owners for field study 10.2 Manufacture µX-C units for field study 10.3 Install, monitor, and validate µX-C units and buildings used in field study	**M10.1 Secure supplemental funding** – *Secure at least $250,000 in additional funding from NYSERDA and project partners, sufficient for conducting a technology demonstration at a minimum of two sites with a total of at least 50 µX units*. Actual performance (completed 12/31/19): This milestone was achieved when the New York State Energy Research and Development Authority (NYSERDA) committed to provide

	$300,000 through its "Advanced Clean Energy (ACE) Exploratory Research" program. **M10.2 Secure commitments from building owners/occupants –** *Secure commitments from at least two building owner/occupants that agree to host a total of at least 50 µX units and participate in study protocol for a duration of at least four months*. Actual performance (not completed): During FY21 Q1 and Q2, team members recruited eight potential field trial sites. Preliminary evaluations with each site were conducted by phone. Follow-up site visits were made to evaluate four sites, three of which were found to be viable candidates. The process to make final selections was "paused" in mid-March 2020 when New York State restricted workers in "non-essential" businesses from working in their workplaces due to the COVID-19 pandemic. Continuing impacts of the COVID-19 pandemic prevented completion of this milestone during the original performance period. Team members are continuing to pursue conducting a field trial post award. **M10.3 Manufacture at least 50 µX-C units –** *Manufacture at least 50 units and deploy the units at least two field test sites that have committed to participate in the study protocol for at least four months*. Actual performance (partially completed 10/31/21): Project partner Air Innovations manufactured 50 units. Deployment at field test sites is pending completion of milestone M10.2 that will be conducted post award due to delays caused by the COVID-19 pandemic. **M10.4 Produce report evaluating performance of µX units –** *Produce report evaluating performance of µX units for energy savings and demand reduction, feedback received from participants, and value proposition for future commercialization*. Actual performance (not completed): Team members will complete this milestone following a field trial that is conducted post award.

Project Activities

This project successfully developed a Micro-Environmental Control System (µX) that was conceived to meet requirements of the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) DELTA program, which envisioned saving 1.8 QBtu in primary energy use nationally by "Delivering Efficient Local Thermal Amenities" to maintain occupant comfort when thermostat set-points are changed by 4°F (increased from 75°F to 79°F for cooling and decreased from 70°F to 66°F for heating). The µX unit that is designed to maintain thermal comfort of office workers throughout a nine-hour workday. The unit is a compact, quiet, and ergonomic device that is designed to be located under an office workstation, as shown in Figure 1.


Figure 1. Micro-Environmental Control System (µX)

When room air temperatures are outside the comfort range, the µX operates to create a personalized thermal microenvironment at each occupied workstation. In heating mode, the µX maintains occupant comfort using a foot heating mat with an infrared reflective box. In cooling mode, µX-DR units use a low-power variable-speed fan to circulate ~20-40 cfm (~34-68 m^3/h) of warm room air through an innovative energy storage heat exchanger that contains ~22lb (~10kg) of a frozen phase-change material (PCM) at ~60-65°F (~16-18C). In the evening, a highly efficient (COP>5.0) micro vapor compression system within each µX unit operates to re-freeze the PCM, storing ~2000 BTU (~600 W-h) of cooling capacity for use during the next day. The main components of the µX micro vapor compression system are shown in Figure 2. The micro vapor compression system includes a new high-performance micro-scroll compressor that was developed specifically for this application and is smaller than any of its type, minimizing the amount of power needed.

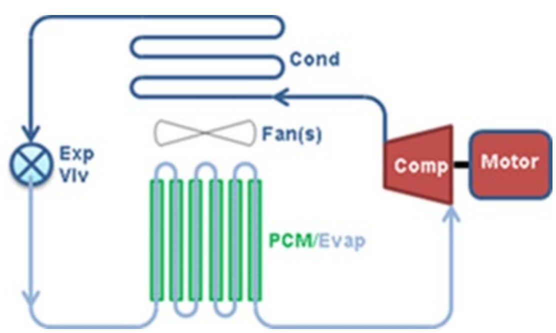

Figure 2. µX Micro Vapor Compression System,
including phase-change material (PCM) in innovative energy storage heat exchanger.

The cooling capacity of each µX unit is sized to meet the DELTA program goal of maintaining occupant comfort throughout an entire nine-hour workday when thermostats have been raised from 75°F to 79°F.

In a companion project funded by the New York State Energy Research and Development Authority (NYSERDA), the team developed µX-DR, a derivative version optimized to maintain occupant comfort during four hours of HVAC curtailment for summer demand reduction. The µX-DR uses the same micro vapor compression system as the µX but its PCM heat exchanger has a different geometry and it uses a different airflow schedule to deliver increased cooling during the DR period, when room air temperatures are raised to as high as 83°F.

Over the course of the three-year ARPA-E DELTA project and the companion NYSERDA project, the µX team developed and evaluated four versions of the unit, advancing the concept to Technology Readiness Level 6. To date, the capabilities of individual proof-of-concept prototypes of the µX and µX-DR units were verified in tests that were conducted with: 1) units in psychrometric chambers, 2) an instrumented manikin in a laboratory, and 3) human subjects in laboratories that simulate office environments. Tests have verified that the µX prototypes meet or exceed all of the performance targets of the ARPA-E DELTA program. Key capabilities of prototypes developed for the ARPA-E and NYSERDA programs include:

- Ability to remove more than 23W (78 Btu/h) from the occupant throughout an entire 9-hour workday, which is sufficient to maintain comfort of office workers when thermostats have been raised from 75°F to 79°F to save energy for air conditioning;
- Use of thermal storage to shift operation of the vapor compression system from day to night, achieving gains in the energy efficiency of the overall system and reducing daytime acoustic impacts to the sound of a fan; and
- Ability to deliver more than 60W of heating to the personal microenvironment, which is sufficient to maintain worker comfort when thermostats have been lower from 70°F to 66°F to save energy for heating.

Tests with human subjects performed by the µX development team in laboratories that simulate office environments verified the capabilities listed above.

At the successful conclusion of all milestones in the original nine Tasks, ARPA-E authorized a tenth Task contingent on securing commitments of matching funding from NYSERDA and project partners. The tenth Task added four milestones associated with conducting a field trial of at least 50 µX units deployed in two buildings for at least four months. The COVID-19 global pandemic prevented the team from completing the field trial during the original performance period, and this testing will now be conducted post award.

Project Outputs

A. Journal Articles

Kong M., Dang T.Q., Zhang J., Khalifa H.E. (2017) "Micro-environmental control for efficient local cooling," *Building and Environment*, doi: 10.1016/j.buildenv.2017.03.040.

Khalifa, H.E., and Koz, M. (2018) "Phase change material freezing in an energy storage module for a micro environmental control system," *J. Thermal Science and Engineering Applications*, Vol. 10, Dec. 2018.

M. Koz, and H.E. Khalifa (2018) "Phase change material melting in an energy storage module for a micro environmental control system," J. *Thermal Science and Engineering Applications*, Vol. 10, Dec. 2018.

Kong, M., Dang, T.Q., Zhang, J., and Khalifa, H.E. (2019) "Micro-environmental control for efficient local heating: CFD and manikin test verification," *Building and Environment*, Vol. 147, pp. 382-396.

B. Papers

Khalifa, H.E., and Koz, M. (2016) "Numerical investigation of the freezing of a phase change material in a thermal storage device with an embedded evaporator," paper HT2016-7409 presented at ASME 2016 Summer Heat Transfer Conference (HT2016), July 10-14, 2016, Washington, DC.

Koz, M., and Khalifa, H.E. (2016) "Numerical investigation of the melting of a phase change material in a thermal storage device with embedded air flow channels," paper HT2016-7412 presented at ASME 2016 Summer Heat Transfer Conference (HT2016), July 10-14, 2016, Washington, DC.

Kong, M., Zhang, J., Dang, T., and Khalifa, H.E. (2017) "Delivering efficient local cooling/heating using a micro-environmental control system (µX), presentation at 2017 ASHRAE Winter Conference, January 28-February 1, 2017, Las Vegas, NV.

Kong, M., Zhang, J., Dang, T., and Khalifa, H.E. (2018) "Experimental evaluation of the micro-environmental control system in maintaining thermal comfort," paper presented at Indoor Air 2018, July 22-27, 2018, Philadelphia, PA.

C. Status Reports

None.

D. Media Reports

Bogucz, E. (2015) "Fit for a Princess: Next-Generation Personal Controls Deliver Whole-Building Energy Savings and 'Precision IEQ'," Green Building Information Gateway, posted March 9, 2015, http://insight.gbig.org/fit-for-a-princess-next-generation-personal-controls-deliver-whole-building-energy-savings-and-precision-ieq/

E. Invention Disclosures

Micro Environmental Control System, H. Ezzat Khalifa, Disclosure Date: 8/26/2014 (DOE S-143023)

Scroll-Type Machine, James William Bush, Disclosure Date: 1/1/2017 (DOE S-143062)

Method for Estimating the State of Charge in a Latest Heat Thermal Storage Device, H. Ezzat Khalifa, Disclosure Date 6/6/2018 (DOE S-143442)

F. Patent Applications/Issued Patents

US 10,774,833, EP 3568571: Scroll-Type Machine

US 10,782,052, CA 2,962,291: Micro Environmental Control System

US 10,955,151: Cooling Charge Determination for a Local Thermal Management System

G. Licensed Technologies

None to date

H. Networks/Collaborations Fostered

The projects fostered collaborations among academic and industry partners of the Syracuse Center of Excellence in Environmental and Energy Systems (SyracuseCoE).

I. Websites Featuring Project Work Results

https://syracusecoe.syr.edu/arpa-e-awards-3-2-to-syracuse-university-syracusecoe-researchers-for-personal-air-conditioning/

https://news.syr.edu/blog/2018/03/12/su-research-team-selected-to-present-energy-saving-research-at-arpa-e-energy-innovation-summit/

http://www3.dailyorange.com/2018/03/syracuse-university-team-presents-energy-saving-micro-air-conditioner/

https://www.youtube.com/watch?v=XkT03J0xADw

J. Other Products

None to date.

K. Awards, Prizes, and Recognition

None to date.

Follow-on Funding

Additional funding committed or received from other sources (e.g. private investors, government agencies, nonprofits) after effective date of ARPA-E Award.

TABLE 2. FOLLOW-ON FUNDING RECEIVED.

Source	Amount
New York State Energy Research and Development Authority (NYSERDA)	$400,000
NYSERDA	$300,000