DELTA Program Overview

B. PROGRAM OVERVIEW

1. SUMMARY

Building heating, ventilation, and air conditioning (HVAC) account for 13% of energy consumption in the United States.[1] The DELTA program seeks to enable saving 2% of domestic energy use by funding the development of Localized Thermal Management Systems (LTMS). LTMS modify the local thermal envelope around the human body rather than the building. When implemented in a built environment, LTMS are expected to enable an expansion of the temperature setpoints in buildings. ARPA-E analyses demonstrate that a potential energy savings for building heating and cooling >15% is available when compared to traditional HVAC setpoints.

ARPA-E envisions DELTA supporting a broad range of LTMS that would enable the energy savings and emissions reduction objectives described in this FOA. Such technologies may range from on-body wearable devices to off-body installed systems. Installed systems could provide near range (< 1 m) and long range (>1 m) energy transfer to the human body without substantially heating or cooling the surrounding air. ARPA-E expects adoption of LTMS for both the commercial and residential sectors. Due to the lower cost and ease of implementation, it is expected that wearable technologies are more likely to make early penetration into the residential sector. ARPA-E recognizes the tremendous opportunities for energy savings offered by LTMS due to their inherent high energy efficiency, low capital installation cost, ease of upgrading and ability to offer personalized thermal environmental control. This FOA presents a radical shift of thermal comfort management away from centralized building systems to distributed, local solutions. This approach will leverage recent and future advancements in distributed sensing, communications, control, innovative materials and wearable technologies for the development of quickly deployable devices to significantly improve building HVAC efficiencies. While the scope of this program focuses on LTMS for quick adoption in existing buildings, our long term vision is that LTMS solutions may eventually reduce our reliance on tightly controlled building environments, thus enabling radical new sustainable architecture in next generation energy-efficient building designs.

2. MOTIVATION

The Need to Reduce Building HVAC Energy Consumption

Heating and cooling of buildings represents more than 13% of all energy used domestically[2], about 12 Qbtu of energy annually (primary) and accounts about 13% of the domestic greenhouse gas emissions. Approximately 4 Qbtu of electricity is used for cooling. The US consumes about 8 Qbtu per year on space heating, with ~2 Qbtu from electricity, and the rest is mostly from fossil fuels (natural gas and heating oil). Consequently, reducing the energy consumption for heating and cooling by 15% can have a transformative impact on the nation's electricity usage, consumption of fuels, and greenhouse gas emissions.

3. CURRENT APPROACHES

Building HVAC Improvements and the Retrofit Challenge

Due to the potential for significant energy savings, there are many ongoing efforts to achieve improved building heating and cooling efficiency. Current approaches can generally be categorized as either improved efficiency of HVAC components and systems or improved control of HVAC systems. Energy efficient technologies under current development

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[1] Estimation base on Energy Information Administration's (EIA) Annual Energy Overview 2014 Early Release Overview, http://www.eia.gov/forecasts/aeo/er/tables_ref.cfm, retrieved March 2014.

[2] Buildings Technologies Program, Energy Efficiency and Renewable Energy, U.S. Department of Energy: 2011 Buildings Energy Data Book, March 2012.

include, but are not limited to, geothermal heat pumps, heat exchangers, new working fluids, more efficient fans and compressors, magnetic cooling, and absorption cooling. Advanced solutions, such as walls with variable insulation that modulate the thermal flow in and out of building structures are also being pursued.[3] Improved temporal control is provided by digital thermostats. However, improved spatial control requires a reconfiguration of the building interior or complete replacement of the building HVAC units. It is highly unlikely that spatial control with current building HVAC technologies will reach the resolution of the individual occupant.

Furthermore, a fundamental disadvantage preventing adoption of HVAC improvements are high costs. Retrofitting existing buildings with new technologies is not cost effective because of the extremely long service life of many building components (e.g, residential HVAC systems are designed for 10 to 25 years). Moreover, the building envelope is designed to last between 20 to 50 years, with the whole building lasting from 40 to 120 years. Building retrofit often has a payback period of longer than 5 years, which is too long to be of interest to the building owners as opposed to maintaining the status quo with inefficiently operating systems. It is thus essential to develop technologies that can be cost effectively implemented into existing buildings.

4. CHALLENGE AND OPPORTUNITY

Human Comfort Perception and Challenges with Setpoint Efficiency

The primary function of building heating and cooling is to maintain occupant comfort. Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55).[4] P.O. Fanger's work [5] represents the foundation for the standards used both by the International Organization for Standardization (ISO 7730 2005) and the American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE 55 2010). Fanger's climate chamber experiments yielded the Predicted Mean Vote (PMV) formulation that has been widely adopted as the standard for thermal comfort for conditioned environments.

Based on the PMV model, the ANSI/ASHRAE Standard 55 provides recommendations for operational parameters for buildings, which includes a goal of ensuring at least 80% satisfaction rate among building occupants. As expected, human thermal comfort is strongly influenced by personal physiology. Consequently, it is not possible to achieve a 100% satisfaction rate for a given set of environmental conditions. The PPD (Predicted Percentage Dissatisfied)-PMV correlation (Figure 2) illustrates this distribution as recommended by the ISO 7730 standard.

[3] F. Kuznik et al., Renewable and Sustainable Energy Reviews, 15(1) (2011) 379-391; *See also* Department of Energy, Energy Efficiency Renewable Energy, Building Technology Office, https://www1.eere.energy.gov/buildings/technologies/building_envelope_research.html, accessed 5/30/2013..
[4] ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy.
[5] Fanger, P. O. 1972. Thermal Comfort. New York:McGraw-Hill.

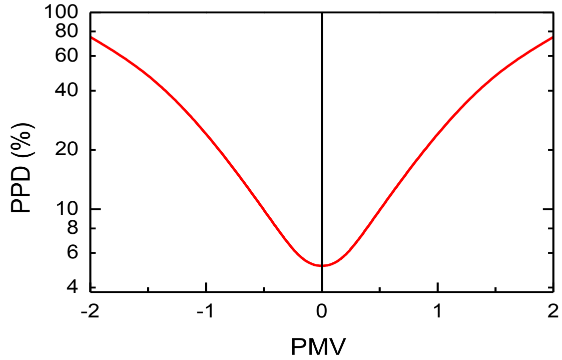

Figure 2. The PPD-PMV relationship based on Fanger's model[6]. Note: even at PMV of 0 which defines thermal neutral, the PPD value does not go to 0, reflecting the complexities of thermal comfort.

The operating temperature range or the neutral-band, the temperature range between setpoints where no action is taken by a building HVAC system, is usually between 70 and 75°F. This practice is tighter than the ANSI/ASHRAE standards with acceptable target temperatures of 68°F during the heating season and 76°F during the cooling season, with appropriate humidity levels. The reasons for the narrowing of neutral bands are many and complex. One of the primary reasons is poor building control and lack of zone resolution. The PMV model assumes a uniform building thermal environment, while in reality wide temperature gradients exist within the building. In addition, complaints by building occupants tend to drive the building managers to tighten the neutral band further, resulting in even higher energy consumptions and inefficiencies.[7]

Setpoint Expansion as an Energy Saving Mechanism

Since the goal of an HVAC system is to maintain the building interior at temperatures that are different from the outside, the actual setpoint has a large influence on the energy required to operate the system. According to Fourier's law, heat flow through the building envelope is proportional to the temperature gradient across it. Thus, the thermal exchange rate across the building envelope is driven by the temperature difference between inner and outer surface temperatures of the building. When the interior temperature is closer to the exterior temperature, thermal exchange will be smaller, which in turn, reduces the energy consumption of the HVAC to maintain a steady interior temperature.

A number of published findings have quantified the effect of the setpoint on HVAC energy consumption and the potential for LTMS to enable energy savings via a setpoint change. For example, Hoyt et al. calculated the percent annual energy savings for four different cities when the setpoint is expanded from a baseline of 70.5-75°F (Figure 3).[8] For the city of Phoenix, lowering the setpoint in the winter months to 66°F results in an annual savings of ~14% while raising the setpoint in summer months to 79°F results in an annual savings of ~20%. Consequently, a setpoint of 66-79°F would save a total of ~34% annually versus the comparative baseline building. The potential savings may vary based on location and climate, but is estimated at over 20%. Note that the estimation did not consider downsizing the HVAC unit, only changing the cycling time of an existing unit. Additional energy savings could be realized through reduction of the HVAC unit size enabled by a wider setpoint range. Based on this study, ARPA-E has determined a very conservative estimate of 15% savings for an expansion of setpoints by 4°F in each direction.

[6] ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy.

[7] Federspiel, C. C., 2000, "Predicting the Cost and Frequency of Hot and Cold Complaints in Buildings," International Journal of HVAC&R Research, 6(4), 217-234.

[8] Hoyt, T., H.L. Kwang, H. Zhang, E. Arens, T. "Energy savings from extended air temperature setpoints and reductions in room air mixing." International Conference on Environmental Ergonomics August 2-7, 2009.

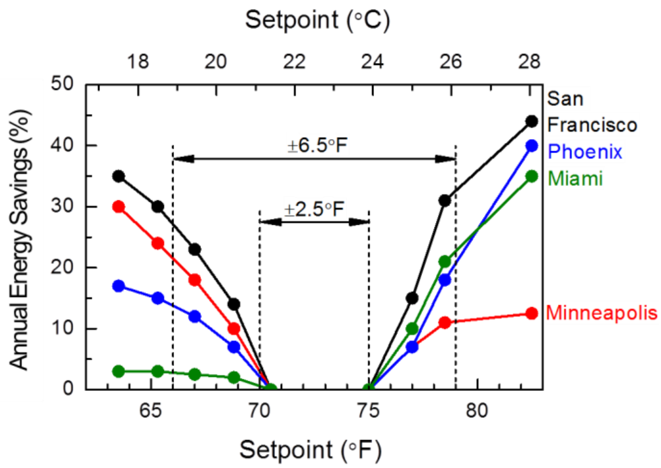

Figure 3. Percent energy savings for widened air temperature setpoints relative to conventional setpoint range in San Francisco, Miami, Phoenix, and Minneapolis. The percentage savings for lowering the setpoints in the winter are calculated by assuming no change in the summer setpoints (75°F). Similar calculations are performed for increasing the setpoints in the summer. Consequently, the percentage savings from the summer and the winter are approximately (and conservatively) the summation of the percent savings.

5. PROGRAM APPROACH

The Inherent Energy Efficiency Advantages of LTMS

To enable expansion of the building setpoints, it is necessary to provide supplemental thermal management to the building occupants to maintain thermal comfort. LTMS can fulfill this role and lead to significant overall energy savings because LTMS are inherently more localized in their delivery of thermal energy than building HVAC systems.

The thermal exchange rate for a thermal envelope is proportional to the surface area and inversely proportional to the thermal resistance. For a temperature gradient driven heat flux, the large difference in surface area between a building and a person is the factor that drives the potentially large energy savings with LTMS. The average adult has a surface area of 1.8 m^2.[9] The building surface area per person is dependent on the building type. As an illustrative example, consider a residential home with a floor area of 185.8 m^2 based on a rectangle 15.24 m long by 6.1 m wide. With an envelope height of 6.1 m, this home's thermal envelope surface area is 334.45 m^2. Assuming the house has four residents, the surface area per resident will be 83.6 m^2, which is over 46 times the surface area of a person.

The effect of the large difference in the surface area can be partially offset by the larger thermal resistance associated with building insulation compared with that for clothing worn by building occupants. For example, building walls can have a thermal resistance 10 times that of full business attire clothing. Unfortunately, window glass is a poor insulator, with a thermal resistance on par with clothing.[10] By including windows, which often occupy more than 30% of building exterior, the overall effective thermal resistance, for the home in this example, decreases to 5 times that of a full business suit. Consequently, the thermal resistance is an order of magnitude lower than what is necessary to compensate for the large surface area. In addition, the thermal resistance of a piece of clothing is easily adjustable, while changing the thermal resistance for an existing structure is extremely difficult and expensive.

Other Advantages of LTMS

In addition to tremendous potential for energy savings, LTMS offers other advantages over current building HVAC systems.

[9] ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy.
[10] Cengel, Y. & Ghajar, A. Heat and Mass Transfer: Fundamentals and Applications. McGraw-Hill Higher Education, 2011.

Improvement in thermal comfort for building occupants. As has been shown in Fanger's model, it is not possible to achieve 100% thermal comfort for all building occupants using a single setpoint, no matter the setpoint. In addition, the ASHRAE standards mandate achieving thermal comfort for 80% of the occupants. Field data show that the 80% value is rarely achieved, reflecting the fundamental limitations of today's HVAC systems.[11] These lack the high resolution zone control necessary to cater to individual thermal management needs. In contrast, LTMS can be viewed as the quintessential individualized zone control. In principle, 100% thermal comfort is achievable when personal zone control is implemented. This has been demonstrated in previous field studies.[12]

Energy efficiency improvement beyond buildings. In the case of wearable technologies, the building occupant will continue to have access to the technology after exiting the building. Outside environments can be far more extreme than the indoor environment controlled by an HVAC system within a specified temperature band. However, the basic functionality of wearables with advanced thermal management properties will continue to assist in maintaining personal thermal comfort outside the building. For example, these technologies could buffer the impact of abrupt temperature changes at the exit of the building. In fact, such a benefit can serve as a powerful incentive for early adoption.[13] Moreover, these technologies could reduce the power load needed for air conditioning in automobiles; this could be especially impactful on the driving range of electric vehicles.[14]

Low capital investment with overnight installation in existing buildings. ARPA-E envisions LTMS retrofit solutions as small and easily installed without the need to significantly reconfigure the building interior or alter the building structure itself. In addition, wearable technologies could be rapidly adopted based on the short lifecycle of common apparel.

Challenges Facing Current LTMS Approaches

The potential of LTMS to provide high quality, individualized thermal comfort is well recognized. As a result, numerous commercial products exist.[15] However, cooling is by far more challenging than heating, primarily due to the problem of dealing with rejected heat. For personalized cooling, a desktop cooling unit can blow chilled air towards the occupant. One such device[16] uses a thermoelectric module to deliver cold air; however, with any heat pump device, heat must be rejected from the device and is typically done so at the rear of the unit, which is also very close to the occupant and has a net effect of raising average room temperature. This desktop cooling unit only consumes 60 W but performs poorly (not effective beyond 0.3 m) and is too costly ($140) for widespread adoption. Various evaporative coolers have been developed, but they invariably increase the indoor humidity, and the building HVAC will incur a heavy load to bring down the humidity. For wearable technologies, an air-conditioned jacket was marketed in Japan[16]. It uses a fan that puffs up the jacket to create airflow within, which is then exhausted at the cuffs and collar. It is unsuitable for indoor use in an office environment due to very poor aesthetics that limit adoption. Various cooling vests were also developed that use evaporation of water to remove heat from the wearer. However, they are usually bulky, heavy, and only suitable for occupational uses such as firefighting and factory workers.

For stationary office use, personal environment modules have been developed which primarily consist of air nozzles targeting the upper body and a radiant panel heating the legs.[16] While effective, they require either a pressurized floor plenum or individual ducting to every workstation, both of which are costly to retrofit into existing office settings. In addition, the occupant is required to place feet very close to the heating panel, greatly restricting any movement. More recently, a ductless task air conditioning (DTAC) unit was developed.[16] This unit can provide refrigerated air while storing the exhausted heat in a phase change material, to be discharged when the space is not occupied. Each unit is projected

[11] Goins, J. Moezzi, M. Linking occupant complaints to building performance. Indoor Environmental Quality (IEQ), Center for the Built Environment, Center for Environmental Design Research, UC Berkeley. http://www.tandfonline.com/doi/abs/10.1080/09613218.2013.763714.
[12] T. Law, The future of thermal comfort in an energy-constrained world, Springer, 2013, p. 186
[13] Martin, Claire. *Rolling Up Their Sleeves, as a Team.* The New York Time: New York ed. p. BU5, May 19, 2013.
[14] Rugh, J.P. "Electric Drive Vehicle Climate Control Load Reduction." (2012, May 14). Retrieved from: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/veh_sys_sim/vss090_rugh_2012_p.pdf.
[15] T. Law, The future of thermal comfort in an energy-constrained world, Springer, 2013, p. 204.
[16] E. Aren, Defining and Improving Personal Comfort: in the News and in the Lab. Centerline, winter 2013.

to consume 200 W and costs approximately $300. The potential of the laboratory prototype of reaching market adoption is too early to tell.[17]

Localized heating is much easier to implement and heaters are usually low cost and can be flexible. However, most of the portable heaters on the market consume very large amounts of power (~ 1500 W typical).[18] Radiative heaters, such as infrared heaters, can in principle be of very high efficiency due to lack of transmission loss in air. However, efficiency drops significantly when the heating targets move slightly off the transmission path. In this case, most of the radiation is absorbed by the first object in its path, such as the floor or wall, where it is converted to heat that is subsequently transmitted to the occupants by convection, thus negating the inherent advantage of radiative heating. Furthermore, infrared heaters also have emission spectra that tend to heat exposed skin much more efficiently than clothing. This is due to the strong absorption by water at approximately 3 m and coincides with the emission peak of many infrared sources. As a result, overhead infrared heaters tend to overheat the exposed areas of the human body (face and head) and under-heat the clothed areas (feet and legs), creating discomfort due to the thermal asymmetry. A final challenge with using a high power infrared heater as part of a building infrastructure is its strong visible emission. The visible appearance of the heaters greatly impacts the aesthetics of building interior. As a result, these heaters have only been popular with outdoor or large warehouses where convective heating is impractical.

In summary, despite the potential of great energy savings, existing LTMS have not enjoyed adoption in today's building environment due to one or more of the following reasons: poor thermal performance, low energy efficiency, high cost, poor aesthetics, and location specific sensitivities (e.g., noise, immobility, thermal asymmetry). It is the primary goal of DELTA to support the development of transformational next generation LTMS that can overcome these challenges.

B. PROGRAM OBJECTIVES

1. Achieve Thermal Comfort in an Expanded Ambient Temperature Range of 66 to 79°F

To expand the neutral band for buildings from 70-75°F to at least 66-79°F, or an expansion of 4°F in each direction, a local thermal envelope around individuals is needed to manage the thermal balance so as not to sacrifice thermal comfort. One could employ the PMV model to estimate the thermal compensation required to enable the new setpoints. Analysis shows that a change in thermal exchange rate of 15 W/m^2 is required for a change of 3.6°F.[19] Similarly, if one only tries to change clothing insulation, a change of 20% in thermal resistance is required from a baseline value of 0.279 m^2F/W, or 0.056 m^2F/W. In order to enable some simple scaling, we consider that the steady state heat flux through a planar wall can be expressed as:

$$q'' = (1/R) * (T_o - T_1)$$

where T_1 is the ambient temperature, T_o is the skin temperature, and R is the overall thermal resistance. Assuming that the thermal resistance does not change and T_1 changes to a new temperature, T_2, the change in heat flux is:

$$\Delta q'' = (1/R) * (T_2 - T_1)$$

and the percentage change in heat flux is:

$$\Delta q''/q'' = (T_2 - T_1)/(T_o - T_1)$$

[17] T. Law, The future of thermal comfort in an energy-constrained world, Springer, 2013, p. 206
[18] "Portable Heaters," Retrieved from http://energy.gov/energysaver/articles/portable-heaters, in March 2014.
[19] Fan, J. "Human Physiology & Clothing, Personal Thermal Management Systems to Reduce Building Energy Consumption," November 12 & 13, 2013. Retrieved from: http://www.arpa-e.energy.gov/sites/default/files/documents/files/Personal_Thermal_Workshop_Fan_Presentation.pdf.

Since ambient skin temperature is at a comfortable state around 93°F, when T_1 = 75°F and T_2 = 79°F, Δq"/q" is 22.2%. Similarly, when T_1=70°F and T_2 = 66°F, Δq"/q" is -17.3%. For an adult human in a sedentary state, the base metabolism 58.2 W/m^2 and an average adult has a surface area of 1.8 m^2, resulting in a total metabolism of 105 W[20]. In other words:

- If the ambient temperature is raised from 75 to 79°F, a removal of 23 W, or 22% is needed to maintain the same skin temperature;
- If the ambient temperature is lowered from 70 to 66°F, a supply of 18 W, or 17% is needed to maintain the same skin temperature.

Alternatively, the thermal balance can be achieved by changing the thermal resistance. For a change in ambient temperature from T_1 to T_2, the same heat flux can be maintained by changing the respective thermal resistance from R_1 to R_2, such that:

$$R_2/R_1=(T_o-T_2)/(T_o-T_1)$$

- The percentage change needed in the thermal resistance to maintain the same heat flux is the percentage change in heat removal or supply with same thermal resistance.

2. Other Considerations to Ensure Thermal Comfort

In the ANSI/ASHRAE 55 standard, building HVAC design parameters are chosen to result in a PPD value of < 10%. Further, an additional 10% of occupants are assumed to be dissatisfied due to reasons not accounted for by the PMV model. This allowance reflects the complex nature of thermal comfort. Many factors contribute to a deviation of the PMV model, among which thermal asymmetry is an important consideration.

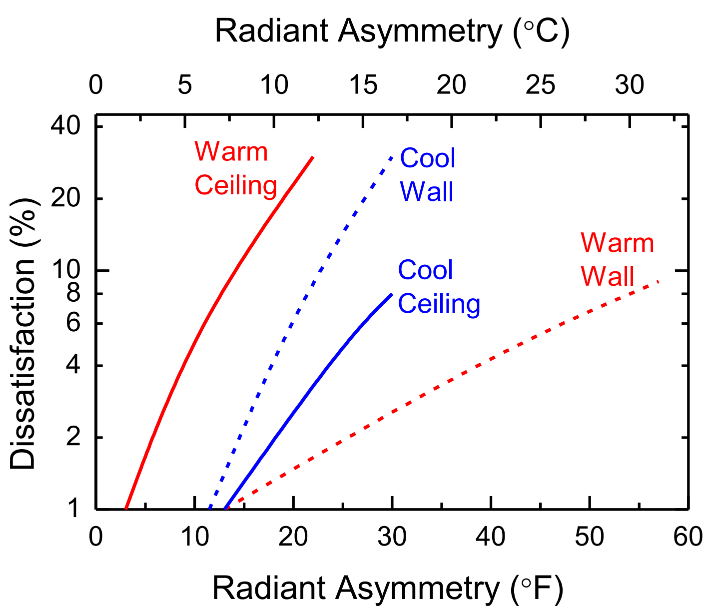

Figure 4. The percentage of occupants dissatisfied as a function of radiant temperature asymmetry. Note that the warm ceiling effect is the most undesirable, reflecting the disadvantage of overheating one's head.

[20] Bradshaw, V. The Building Environment: Active and Passive Control Systems, 3rd Edition, Wiley Publishing, May 2006.

Figure 4 shows the percentage dissatisfied occupants as a function of radiant temperature asymmetry. In particular, a ceiling with a temperature higher than other faces of a room has the most significant impact. A difference of 12°F will result in 10% dissatisfaction. This is due to the fact that humans generally prefer cooler heads and warm feet rather than the other way around. It is thus important that:

- Any local thermal envelope solution shall not aggravate undesirable thermal asymmetry, most commonly overheating the head.

3. Energy Efficiency of Building Local Thermal Envelope

Since the goal of the program is to use a local thermal envelope to reduce the reliance on a tightly controlled building envelope, the energy required to run the LTMS has to be substantially smaller than the energy saved by the building HVAC when the setpoint is widened. The average HVAC energy use per person in commercial buildings in the United States is approximately 2.4 MWh/year.[21] Assuming HVAC is operational on 261 days and for 10 hours per day, the power consumption would be 937 W on average with symmetrical heating and cooling seasons. By selecting a 4°F setpoint offset the expected savings will total about 22% or ~206 W at the system level. With a target savings of 15%, 65 W of power can be allocated to operate the LTMS. This value is much higher than the 23 W required to compensate for the temperature difference, allowing the use of technologies operating with a Coefficient of Performance (COP) of 0.35 or higher.[22] However, it is worth noting that many of the technologies, such as those modulating thermal loss rates from the human body, can have a COP much greater than 1. Such technologies will be preferred since they offer much greater energy savings and expect shorter payback periods. Therefore, DELTA will support:

- Technology concepts that can be developed into a LTMS with a minimum sustained COP of 0.35.

4. Economics

As far as cost targets for the LTMS, DELTA has a goal of a 3-year payback period, including both capital and operational costs. The 141 W/person saving equals to ~20$/year assuming an energy price of 5.4 cents/kWh.[23] Therefore,

- Technologies should cost less than 60 $/person for a 4°F change in setpoints in each direction

For certain wearable technologies, such as apparel and shoes, ARPA-E estimates the cost requirements as the following based on residential applications. In 2011, the per capita HVAC energy expense at home was ~$352 while the per capita clothing and shoe expense was $682.[24] For a 15% savings in energy expenses, the allowable increase in clothing and shoe expenses is ~ 8%. Therefore,

- Wearable technologies, such as apparel and shoes, should not have an increase in cost of >10% for a 15% energy savings.

[21] Estimation based on Energy Information Administration's (EIA) 2003 Commercial Buildings Energy Consumption Survey (CBECS) Database located at http://buildingsdatabook.eren.doe.gov/CBECS.aspx. Selected commercial office building sampling approximately consumed 12.2 kWh/sqft for heating and cooling the sampled offices. The expected average occupancy for this building sampling was ~200 sqft per occupant as indicated in NREL/TP-5500-46861, February 2011, "U.S. Department of Energy Commercial Reference Building Models of the National Building Stock".

[22] COP is energy delivered to the occupant divided by the wall plug energy consumption by the LTMS.

[23] Estimation based on EIA's Annual Energy Overview 2014 Early Release Overview. Price average considers the relative contribution from electricity, natural gas, and heating oil and their respective prices.

[24] Estimation based on EIA's Annual Energy Overview 2014 Early Release Overview. Apparel purchase estimations are based on U.S. Bureau of Labor Statistics March 2014 Report 1046. Consumer apparel expenditures in 2011 were $1740 per household with a household occupancy factor of ~2.55 individuals per home resulting in a per capita annual expenditure of $680.

5. Other Attributes of LTMS that Impact Technology Adoption

In order for any LTMS solutions to make an impact in building energy savings, they not only need to provide the thermal performance and cost but also need to meet or exceed the quality of experience offered by current HVAC systems. Such quality, due to the close proximity and direct interaction with the human body, can be quite subjective. However, in order to facilitate wide spread adoption by the consumer, it is important for any LTMS technology to pay close attention to the issue of quality of experience. In this section, we briefly discuss the various aspects of experience quality that can be important to consider.

<u>Automated control.</u> Current HVAC systems usually do not require frequent user intervention to achieve comfort for the majority of the occupants. Despite the potential benefits of providing individual users with personalized control as discussed above, LTMS solutions should not require user intervention to achieve comfort, although providing the option of user intervention is considered highly beneficial.

<u>Range of motion.</u> One basic feature of the current HVAC system is that it covers the entire building space regardless of location. Consequently, any LTMS solution needs to offer a similar range of motion. An exception is made for technologies targeted at sedentary office workers. In that case, however, a limited range to enable freedom of motion is desirable (see next section).

<u>Aesthetics of non-wearable systems.</u> Current HVAC systems are only visible to the occupants as vents on ceilings, walls, and edge of flooring. Any installed systems as a retrofit to the existing building should aspire to match the architectural designs of the building so that the added LTMS does not present a major disruption in both space utilization and aesthetics. For office furniture-related solutions, they should not occupy significant space, so as to avoid interference with other office functions.

<u>Discrete wearable systems.</u> The aesthetics of wearable items is the most subjective among all the potential LTMS solutions, although they potentially offer the greatest benefit in energy savings and the largest market. However, fashion is a highly personal choice that makes it difficult to define. Nevertheless, wearable LTMS, such as clothing and devices, should aspire to enhance rather than limit fashion choices. Some general guidelines are possible:

- LTMS should not add significant weight;
- LTMS should not impose strict restrictions in type of fabric, color, texture;
- LTMS may be separable from garments so that consumers have the choice of freely using clothing without advanced thermal management properties.

C. TECHNICAL CATEGORIES OF INTEREST

DELTA aims to support the development of transformational technologies that establish a local thermal envelope around the human body. These technologies are expected to enable a widening of the temperature setpoints in buildings to lower than 66°F in winter months and higher than 79°F in summer months, while maintaining the thermal comfort of building occupants above ANSI/ASHRAE standards. ARPA-E envisions supporting a broad range of technologies that can achieve these objectives.

Such technologies can range from on-body wearable technologies, to near range (<1 m) energy transfer, to direct energy transfer to the human body from a distance (>1 m) without substantially heating or cooling the surrounding air. Figure 5 illustrates the three approaches as well as a system level approach that employs any combinations of the three primary approaches.

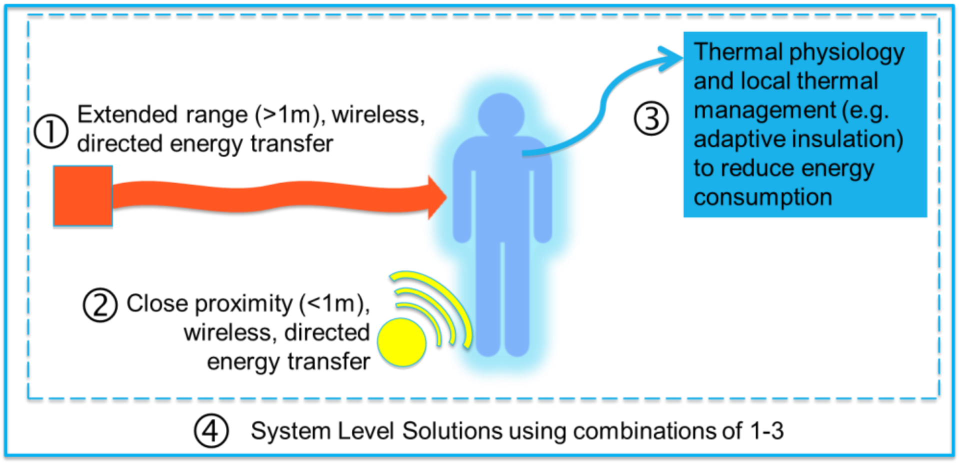

Figure 5. Energy transfer approaches to build a thermal envelope around the human body.

ARPA-E emphasizes that while the three approaches are categorized based on their proximity to the human body, proposed concepts need not be confined by a separated approach. In fact, these approaches can be utilized synergistically to achieve the programmatic goals.

ARPA-E strongly encourages submissions that address both localized heating and cooling. However, submissions that address only heating or cooling are permissible, but must meet the program metrics. Given the historical technical challenges in creating localized cooling systems, submissions in this topic area are especially encouraged.

Appropriate team expertise for this FOA is a good understanding of basic human thermal physiology, thermal management, materials science, building heating and cooling systems, device fabrication, testing, and modeling. For wearable technologies, it is appropriate to have participation from designers and experts in consumer product adoption.

Below are the technical categories of interest, along with some representative example technologies of interest. However, approaches that are beyond these examples that meet the program metrics are equally encouraged.

Category 1: Extended range (> 1 m) wireless energy transfer

This category seeks technologies that can uniformly heat or cool occupants remotely. The deliverable is a technology demonstration in a two-room, 6.1 m x 7.62 m floor area or equivalent building interior. This definition is intended to simulate both residential and small business office settings.

Examples of technologies of interest:

- Technologies that uniformly heat or cool the human body without substantially heating or cooling ambient air away from it and creating greater thermal asymmetry, including but not limited to directional energy transfer coupled with low cost tracking technologies;
- Technologies that can sense the human body temperature distribution and adjust the generation and transmission of energy to achieve optimum uniformity and comfort.

Category 2: Near range (< 1 m) wireless energy transfer

This category seeks technologies that are deployed to provide thermal comfort to building occupants who largely remain stationary, such as within an office environment. The deliverable is a technology demonstration, including both hardware and software, in a typical office setting composed of a desk and a chair.

Examples of technologies include:

- Cooling solutions for workstations without generating hot exhaust in occupied spaces;
- Low cost cooling solutions coupled with efficient heat storage;
- Physiological modeling coupled with experimental implementation of solutions that aid in minimizing cooling and/or heating requirements; and
- Office or home furnishings including chairs, desktop items, floor mats, bedding, and other items.

Category 3: Wearable technologies

This category seeks technologies that are wearable by building occupants to maintain thermal comfort within wider temperature setpoints of 66-79^{o}F. The deliverable is a device or completed wearable garment, shoes, and/or accessory.

Examples of potential technologies include:

- Wearable devices, shoes, apparels and accessories;
- Items that do not significantly impact aesthetics, such as shoe insoles, under garments, other wearable devices such as badges or small portable electronics devices such as mobile phones;
- Clothing with tunable insulation materials that control microstructure including porosity and thickness;
- Clothing with tunable emissivity and/or conductivity;
- Wearable items that create skin surface convection to promote cooling; and
- Wearable items that promote active cooling.

Category 4: Combination of Categories 1 to 3

This category supports technologies that seek to synergistically utilize combinations of categories 1 through 3. Specifically, the category encourages submissions in:

- Combined technologies that achieve the desired thermal effect with increased effectiveness compared with individual technologies;
- Combined technologies that offer reduced cost and ease of installation in existing buildings.

D. TECHNICAL PERFORMANCE TARGETS

Definition of Thermal Envelope and Reference Building Environment

For the purpose of defining program metrics, ARPA-E defines a thermal envelope around the human body as a 1.83 m tall, 0.91 m diameter cylinder when the occupant is standing and a 1.22 m tall, 1.22 m diameter cylinder when the occupant is seated. While these representations of the human body are gross simplifications, they do enable the definition of the thermal transport problem. We also define the target building interior floor area to be a 6.1 m x 15.24 m made of two rooms of equal size, 6.1 m x 7.62 m.

In addition, regarding the thermal and cost targets: while DELTA has a *minimum* goal of achieving 4°F expansion of the building setpoint in each direction. Applicants are strongly encouraged to propose technologies that far exceed this goal. Consequently, the thermal and cost targets are set for a per degree expansion and a minimum expansion of 4°F.

Metrics for Categories of Interest

ARPA-E is interested in receiving proposals that address the below metrics in the following categories. A single technology that can address multiple categories is encouraged. However, if so proposed, the technology must address the metrics from all categories.

Applications are required to meet all of the Primary Metrics and a majority of the Secondary Metrics. Applications should provide the necessary analysis, modeling, and/or experimental results to justify how each of the metrics is addressed. In particular, applicants are strongly encouraged to provide the following information:

- Describe the thermal performance metrics using the definitions provided in the FOA, e.g., COP as defined in Footnote 23;
- Define the full specs of the deliverables including weight, volume, thermal performance, and where applicable, power consumption, response time to moving speed, among others;
- Provide modeling and calculations to quantitatively substantiate any claims of thermal performance; clearly define the targeted ambient temperature; illustrate the thermal flux in the system including all interfaces; describe the size and boundary of the local thermal envelope, and detail how the performance will be measured.

The summary table below (Table 1) contains key data specifications for DELTA that Applicants may find useful in preparing their applications.

Table 1. Selected data specifications for FOA calculations

Description	Specification
Baseline (Current) thermal neutral band	70°F-75°F
Expanded thermal neutral band	66°F-79°F
Optimal building relative humidity range	30-60 %
Human skin temperature	93°F
Average human heat generation	58.2 W/m^2
Average human surface area	1.8 m^2
Approximate human body occupancy volume as a cylinder – standing	H= 1.83 m, Dia.= 0.91 m
Approximate human body occupancy volume as a cylinder – seated	H= 1.22 m, Dia.= 1.22 m
Cooling needed to expand to 79°F	23 W/person
Heating needed to expand to 66°F	18 W/person
Average commercial office occupancy	18.6 m^2
Average residential occupancy	56.2 m^2
Average commercial office HVAC use	0.937 kW/person
Average residential HVAC use	2.44 kW/person
Demonstration building floor area	6.1 m x 15.24 m
Demonstration room floor area	6.1 m × 7.6 m
Household occupancy factor	2.55 people/home
Residential per capita annual heating and cooling expenditure	$352

Household annual apparel expenditure	$1740

Category 1: Extended Range (> 1 m) Wireless Energy transfer

Primary Metrics

ID	Property	Metric
1.1	Thermal Performance	Adaptively provide or remove > 6 W/°F [25] and > 23 W total from the defined thermal envelope without increasing undesirable thermal asymmetry on the occupant[26]
1.2	Minimum COP	0.35
1.3	Range of Motion	Entire building interior with tracking capable of following an occupant moving at 1 m/s
1.4	Cost	0.0375$/ft^2/°F and 0.15$/ft^2 if only heating or cooling is addressed (30$ per occupant with occupancy of 200 ft^2/person and a 4°F offset in a single direction; 60$ per occupant for 4^{o}F offset in both directions).

Secondary Metrics

ID	Property	Metric
1.5	Operability	Automated control by building with the option to be overridden by the occupant
1.6	Safety	Meet OSHA standards
1.7	Appearance	< 5% increase in visible light on occupant; <5% increase in noise

Category 2: Near range (< 1 m) wireless energy transfer

Primary Metrics

2.1	Thermal Performance	Adaptively provide or remove > 6 W/°F and > 23 W total from the defined thermal envelope without increasing undesirable thermal asymmetry on the occupant; for cooling solutions, air temperature in the thermal envelope has to be lower than ambient
2.2	Minimum COP	0.35
2.3	Range of Motion	A semicircle with a 0.61 m radius from the source of the energy supply[27]

[25] °F refers to per degree of setpoint expansion
[26] Undesirable asymmetry refers to an increased asymmetry vs a baseline
[27] This requirement is waived for concepts where end-users are intended to remain stationary while using the device , e.g, such as chairs or bedding

2.4	Cost	60$/occupant annually for a 4°F offset in both directions, or 7.5$/°F of change.

Secondary Metrics

ID	Property	Metric
2.5	Operability	Automated control by building with the option to be overridden by the occupant
2.6	Safety	Meet OSHA standards
2.7	Appearance	Compatible with common office environment

Category 3: Wearable technologies

Primary Metrics

ID	Property	Metric
3.1	Thermal Performance	Adaptively provide or remove > 6 W/°F and > 23 W from the defined thermal envelope per occupant
3.2	Minimum COP	0.35
3.3	Range of Motion	Entire building interior
3.4	Cost	< 20$/person/year or < 10% of selling price increase over baseline apparel technology assuming a 4°F setpoint expansion in both directions. < 10$/person/year or < 10% of selling price increase over baseline is required assuming a 4^{o}F setpoint expansion for technologies that only heat or cool.

Secondary Metrics

ID	Property	Metric
3.5	Operability	Fully autonomous but with optional capability to be overridden by the occupant and to communicate with the building
3.6	Safety	Meet OSHA standards
3.7	Durability	Meet ASTM standards of 50 washing and drying cycles
3.8	Appearance	Preferred to be detachable from current apparel Preferred to exhibit no visible surface change Preferred to exhibit no interference with consumer color or texture choices Preferred to require negligible power

3.9	Weight	< 10% increase over baseline apparel
3.10	Interaction with building	Preferred to provide temperature and humidity information to the building

Category 4: Combination of Categories 1 to 3

Technologies proposed that use a combination of Category 1 to 3 technologies should meet the thermal and cost metrics as defined in the combined categories cumulatively. For example, if a variable insulation wearable technology can sustain a heat dissipation of 10 W, then a wireless energy transfer technology could provide the remaining 13 W needed to achieve the 23 W thermal power goal. In addition, technologies should meet the secondary metrics as defined in the categories appropriate for the combination.

E. APPLICATIONS SPECIFICALLY NOT OF INTEREST

- Installed systems that promote air movement with regular patterns without lowering air temperature, e.g, high efficiency fans.
- Technologies that increase the absolute indoor humidity.
- Technologies that require major change in common business and casual dress practices (for example, wearing hats indoors).
- Technologies that focus on zone control improvement by using better insulation between different zones (e.g, individual control for each room).
- Technologies that improve building thermal envelope and HVAC appliances that do not aim at creating a local thermal envelope around human body.
- Technologies that rely on human psychological effects (e.g., temporal allesthesia).
- Technologies that involve the intake of chemicals by the human body in any manner, including but not limited to: oral, transdermal, inhaling, or injection pathways.

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical parameters specified in Section I.E of the FOA
- Applications that were already submitted to pending ARPA-E FOAs.
- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.
- Applications for basic research aimed at discovery and fundamental knowledge generation.
- Applications for large-scale demonstration projects of existing technologies.

- Applications for proposed technologies that represent incremental improvements to existing technologies.
- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).
- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA and as illustrated in Figure 1 in Section I.A of the FOA.
- Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).
- Applications that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy.